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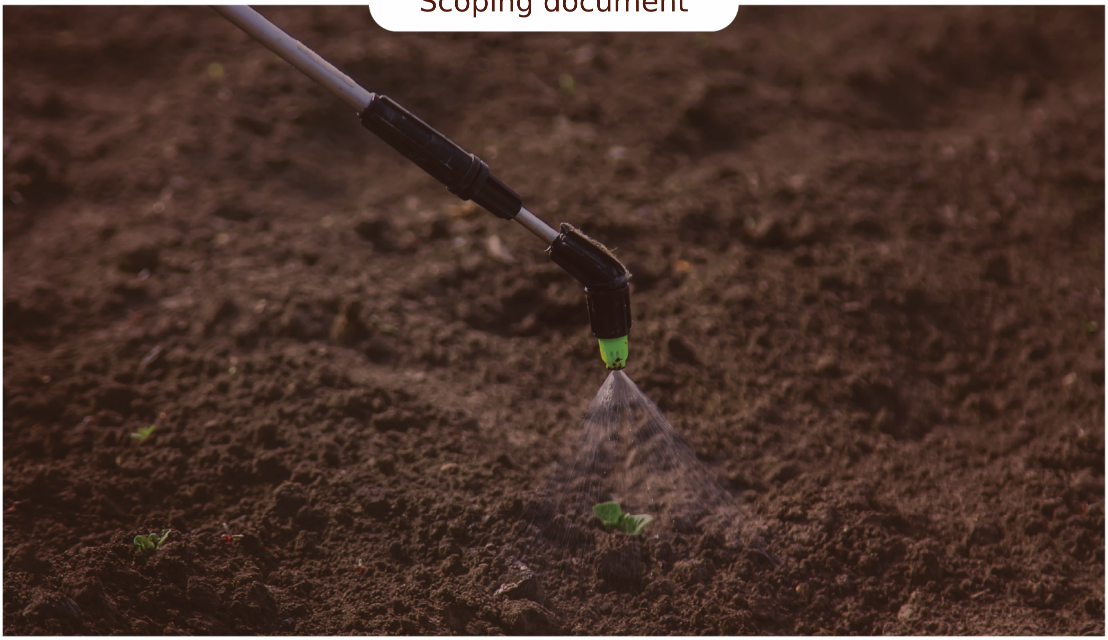
SOLO Pesticide pollution and restoration

Scoping document



Outlook on the knowledge gaps to soil pollution and restoration

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Contributors and Reviewers

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Abreviations

The abbreviations which are used in the text are listed in Table 1.

Table 1.
Abbreviations

AMR	Antimicrobial drug resistence
AMF	Arbuscular mycorrhizal fungi
AOM	Ammonia-oxidizing microorganisms
ARGs	Antibiotic resistance genes
CMEF	Common Monitoring and Evaluation Framework
CUPS	Commonly Used Pesticides
EC	European Commission
EEA	European Environmental Agency
EFSA	European Food and Safety Authority
EU	European Union
FAO	Food and Agriculture Organization of the United Nationas
GA	General Agreement of the SOLO project (official documentum)
GHG	Greenhouse Gas
ICM	Integrated Crop Management
IMPEL	European Union Network for the Implementation and Enforcement of Environmental Law
IPCHEM	Information Platform for Chemical Monitoring
IPM	Integrated Pest Management

JRC	Joint Research Centre
LUCAS	Land Use/Cover Area frame Survey
NGO	Non-Governmental Organizations
NOEC	No-Observed-Effect Concentration
OECD	Organisation for Economic Co-operation and Development
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorniated biphenyls
PFAS	Per- and polyfluoroalkyl substances
POPs	Persistent Organic Pollutants
PRTT	Pollution and Restoration Think Tank
SML	Soil Monitoring Law (officially: Soil Monitoring and Resilience Directive)
SSDs	Species Sensitivity Distributions
SUD	Sustainable Use of Pesticides Directive
SUR	Sustainable Use of Pesticides Regulation
TCA	True Cost Accounting
UNEP	United Nations Environment Programme

1. Introduction

This paper is a summary of the preliminary results of the work of the Soil Pollution and Remediation Think Tank (PRTT) based on the previous scoping documents that underwent various reviews. PRTT was established as one of the 9 Think Tanks (TT) of the SOLO Soils for Europe project. The project’s final aim is to deliver actionable transdisciplinary roadmaps for future soil-related research activities in the European Union (EU), which contribute to achieving the objectives of the Soil Mission. The task of the TTs including the PRTT's is to identify knowledge gaps and novel avenues for European soil research, innovation, and action in the context of the Soil Mission specific and operational objectives. The paper consists of three main sections.

The first section provides an introduction, including an overview of the overall scope of the PRTT and stakeholders’ engagement. The second section introduces the conceptual framework developed for the review of the state of the art, knowledge gaps, actions and bottlenecks, and provides an assessment of the state of the art specific to pollution and remediation within the context of PRTT’s scope. The third section provides the summary of the top 10 knowledge gaps identified during the prioritization process, along with their description, suggested actions and bottlenecks which may hamper needed actions, and need to be overcome.

The preliminary results reflect the intertwined nature of the knowledge gaps. During the further iterative process of the SOLO project, combining stakeholder engagement and literature review, each of the knowledge gaps, their prioritisation, actions and bottlenecks, will be further analysed in detail. The final deliverable will provide a roadmap with a final list of prioritised knowledge gaps, concrete actions for research and innovation, and associated bottlenecks. In the SOLO project context, two types of knowledge gaps are acknowledged: knowledge development gaps and knowledge application gap. By definition, a '*knowledge development gap*' is a knowledge gap that requires generating new information or understanding by research or innovation, inclusive of both natural and social sciences and humanities' contributions. While, a '*knowledge application gap*' is a knowledge gap that requires research or innovation to find and/or test new mechanisms that allow the effective implementation of already existing information or understanding to improve soil health. This knowledge gap hence concentrates on the deficient links between available knowledge and its implementation and application. Regarding actions, by defintion an '*action*' encompasses a spectrum of technical, social and economic strategies, approaches, measures, and/or solutions aimed at addressing identified knowledge gaps. These actions are aligned with the R&I priorities outlined in the Soil Mission framework. They serve as the means to achieve the research and innovation goals set forth by the Commission. In the SOLO roadmaps, each knowledge gap type can be addressed by both research and innovation actions. Finally, bottlenecks are barriers that hinder a successful implementation of suggested actions to solve both types of knowledge gaps. With the described content, the final roadmap shall support reaching the Soil Mission Objectives.

Soils, being largely hidden, have been overlooked, up until recently, by EU and national laws and policies, and given less importance than air, water and marine environments. However, the interconnectedness between air, water and soil, specially in terms of the transport of contaminants and pollution management has been recognised not only in the scientific literature but also in the Zero Pollution Action Plan (European Commission 2021a). Healthy soils can perform several functions and provide a wide variety of ecosystem services (supporting, regulating, provisioning and cultural Millennium Ecosystem Assessment 2005, EEA 2023a). They are essential to human health, to biodiversity, nutrient cycling, sustainable plant production, natural pest control, good water quality, water retention, carbon storage and erosion management (GIZ 2021). Soils are estimated to harbour 59% (Anthony et al. 2023) or up to more than 99.9% (Blakemore 2025) of Earth's species and possibly more. For example, at least 90% of fungi, 85% of plants and 50% of bacteria are living in soils (Anthony et al. 2023), and provide the basis for healthy ecosystems and human health (European Commission et al. 2020). Soil pollution is one of the main factors compromising soil functions (Rodríguez-Eugenio et al. 2018, FAO & ITPS 2015), thus soil health. Soil pollution has an impact on soil biodiversity, soil functions and ecosystem services and on human health and well-being.

Due to their strong linkages to environment, nature, biodiversity, ecosystem functioning, agriculture, human and animal health, and water and climate, soil pollution and restoration are relevant and connected to a wide framework of EU policies and legislations (European Commission 2023a,European Commission: European Environment, Joint Research Center et al. 2024). Specific EU legislation on soils has been lacking for many years. The Soil Strategy reviewed the state of soils back in 2004-2005. Now almost twenty years later, we are still facing similar problems/issues. As part of The European Green Deal and the Biodiversity Strategy for 2030 (Montanarella and Panagos 2021), an EU Soil Strategy for 2030 was published in 2021, setting out a framework and measures for the protection, restoration and sustainable use of EU Soils (European Commission et al. 2020, Panagos et al. 2022a). A linked policy process for the development of a draft of Soil Law was initiated, leading to the publication of the proposal for an 'EU Directive on Soil Monitoring and Resilience' ('Soil Monitoring Law', SML) by the European Commission (EC) on 5th of July 2023. At the time of writing, as a result of the trilogue negotiations (involving representatives of the European Parliament, the Council of the European Union and the EC) a provisional agreement was reached between the Parliament and the Council on April 10, 2025. On June 4, 2025 the EU Parliament's Committee on the Environment, Public Health and Food Safety voted in favour of the agreed text and final voting on it by the Council and the Parliament is expected in early Autumn. Soil protection, regardless of the the lack of a separate EU legislation dedicated to soil prior to the publication of the SML proposal, has been, or is, part of different environmental legislations, and environmental relevant policies such as the Common Agricultural Policy. However, implementation issues relevant to soil pollution have been raised in reports of the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL 2010, IMPEL 2017) and in the reports of the European Court of Auditors (European Court of Auditors 2020a, European Court of Auditors 2020b), as well.

There have been several EU legislations and proposals that are directly related to the soil policy framework and mentioned as relevant in reaching the main goals. One of them was the proposal of the European Commission on a Sustainable Use of Plant Protection Products Regulation (SUR) (European Commission 2022b), which would have replaced the current Directive on Sustainable Use of Pesticides (SUD). The proposal aimed to reduce the use and risk of pesticides by 50% by 2030, (a goal of the Farm to Fork Strategy), and lead to the effective implementation of Integrated Pest Management (IPM). However, the proposal was rejected by the European Parliament in November 2023, and retracted by the European Commission in February 2024. Although IPM has been mandatory since 2014 under SUD, implementation in member states has been lacking, as well as implementation of other obligations of the SUD (European Court of Auditors 2020b, European Parliamentary Research Service 2018, European Commission 2020b). The outcome of the Strategic Dialogue on the Future of EU Agriculture highlights the importance of effective implementation of current evironmental and social legislation, the protection of soil health, and the reduction of inputs such as pesticides and fertilisers; in that framework the Commission is also expected to tackle the lack of implementation of the current SUD, including the lack of implementation of IPM.

The two main guiding documents setting the policy frameworks for soil and directly addressing soil pollution are:

1. the Implementation Plan of the Soil Mission, which is also an important component of the European Green Deal (European Commission 2021b) and:

2. EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' (European Commission 2021a). As part of the EU's zero pollution ambition, the Chemicals Strategy for Sustainability Towards a Toxic Free Environment was also developed (European Commission 2020a).

These policy documents specify the problem areas regarding soil health (polluting economic sectors/activities and polluting agents) and identify targets, based on assessments of the state of the art regarding soil health, identified needs and feasibility of reaching specific goals. One of the outcomes of the implementation of these elements is the SML proposal.

The aim of the SML proposal published is to be a cornerstone in reaching the objectives of the EU Soil Strategy for 2030 and the Soil Mission. The SML proposal is much needed and widely welcomed; however, it was also criticised by scientists, civil society and drinking water companies (Wageningen University 2023a, EEB 2023, EurEau 2023, Umwelt Bundesamt 2023) because it does not address all goals and targets identified in the policy documents. Therefore, improvements in the proposal and/or further legislative proposals are needed in order to reach healthy soils by 2050. The lack of clear rules and objectives, the lack of focus on soil biodiversity and diffuse pollution and the lack of linkages with water pollution and legislation, have been identified as essential shortcomings of the proposal by the scientific community (EEB 2023, EurEau 2023, Wageningen University 2023b, Pieper et al. 2023, Kotschik et al. 2024). Moreover, during the plenary vote in the European Parliament in April 2024, essential provisions of the proposal were drastically watered down, further compromising the potential impact of the proposal (European Environmental Bureau 2024). The revised version of the SML waiting for adoption has incorporated new provisions to ovecome some of the concerns raised and it is an important step further.

The current PRTT used the problem areas described in these documents as a starting point to identify the state of the art and knowledge gaps, and to provide input for roadmap co-development. Roadmap co-development in this case means the involvement of stakeholders from various fields related to soil pollution and restoration to jointly develop a roadmap towards programs which reveal the actions to be taken in prioratised manner. The PRTT will focus on soil pollution, soil restoration and remediation, while also taking into account the impact on and of soil pollution regarding connected systems such as crops and vegetation, water bodies (groundwater, surface water), air, (air or water borne pollution or pollution through leaching and volatilization processes) and overall ecosystem health and ecosystem functioning.

1.1 Scope (specific to PRTT)

The above two strategic documents, namely the Implementation Plan of the Soil Mission, and the EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' set specific targets related to limiting soil pollution.

As a basis, the PRTT aims to provide an analysis of the state of the art and an assessment of knowledge gaps, potential (innovative) solutions and actionable research regarding formulated goal’s objectives, targets and indicators based on the two main policy documents. PRTT will address the complexity of the issues involved in soil pollution and reflect on their intertwined nature by highlighting the need for a holistic approach and integration of soil aspects to all relevant policies (the need for such an approach is well demonstrated by the Impact Assessment Report accompanying the SML (European Commission 2023c). It is important to identify policy areas that are directly linked to soil pollution, because the various policy instruments used in those fields do have intentional or unintentional impacts on pollution that should not be ignored but explored through well-defined research questions.

Table 2. below indicates the concrete Targets, Baseline and Soil health indicators of the Soil Mission to be achieved by 2030 (European Commission 2021b, p. 16) and viewed as capable of contributing to meet the 2050 target: *Air, water and soil pollution is reduced to levels no longer considered harmful to health and natural ecosystems and that respect the boundaries our planet can cope with, thus creating a toxic-free environment* (*European Commission 2021a*, European Commission 2021b). It means, that e.g. based on the targets indicated in the table, the percentage of lands under organic farming has to be increased from 8.5% to 25% by 2030.

Table 2.

Targets and proposed soil health indicators for the mission objective: Reduce pollution and enhance restoration in the Soil Mission Implementation Plan. (Source: Soil Mission Implementation Plan, p 16)

Mission targets in line with EU and global commitment	**Baseline**	**Soil health indicators**
1: reduce the overall use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50% 2 reduce fertilizer use by at least 20% 3: reduce nutrient losses by at least 50% 4: 25% of land under organic farming 5: Reduce microplastics released to soils to meet 30% target of zero pollution action plan 6: Halt and reduce secondary salinization	27% - 31% of land with excess nutrient pollution Soil contamination: 2.5% (non-agricultural), 21% (conventional arable), ca. 40-80% of land from atmospheric deposition depending on the pollutant. Farmland under organic agriculture: 8.5% (2019)	Presence of soil pollutants, excess nutrients and salts

The listed targets and indicators of the Soil Mission do not address all pollution problems identified in the Support Material, nor those in the Zero Pollution Action Plan as it is demonstrated by the background working documents of the SML. While the targets, baselines and indicators are clear reflections of the intention to reduce pollution to a level that is no longer harmful to soil, health and natural ecosystems, there are some aspects that need further clarification to make the targets operational such as baseline year for calculating percentages. In some cases these negotiations have been already taking place outside of the Soil Mission (e.g. the reduction of the use of pesticides) which demonstrates the interlinkages and intertwined nature of the various policies.

1.2 Engagement within the PRTT

The science-policy-practice interface is a hot topic of scientific research (Miles et al. 2017) and especially relevant to environmental issues (Cvitanovic and Hobday 2018) within the context of the circular economy and sustainability (Kujala et al. 2023, Heikkinen et al. 2023). One of the primary benefits of stakeholder engagement (Kovács et al. 2021; Stankovics et al. 2024) is the creation of links between science and society, providing access to additional information or resources, and improving the relevance or utility of the research to users and beneficiaries. Concretely, through engagement, the project's results can be tailored to local contexts, increase the possibility that the outcomes are applied, and therefore, have a positive impact. Stakeholders engagement and the diversity of stakeholders' background and organisational affiliation promotes cross-fertilization of knowledge and innovation. (González-Piñero et al. 2021)

Identification of the stakeholders

Identification of relevant stakeholders has been, and still is, a process partly linked to the conceptual framework (Figure 3.). While the General Agreement of the SOLO project (GA) set the main categories (policymakers, civil society, practitioners, industry agents, scientists) of stakeholders to be approached, the conceptual framework served as an additional aspect of consideration. While using the snowball method (Durham et al. 2014), it was important to find examples for all of the stakeholder categories of the conceptual framework reflecting:

- on how the impact of pollution affects them (negatively or positively) and:
- on what kind of relationship they have with decision making (influencing and making/taking decisions).

Agricultural and non-agricultural human activities, regional representation and decision making levels (EU, regional, national, local) were considered. PRTT's choices of stakeholders promotes the science-policy-practice interface by having stakeholders from science, policy and practice. The stakeholder involvement process resulted in a good representation both regarding geographic origin and professional background. Stakeholders can be grouped to various categories, based on professional and/or scientific background, organisational affiliation, sectors (agriculture, non-agriculture). The numbers of stakeholders change according to the categories applied (e.g. when organisational affiliation is not playing a role, the number of scientists is the highest as it is shown by comparing the data of Figure 1 a), b) and c)). Figure 1. d) on sectors is a good indication of the intertwined nature of sectors.

Most of our stakeholders fit into more than one of the categories. This helps to overcome the issues (e.g. hindrance of trust, causing conflicts) raised in relation to diversity of organisations in innovation projects reported in some studies (González-Piñero et al. 2021). The issues raised there are relevant to stakeholders and stakeholder engagement, as well. Successful collaboration with stakeholders is dependent on trust built between them and the engaging partner, and how conflicting views and interests of stakeholders are handled by the project partners. Miscommunication stemming from the diversity of stakeholders is often the source of misunderstanding and conflicts. Stakeholders fitting under more than one category could be instrumental in overcoming those issues, since they may understand and be familiar with the language and the position of the others.

Fig. 1 is a demonstration of it reflecting the stakeholders (in total 21) at the time of the preparation of the first version of the scoping document.

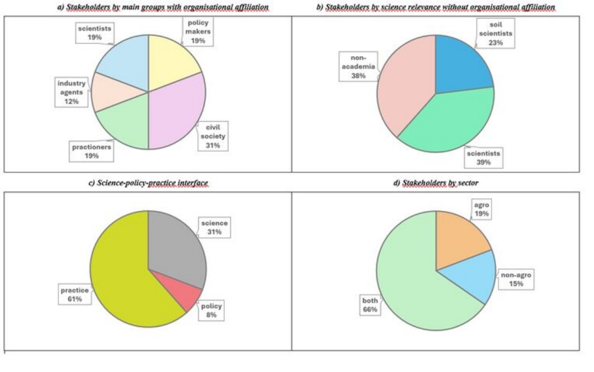

Figure 1. doi

Introduction of stakeholders by different categories (created by the PRTT)

Figure 1. a) reflects on the GA categories and mainly organisational affiliation was applied to distinguish between the stakeholders:

- Policy maker: member of policy making bodies and public institutions with the task of preparing/developing/implementing/reviewing policy
- Civil society: non-governmental organizations (NGOs), giving voice to the citizens
- Practitioners: farmers, advisors without organisational affiliation
- Business: business organisations and business interest groups
- Scientists: Scientists (including PhD students) having affiliation to academic (education and/or research) institutions.

Figure 1. b) makes a distinction between scientists and non-academia stakeholders, breaking down the scientists category into two subcategories for making the number of soil scientists in the scientist group visible.

Figure 1. c) is to show the numbers of stakeholders relevant for the science-policy-practice interface:

- Science: all scientists irrespective of organisational affiliation
- Policy: non-scientists policy makers
- Practice: all non-scientists other than policy makers

Figure 1. d) is a reflection on the conceptual framework's (Figure 3.) categories on human activities (agriculture, non-agriculture). The category 'both' indicates that the stakeholder has interest in both sector relevant categories (e.g. health authorities, environmental NGOs).

Stakeholder engagement process

Stakeholders have been engaged from the very early stage of development of the scoping document. Most of the stakeholders were individually approached and the project explained to them. Their reflections had influenced the first draft of the document, particularly the system-approach of Figure 3. The first draft of the scoping document was sent to all stakeholders, and based on their availability, they reflected on the content during semi-structured interviews, or just shared their opinions in oral or written form. Stakeholders' comments were integrated into the current version. Figure 2. (Fig. 2) depicts this process based on the snowball effect relevant to both stakeholders chosen and literature reviewed.

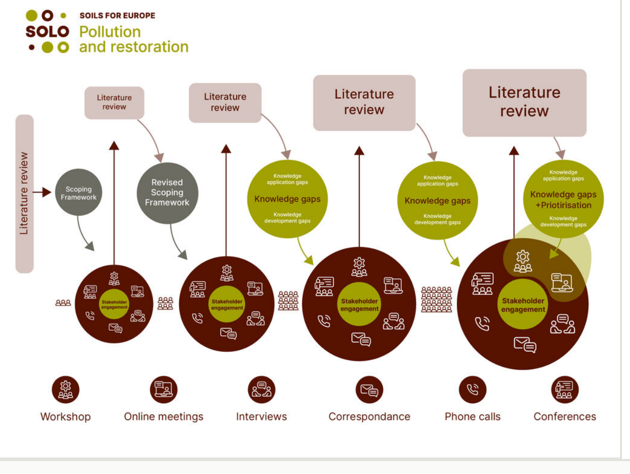

Figure 2. doi

Visualisation of the methodology of developing a priority list of knowledge gaps: Iterative process and snowball effect approach of literature review, engagement with stakeholders (feedback, validation) and prioritisation. (created by the PRTT with PENSOFT)

Stakeholders expressed their views on the presentation of the content and also on the issues addressed in the document as a whole and particularly in the figures, and tables. Stakeholders' opinions were summarised based on the content of their feedback into two main categories: Format (F) (e.g.: transparency of the figures and tables), and Substance (S), the latter category being broken down into three subcategories depending on what action it required: to add (Sa), to complete (Sc), to improve understanding (Siu). The scoping document was modified after assessment and evaluation of the comments. All comments were relevant and useful. The format of the figure has been changed, and some of the suggestions were integrated into the document. However, not all of the comments were directly inserted, in some cases further elaboration of the topic was sufficient. The same approach was followed concerning this Revised document.

Table 3. summarises the comments on the first drafts of the scoping document and their acceptance by the main categories of the stakeholders.

Table 3.

Stakeholder's reflections on the first draft (created by the PRTT).

Stakeholder by categories	**Overall feedback**	**Categories of specific comments**	**Integrated into the document** (*X=yes, 0=no*)
Scientist	positive	Sa, Siu	X
Practice	positive	F, Sc, Siu	X
Civil society	positive	Sa, Sc	X
Policy	positive	Sa, Sc, Siu	X
Business	positive	Sa, Sc,	X
...			

2. State of the Art

The state of the art in the soil pollution and restoration domain will be further reviewed during the next phases of the project. In this section, we lay down the principles and methods to develop a comprehensive overview of the domain, and provide a summary of relevant available knowledge, literature and stakeholders' views and experiences. It should be noted that the literature review was limited to literature available in English. Knowledge and knowledge gaps recognized and published in other languages than English could not be considered. However, taking the importance of site specificity and methodological diversity (relevant to pollution/contamination, pollutants/contaminants) into account it is of the utmost importance to gain insight of research results of the member states' scientific community, and the views of the stakeholders published and expressed in their native language.

Based on scientific evidence, soil-pollution-relevant documents of the EU, the Food and Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP) the Organisation for Economic Co-operation and Development (OECD), have emphasised the significant negative impact of soil pollution and land contamination on nature, its ecosystem services and human life. However, the use and the meaning of the terms 'pollution' and 'contamination' is not systematic in those documents and in the literature. The words 'pollution' and 'contamination' have different meanings but are often used as if they are interchangeable (Rodríguez-Eugenio et al. 2018). EU documents like the Zero Pollution action plan refer to the definition of the Directive 2010/75/EU, Article 3(2) (European Parliament and European Council 2010): ' *Pollution means the direct or indirect introduction, as a result of human activity, of substances, vibrations, heat or noise into air, water or land which may be harmful to human health or the quality of the environment, result in damage to material property, or impair or interfere with amenities and other legitimate uses of the environment*'. While in the FAO document on soil pollution a different term is used: "*soil pollution: refers to the presence of a chemical or substance out of place and/or present at higher than normal concentration that has adverse effects on any non-targeted organism*." (Rodríguez-Eugenio et al. 2018, FAO 2020) The difference between the two terms are important. The EU term is more anthropocentric. Concerning contamination, definitions on contaminant or contamination vary according to the topic or the approach of the document. While in the same EU directive (European Parliament and European Council 2010) the terms 'contamination', or 'contaminant' , are not defined, and contamination is referred to only in the definition of the 'baseline' report, the SML proposal waiting for adoption provides for a broad definition of 'contaminant' by extending the scope of the term to a substance liable to cause contamination of both soil and bedrock or parent material. The FAO document on pollution uses the term 'contamination' with no reference to human activities, while the joint report of the FAO and UN on the world's natural resources defines contaminant by using the ISO definition (Rodríguez-Eugenio et al. 2018). While the differences can be justified, it makes comparative analysis difficult, especially when data mining tools are used.

Similar issues should be solved concerning the terms of ecosystem services due to the differences between the terms of the Millenium Ecosystem Assessment Report (Millennium Ecosystem Assessment 2005), the Intergovernmental Science-Policy Platform's reports (Rounsevell et al. 2018) and the EU's applied Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018).

We identified the diversity of the definitions which makes harmonised review difficult. However, the elaboration of the issues based on the conceptual framework of the PRTT does not require harmonisation at this stage. During the next phase of the project the issues related to definitions will be addressed. For the time being, the terms are used as in the original sources.

2.1 Current state of the knowledge on soil pollution and restoration - System-approach and conceptual framework

A system-approach was developed to comprehensively tackle all aspects of the soil pollution and soil restoration/remediation domain by using the above-mentioned documents as a starting point, the literature review listed under Reference and the feedbacks from our stakeholders. The following studies provided more input for the development of the system-approach framework shown in Figure 3. (Fig. 3). Adhikari and Hartemink (2016), Babí Almenar et al. (2021), Bouma (2014), Greiner et al. (2017), Jónsson and Davíðsdóttir (2016), Lacalle et al. (2020), O'Riordan (2021), Pulleman et al. (2012), Stolte (2016), Vári et al. (2021), Velasquez and Lavelle (2019), Villa et al. (2014), Stavi et al. (2016), Dushkova et al. (2021), Wade (2022), JRC and Maes (2020), Ponge (2015), Wood and Blankinship (2022).

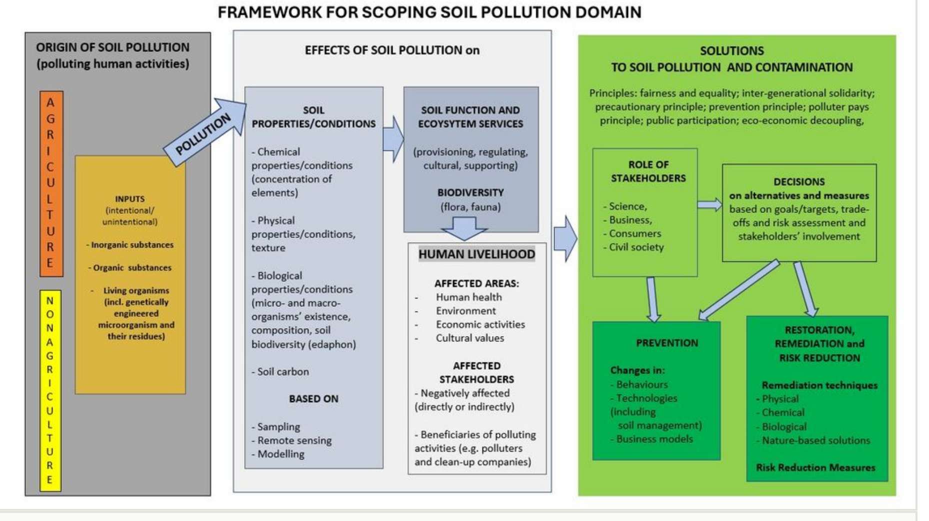

Figure 3. doi

Refined concept overview of System approach to identify interlinkages between domains related to soil pollution/contamination (created by the PRTT).

Putting soil health into the centre of the system-approach allows us to highlight all elements that are relevant for reaching the Soil Mission objectives of 2050, to demonstrate the complexity of pollution issues including the intertwined nature of policies and to provide a framework for assessing the state of the art, the knowledge gaps and to identify key research questions. A schematic overview of this system approach and the components of the system are presented in Figure 3. It is an updated version of the framework presented in the scoping document as a result of the iterative process (shown in Figure 2.) regarding the identification and fine-tuning of the knowledge gaps/actions/ bottlenecks. Three main domains were identified as pollution relevant during the scoping process along with the principles that should be integrated into all domains, since they reflect on pollution relevant social and economic aspects. The development of the framework was driven by the Soil Mission Objectives relevant to PRTT which prioritise pollution from agricultural activities over other sources and sets specific targets for agriculture, compared to the general targets for other sources without making distinction between polluting human activities and/or sectors.

The three domains:

1. **Soil pollution**: identification and assessment of the extent of polluting agricultural and non-agricultural human activities, pollution originating from intentional or unintentional introduction of potential pollutants including (i) inorganic substances, (ii) organic), (iii) living organism (with characteristics of becoming biological pollutant) based on (i) soil descriptors and (ii) criteria reflecting on soil health.
2. **Effects of pollution**: identification and assessment of the extent of the impact of soil pollution on i) soil properties and conditions including linkages with other polluting pathways, ii) ecosystem services, soil functions and biodiversity and iii) human livelihoods reflecting on (a) the negatively affected (directly or indirectly), and (b) the beneficiaries of polluting activities (e.g. producers of polluting substances, polluters and clean-up companies).
3. **Solutions to soil pollution**: Identification of availability of and need for both solutions focused on *(i)* pollution prevention and *(ii)* restoration and remediation, as well as *(iii)* the assessment of the role of different stakeholders influencing decision making (scientists, business, civil socety, consumers) and policy decisions/frameworks in view of (implementation of) solutions, *(iv)* decision makers. Individual stakeholders or groups of stakeholders can belong to one or more of mentioned categories.

The relevant principles for reaching soil pollution reduction targets (2030 and 2050) that should be integrated into all domains:

- **Fairness and equality**: distribution of and access to natural resources should be fair providing equal opportunity to everyone
- **Intergenerational justice**: refers to the close relationship between generations and mutual respect (Rockström et al. 2023)
- **Precautionary Principle**: allows measures to be taken to avoid risk of environmental harm, even in the face of scientific uncertainty
- **Prevention Principle**: allows preventive measures to prevent the occurrence of environmental damage
- **Polluter Pays Principle**: costs related to environmental damage should be borne by those who caused it
- **Public Participation**: the public is involved and is given early and effective opportunities to participate in all stages of the process elaborating preventive measures, when all options are still open
- **Eco-Economic Decoupling**: breaking the links between economic growth and environmental pressure.

2.2 Summary of the State of the Art on Soil Pollution and Restoration

This part provides a summary of the state of the art in the domain of soil pollution and restoration, based on relevant literature reviewed and inputs of stakeholders gathered so-far. The state of the art will be further developed during the next phases of the project. Specifically, it will be strenghtened with further reviews of key relevant grey and scientific literature, as well as with information and outcomes from relevant projects, and stakeholders' inputs.

2.2.1. Sources and scope of soil pollution

In this subsection, a first overview is given of important factors contributing to soil pollution. This overview will be extended and further elaborated during the following phases of the project. In subsections 2.2.2 and 2.2.3, a first summary of important impacts of soil pollution is provided. Two main types of soil pollution are mostly considered in literature: point-source soil pollution and diffuse soil pollution. However, based on the literature human induced soil pollutions can be categorised by

- **the source of pollution** (point-source soil pollution–diffuse soil pollution),
- **main sectors and drivers identified for pollution** (industry, agriculture, waste, mining, hazards, military activities and lately firefighting (European Commission: European Environment, Joint Research Center et al. 2024). Note, that the six drivers (technology and management, demography, policy and institutional arrangements, economy, nature and environment, socio-cultural context) identified by SOLO regarding four land uses (nature, urban, agriculture, forest) are relevant to all TTs (Chowdhury et al. 2024).
- **type of pollutants and their properties** having negative impact on soil properties, soil biodiversity, soil functions/ecosystem services and or human health,
- **degradation pathways**
- **the direction of transportation** via air and water (to of from soil),
- **decision making and the intention** (intentional/unintentional) of human activity related to input of potential pollutants.

In the literature reviewed, there is no separate category for decision-making aimed at reaching a balance between input and output of substances and where pollution is the result of an imbalance between input and output. In the case of agriculture, farmers continuously need to make decisions by taking into consideration all the aspects that may have an impact on the balance (crop choice, soil’s properties, site specific conditions, timing, etc.), while In the case of non-agriculture activities, the balance is “established” during the development of the technology, thus the user of the technology does not have to, and is not allowed to, make any decision in this regard based on the technical descriptions of the product and/or safety procedures.

Concerning nutrient (nitrogen and phosphorus) soil pollution, it is important to emphasise that it is caused by the surplus (input minus crop uptake), while nutrient deficiencies (negative nitrogen and phosphorus) lead to nutrient mining affecting soil fertility and the capacity of soil production function (Rodríguez-Eugenio et al. 2018, Majumdar et al. 2016). European Commission: European Environment, Joint Research Center et al. (2024)Majumdar et al. 2016Rodríguez-Eugenio et al. (2018)

Relevant information on some of the above categories are summarized below.

The source of pollution:

- ***Point-source soil pollution***

Point-source soil pollution is associated with sites where accidental or intentional spillage took place, and current or former industrial, waste disposal, mining, transport infrastructure and storage sites. Inorganic and organic pollutants, heavy metals, Persistent Organic Pollutants (POPs) and Polycyclic Aromatic Hydrocarbons (PAHs) are pollutants often involved in point-source soil pollution. The revised urban wastewater treatment directive underlines the negative impact of micropollutants and the need to monitor and to introduce quaternary treatment in order to remove micropollutants like pharmaceuticals and plastics (European Parliament and European Council 2024).

Point-source pollution also frequently involves historic contamination. Available data on the number and the area extent of contaminated sites in the EU are characterised by large knowledge gaps. The JRC estimated in 2018 that EU-28 counted about 2.8 million potentially polluted sites: sites where polluting activities are taking place or took place (Paya Perez and E.N. 2018). An EEA report published in 2022, based on national registries, showed that in 2016 1.38 million potentially contaminated sites were registered. About two-thirds of contaminated sites could be potentially historic (e.g. brownfields) (EEA 2022b). In 2016, 115,000 contaminated soils were estimated to be remediated in the EU; about 8.3% of the currently registered potentially contaminated sites. It is estimated that at least 166,000 additional sites are in need for remediation or measures which reduce risk (EEA 2022b, European Commission 2023a). Historic contaminated sites don't fall under current legislation regarding industrial pollution prevention, such as for example the Industrial Emissions Directive (European Parliament and European Council 2010). The the SML proposal, waiting for adoption does include provisions on identification, assessment and management of contaminated sites, and aims to at least partly fill this policy gap. Also, data on remediation of contaminated sites are scarce/limited.

- ***Diffuse Soil Pollution***

Diffuse soil pollution involves soil pollution whereby substance is transported under a gradient of chemical potential, activity or concentration that often spreads over large areas, and in general doesn't originate from an easily identifiable, single source. These characteristics cause important challenges in assessing the full scope of diffuse soil pollution. Diffuse pollution often leads to chronic exposure to lower concentrations of pollutants, while the health and ecotoxicological impact of chronic exposure are difficult to assess, and have been less researched. Agro-chemicals, fertilizers and manure are important contributors to diffuse soil pollution, as well as road traffic and the diffusion of point-source pollution. Often, diffuse soil pollution is further transported by air and water. Important diffuse soil contaminants are listed below (Paya Perez and E.N. 2018,IUNG 2019, Rodríguez-Eugenio et al. 2018).

Selection of key pollutants and their properties:

- ***Pesticides***

Agro-chemical soil pollution, including pesticides, has been identified as a major soil threat (Stolte 2016). Different studies (Chiaia-Hernandez et al. 2017, Hvězdová et al. 2018, Orton et al. 2013, Pose-Juan et al. 2015, Qu et al. 2016, Silva 2022, Silva et al. 2023, Franco et al. 2024) have already provided data on the distribution of currently approved or banned pesticides in soils. However, a comprehensive overview on pesticide residues in the soils in Europe through regular monitoring programs has been lacking, with existing data originating from different methods and analyte lists, and different sampling periods and strategies used among different studies, etc. (Institute of Environmental Sciences (CML), Leiden University and Royal HaskongingDHV 2024).

An important source of information on the presence of pesticide residues in European soils is the work of Silva et al. (Silva et al. 2019, Silva et al. 2022, Silva et al. 2023, Silva 2022, Franco et al. 2024). A pioneer, large-scale study analysed 76 pesticide residues in 317 EU agricultural topsoils showed that 83% of soils contained 1 or more residues, while 58% of soils contained mixtures of different pesticides (Silva et al. 2019). These findings were corroborated by a larger and more comprehensive study, conducted in the framework of the H2020 SPRINT project. A total of 209 pesticide residues were tested in 625 environmental samples in different matrices (soil, crop, outdoor air, indoor dust, surface water and sediment), across 10 study sites (Silva et al. 2023, Knuth et al. 2024). In 86% of the complete set of samples at least one residue was measured, and in 76% of samples mixtures of different pesticides residues were found. 201 of the samples were taken in soils, and revealed occurrence of 100 different pesticides. In soils of conventional farms, 99% of the samples contained pesticides, while 96% contained mixtures of at least two pesticide residues. For soils of organic farms, these numbers were 95% and 79% respectively.

The most frequently detected substances were p,p′dichlorodiphe-nyldichloroethylene (DDE p,p′), aminomethylphos-phonic acid (AMPA), a degradation product of glyphosate, hexachlor-obenzene (HCB), chlorpyrifos, and glyphosate. Total concentrations of pesticides in conventional fields reached a maximum value of 28.678 ug/kg, and 5.458 ug/kg in organic soils.

The study of Silva et al. (2019) made use of 317 samples from the 2015 LUCAS survey (Land Use/Cover Area frame Survey) (Orgiazzi et al. 2022, Franco et al. 2024). The 2018 LUCAS program included a pesticide module, which may be extended at least in terms of sample coverage in future LUCAS programs, in line with the SML.

Although still limited, the available data show that mixtures of pesticide residues are the rule rather than the exception, in soil and connected matrices. Large-scale, harmonized monitoring of mixtures of pesticides residues is urgently needed to evaluate risk for ecosystem and human health (Silva et al. 2023), accounting also for transport of residues in and on soil.

Limited data is available on the actual application of (individual) pesticides, which will change with the implementation of the Regulation on Statistics on agricultural inputs and outputs (European Commission 2022c). Pesticide sales data, a proxy for actual applications, show that pesticide use in the period 2011-2022 has remained relatively stable, hovering between 370,000 ton and 320,000 (Eurostat 2022b), with sales for some years, e.g. 2019 (333,000 tonnes) and 2022 (322,000 tonnes), decreasing, and for others, e.g. 2020 (346 000 tonnes) and 2021 (355 175 tonnes), increasing (Eurostat 2025).

- ***Persistent Organic Pollutants (POPs)***

Important sources of POPs are emissions from agriculture, combustion and industry, and from disposed commercial products (e.g. plastic containing POPs). The waste sector is relevant for the more recent POPs, for example through application of sludge. Data on POPs pollution of soils are very limited. For example, a EU study from 2011 (European Commission 2011) included only limited data on 4 POPs pollutants in soils. Under the Stockholm Convention, data on POPs for 2021 (UNEP 2021a) were gathered, however important data gaps remain. Long-term POPs pollution trends have shown no decline in Benzo(a)pyrene (B(a)p) air pollution and high concentrations of polychlorinated dioxines and furans (PCDD/Fs) in Europe (TF HTAP 2021).

Also, for emerging contaminants, such as the widely used Perfluoralkyl chemicals (PFASs), an important lack of data exists. PFASs resist degradation, and are easily transported over long distances. PFASs pollution is widespread, including in soils, water and waste. Remediation of sites polluted with PFASs is technically challenging and costly (Council of the European Union 2019).

- ***Pharmaceuticals (including veterinary products) and personal care products***

An estimated 5,507.4 tonnes of active substance of antimicrobial Veterinary Medicinal Products were sold in Europe in 2020 (EU-27, UK, Iceland, Norway and Switzerland). In the period 2011-2020, a decrease of 43.2% was reported in sales of the 25 countries providing annual data to the European Medicines Agency (European Medicines Agency 2021). Through manure application, veterinary products end up in the soil (Gros et al. 2019), while pharmaceutical and personal care products can pollute soils through sewage sludge application (Gworek et al. 2021). No comprehensive data exist on the scale of contamination of these compounds in the EU. The continuous release of antibiotics into the environment is of important concern. The majority of antibiotics are not completely metabolised in humans and animals, and a high percentage is discharged into water and soil through animal manure, municipal wastewater, sewage sludge and biosolids (Perruchon et al. 2022). Antimicrobial drug resistance (AMR) poses an important challenge (Cycoń et al. 2019). Manure can also be a source of antibiotics from veterinary medicines (Antikainen et al. 2008, Panagos et al. 2022b).

- ***Plastics and microplastics***

Plastic pollution, including microplastics and nanoplastic has emerged as a growing concern for soil health. Available data from Eurostat (Eurostat 2022a) indicate that the generation of plastic was increasing from 9.5 million tonnes in 2004 to 17.2 million tonnes in 2018. The fate of plastics once they enter terrestrial systems is poorly understood. Agricultural activities are a major source of soil plastic pollution, through the use of mulching (estimated rate of 100,000 tonnes per year in the EU), application of sewage sludge (31,000 to 42,000 tonnes yearly) (Lofty et al. 2022), polymer-coated fertilizer and pesticides, plastic used in greenhouses, crop protection nets and irrigation systems (EIP AGRI 2020). In addition to direct agricultural use, microplastics reach soils through multiple diffuse sources, leading to the widespread presence of microplastics in the environment and in food. Degradation of macroplastics and cosmetics are sources, and also tyre wear is estimated to be an important source of microplastic pollution (Baensch-Baltruschat et al. 2021). Furthermore, plastics can enter soils through compost and organic amendments, industrial activities, landfill emissions, and mismanaged plastic waste. Even biodegradable plastics, such as starch-based or polylactide (PLA)-based films, are not exempt from contributing to soil pollution. Although marketed as environmentally friendly, these materials often fail to fully decompose under field conditions. They tend to fragment into smaller particles, adding to the pool of microplastics in soils (Meng et al. 2023,Briassoulis 2004, Whitacre 2014 de Souza Machado et al. 2018). The environmental behaviour of these so-called bio-microplastics is not well understood, and their long-term effects on soil ecosystems, including microbial activity, plant development, and pollutant transport, remain largely unknown. An important and underexplored pathway of soil contamination is the leaching of chemical additives from plastics (Macan et al. 2024). Plastics often contain phthalates, bisphenols and other additives, which may leach into soil and groundwater. In addition, other environmental pollutants (e.g. pesticides, heavy metals, POPs) can adsorb on the surface of microplastics, potentially enhancing their mobility and bioavailability in soils. This carrier effect represents a poorly understood risk to soil ecosystems. Despite growing evidence of widespread contamination, systematic data on the distribution, composition, and impacts of microplastics in European soils remain highly limited. There is also limited understanding of how microplastics affect key soil functions such as nutrient cycling, water retention, and soil biodiversity. Large-scale, harmonized assessments are urgently needed to better quantify the presence and risks of microplastics in soils, especially in the context of their interactions with other soil pollutants and their persistence over time.

- ***Nutrients***

More than 70% of ecosystem area in the EU is at risk of eutrophication due to excess nitrogen deposition (EEA 2024). In the EU+UK, a worrying 74% of agricultural area receives excessive nitrogen inputs. Also, phosphorus has accumulated in agricultural soils in Europe, after the introduction of phosphorus-containing fertilizers in addition to manure. Large areas face surpluses of phosphorus. The primary cause is fertiliser and manure application, livestock density and soil degradation (erosion and leaching) in agriculture (European Commission: European Environment, Joint Research Center et al. 2024, European Environment Agency 2018, European Environment Agency 2019, Velthof et al. 2011).

This surplus of nitrogen in soil leads to an acceleration of microbial nitrification that further stimulates emissions of nitrous oxide, a highly potent greenhouse gas (GHG), and contamination of groundwater via nitrate leaching (Kuypers et al. 2018). Antikainen et al. 2008Panagos et al. 2022Majumdar et al. 2016European Commission: European Environment, Joint Research Center et al. 2024Rodríguez-Eugenio et al. 2018

- ***Heavy metals***

About 6.24% of EU agricultural area is estimated to contain high concentrations of heavy metals (concentration above the guideline value set by the Finnish legislation for contaminated soils in agricultural areas) (Ministry of the Environment, Finland 2007). Copper, lead and zinc are estimated to be accumulating in EU soils, while for cadmium a net decline is estimated (De Vries et al. 2022). High concentrations of copper are found in vineyards and orchards in humid climates, because of a high use of fungicides (Ballabio et al. 2018). Ballabio et al. (2021) found that EU hotspots of mercury are located close to mine areas, coal-fired power plants and chlor-alkali industries.

Concerning the assessment of soil heavy metal contamination and remediation needs Tóth et al. (2016) highlights that European countries have a number of approaches to define risk levels associated with different concentrations of heavy metal in soil (Carlon 2007, Ferguson 1999). It underlines that the Finnish standard values represent a good approximation of the mean values of different national systems in Europe (Carlon 2007) and India (Awasthi 2000) and they have been applied in an international context for agricultural soils as well (UNEP et al. 2013).

Beyond agricultural soils, data on heavy metals are limited. Panagos et al. (2021) estimated that the average concentration of mercury in EU topsoils amounted to 103g/ha. About 6 tonnes per year would be transferred downstream via transport of sediments (EU27 + UK). Tóth et al. (2016) indicated that heavy metal concentrations in soils are very unevenly distributed through the EU, with many sites of highly concentrated pollution.

Pourret and Hursthouse (2019) have suggested to use the term 'Potentially Toxic Elements' instead of 'heavy metals' when reporting environmental research. During our further work within the PRTT, we will explore this option.

2.2.2 Impacts of soil pollution on biodiversity and ecosystems

Different studies have indicated important negative impacts of soil pollution on ecosystems and their services (water purification, water retention, food production, biodiversity, etc.) (Morgado et al. 2018, Rodríguez-Eugenio et al. 2018, Panneerselvam et al. 2022).

For example, pesticide residues in soil hold risk for biodiversity, ecosystems and their services, and get transported to/taken up by other matrices (water, air, indoor dust, food, microorganisms/microbiota, animals, humans). Many pesticide residues are persistent, bioaccumulative or toxic to non-target species (Silva et al. 2019, Silva et al. 2023.) Pesticide residues in soil are shown to negatively impact soil macroorganisms, microbiota and the microbiome (Gunstone et al. 2021, Beaumelle et al. 2023, Pelosi et al. 2021, Riedo et al. 2021, Walder et al. 2022, FAO et al. 2020). Pesticide pollution in soils can alter processes in the rhizosphere, impact plant growth and resistance against pests, alter the composition of soil microorganisms, and can lead to an increase of pathogens and decrease of beneficial organisms. Also, changes in nutrient composition in roots, leaves, grape juice and xylem sap have been observed after pesticide applications (Brühl and Zaller 2021, Klátyik et al. 2023, Mandl et al. 2018, Ruuskanen et al. 2023, Zaller et al. 2018, Zobiole et al. 2010). Negative effects on soil organisms also impact fauna dependent on soil organisms, e.g. farmland birds (Rigal et al. 2023).

The excess of fertilizer and manure cause extensive negative impacts on waterways and biodiversity. E.g. mycorrhizal fungi, essential for many soil functions and services, are negatively affected by excessive nutrients (Origiazzi 2016). The multifunctionality of soils, and the trade-offs between excess nutrients and other soil functions, are assessed by Vazquez et al. (2020).

Pharmaceuticals, such as antibiocs, can affect soil microorganisms, for example by changing their enzyme activity and ability to metabolize different carbon sources, and by altering the overall microbial biomass and relative abundance of different groups (Cycoń et al. 2019).

Microplastics can impact soil physicochemical properties (e.g. increase bulk density, decrease porosity and water holding capacity), soil micro-organisms, macro-organisms, plant growth and can leach toxic chemicals (Lofty et al. 2022, Vasileiadis et al. 2018 Vaccari et al. 2022).

Although, negative (potential) impacts of different soil pollutants on biodiversity and ecosystem functioning have been shown by a variety of studies, the long-term impact of the cumulative effects of different soil pollutants or the interactive effects of these different groups of pollutants, being present concurrently in agricultural soils (i.e. plastics and pesticides), on the variety of different organisms exposed remains unknown. In general, there is a lack of long-term studies that also evaluate the impact of mixtures and cumulative effects on a wide range of organisms and ecosystem services.

2.2.3 Impacts of soil pollution on stakeholders

Different studies have indicated that soil pollution directly affects human health. Soil pollution can contaminate food, which can pose risks for human health. Many links have been described between increased risks for a variety of illnesses and health impacts, and pollutants frequently found in soils, such as arsenic, lead, and cadmium, organic chemicals such as polychlorinated biphenyls (PCBs), PAHs, pharmaceuticals such as antibiotics, pesticides and micro-plastics (Rodríguez-Eugenio et al. 2018, Cox et al. 2019, European Commission 2019, Lim 2021). Rodríguez-Eugenio et al. (2018) underline the potential risks of contaminated soil for human health, including uptake from dust and vapours by farm workers, skin contact and ingestion of soil. Also, soil pollution/ contamination can be responsible in many cases for vector-borne diseases such as dengue, chikungunya, Zika, malaria, that are growing human health risk of the local population getting infected and transmitting the infection exponentially. (Krystosik et al. 2020, FAO et al. 2020, George et al. 2024).

Tolerable daily intake values for pesticide residues are likely to underestimate the risk to consumers, as they don't account for mixture effects. Pathways other than ingestion or food, such as inhalation or skin contact, are seriously underestimated. Soil pollutants, such as pesticide residues, can accumulate in the lighter top layer of the soil, and get transported by the wind and inhaled by animals and humans. Pesticide residues have also been shown to accumulate in indoor dust (Navarro et al. 2023). A recent paper by Matsuzaki et al. (2023a) highlights the potential links between pesticide exposure and the microbiota-gut-brain axis.

Overall, there is an important lack of research on the impacts of mixtures of soil pollutants people are exposed to, including on impacts on humans from long-term exposure to soil pollutants. Here the "exposome" is relevant: the measure of all the exposures of an individual throughout a lifetime and how those exposures relate to health. There is also an important link between the impact of soil pollutants on (soil) biodiversity and human health, as soil pollutants can lead to the selection for harmful taxa and to an overall decrease in diversity of microbiota, also leading to effects on the human microbiome. More and more research also refers to the impacts of soil pollutants on the gut microbiome, and potential links with health conditions, including neurological illnesses. Soil pollutants can lead to advantages for harmful microbiota, for example through antibiotics resistance (Roslund et al. 2024).

Soil pollution is associated with important economic and social impacts and costs. For example, soil pollution can negatively impact health, land availability, water quality, water retention, crop growth/food production and other ecosystem services (Adhikari and Hartemink 2016, Bouma 2014, Greiner et al. 2017, Jónsson and Davíðsdóttir 2016, JRC and Maes 2020, Lacalle et al. 2020, O'Riordan 2021, Pulleman et al. 2012, Stavi et al. 2016, Stolte 2016, Velasquez and Lavelle 2019).

2.2.4 Solutions to soil pollution

Solutions to soil pollution include prevention of pollution and remediation/restoration of contaminated sites. Prevention of soil pollution (due to intentional inputs of potential pollutants or unintentional inputs of pollutants) is a must in order to reach the Soil Mission Objectives. It is important to underline, that on the one hand, routine handling and use of chemicals in industrial activities often result in negative impact on soil and/or groundwater. This may occur when certain chemicals – earlier believed less harmful – prove to be hazardous to human health or the environment. This has happened earlier with certain chlorinated hydrocarbon compounds or with PFAS/PFOS compounds more recently. On the other hand, pollution due to unintentional inputs of pollutants are most commonly caused by chemical accidents. Since 1992 the OECD has published three guides on preventive measures relevant to accidents. Acknowledging the chance of accidents, the OECD developed its guideline Prevent-Preparedness-Response around three phase before, during and after accidents (OECD 2023b). FAO publications also addresses the prevention and risk management issues of agriculture induced soil pollutions (Drechsel et al. 2023), or the hidden costs that includes economic, environmental and social costs linked to the agrifood system (FAO 2023, FAO 2024a)

Prevention of soil pollution is a cycle of processes that consists of different, but interlinked phases:

- acceptance or refusal of a new substance (including potential biological pollutants) and/or process, technology for use,
- setting the rules for application (including but not limited to legislation),
- application (including the monitoring and surveillance of applications, enforcement of laws, and preparedness to accidents) and adaptation to the site specific conditions,
- adjustment if negative impacts occur (including changes in using/applying substances/processes/technologies, and emergency response in case of accidents),
- remediation to prevent further pollution (including follow up to incidents).

Below, we present examples in agricultural and non-agricultural soil pollution issues showing how the phases of prevention and remediation/restoration are interlinked.

Agriculture

Different practices and management tools are available to decrease soil pollution. IPM, Integrated Crop Management (ICM) and agro-ecological practices have been shown to provide effective approaches to minimizing inputs of pesticides and fertilizers, and maximizing ecosystem functioning and services, such as biological pest control. These approaches are based on increasing the resilience of the crop, while agro-chemicals such as pesticides are only used as a last resort, if needed, instead of prophylactic or calendar-based practices (Rodríguez-Eugenio et al. 2018, IPM Works 2022). Different EU legislations and initiatives are in force or in development which can contribute to reduction of soil pollution originating from agricultural activities.

Non-agricultural soil pollution

Remediation techniques are often divided into in situ (on the site) and ex situ (off the site) remediation, and include physical, chemical and biological treatments. Physicochemical treatments are often characterized with high speed and efficiency, but also with high costs and labour, and potential destruction of soil functionality. The field of remediation techniques has developed over time to a focus on effective restoration of soil quality and preservation of the environment, while minimizing the damage caused by clean-up interventions. Recent developments have also reflected the aim to promote clean-up strategies which also address climate change effects (Grifoni et al. 2022). Several in-situ chemical treatment technologies are emerging, including In-Situ Chemical Oxidation (ISCO) and In-Situ Chemical Reduction (ISCR) methods. Biological treatments provide eco-friendly features and larger social acceptance, but often require long periods. A wide variety of biological techniques have been developed and successfully applied. Microbiological methods aim to utilize the decay processes, when selected microbes utilize the pollutants for their growth, finally resulting in the elimination of the pollutants. These methods are widely used in practice.

Lacalle et al. (2020) provide an overview of biological methods of polluted soil remediation for an effective economically-optimal recovery of soil health and ecosystem services. Methods include phytoremediation, phytoextraction, phytostabiliziation, phytomanagement, bioremediation and vermiremediation. Specific challenges are associated with soils contaminated with multiple pollutants. The interaction between organic and inorganic pollutants can change bioaccessibility and solubility of pollutants and their biotoxicity and metabolic processes. For pollutants that are relatively new to the environment, such as PFAS, important challenges remain due to unknown pathways of degradation. Also, competition or joint-adsorption on binding sites poses a challenge. For mixed contaminated soils, successful combinations of chemical and biological remediation techniques have been discussed, although more research is needed (Aparicio et al. 2022, Lacalle et al. 2020). More research is needed on the potential of nature-based solutions and the use of microorganisms for bioremedation processes. In general, more research is needed to improve efficiency, feasibility, costs and time-efficiency of remediation techniques for a variety of different contaminants and soil conditions. As mentioned in the documents, those are significant knowledge gaps (Aparicio et al. 2022, Grifoni et al. 2022, Huysegoms and Cappuyns 2017, Lacalle et al. 2020, Ministry of the Environment, Finland 2007, Mulligan et al. 2001, Smith 2010). Different EU legislations and initiatives are in force or in development which can contribute to reduction of soil pollution originating from industry, traffic and waste.

2.2.5 Social and economic tools to prevent soil pollution and their fitness-for-purpose

Important reoccurring aspects regarding socio-economic and market tools relevant to tackling soil pollution are the need for implementation of the polluter pays principle, as well as for the targeted use of public funds. Current legislation and funding does not always secure linkages between funding and protection of the environment and enhancement of ecosystem services (OECD 2023a). The polluter pays principle is insufficiently included in legislation, while the loss of ecosystem services associated with soil degradation is not integrated into economic optimisation of economic actors. Stakeholders underlined that several questions should be raised, such as: *Is it possible to devise fiscal or other financial measures to mitigate pollution in a way that spreads the cost of mitigation in an equitable fashion thus diminishing political opposition? To what extent is it possible to add self-regulation to the range of regulatory mechanisms? What is* *the price structure of the food chain downstream from the farm gate to the final consumer, and how it may affect the use of the polluter pays principle? How to tackle long-term effects of pollution and how to make the polluter accountable for it? How to deal with pollutants crossing borders? How could and should different legislations be applied? Is there an alternative to public funding of historic pollution where the polluter no longer exists*? The answer to the question 'Who should cover remediation costs of historic pollution?' remains often a challenge (European Commission 2023a). An important potential instruments is a pollution levy, e.g. a pesticide levy, which is used in Denmark (Nielsen et al. 2023). Austria has a well-designed tax on landfill, incineration and other forms of waste disposal: the waste disposal tax (Altlastenbeitrag) (European Commission 2021c). The questions raise the general question on 'What principle/principles should be applied?'. All principles mentioned in the conceptual framework should be considered during the review of the tools. The application of the precautionary principle is utmost important in preventing soil pollution and its negative impact.

2.3. Prioritization of knowledge gaps

In the initial phase of the project, the PRTT carried out a first appraisal of knowledge gaps regarding soil pollution and restoration, based on an assessment of available knowledge gaps' reviews, findings of former relevant projects, a review of a selection of key grey and scientific literature and exchanges with stakeholders involved. The preliminary knowledge gaps identified in that first phase were divided into four groups:

1. Definitions, scope, sources and loads of soil pollution,
2. Affected soil properties, ecosystem services and impacts on livelihoods,
3. Affected/Involved stakeholders and their role,
4. Solutions to soil pollution and needed conditions.

Fig. 4 summarised these initially identified knowlede gaps, in their respective groups.

The knowledge gaps identified during the first phase show that the first two groups of knowledge gaps in Figure 4. fall mainly within the first two domains (soil pollution and effects of pollution) of the conceptual framework (Figure 3.), while the second two address the issues of the second and third domains (effects of pollution, solutions to pollution) of the framework.

The previously identified knowledge gaps were reviewed, and reformulated through an iterative process with stakeholders described above. During the prioritization process, which included voting on knowledge gaps by stakeholders involved in the different SOLO TTs during 1) an in person meeting in Sofia, Bulgaria on 5-6 November 2024, and 2) an online meeting on 27th November 2024, the knowledge gaps below in Table 4. were identified as the top ten knowledge gaps. Each knowledge gap was identified either as a 'knowledge development gap' and/or a 'knowledge application gap'.

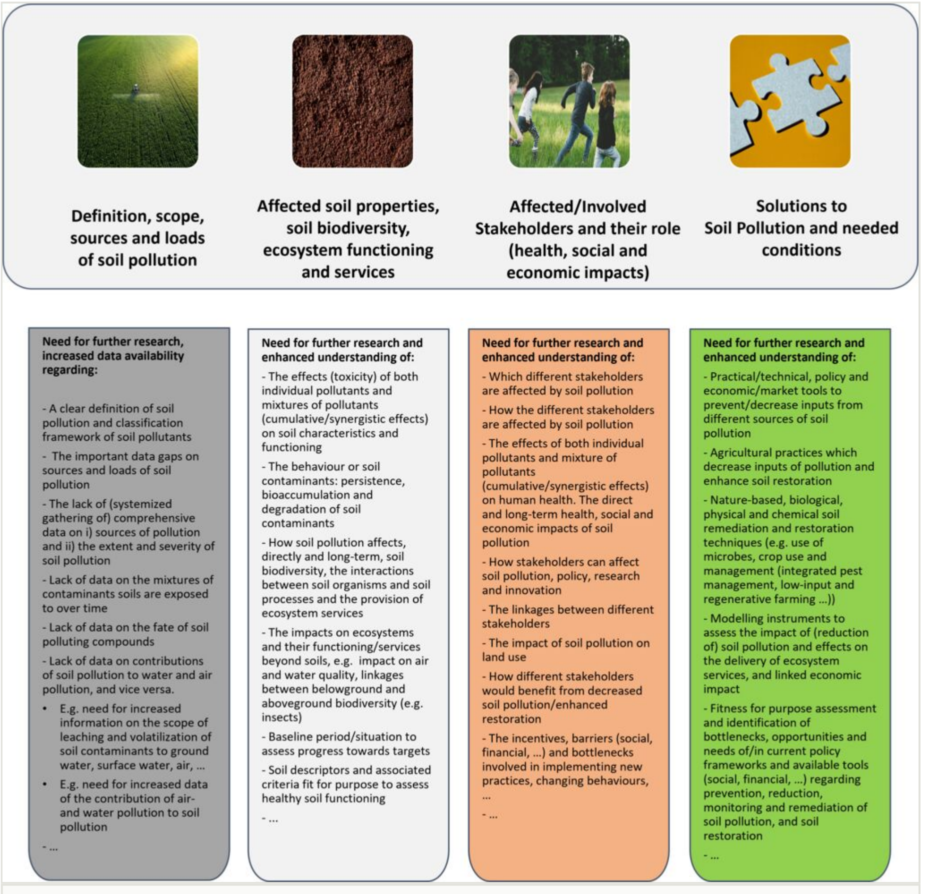

Figure 4. doi

Overview of preliminary identified knowledge gaps regarding soil pollution and restoration (created by the PRTT)

Table 4.

Ranking of the top 10 knowledge gaps identiefied (a full list of all identified knowledge gaps is given in subsection 3.3)

Rank	Knowledge gap	Type of knowledge gap
1	Impact of soil pollutants (individual and mixtures, short-term and long-term) on soils and soil ecosystem services	Knowledge development gap and Knowledge application gap
2	Socio-economic and market tools to prevent soil pollution and their fitness-for-purpose	Knowledge development gap and Knowledge application gap
3	Impact of soil pollutants (individual and mixtures, short-term and long-term) on human health	Knowledge development gap and Knowledge application gap

Rank	Knowledge gap	Type of knowledge gap
4	Data gaps on soil pollution and lack of systemized monitoring and methodologies	Knowledge development gap and Knowledge application gap
5	Technical/practical tools to remediate soil pollution and restore soils	Knowledge development gap and Knowledge application gap
6	Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air	Knowledge development gap and Knowledge application gap
7	Baseline, indicators/descriptors and quality thresholds/criteria	Knowledge development gap and Knowledge application gap
8	Overall impact of soil pollution on wider ecosystem functioning (beyond soils)	Knowledge development gap and Knowledge application gap
9	Technical/practical tools to prevent agricultural soil pollution	Knowledge development gap and Knowledge application gap
10	Knowledge gaps regarding the implementation and upscaling of preventative measures to address agricultural soil pollution	Knowledge application gap

3. Roadmap for PRTT

This section provides a review of the knowledge gaps. It starts with the top 10 knowledge gaps identified in the rank order indicated in Table 4. Compared to the discussion of the three key knowledge gaps under 3.1., the other top seven knowledge gaps' discussion under 3.2. is shorter in length (as required by the template provided to each TTs by the project's leadership) and thus in depth. The rank order of the knowledge gap (within the top 10) is indicated by the number in the brackets. All introductions of the knowledge gaps include: 1. a summary, and information on 2. the state of the art, on 3. actions and on 4. bottlenecks. Subsection 3.3. provides the list of the knowledge gaps currently identified. For the top ten knowledge gaps the information includes: 1. ranking, 2. title, 3. shortened summary, 4. type of the knowledge gaps, 5. actions, 6. type of actions, 7. timeframe for actions, 8. bottlenecks. For the knowledge gaps outside of the top 10 knowledge gaps only the title and a short description is given. The number in the 'ranking' column does not reflect priority.

The introduction of the top 10 knowledge gaps does not cover all three domains of the conceptual framework. The focus reflects the main issues elaborated in the referenced literature. Table 5. below links the knowledge gaps to the conceptual framework's domains. It is important to note that the indication of a domain does not mean that all aspects of it are discussed under the given knowledge gap.

As it is shown by the Table 5., the knowledge gaps are not yet linked to all domains of the Conceptual Framework. This exercise will be completed in the next phase. Table 5. in its present form serves as a guideline towards the future work of the PRTT. PRTT's aim is aim to provide an optimal level of generalization of the issues relevant to all domains of the conceptual framework, and to the Soil Mission Objectives.

Table 5.

Table 5. Links between the knowledge gaps (as currently definied) and the conceptual framework's domains

1. *Soil Pollution*: SPo: origin of soil pollution, SPi: input (properties of polluting agent); 2. *Effects of Pollution*: EPpc: Effect on soil properties/conditions, EPfesb: Effect on soil functions and ecosystem services, biodiversity, EPhul: Effect on human livelihood; 3. *Solutions to soil pollution*: SSPdec: decision for action (prevention/remediation), SSPprin: principles of the conceptual framework, SSPprev: prevention against polluting event or process, SSPrest: restoration/remediation, risk reduction

Rank	Knowledge Gaps	Soil Pollution	Effects of Soil Pollution	Solutions to Soil Pollution
1.	Impact of soil pollutants (individual and mixtures, short-term and long- term) on soils and soil ecosystem services	SPo SPi	EPpc EPfesb	SSPdec SSPprev
2.	Socio-economic and market tools to prevent soil pollution and their fitness-for- purpose	SPo SPi	EPhul	SSPprin SSPdec SSPprev SSPrest
3.	Impact of soil pollutants (individual and mixtures, short-term and long- term) on human health	SPo SPi	EPpc EPfesb EPhul	SSPdec SSPprin
4.	Data gaps on soil pollution and lack of systemized monitoring	SPo SPi	EPpc EPfesb EPhul	SSPprev
5.	Technical/practical tools to remediate soil pollution and restore soils	SPo SPi	EPpc EPfesb EPhul	SSPrest SSPdec
6.	Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air	SPo SPi	EPpc EPfesb EPhul	SSPdec SSPprev SSPrest
7.	Baseline, indicators/descriptors and quality thresholds/ criteria	SPo SPi	EPpc	SSpdec
8.	Overall impact of soil pollution on wider ecosystem functioning (beyond soils)	SPo SPi	EPpc EPfesb	SSPdec
9.	Technical/practical tools to prevent agricultural soil pollution	SPo SPi		SSPdec
10.	Knowledge gaps regarding the implementation and upscaling of preventative measures to address agricultural soil pollution		EPhul	SSPdec SSPprev

3.1 Key knowledge gaps

Under this heading the top three knowledge gaps which received the most votes during the prioritisation process are introduced.

3.1.1 Impact of soil pollutants (individual and mixtures, short-term and long-term) on soils and soil ecosystem services

Summary of the Knowledge Gap (Knowledge Gap 1)

The impacts of soil pollution are far-reaching and multifaceted, and pose significant challenges to environmental sustainability, public health and socio-economic well-being. Significant knowledge gaps exist concerning the impact of soil pollutants on soil characteristics, including on soil properties, soil biodiversity, soil functioning, aboveground organisms and the delivery of ecosystem services. For the majority of pollutants, there are no comprehensive (eco)toxicity data, and hence risk assessments, available (e.g. pesticides, volatiles, antibiotics, microplastics). Large data gaps remain on i) cocktail/mixtures and ii) cumulative and synergistic effects, while mixtures of soil pollutants in soils reflect the factual status. Large data gap exists on cocktail/mixture/ cumulative/synergistic effects, including a general lack of knowledge on individual substances (presence and interactions in soil, transport and fate, mobility and persistence, ecotoxicological properties, bioaccumulation and bioavailability, exposure of and risk to the environment)

State of the Art

The impacts of soil pollution are far-reaching and multifaceted, and pose significant challenges to environmental sustainability, public health and socio-economic well-being (De Vries et al. 2022European Commission: European Environment, Joint Research Center et al. 2024). Soil pollution is a main factor of decline in soil biodiversity (Tibbett et al. 2020 Gardi et al. 2013).

When data on toxicity and risk are available, they often focus on one pollutant and source, and are limited to a small set of test organisms, usually single species (animals, plants, bacteria, fungi) that are easy to breed, during a short time frame, focusing on a single toxic endpoint, in controlled (laboratory) conditions.

Cocktails of pollutants in soil include both co-occurrences of different pollutants within the same group of chemicals (e.g. different pesticides) and the co-occurrence of pollutants from different chemical groups (e.g pesticides and plastics). It is essential that the impact of long-term effects of mixtures of pollutants in field conditions is taken into account, to assess the probable impacts of soil pollution on long-term soil health and ecosystem functioning. Although available research clearly shows the extensive impacts and risks of soil pollution on soil characteristics, biodiversity and the delivery of ecosystem services, large data gaps still remain. The high complexity of soil and interactions of soil compounds, organisms and contaminants provides a large challenge in assessing the full impact of soil pollution on the delivery of ecosystem services. (Rodríguez-Eugenio et al. 2018, Vieira et al. 2024)

The knowledge gaps regarding the impact of soil pollution on soil biodiversity and soil ecosystem services are multifactorial. 1) To date, the full scope of soil pollutants remains unknown, with only a selection of pollutants being measured, and harmonised monitoring data lacking. 2) Also, for the pollutants for which more data are available, comprehensive risk assessment is mostly lacking, as risk assessment mostly focuses on single pollutants and their short-term impact on single organisms, as described above. 3) Although available research shows the presence of complex mixtures of soil pollutants mostly everywhere, the impact of the combined effects of these mixtures is largely unknown. For a number of decades, it has been recognized that an integrative approach focused on complex mixtures of pollutants is needed to increase understanding of their full extent and potential impacts (Reeves et al. 2001, Albert 1987). Available research shows the extensive negative impact of soil pollution on biodiversity and ecosystem services. Some first steps have been taken to work towards more integrative approaches to assess the full impact of soil pollution on soil biodiversity and ecosystem services, and a more integrative assessment of soil pollutants. The SML includes calls for chemical and biological indicators as soil descriptors, for the assessment of soil health. Andres et al. 2022 suggested an indicator for in-soil organisms, and used ecotoxicological data, chemical occurrence and habitats for the indication of risks. However, available knowledge is still very limited, and extensive knowledge gaps remain. Based on review of literature and exchange with stakeholders, the following main groups of pollutants are addressed under this knowledge gap: pesticides, plastics, veterinary medicines, metals, excess of nutrients, pesticides and emerging contaminants/forever chemicals, with references to common features and differences. During the further work within the PRTT, the range of contaminants discussed might be further expanded.

All mentioned pollutants are major soil contaminants. They are either intentionally (pesticides, nutrients) or unintentionally (metals, veterinary medicines, plastics) released in soils where they impose adverse effects on non-target organisms. Amongst them, soil macro-organisms, mesofauna and microbiota constitute a key protection goal considering their contribution in key ecosystem services as they modulate soil fertility and soil structure, produce and store GHG, and degrade organic pollutants (Fierer 2017). The impact of soil pollution also reaches much further than soils, and leads to contamination of the wider, aboveground ecosystems, air and water bodies (groundwater, drinking water, freshwater and marine water) (Albaseer et al. 2025, Vieira et al. 2023). Despite the common features, all of them have their own characteristics.

Pesticides

Use of pesticides is widespread, and diffuse pollution by agro-chemicals has become a major soil threat (Stolte 2016, Silva et al. 2019; FAO et al. 2020, Vieira et al. 2023). Sabzevari and Hofman (2022) reviewed the worldwide occurrence of Commonly Used Pesticides (CUPs) in agricultural soils. Franco et al. (2024) identified risks for in-soil organisms on an European scale.

Complementary, Silva et al. (2023) highlighted the presence of pesticide residues across European environments, underscoring the need for better public data accessibility to track and eventually also regulate such pollutants. Nowadays, multiple efforts are made to create such datasets which will hopefully help us in the future (e.g. IPCHEM, NORMAN). In general, current risk assessment does not capture cumulative, combined and chronic exposure to pesticides, and resulting impacts on soil biodiversity, overall biodiversity and ecosystem functioning (Honert et al. 2025, Devos et al. 2022, Bopp et al. 2019, Sousa et al. 2022, EEA 2023b, van Gestel et al. 2020, Knillmann and Liess 2021). Risk assessment and research also focus mostly on the impact of single active substance or pesticide products, while large data gaps remain on the impact of tank mixtures (when different pesticide products are mixed and applied together) and environmental mixtures (the presence of different pesticide residues and other pollutants in the environment). More research is available on the toxicity and impact of active substances of pesticides, than on the impact of pesticides products (active substance, co-formulants and adjuvants), while pesticide products are often more toxic than the active substances (Mesnage and Antoniou 2018, SAPEA 2018). Thresholds for a few pesticide residues, metabolites have been part of the legislation of a few European countries (Carlon 2007), but mostly for currently banned and highly persistent pesticides (e.g. DDTs, HCHs, Atrazine). Furthermore, the lack of data on pesticide mixtures in soils, as well as data on the total load of diffuse contamination in soils, have prevented validation and improvement of current risk EU assessment of active substances, degradation of products and pesticides. The latter is currently based on prediction of environmental concentrations, based on recommended application rates. Only a few species are used in EU pesticide risk assessment. Research has pointed to the lack of field data and lack of information on mixture and cumulative effects on soil organisms, including non-standard and native species and communities, soil functioning and ecosystem services (Geissen et al. 2021).

As mentioned earlier, Silva et al. (2019) found that 80% and 58% of 317 soil samples across the EU contained respectively pesticides and mixtures of pesticides, with in total 166 different pesticide combinations. Silva et al. (2023) also measured pesticides in 201 soil samples in the framework of the H 2020 Sprint Project. They found 100 different pesticides, with the large majority (79%-99%) of samples containing mixtures of pesticides. Soils under organic farming mostly contained persistent, long-banned pesticides, while soils under conventional farming contained also recently banned and currently approved pesticides. The researchers conclude that non-approved compounds represent a significant part of the cocktails found, and should be accounted for in risk assessment. They also recommend re-evaluation of pesticides persistence. They point out that European Food and Safety Authority (EFSA) risk assessment currently focuses on single active substances, standard ecotoxicological tests and modeling exercise, with a few standard organisms, endpoints and conditions.

Research shows that pesticide contamination extends to landscape level, far beyond farmland. E.g. Brühl et al. (2024) found widespread contamination of soils and vegetation with pesticides and Silva et al. (2023) found widespread contamination of soils, air, water, sediments and indoor dust. Also in nature reserves, insect communities are not safe from pesticide exposure (Brühl et al. 2021). Brühl and Zaller (2019) pointed out as well that long-term and cumulative effects of pesticide mixtures are not considered in the current risk assessment of EFSA. They highlight as well that indirect food web effects of pesticides are not considered: e.g. the reduction of flowers and hence of food sources of bees is not included in current risk assessment. In 2024, EFSA received two mandates from the EC to review the outdated risk assessment for plant protection products. An outline for the revision of the terrestrial ecotoxicology guidance document and for the development of an approach on indirect effects has been already published (EFSA 2025).

Honert et al. (2025) underline that current pesticide use is recognised as the largest deliberate input of bioactive substances into terrestrial ecosystems, and one of the main factors responsible for the current decline in insects in agricultural areas. Analysing 93 active substances in monthly soil and vegetation samples over a year, a total of 71 active substances were found, with up to 28 in single soil samples. The concentration in the topsoil remained almost constant year-round, and peaked in vegetation in summer. The authors call this particularly worrying, as adult insects are mainly active (in vegetation) in summer, and adult insects or larvae living in the soil are chronically exposed to several pesticides. They point out that the constant presence of pesticide mixtures is not part of the regulatory environmental risk assessment procedures for pesticide regulation. Mixtures are addressed only occasionally in formulated products with up to 4 active substances. Therefore, authorities are urged to ensure that chronic contamination of complex pesticide mixtures is incorporated in authorisation procedures and risk assessment. Additionally, given that large-scale contamination is expected throughout the year, and only a fraction of used active substances is analysed, the calculated risks are supposed to be even higher. The authors conclude that only reductions in pesticide risk can change the current observed declines in insects, and that even with refinements of, for example focusing on regulatory adjustments, a comprehensive EU strategy must be adopted to decrease overall pesticide use and transition toward ecological farming methods. (Brühl and Zaller 2019, Honert et al. 2025, Mauser et al. 2025).

The adverse effects of pesticides on beneficial soil fungi and earthworms and other soil macro- and microbiota were described by several authors (Pelosi et al. 2021, Riedo et al. 2021, Klátyik et al. 2023). Wan et al. (2025) reviewed 1705 studies, concluding that pesticides cause negative responses of growth, reproduction, behaviour and other physiological biomarkers for non-target plants, animals (invertebrates and vertebrates) and microorganisms (bacteria and fungi). Similar to other experts, the authors underline the need for better risk assessment, as risk assessment currently focuses on a limited number of easily cultured model species, and are therefore unlikely to capture the variety of responses to pesticide exposure seen across the diversity of species and communities found in both managed and natural systems. Therefore, there is a need of cross-taxa synthesis of pesticide effects, and for integrating long-term low-level exposure, cumulative effects at the landscape level and synergistic interactions between active ingredients.The authors suggest that post-licensing biodiversity monitoring could help address this problem, and conclude that unless changes occur, the hazard of severe, unexpected and long-term impacts on biodiversity and ecosystem functioning will remain unacceptably high (Wan et al. 2025). Kotschik et al. (2024) and Pieper et al. (2023) also claimed for the feedback from monitoring results in regulation of chemicals.

Gandara et al. (2024) screened more than 1000 agrochemicals in a fruit fly model and found that the majority had behavioural effects at sublethal levels and even more compromised survival after acute exposure. When combining agrochemicals at field-realistic levels, the researchers found widespread changes to larval development, behaviour and reproduction.

Beaumelle et al. (2023) reviewed available data on the impact of pesticides on soil invertebrate communities, looking at abundance, biomass, richness and diversity of natural soil fauna communities across a wide range of environmental contexts. Their review shows that pesticides overall decreased the abundance and diversity of soil fauna communities, with more outspoken effects on diversity than on abundance. Scenarios with multiple substances, insecticides and broad-spectrum substances showed most detrimental effects. There was no evidence found that the effects of pesticides dampen over time: long-term and short-term studies showed similar effect sizes. The study found that pesticide use erodes a substantial part of global biodiversity, having significant detrimental non-target effects on soil biodiversity, and threatening the health of ecosystems. Gunstone et al. (2021) reviewed nearly 400 studies on effects of pesticides on non-target invertebrates which have egg, larval or immature development in the soil. The reviewed studies included unique species, taxa or combined taxa and different pesticide active ingredients or unique mixtures of active ingredients. Of the 2800 tested parameters, with each parameter representing a change in a specific endpoint after exposure of a specific organism to a specific pesticide, 70.5% of tested parameters showed negative effects, while 1.4% showed positive effects and 28.1% showed no significant effects. The authors conclude that all types of pesticides pose clear hazard to soil invertebrates, with evident effects for all studied classes of pesticides, in a wide variety of soil organisms and endpoints, and in both laboratory and field studies.

Franco et al. (2024) performed an evaluation of the ecological risk of pesticide residues from the European LUCAS Soil Monitoring 2018 survey, which assessed 118 pesticide residues in more than 3773 soil sites across whole Europe. The study presents two mixture indicators for soil based on the lowest and median of available No Observed Effect Concentration (NOEC) from publicly available toxicity datasets, to respond to the policy need to develop risk-based indicators for pesticides in the environment. The mixture risk indicator based on the NOECsoil,min which is currently used in the ERA of ppp exceeds 1 in 14% of the sites and 0.1 in 23%. The exceedance of 1, indicates a high risk for in-soil organisms due to analysed mixtures in soil samples. Across the 73 sites monitored in LUCAS 2015 and LUCAS 2018 both campaigns, the risk indicator increased slightly.

Undesirable effects on soil microbiota can now be well-documented using advanced and standardized molecular tools (Karpouzas et al. 2014a, Karpouzas et al. 2014b; Vasileiadis et al. 2018 Vischetti et al. 2020). However, at regulatory level obsolete low-resolution methods like the OECD 216 N transformation test are still in place to evaluate toxicity of pesticides on the soil microbiota (Karpouzas et al. 2022; Pedrinho et al. 2024).

Ammonia-oxidizing microorganisms (AOM), modulating nitrification in nitrogen cycling, and arbuscular mycorrhizal fungi (AMF), obligate symbionts of most terrestrial plants, have been identified as potent bioindicators to assess the toxicity of pesticides on the soil microbiota (Karpouzas et al. 2016, Ockleford et al. 2017). New methods like amplicon sequencing in combination with tools like Species Sensitivity Distributions (SSDs) could be used to quantify effects of pesticides, although standardization of these approaches is still missing.

Shortcomings in risk assessment are also underlined by PAN Europe 2024, who highlights that the tests within the EU guidance document on ‘non-target’ arthropods are very limited and insensitive, allowing the mortality of as much as 50% of the population with the spraying of a single pesticide. They call for the need for independent (from business interest), transparent, science-based guidance documents to allow for the effective protection of the environment, including non-target arthropods.

Drift of pesticides, for example through runoff, the transport of pesticide residue attached to soil particles and volatilization from soils, is also described by many researchers as a danger to biodiversity (Albaseer et al. 2025). Drifting pesticides, find the authors, have profound impact on biodiversity, harming non-target plants, insects, fungi and other organisms both near application sites and in distant ecosystems. Pesticide drift has been linked to over 50% reductions in diversity of wild plants, within 500 m of fields.

Plastics are emerging and persistent contaminants whose relevance for soils was highlighted relatively recently (Nizetto et al. 2016). Weathering of plastics gives birth to micro-plastics (< 5 mm) which could impose adverse effects on the soil fauna (Huerta Lwanga et al. 2016, Quigley et al. 2024), affect soil structure and porosity and eventually impose undesirable effects on the soil microbiota (de Souza Machado et al. 2018). This could be assigned to additives that could diffuse from plastics in the soil matrix and have direct toxic effects on the soil microbiota (Zhu et al. 2022). Beyond that, the surface of plastic fragments constitutes a unique micro-niche for microbial colonization (called plastisphere) where other organic pollutants could adsorb and directly interact making plastisphere an arena of microbial interactions and rapid evolution (Rillig et al. 2024, Puglisi et al. 2019). The outcome of these interactions is only now starting to unravel with first evidence suggesting that plastics act as vectors of human pathogens and ARGs (Zhu et al. 2022), while their interactions with the other organic pollutants affect their dissipation (Lamprou et al. 2025). Recent evidence suggests that the co-occurrence of multiple stressors in soils could magnify the negative effects on the soil microbiota (Rillig et al. 2023), and that this aspect should be clearly considered in future studies. Further evidence also highlights potential detrimental effects on soil fauna and their associated gut microbiomes (Boughattas et al. 2024).

Another barrier in, especially, microplastic research is the fact that there are no standardized methodologies for the detection, quantification, and characterization of microplastics. This barrier makes it very difficult to compare different studies. Secondly, there is also a scarcity of long-term data on the fate, degradation, and potential accumulation of microplastics in soil ecosystems, particularly concerning their interactions with soil organisms and effects on ecosystem services. Microplastic transport through leaching represents another challenge. Finally, a difficulty that is often overlooked is that addressing the impact of microplastic pollution in soils requires collaboration across disciplines. This includes soil science, polymer chemistry and toxicology. However, limited interdisciplinary communication and data sharing can hamper comprehensive research efforts.

Veterinary medicines such as antibiotics and anthelmintics, end up in soil either directly through faeces deposition of grazing animals (grasslands) or manuring of agricultural soils (Fernández et al. 2011, Fang et al. 2023). Navrátilová et al. 2021Udikovic-Kolic et al. 2014 Besides that, the presence of antibiotics and anthelmintics in soils have been associated with strong adverse effects on the soil microbiota and particularly on AOM (Lagos et al. 2023, Lagos and Karpouzas 2023) and AMF (Gkimprixi et al. 2023) with reciprocal effects on soil fertility and plant productivity.

Despite extensive gaps remaining, **metals** are among the pollutants for which already more information is available regarding their effects on biodiversity. For example, metals and metalloids can impact microbial communities in soil, and impact different processes, such as carbon storage and cycling (Azarbad et al. 2015, Vieira et al. 2024). Faggioli et al. (2019), showed that Pb contamination can decrease abundance and richness of arbuscular mycorrhizal fungal communities. Important is also that the use of fertilizers can introduce heavy metals and other soil pollutants (Mantovi et al. 2003). Tőzsér et al. (2019) found that ground beetles can indicate extreme soil metal pollution.

Excess nutrients have an important impact on soil, water bodies, biodiversity and overall ecosystem functioning. Particularly nitrogen and phosphorus can transport to surface water bodies and groundwater, leading to eutrophication, loss of biodiversity, and oxygen-depleted waters (Lundin and Nilsson 2021). E.g. mycorrhizal fungi, essential for many soil functions and services, are negatively affected by excessive nutrients (Origiazzi 2016). Excess nitrogen also contributes to air pollution, with deposition of nitrogen one of the main driver of loss in plant biodiversity (Bobbink et al. 2010). Moreover, excess nitrogen in soil can cause increased emission of N_2O, an important GHG. (McDonald et al. 2021, Pan et al. 2022).

More than 70% of ecosystem area in the EU is at risk of eutrophiciation due to excess nitrogen deposition (EEA 2024). In the EU+UK, a worrying 74% of agricultural area receives excessive nitrogen inputs. Large areas also face surpluses of phosphorus. The primary cause is fertiliser and manure application, livestock density and soil degradation (erosion and leaching) in agriculture (European Commission: European Environment, Joint Research Center et al. 2024, European Environment Agency 2018, European Environment Agency 2019, Velthof et al. 2011).

This surplus of nitrogen in soil leads to an acceleration of microbial nitrification that further stimulates emissions of nitrous oxide, a highly potent greenhouse gas (GHG), and contamination of groundwater via nitrate leaching (Kuypers et al. 2018). Also, phosphorus has accumulated in agricultural soils in Europe, after the introduction of phosphorus-containing fertilizers in addition to manure. Manure can also be a source of antibiotics from veterinary medicines (Antikainen et al. 2008, Panagos et al. 2022b). Since the 1950s, the increased use of fertilisers has increased crop production. In India total grain production in 1995 was reached by 57 % more fertilizers than used in 1950 (Majumdar et al. 2016). However, their excessive and inefficient use has led to nutrient excesses and losses. The same has been experienced in the EU (European Commission: European Environment, Joint Research Center et al. 2024). The negative long-term effects on soil, water, biodiversity and human health have been ignored for a long-time. It has been argued that excess use of nitrogen may even have a countereffect on yield due to its negative impact on soil properties, soil life (Rodríguez-Eugenio et al. 2018) resulting in lower income to farm.

Emerging contaminants and 'forever-chemicals'

Specific knowledge gaps are related to the lack of knowledge on the presence and therefore also of the effects of emerging contaminants on soil biodiversity and ecosystem services. Also, PFAS or 'forever-chemicals' are important soil pollutants, and characterized by specific concerns, due to their highly persistent nature, widespread use and toxicity at low concentrations (Brunn 2023, European Commission: European Environment, Joint Research Center et al. 2024). Ultrashort-chain PFAS such as Trifluoroacetic acid (TFA), irreversibly accumulating in different matrices across the EU, are described by researchers as a global threat, due to their important environmental and health concerns (Arp et al. 2024).

Impact on Soil Ecosystems and Functions, and Modelling

Soil pollution leads to impairments in ecosystem structure and functions (carbon transformations, nutrient cycling, maintenance of the structure and regulation of biological populations). Mining, agriculture, forestry and waste disposal jeopardize the functional biodiversity compartment of the ecosystem, which will also lead to destruction of the provision of goods and ecosystem services (Morgado et al. 2018).

Although some studies have carried out economical assessments of e.g. the impact of agriculture on the environment (Kurth et al. 2019), the environmental externalities of soil pollution have not been fully assessed across Europe. Likewise, benefits of decreasing soil pollution and positive impacts of restoring soil health on biodiversity and ecosystem services, including long-term, sustainable production of food, have not been comprehensively included in current evaluation assessments, including in existing models. For example, models assessing the impact of reducing pesticides often do not consider the medium- and long-term positive impacts regarding crop production which would result from soil restoration and enhancement of ecosystem services, such as increased pollination, natural pest control and protection against erosion.

The impact of soil pollution reaches far beyond soil ecosystems. The **interlinkages of soil pollution with air and water pollution** on the one hand, and **the impact of soil pollution**

on wider ecosystems, beyond soils on the other hand, are also among the 10 identified priority knowledge gaps, which are further discussed.

Actions

- Ambitiously enhance systematic monitoring of soil pollution, to fill in the extensive gaps on presence of pollutants in soils,
- Include in environmental risk-assessment long-term, low-level, chronic, cocktail/ mixtures and cumulative/synergistic effects, feedback monitoring results in the authorisation of chemicals, as well as the indirect impacts, and impacts on landscape-level and ecosystem functioning/services, to integratively assess the impact on soil biodiversity and ecosystem services,
- Include all relevant studies in risk assessment, and ensure transparency,
- Research/action on prevention and remediation of soil pollution, e.g. transitioning to ecological farming methods and investing in nature-based solutions,
- Include impact of soil pollution on ecosystem functioning/services in modelling to support policy making decisions.
- Enhanced research on individual substances (presence and interactions in soil, transport and fate, mobility and persistence, ecotoxicological properties, bioaccumulation and bioavailability, exposure of and risk to the environment)

Bottlenecks

- The high complexity of soil and interactions of soil compounds, organisms and contaminants hinders the assessment of the full impact of soil pollution on the delivery of ecosystem services.
- Lack of systemized monitoring, and limited capacity leads to data gaps which hinder the determination of the level and spatial extent of pollutants in EU soils, both for point-source and diffuse pollution.
- Various and varying attitudes and, perceptions of actors involved in soil pollution hinder directing and attributing needed means and efforts to the identification and the assessment of the impact of soil pollutants and the extent of soil pollution.

3.1.2 Socio-economic and market tools to prevent soil pollution and their fitness-for-purpose

Summary of the Knowledge Gap (Knowledge Gap 2)

While the relationship between prevention of soil pollution and socioeconomic issues is two-fold, there is lack of a comprehensive framework and corresponding tools to tackle it. There is a need for developing tools that are capable of addressing and reflecting both sides of the coin and can simultaneously take into account their specific socioeconomic issues, and conflicting nature. There is no framework that addresses, on the one hand, the question of which socioeconomic changes and market tools can prevent soil pollution, and, on the other hand, how prevention of soil pollution changes those socioeconomic issues, while considering temporal and spatial context. In the first case, the focus is on the polluter and the polluting activity. In the second case, those who are exposed to soil pollution and its consequences are the focal point. In both cases, it is essential to have a clear understanding of the relationship between the socioeconomic status of the population and the impact of soil pollution/prevention on that status. There is a need for an analytical framework for the review of the underpinning factors of the negative impacts of pollution and prevention, addressing what levers can be activated for turning around those impacts, what kind of new tools have to be developed, and how existing tools could be applied and/or adapted to reach the EU's goals related to soil health.

State of the Art

Socio-economic and market tools reflect the European social and economic model. As stated in the report of the working group “social and economic model”, the European model is depicted by principles (solidarity and cohesion) and common values (freedom, equality, social justice, dialogue, respect for human rights based on equality among member states) that determine the model’s characteristics and lay down the bases for sustainable development. While the European economy is a market economy, the principles of the model require that “*economic growth must serve to boost overall social wellbeing, and not take place at the expense of any section of society, especially young people*” (EC working group 2007). The adjective “socioeconomic” used in various terms describing status, development, growth etc. is always a reflection of the European model and should be interpreted in that context.

A large number of scientific papers exist acknowledging, describing and elaborating on the negative impacts of soil pollution on soil health, soils functions/ecosystem services and human health and addressing socio-economic impacts, and market tools, market failures and the need to change the regulatory framework. They are reflected in policy papers and reports (FAO 2015, FAO 2018, FAO 2020, FAO 2024b, UNEP and FAO 2021, UNEP et al. 2013, European Environment Agency et al. 2024, European Environment Agency 2019, European Environment Agency 2018, EEA 2022a, EEA 2022b, EEA 2023a EEA 2019) OECD publications could become guidelines in assessing and developing tools and in evaluating their fitness-for-purpose (OECD 2008, OECD 2012, OECD 2020, OECD 2021, OECD 2023a, OECD 2023b, OECD 2024).

The structure and the logic of those papers can fit into the DPSIR model widely used by the EEA for analysing environmental issues (Stanners et al. 2007). Many of them assess the state of soil (S), identify pressures (P), and impact (I) and look for drivers (D), before calling for policy changes (Response – R). Based on this model, a complex response needs to be developed addressing all elements of the DPSIR model in order to mitigate or cease pressures resulting in a decreased or even zero negative impact.

As part of the SOLO project, drivers relevant to soil mission objectives were summarized. (Chowdhury et al. 2024) In the study, six categories of drivers were identified: 1. technology and management, 2. demography, 3. policy and institutional arrangements, 4. economy, 5. nature and environment, 6. socio-cultural context regarding four land uses (nature, urban, agriculture, forest). For all categories, the relevance of the drivers was assessed, identifying whether they are relevant everywhere, within the EU, or within a specific region or member state. Out of the 451 studies, 82 were related to soil pollution (agriculture 52, nature 16, urban 11, forest 3). There are significant differences in the data on soil pollution drivers for the different land use categories, the ranking corresponding to the number of studies. The site specificity of soil health and soil pollution issues could be underestimated since more than half of the agriculture and nature drivers' relevance was indicated at member state level only. Another review study on drivers identified four main groups related to human activities (1. industry and mining, 2. urban areas and transport, 3. agriculture, 4. hazards and military activities) as the main sources of pollution. It pointed out, that the reviewed studies adhered different importance to pollutants based on land use (Vieira et al. 2024).

In 2002 the EC published a Communication (European Commission 2002) on the impact assessment to improve policy quality and coherence by simultaneously giving consideration to economic, social and environmental issues. The EC gave examples of impacts which should be reviewed during the impact assessment process. The *economic impacts* included macro- and micro-economic impacts relevant to economic growth, competitiveness, compliance costs (including implementation costs for public authorities), innovation and technological development, investments, market shares, trends in consumer prices. *Social impact* examples referred to various human rights, employment, health and safety issues, consumer rights, social capital, security, education, training and culture and their distributional effects on income at different levels (sector, groups, workers, consumers). Examples of *environmental impacts* linked the negative and positive impacts to changes in the status of the environment manifested in climate change, air, water and soil pollution, land-use change, biodiversity loss, and decrease in public health (European Commission 2002).

The need to assess and evaluate socioeconomic factors and impacts of projects, and to foster socioeconomic development, have been key issues for decades. In 2002, the socioeconomic tools for sustainability impact assessment were summarized (Tamborra 2002). The Summary's aim was to provide tools for assessing the economic, social and environmental impacts of a regulatory approach in order to promote sustainable development. The main two objectives were the integration of economic and ecological dimensions by developing integrated models and finding ways to show the value of health and environmental damage in monetary terms, thus assessing those external costs of human activities. Socio-economic survey tools (Liswanti et al. 2012) could become important source of information on the socio-economic status of stakeholders and their interest in prevention of soil pollution and remediation. The integration of the various aspects is challenging especially regarding agriculture, where the diversity of the natural, environmental, historical, social, cultural, economic factors among the member states is significant (Andrejovská and Glova 2022). While Darnhofer et al. (2010) argue that resilience thinking can integrate ecological, economic and social aspects into farming systems, D'Adamo et al. (2020) emphasise the challenges in taking all three into consideration when developing the new socio-economic indicator for bioeconomy sectors. They underline that the lack of relevant environmental data was the reason why the environmental aspects could only be integrated in the future. It would be important to review whether the new socioeconomic indicator could be used and further developed to tackle the issues regarding prevention of soil pollution and/or remedation.

The need to assess the socioeconomic impact has been part of the earlier and recent Horizon project calls, and evaluation (EC DG R&I 2017, European Commission 2018). The calls refer to different socioeconomic aspects, however, they do not necessarily specify which factors, nor which status, to consider.

In 2018 the EC published a document (European Commission 2018) to help the assessment of socio-economic and environmental impacts of Europe's R&D program. The guide refers to the use of the Nemesis model (EC JRC 2020). The Nemesis model (a macro-sectoral model with a recursive dynamics) is a decision support tool, helping to make a choice between different policies taking into consideration management, budget and design issues. (European Commission 2018, Akcigit et al. 2022).

The European Commission regularly reviews the implementation, the results and the impacts of the Common Agricultural Policy by applying the common monitoring and evaluation framework (CMEF) (EC DG for Agriculture and Rural Development 2015, European Commission DG Rural Development 2017). CMEF provides indicators (output, result, impact, context indicators) evaluating the implementation against the set objectives of the programme.

In 2023 FAO introduced the concept of true cost accounting (TCA) (FAO 2023). By definition TCA is "A holistic and systemic approach to measuring and valuing the environmental, social, health and economic costs and benefits generated by agrifood systems to facilitate improved decisions by policymakers, businesses, farmers, investors and consumers." TCA helps to uncover hidden costs along the agrifood system and provides a guide for transformation. Hidden cost is defined as "Any cost to individuals or society that is not reflected in the market price of a product or service. It refers to external costs (that is, a negative externality) or economic losses triggered by other market, institutional or policy failures." However, hidden costs do not cover all costs relevant to soil pollution and remediation. While costs associated with pollution (as one of the land degradations), or pesticide exposure was omitted, costs of land-use change and nitrogen emissions were included. In that respect it is important to note that on the one hand, both control of nitrogen emission and land-use changes are part of the pollution prevention tools. On the other hand, the omission of the costs was justified not by the inadequacy of the assessment, but rather by data gaps (lack of global datasets, models for estimating cross-country hidden costs), or by intangible values that cannot be monetized. In 2024, consideration was given to improve the assessment of TCA by integrating the pollution costs of pesticide use into the hidden costs (Lord 2024, FAO 2024a).

The above means that if the limitation of data gaps is overcome the TCA assessment could become a valuable method for identifying hidden socioeconomic costs caused by soil pollution (land degradation) not only in relation to the agrifood system but to other sectors as well. During the TCA assessment process the following levers are reviewed: trade and market interventions, (de)coupled subsidies, general services support, laws and regulations behavioural policies, private capital, voluntary standards. All of them are relevant from the point of pollution and its prevention.

FAO has reviewed the hidden costs in 154 countries. Data for all EU member states (except Cyprus, Luxemburg and Malta) are published in the report. It underlines the diversity of member states, and how TCA assessment made at national level allows country specific conditions (soil health relevant, economic, social, cultural conditions, availability of data) to be taken into account. That is crucial for policy design at national and EU level, as implied often in scientific papers.

Pollution prevention requires transformation of all sources and causes (human activities, market, institutional and policy failures) leading to pollution. Prevention transforms the socioeconomic status of the beneficiaries associated with pollution and the negatively affected stakeholders depending on the principles used (polluter pays or beneficiary pays principle in context with fairness and distributional justice), the method of prevention, for example pesticides substituted by weeding robots, changing land management, soft or hard regulation (Banerjee et al. 2021, Congiu and Moscati 2022), to name but a few. There are several studies analysing these complex issues (Rickert 2004)

Actions

- Research addressing the intertwined nature of stakeholders' socioeconomic relationships and the effect of country specific cultural and historical backgrounds relevant to institutional, market, or policy setups and failures in the context of pollution prevention and the need for behavioural change,
- Comprehensive, consistent and comparative research of the existing tools on socioeconomic issues, how both sides are affected by prevention, and how to fill data gaps,
- Further development and improvement of the tools,
- Testing the tools including the test of the TCA assessment in member states with contrasting levels of data to see how it performs under different circumstances,
- Making the socioeconomic impact of soil pollution and its prevention on the beneficiaries and on the negatively affected more transparent and to highlight trade-offs,
- Data collection on the socio-economic status of the exposed and the polluters, and the impact of the preventive measures on those statuses.

Bottlenecks

- Limited acknowledgement and understanding of the intertwined nature of stakeholders' (polluters and exposed to pollution) socioeconimic relationships hinder further development and improvement of the tools, and the identification of trade-offs.
- Lack of cultural context hinders consistent data collection and comparison of data, and to develop adequate tools for addressing socioeconomic issues stemming from soil pollution prevention and remediations.
- Sector-specific approaches hinder the development of an overarching, comprehensive and consistent framework for soil pollution prevention and remediation.

3.1.3 Impact of soil pollutants (individual and mixtures, short-term and long-term) on human Health

Summary of the Knowledge Gap (Knowledge Gap 3)

Available research clearly shows that soil pollution poses severe risks to human health. People are throughout their life exposed to soil pollutants through different routes. The measure of all the exposures throughout a lifetime is referred to as "the exposome". Drinking water and food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens), ingestion/inhalation of soil particles and dermal exposure are important exposure pathways through which soil pollution can impact human health. Analogous to the research gaps regarding the assessment of the impact of pesticides on the environment, the complete impact of total soil pollution exposure through all exposure routes, taking into account mixture and cumulative effects, chronic low-level exposure, throughout a lifetime (the 'exposome'), on human health remains currently unclear. For example, current risk assessment focuses mostly on e.g. pesticide exposure through food ingestion, while experts point out that exposure via air and skin are important routes of exposure, which are currently not adequately assessed.

State of the Art

A variety of studies have shown the impact of soil pollution on human health. Drinking water and food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens, etc.), ingestion/inhalation of soil particles and dermal exposure (Marin Villegas et al. 2019,Chaparro Leal et al. 2018, Govarts et al. 2023) are important exposure pathways through which soil pollution can impact human health. Among the chemicals or groups of chemicals of major public health concern identified by the WHO are Cd, Pb, Hg, dioxin and dioxin-like substances and highly hazardous pesticides, of which residues are transported from polluted soils to food and water bodies. Also pathogens present in soil may contaminate food, with human health risks (e.g. diarrhea, cancers). Health aspects related to soil pollution vary according to land use (e.g. urban soils are characterised by specific problems and challenges, given the concentration of anthropogenic activities concentrated there, and the high population density). Münzel et al. (2024) underline the links between soil and water pollution, and cardiovascular disease. Robust evidence has shown the links between multiple pollutants, such as pesticides, heavy metals, dioxins and toxic synthetic chemicals to increased risk of cardiovascular disease, while some data also suggest an association between micro- and nanoplasic particles and cariodvascular disease. The authors point out that soil pollution diminishes soil's capacity to produce food, causing crop impurities, malnutrition and disease.

People living in areas with a higher concentration of metals and metalloids in soil are linked to the aetiology of some forms of cancer, increased incidence of mental disorder and all-cause cardiovascular diseases mortality (Vieira et al. 2024, European Commission: European Environment, Joint Research Center et al. 2024, Núñez et al. 2017,Ayuso-Álvarez et al. 2019,Ayuso-Álvarez et al. 2022). Higher rates of lung cancer mortality was found in regions with higher concentrations of cadmium or arsenic (Bartnicka et al. 2023). For some locations, this was supported by increased regional mortality rates caused by cancer types associated with these pollutants (Parviainen et al. 2022). An identified knowledge gap underlined in European Commission: European Environment, Joint Research Center et al. (2024) is that most of the identified studies use the total amount of a given pollutant in soil, rather than considering the bioavailable fraction (Hemphill et al. 1991, Zhao et al. 2020). The uptake of metals by plants may pose significant risks to human health.

Research projects show widespread pesticide contamination in soils, air, waterways, indoor dust, animals and humans. However, systematic monitoring data of pesticide residues are not available. A large body of research shows the links between pesticide exposure and a variety of health impacts. Pesticide exposure has been linked to various types of cancers (non hodgkin lymphoma, multiple myeloma, prostate cancer, leukemia, breast cancer, kidney and bladder cancer, soft tissue sarcomas, hodgkin's disease, testis cancer, melanoma), respiratory diseases (e.g. asthma), neurodegenerative diseases (Parkinson’s disease, Alzheimer's disease), anxiety/depression, thyroid diseases, developmental delays in children and cognitive imparements, cardiovascular diseases, infertility of birth malformations, weakening of immune system and negative impacts on the gut microbiome (Bretveld et al. 2006, Inserm 2021, Nicolopoulou-Stamati et al. 2016, Abou Diwan et al. 2023, Farr et al. 2004, Figueiredo et al. 2021, Gama et al. 2022, Doğanlar et al. 2018, Panzacchi 2025). Certain illnesses, such as types of cancer (in France) and Parkinson's disease (In France, Italy and Germany), have been listed as occupational diseases, due to their high prevalence among farmers and farmworkers (Shan et al. 2023, Bloem and Boonstra 2023, Adhikari and Hartemink 2016, Inserm 2021). Silva et al. (2023) found that 64%, 66% and 76% of pesticide residues found in, respectively, crops, indoor dust and air samples, are linked to adverse human health effects. They found 43% and over 49% of residues in indoor dust and air samples have been linked to highly severe effects (e.g. carcinogenicity, neurotoxicity, endocrine disruption, reproductive/development effects). Similarly to the shortcomings in pesticide risk assessment for the environment, pesticide risk assessment for human health is characterised by extensive shortcomings. Mostly only uptake of pesticides through food is monitored, while exposure routes such as inhalation and uptake through the skin are not, or not well assessed. The uptake through food is underestimating real risks to consumers by not accounting for mixtures. In addition, Hernández et al. (2013)highlighted that the synergistic and mixture effects of pesticides, and the long-term exposure of (low-level) concentrations, are not taken into account in current risk assessment. Co-formulants, which are added to pesticide products, are not assessed. Moreover, different health impacts such as neurological impacts and endocrine disrupting impacts are not adequately, or not, assessed (Bloem and Boonstra 2023). Comprehensive assessments, covering toxicity effects of pesticide mixtures and cumulative effects, long-term low-level exposure, indirect effects, and spatial analysis of long-term pesticide exposure and prevalence of specific health impacts in Europe are needed to assess these impacts further.

Excessive nutrients in soils are linked to important human health risks. For example, nitrogen emission contributes to the development of aerosol and particulate matter air pollutants, impacting human health (European Commission: European Environment, Joint Research Center et al. 2024, Pozzer et al. 2017). Also indirectly, excess nutrients in soil affect human health, through compromising drinking water (Lundin and Nilsson 2021).

It is well documented that the soil deposition of veterinary medicines such as antibiotics and anthelmintics could raises health concerns associated with their plant uptake and translocation to edible plant parts entering the food chain (Navrátilová et al. 2021), and the environmental dispersal of antibiotic resistance genes (Udikovic-Kolic et al. 2014).

Analogous to the impacts on biodiversity and ecosystems, the impacts of soil pollution on human health reach far beyond polluted soils. The widespread drift of soil pollution leads to pollution of water resources (groundwater, drinking water, surface water, the marine environment), to air and indoors (e.g. in houses, schools). Soil pollution leads to the degradation of ecosystem services, with far-reaching impacts on human health. For example, by negatively impacting soil invertebrates and soil microbial communities, pesticide and metal pollution impact carbon cycling and storage (Gunstone et al. 2021, Azarbad et al. 2015,Faggioli et al. 2019). Micro- and nanoplastics also have negative effects on soil properties, with their degradation leading to the release of other contaminants, which can affect soil organisms and plant growth, and accumulate in the food chain (European Commission: European Environment, Joint Research Center et al. 2024). The impact of soil pollution on human health is therefore multi-faceted, as soil pollution not only poses direct health risk due to e.g. dermal absorption, ingestion and inhalation, but also undermines food- and water quality and ecosystem services, holding important risks for food security (Morgado et al. 2018, European Commission: European Environment, Joint Research Center et al. 2024).

Persistent organic pollutants in soils impact human health (van den Berg et al. 2017). Also, uptake of PAHs through contaminated food is associated with a suspected carcinogenic risk.

Concluding, available research clearly shows that soil pollution poses severe risks to human health. People are throughout their life exposed to soil pollutants and other pollutants through different routes. The measure of all the exposures throughout a lifetime is referred to as "the exposome". Dr. Christopher Wild defined the exposome in 2005 as "every exposure to which an individual is subjected from conception to death" (Westmark 2023). The exposome can be highly variable and evolves throughout the lifespan. Understanding how the exposure to different environmental pollutants throughout a lifetime, including soil pollution, impact human health, is key and represents a major knowledge gap. Drinking water and food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens), ingestion/inhalation of soil particles and dermal exposure are important exposure pathways through which soil pollution can impact human health. Analogous to the research gaps regarding the assessment of the impact of pesticides on the environment, the complete impact of total soil pollution exposure through all exposure routes, taking into account mixture and cumulative effects, chronic low-level exposure throughout a lifetime (the ‘exposome’) on human health remains currently unclear. For example, current risk assessment focuses mostly on e.g. pesticide exposure through food ingestion, while experts point out that exposure via air and skin are important routes of exposure, which are currently not adequately assessed.

Actions

- Ambitiously enhance systematic monitoring of soil pollution, to fill in the extensive gaps on presence of pollutants in soils affecting human health,
- Include in human health risk-assessment long-term, low-level, chronic, cocktail/ mixtures and cumulative/synergistic effects (exposure to multicontaminants), as well as the indirect impacts though the impacts on e.g. ecosystem functioning/ services, to integratively assess the impact on human health. Include the ‘Exposome’ in risk assessment,
- Include all relevant studies in risk assessment, and ensure transparency,
- Research/action on prevention and remediation of soil pollution, e.g. transitioning to ecological farming methods and investing in nature-based solutions,
- Include impact of soil pollution on human health, on ecosystem services, in modelling to support policy making decisions,
- Data collection and analysis of individual substances on human health (exposure routes, toxicological properties, the exposome).

Bottlenecks

- The high complexity of soil pollutant mixtures and (indirect) effects on human health hinders systematic monitoring and health-risk assessment,
- Lack of systemized monitoring, and limited capacity leads to data gaps which hinder the determination of the level and spatial extent of pollutants in EU soils, both for point-source and diffuse pollution affecting human health,
- The various and varying attitudes and perceptions of actors involved in soil pollution hinder the directing and attributing needed means and efforts to the assessment of the impact of soil pollution on human health and the development and application of preventive measures and remediation practices.

3.2 Other prioritized Knowledge Gaps

This subsection describes the other 7 prioritized knowledge gaps, which were identified as part of the 10 priority knowledge gaps, next to the 3 key knowledge gaps described above.

3.2.1 (Knowledge gap 4) - Data gaps on soil pollution and lack of systemized monitoring

Summary of the Knowledge Gap

Despite the extensive knowledge on pollutants and their impacts, a clear lack of data on soil pollution still exists. It is linked to a lack of data on soil pollution and systemized monitoring frameworks, which are needed to assess the scope and possible impacts of soil pollution, and to develop management and policy tools.

State of the Art

There are several ways to gather data, including monitoring systems. There are high-resolution on targeted areas (e.g. industrial areas), and low-resolution of general purpose monitoring schemes. While general monitoring schemes like EU's LUCAS and GEMAS have contributed to soil pollution data, specifically on metals and pesticides, the full extent of most soil pollutants remains unknown. This includes newly emerging contaminants, and their possible (future) impact on soil functioning. Data and monitoring of key groups of soil pollutants (e.g. pesticides, pharmaceuticals, biocides, metals, PCBs, PAHs, TPHs, PFAS, micro- and nano plastics, pollutants in sewage sludge and relevant metabolites/byproducts) is key to assess soil pollution levels and risks, and monitor management strategies to achieve healthy soils. For many substances, there is a lack of widely accepted determination/quantification methods in soils and soil organisms. Challenges include associated risks, comparability and error determination.

There is much diversity and complexity in the monitoring of different pollutants. Micro- and nano-plastics, as well as many emerging pollutants, are challenging to monitor.

Although prioritization approaches and practical feasibility are prerequisites for effective gathering of data and monitoring, it is overall essential to monitor as many soil components/contaminants as possible. Materials that are currently not considered pollutants, could pose extensive problems in the future.

Past experience has shown a long delay between substances ending up in soils and the realisation of their negative impacts, resulting in far-reaching, long-term challenges for ecosystems, their services and human health. Currently, there is a lack of understanding of the scope of contaminants/pollutants, including newly emerging contaminants, and their possible (future) impact on soil functioning. Large data gaps exist regarding the presence of emerging pollutants (e.g. pharmaceuticals, endocrine disruptors, hormones, micropollutants (e.g. microplastics) in soils, their behaviour in the environment and their toxicity, transport and bioaccumulation properties in humans. Available research shows that emerging pollutants can raise pollutants of concern, involving high risks for the environment and human health (Vieira et al. 2024, Rodríguez-Eugenio et al. 2018, Covaci et al. 2011). Enhancing and implementing methodologies to measure and predict the presence and impact of newly emerging contaminants are needed.

Data gap issuses are relevant to all types of land uses. Urban soil pollution has been documented through several cases, but has been overall poorly studied. Urban soil pollution is associated with specific challenges related to among other issues, human health (Guillén et al. 2022), water quality (e.g. groundwater pollution OECD 2023b) and risks for pollution of surrounding regions (Liu et al. 2023). Insights in the full impact of urban soil pollution are lacking, as well as clear frameworks and initiatives to tackle urban soil pollution.

Actions

- Review and comparative analysis of EU and national data on soil pollutions (existing and emerging pollutants),
- Review of methodologies, and monitoring systems aimed at identifying site specificities (abiotic and biotic conditions), and shedding light on member state's priorities, economic, institutional, and regulatory constraints/ limitations,
- Development of a monitoring framework and harmonisation of member states methodologies without affecting member states' interest and priorities by the standardization,
- Establishment of an open access database with risk relevance on emerging pollutants to promote well-informed decision-making.

Bottleneck

- Lack of standardised monitoring frameworks and methodologies for measuring pollutants hinders comparative analysis at EU level, the establishment and operation of consistent databases, robust risk assessment and well-informed decision-making.

- High costs and institutional barriers hinder development of monitoring frameworks, harmonisation and comparative analysis.

3.2.2 (Knowledge Gap 5) - Technical/practical tools to remediate soil pollution and restore soils

Summary of the Knowledge Gap

There is need for further development of remediation and restoration techniques, and for further knowledge on how traditional and alternative tools can be effectively and efficiently combined to meet set soil health targets for current and future potential land use. An important aspect is that legislation does not take into account all soil pollution and associated risks, leading to a lack of focus on remediation techniques which focus on tackling pollutant mixtures and emerging pollutants and on restoration. In practice, laboratory analytical programs often provide analysis only for those pollutants listed in the legislation. In this regard, there is a lack of a readily available open access database on new/state-of-the-art techniques/protocols, and new emerging pollutants, in order to support everyday decision-making on remediation.

State of the Art

Chemicals or mixtures of chemicals released into the environment - including soil pollutants - pose an actual risk to soil functions and also to ecological and human receptors. Currently, technical/practical tools have been developed in the light of risk-based land management strategies and the corresponding risk-based soil screening values (risk-based SSV) reflecting on the potential function and future use of the land after remediation (EEA 2023a). There has been a significant shift in remediation technologies and removal of pollutants from soil. Traditional remediation practices (physicochemical technologies) are substituted or combined with alternative techniques (Phang et al. 2024), such as addressing management practices, crop use and the use of microbial technologies. However, there is a need for further research and development to improve remediation effectiveness. Methods include phytoremediation, phytoextraction, phytostabiliziation, phytovolatization, phytodegradation (Sharma et al. 2023) phytomanagement (Evangelou et al. 2015), bioremediation (Sales da Silva et al. 2020, Jiang et al. 2022) and vermiremediation (Xiao et al. 2022).

Specific challenges are associated with soils contaminated with multiple pollutants. The interaction between organic and inorganic pollutants can change bioavailabity and solubility of pollutants and their biotoxicity and biological metabolic processes. (Vieira et al. 2024). For pollutants that are relatively new to the environment, such as PFAS, important challenges remain due to unknown pathways of degradation. Also, competition or joint adsorption on binding sites poses a challenge. For mixed contaminated soils, successful combinations of physicochemical and biological remediation techniques have been discussed, and the positive synergistic impact underlined, however, more research is needed (Aparicio et al. 2022, Lacalle et al. 2020). Microbial technologies carry great potential, however, still need further development regarding increasing efficiency. The process is highly time consuming, which is considered a significant bottleneck in the field of bioremediation. More research is needed on the potential of nature-based solutions and the use of microorganisms for bioremediation processes.

As stakeholders highlighted, the daily practice in the investigation and assessment of impacts uses a set of tools to evaluate the actual risks posed by contaminants or combinations of chemicals. These tools include different threshold-limit values for organic and inorganic chemicals, and also numerical models for qualitative risk assessment processes in order to evaluate the actual risks of the impacts. The practical application of this evaluation and assessment framework needs clear and sound scientific background as a basis for the evaluation and assessment of the rate and risk of the impacts. In practice, the list of recognized contaminants is amended regularly with compounds that were not recognized as priority pollutants or were not focused on before - such the PFAS-PFOS compounds. Typically, laboratory analytical programs of environmental assessments (both for soil or for groundwater) include those compounds that are listed in the relevant legislation. In this way, it may easily happen that samples contain chemicals which are of potential concern remain under the radar, if those chemicals are not yet taken up in legislations. This may lead to wrong conclusions when evaluating the results.

A similar example is soil gas as an environmental indicator or element. Many organic compounds, once released into the soil, tend to evaporate into the soil gas above the groundwater level - in the so-called unsaturated zone. These vapours may affect the multifunctional properties of the top fertile layers of the soil and may also pose a human health risk if migrating into confined spaces like cellars or houses. In many cases this type of risk is leading to the need of an engineering intervention. Yet, soil gas is not even mentioned in many countries in the relevant legislation, as a factor to be monitored or considered. In general, more research is needed to improve efficiency, feasibility, costs and time efficiency of remediation techniques for a variety of different contaminants and soil conditions.

Actions

- Research on the effect of mixtures and emerging pollutants,
- Research on the further development of remediation techniques
- Research on how to improve efficiency and effectiveness of alternative, nature-based techniques, including the review of how traditional and alternative methods could be combined,
- Review and comparative analysis of economic, institutional and policy framework of remediations and the technical solutions,

- Development and introduction of a coordinated mechanism and a task on national and EU level to establish and maintain an open access database with a regular update of scientific research to support the everyday decisions on remediation,
- Review of the laboratory protocols and develop a procedure on how to update them for emerging pollutants.

Bottleneck

- Nature-based solutions are often time-consuming which hinders their further development and application, as well as the development and uptake of nature-based solutions in combination with traditional methods and techniques.
- Limited market interest for alternative remediations solutions hinders research and development of alternative methods.
- Outdated laboratory practices hinder the adoption of new techniques and the assessment of the effect of pollutant mixtures and emerging pollutants.

3.2.3 (Knowledge Gap 6) - Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air

Summary of the Knowledge Gap

Soil pollution contributes to water and air pollution, and pollutants transported by air and water can cause soil pollution, particularly diffuse pollution. Extensive knowledge gaps exist concerning the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of many soil pollutants in soil, water and air. These three compartments need to be adequately assessed to evaluate (the impact of) diffuse soil pollution, demanding complex analysis.

State of the Art

Soil pollution is a major cause of groundwater and surface water contamination. Identified pathways from farm lands include: erosion and water body siltation, runoff contaminated with fresh manure, fertilizers or pesticides, and saline irrigation drainage water affecting downstream ecology, nitrogen and phosphorus overuse (Drechsel et al. 2023).

In urban areas, solid municipal waste dumps pose a threat to groundwater with a significant negative effect on the socioeconomic status of people residing nearby the dumpsites (Parameswari et al. 2012). NOx soil emissions can have important impacts on air quality (European Commission: European Environment, Joint Research Center et al. 2024). Local pollution (e.g. contaminated sites) is, via transportation processes, also often linked to diffuse pollution. The analysis of contaminated soil samples of 112 ecosystems across the globe (including Antarctica), comparing the contamination level between urban greenspaces and nearby natural sites, proved the transportation of soil pollutants and its global effect (Liu et al. 2023). At the same time, pollutants found in water bodies and in the air can be transported to soils, through precipitation or deposition processes. The interlinkages of the different matrices entail important consequences for management of pollution. For example, when groundwater is contaminated, the costs and complexity of bioremediation of soils are also greatly increased. In addition, insufficient knowledge of bioaccumulation and bioavailability of soil pollutants limits our understanding of associated risks. Accumulation of contaminants in one soil organism (e.g. earthworm) can be transferred through the soil foodweb to other trophic levels and reach aboveground organisms (e.g. birds) (FAO and UNEP 2021) The soil polluting human activity (the pollutant used, the timing and the conditions of the application of the pollutant) has an impact on the behaviour, transport and fate of soil pollutants, through its effects on soil functions, and influenced by the abiotic and biotic conditions of the specific site.

Processes of transportation (e.g. wind erosion) and air-water-soil interactions are highly dependent on soil characteristics and climatic conditions. This knowledge is essential for preventing pollution. The integration of such knowledge into decision support systems is crucial for actual prevention of water and air pollution. An example of such a tool is the 'pesticide fate tool' developed during the LandSupport project for the assessment of groundwater vulnerability to specific pesticides, and to guide decision makers in making the right choice in respect of site specificity (Bancheri et al. 2022). This underlines, that site-specific evaluations are needed. The EC’s monitoring report of 2022 on the "zero pollution” ambition (European Commission 2022a) and the the Reports of the European Court of Auditors (European Court of Auditors 2020a, European Court of Auditors 2020b) underline the need to address the influence of human activities on soil pollutants.

Extensive knowledge gaps still exist concerning the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of many pollutants in soil, water and air. These three compartments hence need to be adequately assessed to evaluate (the impact of) diffuse soil pollution, demanding complex analysis (Geissen et al. 2021).

Action

- New research and research update on the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of existing and emerging soil pollutants in soil, water and air, taking into account site specific characteristics,
- Comprehensive and comparative review of human activities’ impact on soil pollutant’s move among the three compartments,
- Comparative review of the existing decision support systems to assess their ability to promote preventive decision making.

Bottleneck

- Institutional barriers (e.g. lack of personnel and laboratory facilities) hinder new research and research updates on pollutants' characteristics and partitioning in different matrices.

3.2.4 (Knowledge gap 7) - Baseline, Indicators/descriptors and quality thresholds/criteria

Summary of the Knowledge Gap

There is a need for baselines and environmental quality standards for the assessment and monitoring of soil health. Natural background concentrations and natural variability of soils, the physical and chemical state, and soil biodiversity are relevant in this regard. Detailed soil monitoring data are missing. Soil health descriptors and accompanying quality thresholds should be established, including a robust set of biodiversity indicators, to allow for systematic and high quality monitoring and soil health assessment.

State of the Art

Setting up the baseline at EU level, assessing different local contexts, and taking into account the industry specific hazards (UNEP 2024, Yacoub et al. 2014) is a prerequisite to effectively implement actions and effective mechanisms to monitor progress towards targets/implementation of measures. It is important to note that the impacts of soil pollutants are site specific, as they depend on soil characteristics and environmental conditions, affecting also their transformation (reactions, fragmentation, etc.), while transport can occur and affect other areas, with other specific conditions.

Pollution is one of the many aspects which can make a soil unhealthy: a polluted soil is considered an unhealthy soil. There are however sites where high contamination level is not due to human activities. It is argued that in such a case soil should not be considered unhealthy, if the natural equilibrium is not disturbed (Vieira et al. 2024).

Different indicators/descriptors/indices and accompanying quality thresholds/criteria for assessing soil health have been described in scientific literature. Vieira et al. (2024) refer to the use of different pollution indices (Brtnický et al. 2019, Ferreira et al. 2022, Kowalska et al. 2018, Ferguson 1999) while Sun et al. (2020) compare the different approaches of China and the UK. Kotschik et al. (2024) underline the need to define and implement biodiversity indicators. Policy frameworks reflect on that diversity (Ferguson 1999, Deseo et al. 2001, EEA 2023a). Andres et al. (2022) suggested to include chemical residues, effect data for soil organisms in combination with occuring habitats to describe effects of chemicals on soil organisms.

However, a lack of understanding and agreement remains on which indicators and criteria to apply to define and assess (the progress towards) soil health, levels of soil degradation, and identify soils which need urgent restoration (e.g. trigger and action values) and prioritisation.

Importantly, robust indicators to monitor effectiveness of soil management (prevention and restoration) strategies to restore soil health are needed. However, before starting monitoring programs of chemical residues in soils, the sets of chemicals to be monitored and other pollution indicators, as well as the sampling methods needs to be defined. Soil organisms such as Acari and Collembola and earthworms have been suggested to be potentially good indicators to assess soil pollution and effectiveness of management strategies (Sahana 2010, Xiao et al. 2022). Moreover, also nematodes are candidates for indicators (FAO et al. 2020).

In order to efficiently set and achieve targets, a clear understanding of baselines, indicators and quality thresholds is key.

Actions

- Review and comparative analysis of the baselines with consideration given to site specificity and natural contamination level,
- Gather knowledge on expectation abundances and diversity of in-soil biodiversity - start with earthworms and develop indicators and criteria for determining **chemical and biological** soil health in view of soil diversity,
- Review and development of environmental quality standards for pollution **and soil biodiversity** monitoring .

Bottleneck

- Ambiguity of the definition of soil health and its indicators hinders comparative analysis and establishing clear baselines, and harmonizing environmental quality standards and targets.

3.2.5 (Knowledge Gap 8) - Overall impact of soil pollution on wider ecosystem functioning (beyond soils)

Summary of the Knowledge Gap

The relationship between soil pollution and ecosystem functioning is not fully understood and/or acknowledged, partly due to insufficient available data. Thus there is a lack of a framework that addresses the various aspects related to the link between soil pollution, prevention and ecosystem functioning in a spatiotemporal context. Soil functions play a key role in why and how soil pollution affects ecosystem functioning. While that role has been extensively researched in a sector specific context, there is a lack of a holistic approach that simultaneously focusses on soil pollution and prevention/remediation/ restoration choices.

State of the Art

Ecosystem functioning refers to the state or trajectory of ecosystems in terms of innate pathways and fluxes of energy, matter, and information occurring through essential *ecosystem processes, such as productivity, nutrient and biogeochemical cycling, and ecological network dynamics, from which is derived the stability that supports ecosystem complexity at a larger scale*' (Correia and Lopes 2023). Soil pollution threatens that stability. Numerous studies have emphasised the importance and severity of the negative impact of soil pollution on the environment, on food security and human health (most recently European Commission: European Environment, Joint Research Center et al. 2024, Vieira et al. 2024).

The need for a comprehensive soil protection has been recognised since the 1990s and the EU acted upon it in the early years of 2000 by adopting thematic strategies addressing all the issues mentioned (Semikolennykh 2008). Since then, science has constantly reinforced, provided new insights, and highlighted the growing severity of human-driven pollution induced disturbance of the ecosystem functioning and its consequences, and the sectoral responses to some of the consequences (for agriculture: FAO 2023, FAO 2024a, Lord 2024, for industry: Obeng-Odoom 2023, Liu et al. 2023). The adoption of the Green Deal and the Zero Pollution Action Plan is the acknowledgement of that threat.

Nature-based remediation technologies use ecosystem services building on the support of soil functions. Thus, if soil functions are put in the centre, four main ways can be identified through which soil pollution affects directly and/or indirectly the ecosystem functioning: ***1.*** the impairment of soil functions due to pollution causing negative changes in soil's physical, chemical properties and its functional biodiversity which are key to the provision of ecosystem services. ***2.*** soil function that provides for the bioavailability of pollutants, making plant uptake possible, leading to accumulation of pollutants in the food chain, ***3.*** the transport of pollutants by water and air, ***4.*** intentional use of soil filtering/ detoxicating and/or plant uptake functions for remediation purposes. Therefore, also when making decisions on remediation technology, decision makers should consider the impact of remediation on the overall ecosystem functioning. All four pathways affect the spatiotemporal scale of soil pollution.

While it is important to promote research shedding light on the links between soil pollution and ecosystem functioning, and innovation of new technologies and land and soil management approaches, the main question remains how to transform our economy (all sectors) to ensure soil health and soil pollution prevention are taken effectively into account, and to ensure the protection of ecosystem functioning as the basis of human existence.

Actions

- Research on the links between soil pollution and ecosystem functioning,
- Review and update the existing data in order to establish the relationship between pollution and ecosystem functioning,

- Development of a comprehensive analytical framework to address spatiotemporal economic, institutional and policy failures and identify decision making levels in order to reach prevention of pollution.

- Systematic monitoring of changes in ecosystem functioning due to soil pollution and/or prevention measures including restoration and remediation

Bottleneck

- Differences in stakeholders' perception on the relationship between soil pollution and ecosystem functioning and on the need for a holistic approach hinder prevention oriented policy development and decision making.,

- Sectoral interests related to soil pollution and prevention lead to policy fragmentation and contradiction, along with disproportionate allocation and/or distortion of financial resources and hinder the implementation of prevention oriented policies.

- Differences in level of detail, sources (different sectors, spatial and time scales, etc.) and structure of data hinder a holistic and overarching framework addressing the impact of prevention of soil pollution and remediation/restoration on ecosystem functioning.

3.2.6 (Knowledge Gap 9) - Technical/practical tools to prevent agricultural soil pollution

Summary of the Knowledge Gap

Although a wide array of management practices and technologies, including IPM strategies, agroecological practices, agroforestry, conservation and regenerative practices, biocontrol, monitoring and precision technologies are available to reduce, minimise or eliminate agricultural soil pollution and restore soil health for many cropping systems, there is still a need to further optimise and develop these existing practices, methodologies and technologies. There is a need for the compilation and translation of best available practices to minimise soil pollution and restoration into crop-specific and pedoclimatic integrated pest/crop management rules. Further research is still needed to develop and/or optimise these sustainable soil management practices and technologies for all cropping systems, climatic and environmental conditions and pests. Sustainable soil management rules should be science-based; practice-proofed and built on experiences in field projects gathering independent scientific expertise and practice. The use of functional biodiversity in increasing natural pest control and decreasing dependence on pesticides is a complex field, which needs specialised adaptation to specific cropping systems and environments. Also, adequate risk assessment systems are needed to effectively and efficiently assess new technologies.

State of the Art

Integrated Pest Management (IPM) is based on preventative measures, increasing natural pest control (beneficial organisms) and the resilience of cropping systems against pests, while only using chemical pesticides when all other methods have been exhausted and failed. In this knowledge gap 9, we highlight a few key aspects of preventative agricultural measures on which research and innovation should focus, to enhance their further development and optimisation.

- **IPM** is considered key in reducing agricultural soil pollution and restoring soil health. Although very developed for a wide variety of cropping systems, more research is indicated to further develop and optimise IPM for all farming and cropping systems, and on the integrative assessment of the full range of benefits associated with IPM, regarding e.g. soil biodiversity and (soil) ecosystem services. E.g. Deguine et al. (2021)have highlighted the lack of research on IPM/gaps in research programs. They highlight that integrative, interdisciplinary research, e.g. on soil and aboveground biodiversity and interactions with agroecosystem components, landscape ecology and its renewed scales are still mostly missing (Begg et al. 2017, Brewer and Goodell 2012, Redlich et al. 2018). The authors state that most research on IPM tends to list and describe tactical solutions separately, in specific contexts (e.g. focusing on a single pest, single crop, specific context), rather than scientifically understanding the advantage of using them together to harness synergy. There is a need for more integrative assessments, which take into account different pests and all management aspects. Important projects which have focused/are focussing on taking into account all aspects of IPM are the European 'Pure' project on field crops (Vasileiadis et al. 2017 Vasileiadis et al. 2018, Lescourret 2017) and the European IPM works project.

- **Agroecology** encompasses the whole food system, and is based on sustainable use of local renewable resources, local farmers' knowledge and priorities, wise use of biodiversity to provide ecosystem services and resilience, and solutions that provide multiple benefits (environmental, economic, social) from local to global. It is based on 13 principles, including maintaining and enhancing soil health and biodiversity (Agroecology Europe 2025). Available research shows the benefits of agroecology for the environment, including soil health, food security and nutrition (Nicholls and and Altieri 2018, Bezner Kerr et al. 2021). More research is needed on best agroecological practices for all relevant EU crops and farming systems. Specific identified research needs to optimise agroecological (and IPM) practices, as described by Deguine (2023), include research on sustainable seed resources and breeding, the electrochemical soil-plant health model and microbiota-mediated plant-soil feedback.

- **Agroforestry** is associated with reductions in soil pollution, e.g. through the minimisation of pesticide use and risk, and the reduction of excess nitrogen and phosphorus residues in soil, effectively contributing to the restoration of soil health, while also reducing the runoff/drift of soil pollution.

- **Biocontrol** measures include the use of macrobials, microbioals, natural substances or semiochemicals to prevent and control pests. Biocontrol has shown to be very effective in a wide range of cropping systems, and decreases in the use of chemicals in the field, as well as decreasing pressure on soils, aboveground biodiversity and human health. The effectiveness of biocontrol depends also on the functional biodiversity present at field and landscape level, which can greatly contribute to the effectiveness of biocontrol. More research is needed on the development of biocontrol agents for a wider variety of pests and cropping systems, and on the interactions between all categories of biocontrol and biodiversity. Also specifically on the impacts of biocontrol on soil health, more research is needed.

- **Mechanical weeding technology/robots**: Nichols et al. (2015)described weed dynamics and the principles of conservation agriculture, combining no-till, crop rotation and surface residue, while underlining the need for further research on tillage-residue interactions and stacked rotation. Jiao et al. (2024) and Lytridis and Pachidis (2024) describe the advances in ground robotic technologies for site-specific weed management. They highlight the importance and significant promise of the technology, and the need for specifically more research on weed identification for real-time in open-field conditions, and combined application of mechanical and laserweeding.

- **Monitoring technology**: Promising research has been done on the monitoring of plant and soil health using technology such as drones, leading to effective application and these practices being applied more widely. More research is still indicated, e.g. regarding the detection of diseases without visible symptoms. While more research already focused on fungal pests, less research has been done for virus, nematic and abiotic diseases. Some crops/fruits, such as grape and watermelon have been researched more than others. While more studies use field images, less studies use leaf or plant images. Therefore, research on small-scale objects such as leaves/individual plants will require higher- resolution visual inspections.

Actions

- Research on IPM, agroecological, agroforestry, and regenerative and conservation practices, to optimise IPM for all relevant EU crops/pests, and to assess all benefits of IPM at landscape-scale level, in framework of soil health, soil and aboveground biodiversity and ecosystem services,

- Research on biocontrol measures, to extend biocontrol options for a wider variety of pests and cropping systems,

- Research on technology/robotics to enhance monitoring of pests/crop health/soil health and mechanical weeding,

- Further expanding, connecting and coordinating living labs, lighthouses and regional networks working on IPM, agroecology, agroforestry, conservation/ regenerative agriculture, to expand testing of sustainable agricultural practices, which minimise or eliminate soil pollution and effectively restore soils,
- Research on 'system innovation', 'system shifts', and the design of alternative cropping and farming systems at regional/landscape level which effectively reduce soil pollution and restore soils.

Bottlenecks

- Diversity in cropping systems, pests, and conditions and farming systems in the EU challenges the development of preventive measures for all farming systems and environmental conditions
- Lack of effective implementation and enforcement of environmental legislation and effective spending of public funds, leading to a lack of clear incentives, drivers and obligations for further development and optimisation of sustainable cropping practices,
- Fragmentation of projects, initiatives and networks working on sustainable agricultural soil management practices hinders the shift to wide implementation of soil health and prevention oriented agricultural practices.
- Conflicts of interests between e.g. agrochemical companies and further development and optimisation of agronomic practices minimising inputs/soil pollution hinder the implementation of preventative and soil health oriented policies.

3.2.7 (Knowledge Gap 10) Knowledge gaps regarding the implementation and upscaling of preventative measures to to address agricultural soil pollution

Summary of Knowledge Gap

While a wide variety of agronomic practices which effectively reduce, minimise or eliminate soil pollution are available (see above), their widescale implementation is still largely lacking. As mentioned above, despite IPM being mandatory in the EU through the Sustainable use of Pesticides Regulation since 2014, multiple analyses of EU bodies have pointed to the lack of implementation of IPM since then. Also the implementation of biocontrol, agroecological, agroforestry, regenerative and conservation practices is lacking. Multiple knowledge gaps still exist regarding the existing implementation gaps related to sustainable soil management practices in agriculture.

State of the Art

IPM is mandatory in the EU since 2014, through the sustainable use of pesticides directive (European Parliament and of the Council 2009, SUD). IPM, as formulated in the SUD, entails the growth of a healthy crop with the least possible disruption to agro-ecosystems, and encouraging natural pest control mechanisms. IPM requires the use of practices and products with the lowest risk to human health and the environment. Although many farmers throughout Europe have been very successfully applying IPM and preventative, low-input and nature-inclusive agricultural practices, while maintaining stable yield and profitability, wide-scale implementation has been lacking (Mora et al. 2023), as was mentioned in the introduction above. Knowledge gap 10 elaborates further on the knowledge gap related to lack of implementation of available practices.

Available research shows that IPM, and agroecological and organic practices are associated with environmental benefits, including for soil health, and associated with stable yields and profitability, frequently increasing profitability. Nandillon et al. (2024) studied 1000 commercial farms in the French DEPHY network and found no correlation between the reduction of pesticide use and changes in economic performance. van der Ploeg et al. (2019) showed that agroecology has a huge potential in offering farmers more sustainable production of healthier food while improving farmer’s incomes. Also Mouratiadou et al. (2024) concluded that agroecological practices are associated more often with positive socio-economic outcomes, although magnitude, temporal aspects and success factors related to the outcomes, as well as trade-offs and system-level effects need further assessment. Lechenet et al. (2017) showed that pesticide use can be greatly reduced through the adoption of different production techniques, and that low pesticide use rarely decreases productivity and profitability in arable farms (Furlan and Kreutzweiser 2015). The European Alliance for Regenerative Agriculture found that regenerative practices led to a higher full productivitiy, higher phtosynthesis, higher soil cover and higher pland diversity, while using 61% less syntetic nitrogen fertiliser and 75% less pesticides (based on the Pesticide Load Indicator), while only slightly reducing yield, and increasing gross margin per hectare with 20% (European Alliance for Regenerative Agriculture (EARA) 2025).

However, despite available research on the success and effectiveness of IPM and agroecological practices, the widespread implementation of sustainable soil management practices, which minimize soil pollution, is lacking.

Soil pollution is associated with many "lock-in mechanisms". Lock-in mechanisms can be described as the barriers and underlying mechanisms that are holding back the transition towards decreasing or preventing soil pollution. The lock-in mechanisms of pesticide use were analyzed elaborately in the framework of the Sprint project (Frelih-Larsen and Sprint project 2022). These lock-in mechanisms include factors related to farmer’s perceptions and views (Vanino et al. 2022), agronomy and research, economics, knowledge and awareness and policy and regulation. The fact that policy, funding and infrastructure mechanisms are focused on supporting a limited set of farming models and major crops poses also an important bottleneck. Current agricultural legislation and funding does not secure linkages between funding and protection of the environment and enhancement of ecosystem services: the lack of linkage between the Common Agricultural Policy funding and the implementation of IPM/ICM and restoration of soil health/minimisation of soil pollution form an important barrier. Barriers to large-scale adoption of IPM have also been identified by Deguine et al. (2021): lack of knowledge, risk aversion, conflicts of interests between agricultural advisers and the lobbying of agrochemical companies, lack of technologies adapted to local contexts, lack of clear and effective policies, lack of collective and interdisciplinary action. Furlan and Kreutzweiser (2015) showed that mutual funds are a key tool for IPM implementation, illustrating this by focusing on the use of insecticides for maize production in Italy.

Lack of implementation of IPM is also linked to the lack of concrete crop-specific rules and guidelines. The EC has recently published a database of 1300 examples of practices, techniques and technologies for IPM (European Commission 2023b), including 273 crop-specific guidelines, accompanied by a study assessing their effectiveness. However, there is a need for further development of this database, to complement it with all available knowledge and existing IPM practices, and to further transform it into a user-friendly database, which can be readily used by farmers throughout Europe, selecting appropriate best available IPM measures for their cropping system and pedoclimate conditions. The European Project Agrowise focuses on the practical implementation of IPM, the development of crop-specific rules and the further development/expansion/improvement of the IPM toolbox.

Also, the supporting framework to implement practices, such as independent (from business interest) advisory systems, and hence access of farmers to alternative management techniques, are absolutely key in implementing available practices much more widely. However, access to independent, high expertise advisory services on IPM and sustainable soil management practices have been lacking in most member states.

Nicholls and and Altieri (2018) find that the revival of traditional agricultural systems can offer promising models of sustainability and resilience, and that the creation of lighthouses, which can offer knowledge sharing and peer-to-peer learning across farming communities, are key pathways to effective implementation of agroecology. The IPM works program is an example of very successful implementation of IPM through the organisation of regional hubs, coordinated by hub coordinators, which allow for regional implementation of IPM, trial-and-error and knowledge exchange.

The expertise gained, and lessons learned through different initiatives involving the reduction of soil pollution and enhancement of soil restoration, such as projects fostering the implementation IPM, agroecological practices, and organic agriculture, should be taken into account. This information should contribute to further analysis of which initiatives and supporting conditions are effective to increase uptake of good practices throughout Europe.

Actions

- Research on the effective implementation of IPM, agroecology and sustainable soil management practices
- Invest funds in the further development, coordination, expansion and connection of regional networks of farmers/lighthouses/living labs working on the practical implementation of sustainable agronomic practices
- Research on needed policy action/implementation/enforcement to ensure alignment of policies and public funds with environmental objectives
- Foster the development of coordinated, independent advisory systems throughout Europe, through the creation of active, living knowledge sharing networks on best available (implementation) practices
- Research on the development of crop- and sector- specific IPM rules, based on scientific expertise and best available practices, to ensure the effective implementation of IPM
- Further develop a toolbox with best available IPM, agroecological and sustainable soil management practices
- Research on key socio-economic drivers, including on insurance mechanisms and integration/inclusion of the whole foodchain, to ensure the effective uptake of sustainable soil management practices/IPM.

Bottlenecks

- Lack of effective implementation/enforcement of current legislation and lack of linkages between environmental objectives and public funding hinder changes and shift towards wide implementation of soil health and prevention oriented agricultural practices .
- Fragmentation of legislation at both national and international level and of existing initiatives (projects, EU/regional networks/national/local networks, etc.) focused on the implementation of sustainable agronomic practices lead to inefficient allocation of resources and hinder shift to prevention and soil health oriented agricultural practices.
- The complexity of the food chain, and accompanying challenges in involving the whole food chain in fostering and ensuring the implementation of sustainable soil management, hinder the shift to soil health-oriented agricultural practices.
- Lock-in mechanism of agricultural soil pollution (e.g. farmers' perception and views on soil pollution, then existing framework of input providers, farmers, processing industry and retail, the current system of allocation of agricultural

funding, etc.) hinder the implementation of prevention and soil health oriented agricultural policy.

3.3 Overview of knowledge gaps

An overview of the 10 knowledge gaps described above, as well of the other knowledge gaps which were identified can found under Suppl. material 1. The table summarizes the knowledge gaps, their types and relevant land uses, actions which are recommended to address these knowledge gaps, including the associated time frames, as well as bottlenecks which may hamper these recommended actions.

Further Steps/Notes

Next steps of the PRTT's work include:

- Continuation of the stakeholder-involved iterative process, where the list of knowledge gaps and their prioritisation, actions and bottlenecks will be revisited, updated and complemented, to arrive to a final set of 10 prioritised knowledge gaps, with accompanying actions and bottlenecks, and an updated list of additional knowledge gaps.
- The step above will potentially include the identification of additional knowledge gaps, which have not yet been prioritised nor listed among the additional list.
- Based on the updated list of knowledge gaps, actions and bottlenecks, which will result from the further iterative process described above, the document , will be further developed and optimised, taking into account feedback from stakeholders, reviewers and further literature review.
- Certain themes relevant to all three domains of the conceptual framework still need further inclusion and development, e.g. the various aspects of decision-making related to forestry, urban areas/contaminated sites, tools to change behaviours, nutrient management, the application of principles. The PRTT will further consult with experts/stakeholders on these specific topics, to strenghten these topics in the next update of the document.
- The PRTT will further develop the aspect of definitions related to soil pollution, specifically regarding how different definitions will have different consequences.
- In addition to the knowledge gaps, actions to solve these knowledge gaps and bottlenecks that may hinder these actions, the further work in the PRTT will included the identificaiton of the actions needed to tackle the identified bottlenecks.

Annexes

Supplementary tables

Monitoring requirements of the SML are set in the Annexes of the SML proposal (European Commission 2023a). Table 6. below clarifies the relationship between the Annexes of the EU SML proposal and the conceptual framework (Fig. 3) of this outlook document.

Table 6.

Table 6. shows the links between Figure 3. and Annexes of SML.

Figure 3.	**Annexes of SML**
1) Soil pollution	**Annex I** Soil Descriptors, Criteria for Healthy Soil Condition, and Land Take and Soil Sealing Indicators
2) Effects of pollution	**Annex II** Methodologies **Annex VI** Phases and Requirements of Site-specific Risk Assessment **Annex VII** Content of Register of Potentially Contaminated Sites and Contaminated Sites
3) Solutions to Soil Pollution	**Annex III.** Sustainable Soil Management Principles --> was deleted during the negotiations of the EU Parliament and the EU Council **Annex IV** Programmes, Plans, Targets and Measures referred to in Article 10 **Annex V** Indicative List of Risk Reduction Measures **Annex VI** Phases and Requirements of Site-specific Risk Assessment

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Supplementary material

Suppl. material 1: Overview of the knowledge gaps on soil pollution and restoration doi

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