D2.3 Soil health risk assessment

Integrating soil health into sustainable and risk-based land management

Document information

Grant Agreement Number	n° 101112889
Project Title	Information-based Strategies for LAND Remediation
Project Acronym	ISLANDR
Project Coordinator	GTK
Project Duration	1 May 2023 – 30 July 2026 (39 months)
Related Work Package	WP2-WP3
Lead Organisation	NOVA
Contributing Partner(s)	[1] NOVA, [2] BRGM, [3] CHALMERS, [4] GTK, [5] CERTH, [6] GreenDecision – GD
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Submission Date	27.02.2026
Dissemination Level	PUBLIC

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History

Date	Submitted by	Reviewed by	Version (Notes)
11.12.2025	Nazaré Couto, Vanessa Correia	Virginie Derycke, Paul Drenning, Kristiina Nuottimäki	1
15.01.2026	Nazaré Couto, Vanessa Correia	Jennifer Harris, Virginie Derycke, Olivier Hullot, Paul Drenning, Kristiina Nuottimäki, Pavlos Tyrologou, Nikolaos Koukouzas, Lisa Pizzol, Elisa Giubilato, Giulia Minolfi, Fabio Rosada	2
26.01.2026	Nazaré Couto, Vanessa Correia	Jennifer Harris, Virginie Derycke, Olivier Hullot, Paul Drenning, Kristiina Nuottimäki, Pavlos Tyrologou, Nikolaos Koukouzas, Lisa Pizzol, Elisa Giubilato, Giulia Minolfi, Fabio Rosada	3
30.01.2026	Nazaré Couto, Vanessa Correia	-	Final version

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Summary

This deliverable supports the objectives of the ISLANDR project by strengthening the integration of soil health considerations into sustainable and risk-based land management (SRBLM), in alignment with the European Soil Strategy, the EU Soil Mission and Directive on Soil Monitoring and Resilience (Soil Monitoring Law; SML). While contaminated land management has traditionally prioritised contaminant reduction and protection of human health, this work responds to emerging policy needs by explicitly addressing soil functionality and ecosystem services within risk-based decision-making.

The main objective of Deliverable 2.3 is to extend risk-based land management approaches to account for soil health, both as a management objective within environmental risk assessment frameworks. The deliverable establishes a coherent conceptual basis for embedding soil health across the contaminated land management lifecycle, from site identification and investigation to remediation planning, verification and post-remediation monitoring.

The deliverable is based on a synthesis of regulatory analysis, scientific literature review and expert input from across the ISLANDR consortium. Key outputs include: (i) the identification of ten entry points where soil health can be integrated into contaminated land management, aligned with the ISLANDR roadmap; (ii) a stepwise decision-support framework linking future land use, soil functions, indicators and remediation strategies; (iii) guidance on land-use-specific soil health indicators, including a minimum dataset of soil descriptors and a colour-coded relevance matrix consistent with the SML; and (iv) a structured review of the impacts of conventional and low-impact remediation techniques on soil functions, highlighting trade-offs between risk reduction and long-term soil functionality.

The deliverable further illustrates how soil health can be operationally incorporated into regional-scale risk assessment for diffuse contamination. These applications demonstrate how soil health information can support prioritisation and preventive management by identifying areas where contamination risks overlap with high soil functional value, while acknowledging current limitations in harmonised, georeferenced datasets.

Overall, this deliverable provides policy-relevant conceptual guidance and supporting tools to promote more holistic and resilient contaminated land management practices across Europe. The framework developed is designed to be transferable across Member States and adaptable to different regulatory and data contexts. Detailed site-scale applications and remediation option testing are addressed in complementary ISLANDR work packages and deliverables, where the concepts presented here will be further operationalised and validated.

Keywords

Soil health, soil functions, remediation, land use, risk assessment

Abbreviations and acronyms

Acronym	Description
C&D	Communication & Dissemination
CSC	Contamination Threshold Concentrations
D	Deliverable
DSS	Decision Support Systems
EJ	Expert judgement
EPFs	Ecological Production Functions
ERA	Ecological Risk Assessment
ES	Ecosystem Services
ESDAC	European Soil Data Centre
EUSO	European Soil Observatory
GRO	Gentle Remediation Options
IR	Integrated Risk
ISCO	In-situ chemical oxidation
ISCR	In-situ chemical reduction
ITA	ISLANDR Testing Area
LoE	Lines of Evidence
LIRT	Low-impact remediation techniques
MCDA	Multi-Criteria Decision Analysis
MNA	Monitored Natural Attenuation
NSZD	Natural Source Zone Depletion
nZVI	zero-valent iron nanoparticles
SML	Soil Monitoring Law
SOC	Soil Organic Carbon
SOM	Soil organic matter
S-P-R	Source-Pathway-Risk
WP	Work Package

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1. Introduction

The European Soil Mission aims to transition towards healthy soils by 2030, by setting up Living Labs and dedicated research programs. The EU soil strategy, first elaborated in 2006 and relaunched in 2021 provides a framework for more sustainable soil management by 2030, which is supported by the *Directive on Soil Monitoring and Resilience*[1] (from now on referred as Soil Monitoring Law; SML), adopted in 2025. As a key component of the *EU biodiversity strategy for 2030*, it contributes to the objectives of the *European Green Deal* helping define goals and indicators for measuring soil health and sustainability.

The European Directive aims to achieve healthy soils across the entire European territory by 2050. All types of soil degradation and all soil categories are included (urban, industrial, agricultural, natural areas). The text is structured around three main pillars: monitoring (Chapter 2), resilience (Chapter 3), and management of contaminated sites (Chapter 4). Each Member State must transpose the directive into national law by December 2028.

Member States will need to structure their territory into soil districts and homogeneous soil units, which will serve as reference levels for assessing soil status and monitoring soil quality. In addition to the usual management of contaminated sites—diagnosis, risk assessment, and remediation—objectives for soil health at district and unit levels must now be integrated. This ensures that remediation actions not only manage health risks according to land use and control sources and transfers but also contribute to achieving soil health objectives defined at the territorial scale.

The SML introduces a monitoring of soil health based on soil descriptors (physical, chemical, and biological parameters) linked to non-binding sustainable target values at the EU level (Annex I – Part A), reflecting long-term objectives. Member States must set operational trigger values for each soil descriptor listed in Part B (Annex I) to prioritize actions and progressively implement sustainable soil management measures leading to good soil health. Additionally, Member States must collect descriptors/indicators from Part C (Annex I) for simple monitoring purposes, without mandatory thresholds.

Beyond monitoring, Chapter 3 and Article 11 focus on soil resilience for managed soils, defined as soils subject to management practices. These practices must be adapted to improve soil health and resilience, considering local pedological conditions (Article 11, paragraph 1, point d).

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[1] https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_3637; https://www.euronews.com/green/2024/04/11/soil-protection-law-survives-plenary-vote-but-considerably-weakened

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Member States must also assess expected effects on soil health and resilience of actions implemented under programs, plans, objectives, and measures listed in Annex III.

1.1. What is soil health?

1.1.1. Concepts

The term *soil health* has evolved over the last decades from a narrow agronomic concept into a broader umbrella that links soils to food security, biodiversity and climate resilience. Early work by Doran described soil health as the ability of soil to function as a vital, living system that sustains productivity, maintains or enhances environmental quality and supports plant, animal and human health (Doran 1994).

There is a broad understanding that soils are not just a source to grow crops, as they also support other ecosystem services (ES). The debate on soil health highlighted that it is not enough to know the amount of a given element in soil; what matters is how soil properties jointly determine functions such as biomass production, nutrient cycling, water regulation and carbon storage (Bünemann 2018). Soils are, therefore, a critical contributor to maintain local and global environmental quality (Rinot 2019).

The recently adopted SML, is underpinned by the concept of “soil health”, which depends on the biological, chemical, and physical properties that support soil functions. Soil functions result from interactions between biotic and abiotic soil components enabling soil to act as a vital living system and the delivery of ecosystem services is often depicted through a cascade model (Figure 1). This model illustrates how biophysical structures and processes support ecosystem functions, which in turn, generate final services that benefit humans and can be economically valued. The (bundles of) soil processes that drive ecosystem services delivery (Bünemann 2018) play a crucial role in this dynamic. At the site level, 6 soil functions are prevalent: organic matter storage, transformation and recycling; water regulation, retention and release; nutrient cycling; contaminants retention, transformation and degradation; physical stability and habitat provision. At a bigger scale in time and space they contribute to air quality, climate regulation or even pedogenesis. Although soils have traditionally been overlooked in ecosystem service classifications, various frameworks have been developed to assess soil-based ecosystem services.

Soil ecosystem services rely on functional processes and properties, where their provision is generally seen as a stepwise process (Haines 2010; Potschin 2016). This is often illustrated by a cascade model, where biophysical structures and processes support

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ecosystem functions (intermediate services), which in turn generate final services that benefit humans and can be economically valued (see Figure 1 for soil examples). Soils have traditionally been neglected in ecosystem service classification and assessment methods such as the Common International Classification of Ecosystem Services, CICES (Haines 2018), though many frameworks and typologies have been developed for soil-based ecosystem services (e.g., Adhikari 2016; Jónsson 2016). Soil ES have been taken up in policy: the EU Soil Strategy for 2030 defining healthy soils as those that are able to provide essential ecosystem services and aims for all EU soils to be in good condition by 2050.

Changes in ecosystem functions influence the potential supply of ecosystem services. (Soil) ecosystem services can contribute strongly to obtaining societal challenges and needs e.g. the Global Sustainable Development Goals (SDGs) (Keesstra 2016).

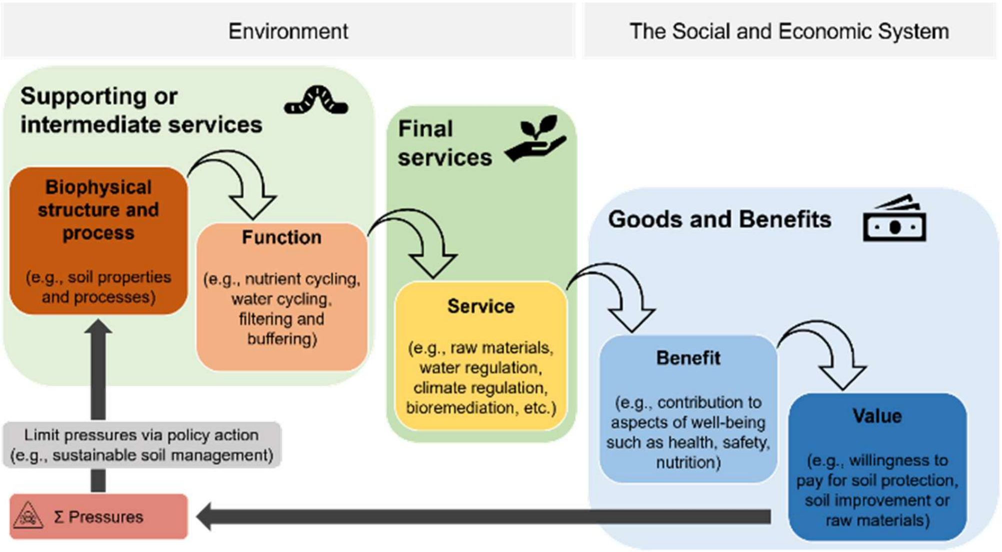

Figure 1. The cascade model, adapted from (Haines 2010), and modified for the soil environment based on (Greiner 2017).

1.1.2. Indicators

A functional approach to soil health assessment generally uses a quantitative, multi-parametric approach with soil quality indicators (or 'descriptors') – describing a physical, chemical, or biological characteristic of soil health (EC 2023). These indicators act as proxies for soil properties and processes linked to key soil functions and ecosystem services (Bünemann 2018; EC 2023). However, selecting relevant indicators for specific contexts and interpreting results to classify soil as 'healthy' remains challenging.

Many attempts have been made to develop a comprehensive method for evaluating soil health. While monitoring soil descriptors helps in diagnosing conditions across different

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land covers, defining a minimum dataset of descriptors that best reflect key soil functions is complex.

Selecting relevant indicators and interpreting results to classify soil as 'healthy' remains a challenge. These indicators fall into three categories:

Physical: (e.g., soil erosion rate, water holding capacity and bulk density) influence water retention, root penetration, and aeration, all vital for plant growth.

Chemical: (e.g., soil acidity (pH), nutrient content, organic carbon, electrical conductivity, heavy metals, contaminants, buffering / adsorption / retention capacity) provide insight into soil fertility, toxicity and nutrients availability.

Biological: (e.g., DNA metabarcoding for fungi and bacteria, basal respiration) reflect biological activity, organic matter content and nutrient cycling, influencing soil structure.

On one hand there is a clear trend towards i) the definition of minimum data sets (MDS) that cover the most critical physical, chemical and biological indicators, ii) the interpretation of indicators in terms of soil functions, and iii) the introduction of new biological tools to assess soil biodiversity. However, there is also a move from single-parameter, agronomy-focused assessments towards multi-indicator, function- and risk-oriented frameworks that align monitoring, modelling and policy at EU scale. Building on these foundations and compromise between measures of indicators with associated costs and their interpretation sometime lacking referential. More recent work treats soil health as an integrative property that reflects the capacity of the soil to respond to management and environmental change while continuing to deliver multiple ecosystem services. Research efforts have been made to review and suggest structures for soil health indicators[2] (Bünemann 2018, Cousin 2025).

1.1.3. Monitoring

Although the EU is moving towards a common soil health framework, until now Member States started from different historical traditions and institutional setups. As a result, national soil monitoring schemes differ from each other and vary in terms of objectives, design, indicator sets and sampling frequency.

Alongside these national systems, the LUCAS Soil module provides the only EU-wide harmonised soil survey, since it covers the entire territory of the European Union, addressing all major land use types simultaneously, in a single sampling period. It has

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[2] https://www.isqaper-is.eu/

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collected around 100 000 samples across the EU (2009, 2015, 2018 and 2022), analysed in laboratory with a standard protocol, creating a consistent baseline for physical and chemical properties as well as, more recently, for biodiversity and pesticide residues (EC, ESDAC 2026).

The current challenge is to connect national monitoring schemes and EU initiatives into a harmonised system. The EU Soil Observatory (EUSO) already hosts reference data about EU soils namely common indicators on soil erosion, soil carbon and soil nutrients. As a complement, the SML wants to pave the way for healthy soils by 2050. It aims to make soil health monitoring obligatory, provides harmonised guiding principles for sustainable soil management and addresses situations where soil contamination poses unacceptable health and environment risks. By requiring Member States to address key soil threats and to assess and monitor soil health, it fosters the design of national monitoring networks that deliver data compatible with an agreed EU indicator set. The idea is to attain an approach that focuses primarily on a core set of indicators and minimum quality criteria (but still allowing for some flexibility, e.g. extra indicators).

1.2. Why should soil health be considered in contaminated land management?

Current contaminated land management primarily focuses on sanitary risk and human exposure when defining future land use. However, soil health and the ecotoxicity of residual contaminants should also be considered as they influence both land-use decisions and remediation strategies. Healthy soils are essential for climate neutrality, a clean and circular economy and preventing land degradation. They are also essential to reverse biodiversity loss, provide healthy food and safeguard human health.

Increasingly the intrinsic value of soil ecosystem services to society as a whole is driving soil health policy in Europe, and the direction of travel in Europe is towards securing widescale improvement in soil health, for example, to preserve and extend soil carbon stocks. Low-impact remediation, such as nature-based solutions utilising plants, bacteria, fungi, and soil amendments, can improve soil health. Soil health is crucial for achieving multiple societal goals such as climate neutrality, a clean and circular economy, and preventing land degradation. Healthy soils are essential for reversing biodiversity loss, providing healthy food, and safeguarding human health. Hence, the concept of soil health is fundamental to the European Soil Mission and the recently adopted SML.

The application of soil health assessment to contaminated land remains limited in contaminated land management practices. However, integrating broader soil health

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assessments into contaminated land management is essential for better decision-making and prioritizing areas for preservation or development (Blanchart 2018; Volchko 2014, 2019; Derycke 2023, 2024; Séré 2024).

Early collaboration between planning and remediation experts enables a coordinated approach, aligning remediation with site redevelopment. Spatial planning strategies should incorporate interim reuse stages promoting multifunctionality within a long-term risk management vision. A stepwise approach helps initiate the transition towards healthier soils by setting realistic, phased goals.

Many attempts have been made to develop a comprehensive method for evaluating soil health. The Soil Mission defines poor soil health as corresponding to "soils poor in organic matter for their type, compacted or contaminated by chemicals such as nutrients, heavy metals, biocide remnants, hormones and medicines at concentrations higher than those allowed by health regulations or plant requirements." According to this definition, contaminated land has no healthy soils, and contaminated soil has long been viewed as waste to be disposed of rather than as a valuable resource to be treated and reused (Gerhardt 2017; Mench 2010), while it can still perform functions to deliver ecosystem services during its transition to new use and a cleaner state. Typically, when the trigger values for contaminant concentrations are exceeded, remediation is legally mandated, but it is important to consider that many remediation techniques can have considerable negative impacts on soil functionality and lead to significant degradation or even destruction of the soil ecosystem that is more damaging than the original contamination (Gerhardt 2017; Swartjes 2011). Instead, soil functioning can also be improved with low-impact, gentle remediation options (GRO) that are nature-based solutions utilising plants, bacteria, fungi and soil amendments to improve soil functionality. Importantly, soil (chemical, physical and biological) health is highly site specific, the improvement of soil health will be gradual, and may evolve over time.

A particular challenge posed by soil health policy goals for contaminated sites management is how to balance a desire for transition to “complete” soil health, with its technical feasibility and its cost to society and the environment. ISLANDR’s opinion is that, depending on the nature of the site contamination problem, soil health recovery should be seen as a long-term goal, which may proceed via a number of interim stages. For example, soil recovery so that it can support landscaping or biomass production may be an appropriate and sustainable strategy, whereas recovery to an extent that supports the production of food crops is not.

Selecting relevant indicators and interpreting results to classify soil as 'healthy' remains a challenge, particularly in the context of contaminated land. While monitoring soil

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descriptors helps in diagnosing conditions across different land covers, defining a minimum dataset of descriptors that best reflect key soil functions is complex. Indicator relevance varies by land cover, guiding sustainable management strategies and determining the most appropriate parameters for assessing of remediation effectiveness. To support this, some studies have successfully used quantitative soil quality indices to evaluate the effects of soil remediation techniques on soil health such as phytoremediation (Burges 2016, 2017; Epelde 2014; Mench 2022) and soil amendments like biochar (Bera 2016, Drenning 2024).

1.3. ISLANDR perspectives for soil health integration in contaminated land management

1.3.1. Soil health fit for purpose

The triggers for considering soil health have tended to relate to the needs for soil functionality in the envisaged use of the site. Remediation techniques can have, in some cases, negative impacts on soil functionality, leading to degradation of soil constituents.

Developing a comprehensive method for evaluating soil health involves SML descriptors to diagnose conditions across different land covers. Defining a minimum dataset of descriptors that best reflects key soil functions is complex, with indicator relevance varying by land cover. This guides sustainable management strategies and determines appropriate parameters for assessing remediation effectiveness.

The targets set for recovery of soil health must also take into account the envisaged use of a site. For example, the soil functionality needed beneath a car park is very different to that needed for an urban public park. The consequences of this are:

- The range of remediation approaches available for a car park end use are wider as the soil health demand is less.
- The remediation objectives for the park area need to take account of soil fertility and phytotoxicity, as well as needing to achieve compliance for mitigating risks to human health, groundwater etc., whereas phytotoxicity and soil fertility are not concerns beneath a car park.
- If an aggressive treatment is used for the public park area some form of soil recovery process may be needed, potentially even topsoil importation, which runs counter to circular economy principles and creates sustainability losses such as carbon costs and road traffic.
- If at some point the land use changes and the car park is repurposed as public open space, then soil health requirements will change (as indeed human health risk assessment would change).

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- The public park creates an opportunity for wider value from improving soil health, for example related to soil carbon and soil as a habitat, as well as perhaps an opportunity for wider services such as sustainable urban drainage, where soil function also supports filtration.

1.3.2. Include soil health in the decision-making process

In the ISLANDR approach, soil health is iteratively added along a site management trajectory from initial desk study and site investigation to remediation, verification and post-remediation redevelopment along the main steps outlined in the roadmap developed in the ISLANDR project (see sub-section 2.1). Steps include identifying soil health indicators according to future use and selecting treatments based on initial and target soil health scenarios. The goal of this systematic protocol (see sub-section 2.2) is to enable collecting data to balance soil health requirements for future use with necessary decontamination levels while avoiding further degradation of soil functions (see soil trajectory sub-section 2.3).

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2. Overview

A systematic protocol was developed to guide through the different tools developed within ISLANDR to cover the different needs of soil health integration in contaminated land management (logigrams, ecological risk assessments, indicators matrix).

This report describes the main elements that allow such coherent integration of soil health into contaminated land management:

- Overall adapted protocol for contaminated land management (Chapter 2);
- Soil health investigation and risk assessment (Chapter 3);
- Matching soil functionality with land use (Chapter 4);
- Impact of remediation on soil functions (Chapter 5).

2.1. Soil health entry points into contaminated land management

As shown in Figure 2, ten entry points were identified within the generic contaminated land management process where soil health considerations can be integrated. These entry points broadly correspond to distinct steps or actions in the process and are aligned with the main phases of the ISLANDR roadmap: Identification, Vision/Initiative, Planning, Realisation/Implementation, and Monitoring & Maintenance. This report does not cover all these steps in detail but provide general guidance through the process outlining where the ISLANDR contributions (Chapters 3 – 5) may be applied.

An overview of these soil health entry points and their correspondence with the ISLANDR roadmap phases, as well as the relevant parts of Deliverable D2.3, is provided in Table 1.

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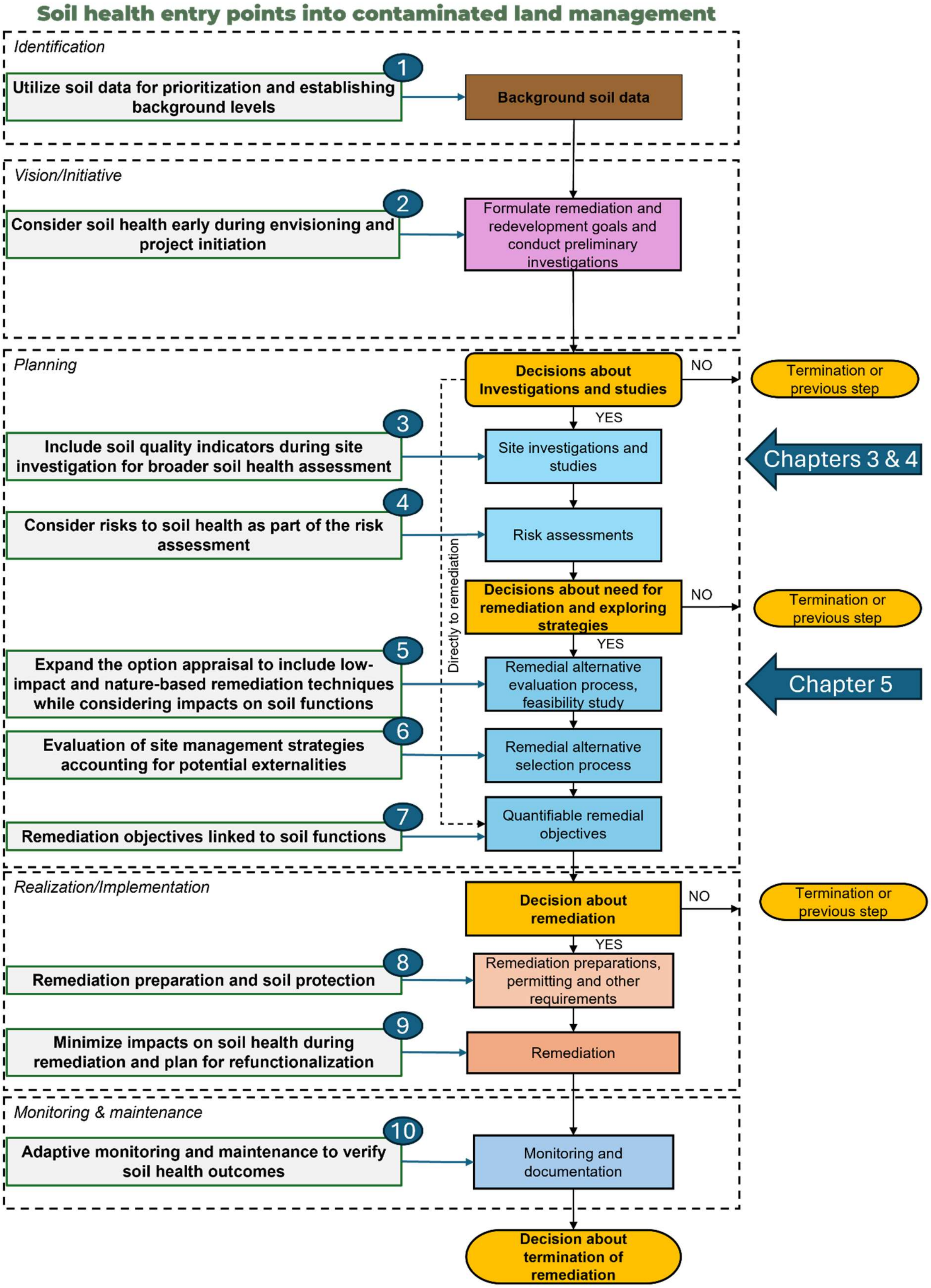

Figure 2. Soil health entry points into contaminated land management

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Table 1. Overview of soil health entry points corresponding to the ISLANDR roadmap phases.

ISLANDR roadmap phases	Soil health entry points	Deliverable D2.3 part
Identification	1. Utilize soil data for prioritization and establishing background levels	WP1 – *D1.4 Roadmap to EUSO*
Vision-Initiative	2. Consider soil health early during envisioning and project initiation	*Chapter 3-4* *soil functionality vs soil use* *including soil health in ecological risk assessment*
Planning	3. Include soil quality indicators during site investigation for broader soil health assessment 4. Consider risks to soil health as part of the risk assessment 5. Expand the option appraisal to include low-impact and nature-based remediation techniques while considering impacts on soil functions 6. Evaluation of remediation techniques and site management strategies should account for potential externalities 7. Remediation objectives linked to soil functions	*Chapter 3-5* *soil functionality vs soil use* *including soil health in ecological risk assessment* *Remediation: Choosing soil trajectories, Choosing remediation techniques*
Realisation	8. Remediation preparation and soil protection 9. Minimize impacts on soil health during remediation and plan for refunctionalization	*Chapter 5* Refining remediation scenarios
Maintenance	10. Adaptive monitoring and maintenance to verify soil health outcomes	*Chapter 3-4* indicators vs soil use including soil health in ecological risk assessment monitoring soil health

The entry points are described briefly below:

1. Using soil data for prioritization and establishing background levels

For improved decision-making regarding soil management, more data regarding both soil contamination (and other degradation) as well as functionality is crucial. These data are necessary to define background concentrations of potentially harmful elements and other hazardous substances and to establish baseline soil quality for comparison and for setting relevant indicator thresholds and remediation goals. By having such data available during the

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early identification phase, planners can identify sites and prioritize action at areas with the greatest risks to human health and the environment for risk management while also preserving or improving soil health at these areas in alignment with comprehensive spatial plans to achieve other goals where soil function plays a critical role such as climate adaption and mitigation, green infrastructure, flood management, etc. ISLANDR WP1 has collected publicly available national and regional datasets serving as geochemical background information and made them available from one address. The ISLANDR metadata catalogue can be accessed in: Metadata catalogue[3] and the data collection process is described in more detail in ISLANDR D1.1.

2. Consider soil health early during envisioning and project initiation

During the early project phases of envisioning future land uses and initiating a project, the remediation and redevelopment goals for a site should highlight soil as a multifunctional resource that should be restored and reused alongside risk reduction instead of as a waste to be disposed of at a landfill. Soil health improvement or preservation may be a wider value of brownfield remediation and redevelopment projects that is important for stakeholders when initiating a project. Also, preliminary site investigations and qualitative risk assessment should consider soil health aspects, e.g., as part of the conceptual site model (CSM) and while formulating remediation targets, and the timeframe for which nature-based solutions may be applicable. The suitability of a site for an envisioned future land use, i.e., fit-for-use, should consider both the required soil functionality and level of risk reduction required. Stated remediation objectives should be linked to the future land use and required soil functionality, adapting the site design and management strategy according to the site-specific conditions while considering the possible negative impacts of remediation and subsequent refunctionalization that may be required.

3. Include soil quality indicators during site investigation for broader soil health assessment (Chapters 3 & 4)

Contaminated site investigations should routinely assess soil parameters in addition to contaminant concentrations. These assessments ought to determine the baseline condition of key soil functions, including organic matter content, structural integrity, water regulation capabilities, and microbial activity, to identify potential vulnerabilities, evaluate recovery prospects, and establish feasible post-remediation uses for the soil. For example, the TRIAD methodology employing different tiers of complexity and lines of evidence (LoE) may be useful to better assess ecological risks to the soil ecosystem as well as functionality. The amount and type of indicators may also vary depending on the future land use. Chapters 3 and 4 explore these considerations in more detail.

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[3] geonetwork.greendecision.eu/geonetwork/srv/fre/catalog.search#/home

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4. Consider risks to soil health as part of the risk assessment

Alongside human health and environmental exposure pathways, the risk assessment should explicitly evaluate how contamination and remedial actions may impair key soil functions (e.g. nutrient cycling, water regulation, habitat provision, organic matter storage), helping to identify unacceptable losses of soil-based ecosystem services even where traditional risk-based contaminant thresholds are met. The development of risk-based thresholds for specific soil functions and indicators or threats can be considered.

5. Expand the option appraisal to include low-input including nature-based remediation techniques while considering impacts on soil functions (Chapter 5)

Option appraisal, including identification and pre-selection of potentially viable alternatives and the systematic evaluation of alternatives to select the most suitable strategy, should be expanded to include low-input including nature-based remediation techniques (Bardos 2026). Also, remediation alternatives should be evaluated based not only on risk reduction, cost, and time, but also on their expected impacts on soil functions, including inhibition or promotion of ecological recovery, allowing options that preserve or restore soil health to be included in the site management strategy by themselves or as part of a treatment chain. The site management strategy should balance trade-offs between risk reduction and soil functionality. There may be different soil health trajectories expected based on the techniques used and future land uses. The impacts of conventional and low-impact remediation techniques on soil functions are explored in more detail and Chapter 5.

6. Evaluation of remediation techniques and site management strategies should account for potential externalities

During option appraisal, the evaluation process should also account for the potential positive and negative externalities from different techniques and the added, wider benefits that may be provided by, for example, nature-based methods. For example, cost-benefit analysis (CBA) could be used to compare techniques based on their overall societal profitability, including externalities, that supports developing business cases for brownfield land, which is covered in more detail in ISLANDR D4.1 and D4.2.

7. Remediation objectives linked to soil functions

In addition to target levels of contamination, remediation objectives should be linked to quantifiable soil quality indicators and soil functions. While specific targets of when a soil is in “good” or “poor” health are still difficult to determine, these metrics should be tracked

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and linked to the project soil health trajectory for a site to achieve the envisioned soil functionality for the future land use.

8. Remediation preparation and soil protection

During remediation planning, soils could be zoned according to their current state of functionality, sensitivity, and intended future use (e.g. biologically active topsoil, subsoil, engineered fill). For each zone, specific requirements could be set for machinery access, excavation depth, stockpiling duration, segregation of soil horizons, moisture control, and reuse or amendment strategies. This ensures that remediation activities achieve contaminant risk reduction while actively safeguarding soil structure, microbial communities, and long-term soil functions needed for post-remediation land use. This type of preparation can also support compliance with regulations such as the SML.

9. Minimize impacts on soil health during remediation and plan for refunctionalization

During remediation, efforts should be made to minimize physical disturbance, extreme temperatures, aggressive chemicals, and other stressors on healthy soils from conventional methods, e.g., by considering a functional approach to remediation by evaluating and mitigating the risks from remediation components to ecological receptors (Burger 2016). Setting soil protection zones and reusing excavated soil should also be applied where possible. Sequential and nature-based remediation, e.g., as part of a treatment chain or soil polishing strategy, should also be considered to mitigate impacts. Rehabilitation or refunctionalization of soil should be treated as an integral part of remediation, rather than an afterthought, with planned interventions such as amendment addition, microbial inoculation, revegetation, or soil mixing to restore soil organic matter, nutrients, etc. that determine functionality and hasten the recover process.

10. Adaptive monitoring and maintenance to verify soil health outcomes

Employ adaptive monitoring and maintenance to ensure compliance and that goals are met regarding both risk reduction and soil functionality. Post-remediation verification should include indicators of soil functional recovery alongside regulatory compliance regarding contaminant levels, particularly where ecological soil reuse is intended. Soil health outcomes should be monitored over time, enabling adaptive management where recovery is slower or uneven, and ensuring that redevelopment and land management practices do not undermine restored soil functions (also connected to deliverable 3.2).

2.2. Framework for selecting contaminated site management strategies for optimising soil health

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A framework to support soil health management within contaminated land management is presented in Figure 3. This framework was developed to guide soil health management throughout the contaminated land management showing how the different entry points detailed separately in the following chapters (Chapters 3 to 5) complement each other and interact through the general process.

The flowchart provided below (Figure 3, steps 1-7) shows several key steps in the workflow for selecting remediation techniques starting from the project initiation and envisioning stage, where future land uses are considered, then matched with the requisite soil functionality and corresponding soil descriptors to assess the soil health of the site. This connects to the site investigation and risk assessment, which should be carried out together with a soil health assessment, to determine contaminants of concern, primary risks to be managed, and the current soil functionality. A list of possible remediation and rehabilitation methods can then be collected and checked against the matrix of impacts of conventional and low-impact remediation techniques to select the remediation techniques most suitable for the situation while considering the possibility for minimizing impacts to preserve soil functionality using low-impact methods and/or planning for refunctionalization following remediation. Considering the steps in this workflow as part of the contaminated land management process should result in a refined choice of remediation method that accounts for both risk reduction and soil functionality.

The framework general aim is to support managing both soil health and soil contamination through the following steps:

- (1) selection of soil indicators matching the intended land use;
- (2) reaching out to soil functionalities according to land use;
- (3-4) establishing targets for both contamination and soil health through risk assessment;
- (5) identify suitable remediation strategies;
- (6) identify remediation techniques’ impact on soil functions;
- (7) refining soil use scenarios and remediation strategies.

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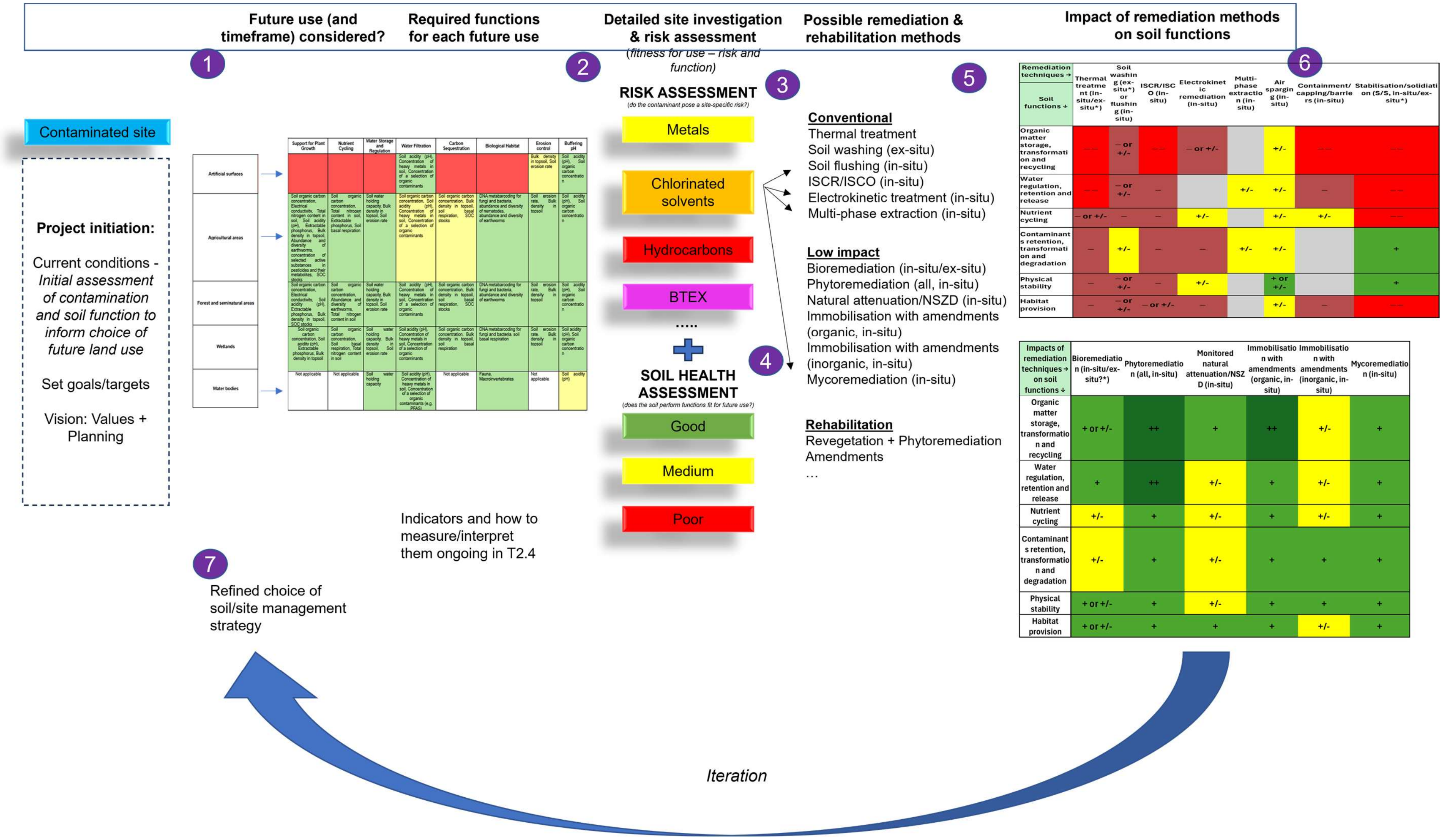

Future use (and timeframe) considered?

Required functions for each future use

Detailed site investigation & risk assessment (fitness for use – risk and function)

Possible remediation & rehabilitation methods

Impact of remediation methods on soil functions

Contaminated site

Project initiation:

Current conditions - *Initial assessment of contamination and soil function to inform choice of future land use*

Set goals/targets

Vision: Values + Planning

① ②

	Support for Plant Growth	Nutrient Cycling	Water Storage and Regulation	Water Filtration	Carbon Sequestration	Biological Habitat	Erosion control	Buffering pH
Artificial surfaces	🟥	🟥	🟥	Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	🟥	🟥	Bulk density in topsoil, Soil erosion rate	Soil acidity (pH), Soil organic carbon concentration
Agricultural areas	Soil organic carbon concentration, Electrical conductivity, Total nitrogen content in soil, Soil acidity (pH), Extractable phosphorus, Bulk density in topsoil, Abundance and diversity of earthworms, concentration of selected active substances in pesticides and their metabolites, SOC stocks	Soil organic carbon concentration, Total nitrogen content in soil, Extractable phosphorus, Soil basal respiration	Soil water holding capacity, Bulk density in topsoil, Soil erosion rate	Soil organic carbon concentration, Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	Soil organic carbon concentration, Bulk density in topsoil, soil basal respiration, SOC stocks	DNA metabarcoding for fungi and bacteria, abundance and diversity of nematodes, abundance and diversity of earthworms	Soil erosion rate, Bulk density in topsoil	Soil acidity (pH), Soil organic carbon concentration
Forest and seminatural areas	Soil organic carbon concentration, Electrical conductivity, Soil acidity (pH), Extractable phosphorus, Bulk density in topsoil, SOC stocks	Soil organic carbon concentration, Abundance and diversity of earthworms, Total nitrogen content in soil	Soil water holding capacity, Bulk density in topsoil, Soil erosion rate	Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	Soil organic carbon concentration, Bulk density in topsoil, soil basal respiration, SOC stocks	DNA metabarcoding for fungi and bacteria, abundance and diversity of earthworms	Soil erosion rate, Bulk density in topsoil	Soil acidity (pH), Soil organic carbon concentration
Wetlands	Soil organic carbon concentration, Soil acidity (pH), Extractable phosphorus, Bulk density in topsoil	Soil organic carbon concentration, Soil basal respiration, Total nitrogen content in soil	Soil water holding capacity, Bulk density in topsoil, Soil erosion rate	Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	Soil organic carbon concentration, Bulk density in topsoil, soil basal respiration	DNA metabarcoding for fungi and bacteria, soil basal respiration	Soil erosion rate, Bulk density in topsoil	Soil acidity (pH), Soil organic carbon concentration
Water bodies	Not applicable	Not applicable	Soil water holding capacity	Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants (e.g. PFAS)	Not applicable	Fauna, Macroinvertebrates	Not applicable	Soil acidity (pH)

Indicators and how to measure/interpret them ongoing in T2.4

③ **RISK ASSESSMENT**

(do the contaminant pose a site-specific risk?)

Metals

Chlorinated solvents

Hydrocarbons

BTEX

.....

\+

④ **SOIL HEALTH ASSESSMENT**

(does the soil perform functions fit for future use?)

Good

Medium

Poor

⑤

Conventional

Thermal treatment
Soil washing (ex-situ)
Soil flushing (in-situ)
ISCR/ISCO (in-situ)
Electrokinetic treatment (in-situ)
Multi-phase extraction (in-situ)

Low impact

Bioremediation (in-situ/ex-situ)
Phytoremediation (all, in-situ)
Natural attenuation/NSZD (in-situ)
Immobilisation with amendments (organic, in-situ)
Immobilisation with amendments (inorganic, in-situ)
Mycoremediation (in-situ)

Rehabilitation

Revegetation + Phytoremediation
Amendments
…

⑥

Remediation techniques → / Soil functions ↓	Thermal treatment (in-situ/ex-situ*)	Soil washing (ex-situ*) or flushing (in-situ)	ISCR/ISCO (in-situ)	Electrokinetic remediation (in-situ)	Multi-phase extraction (in-situ)	Air sparging (in-situ)	Containment/ capping/barriers (in-situ)	Stabilisation/solidiation (S/S, in-situ/ex-situ*)
Organic matter storage, transformation and recycling	– –	– or +/-	– –	– or +/-		+/-	– –	– –
Water regulation, retention and release	– –	– or +/-	–		+/-	+/-	–	– –
Nutrient cycling	– or +/-	–	–	+/-		+/-	+/-	– –
Contaminants retention, transformation and degradation	–	+/-	–	–	+/-	+/-		+
Physical stability	–	– or +/-	–	+/-		+ or +/-		+
Habitat provision	–	– or +/-	– or +/-	–		+/-	–	– –

Impacts of remediation techniques → on soil functions ↓	Bioremediation (in-situ/ex-situ?*)	Phytoremediation (all, in-situ)	Monitored natural attenuation/NSZD (in-situ)	Immobilisation with amendments (organic, in-situ)	Immobilisation with amendments (inorganic, in-situ)	Mycoremediation (in-situ)
Organic matter storage, transformation and recycling	+ or +/-	++	+	++	+/-	+
Water regulation, retention and release	+	++	+/-	+	+/-	+
Nutrient cycling	+/-	+	+/-	+	+/-	+
Contaminants retention, transformation and degradation	+/-	+	+/-	+	+	+
Physical stability	+ or +/-	+	+/-	+	+	+
Habitat provision	+ or +/-	+	+	+	+/-	+

⑦

Refined choice of soil/site management strategy

Iteration

Figure 3. Framework to support soil health management within contaminated land management

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2.3. Soil health trajectories

A remediation target is usually set according to a level of risk considered suitable for a certain land use (residential, industrial, etc.), provided sources and transfer of pollution are under control. Soil health level and soil multi-functionality are also very much dependent on land use. Remediation techniques lie therefore at the crossroads between the need to manage human health risks and the need to manage soil health, sometimes necessitating the inclusion of soil refunctionalization methods after application of pollution treatment techniques. This is illustrated in Table 2 where, for a foreseen land use, a more-or-less high level of remediation and hence risk reduction intensity will be privileged, with typical consequences on soil functionality.

Table 2. Illustration of the "Soil Health–Risk" balance of needs.

Foreseen land use	**Need for speed**	**Need for Risk Reduction**	**Need for broad Soil Functionality**	**Example Methods**
Residential redevelopment	High	Very High	Low	Thermal desorption, soil washing
Mixed-use or green infrastructure	Medium	Moderate	Moderate	Bioremediation, chemical oxidation
Brownfield greening	Low	Low	High	Phytoremediation, monitored natural attenuation

The concept is further illustrated in Figure 4 which shows several "remediation trajectories" depending on land use objectives. For a given situation of contaminated land, if the projected land use is industrial (trajectory 1), with low risk of exposure to soil pollutants, it may be acceptable to implement a technique such as chemical oxidation to mitigate risk, albeit slight deterioration of soil functionality. In the event of the creation of a car park (remediation trajectory 2), thermal desorption may be the preferred method, leading to enhanced decontamination but with detrimental impacts on soil functions, since thermal desorption (heating up to 350°C) leads to the destruction of soil organic matter and microbiota (Liao 2025, O'Brien 2018) and to the relative collapse of soil structure (soil becomes an inert mineral substrate). Remediation trajectory 3 considers the creation of an urban park and therefore refunctionalization is required to restore functionality such as support for plant growth. Trajectory 4 has the same soil use objective as trajectory 3 but opts for bioremediation. While high levels of decontamination may be achieved, the disadvantage of this method may be the time required to achieve decontamination, compared with thermal desorption. On the other hand, bioremediation will tend to preserve soil structure and biological functions and will have a lower cost and carbon footprint than thermal desorption. The final remediation trajectory (5) reduces the

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mobility of the contaminants but stabilizes them in the soil. This is selected here considering the land use objective of biofuel production, which warrants less stringent measures of health risk reduction.

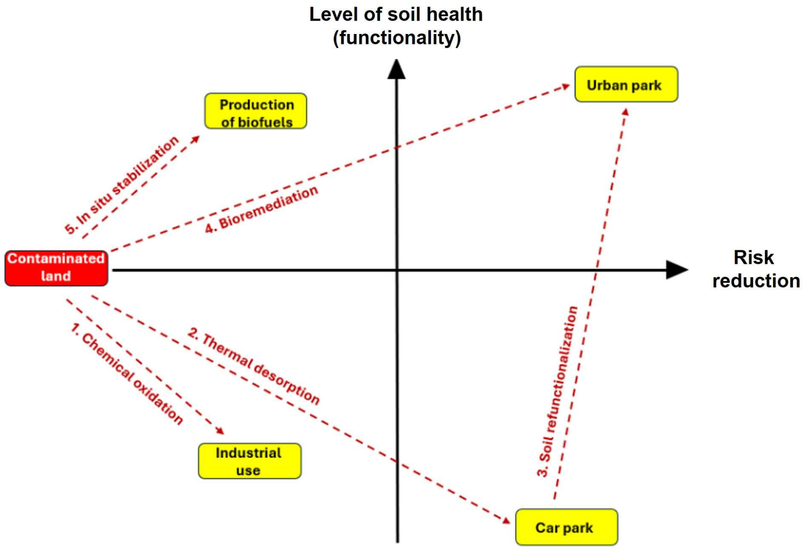

Figure 4. Illustration of different remediation trajectories as a function of foreseen land use.

3. Site investigation for soil health and risk assessment

3.1. Site investigation – contaminants, soil health, TRIAD

Site investigation and risk assessment are organised around a proposed updated TRIAD framework (Figure 5). The idea is straightforward: to measure not only contaminant concentrations, but to look also at soil functions and living communities and then integrate all this information into a transparent ecological risk assessment (ERA).

The principal strengths of the TRIAD approach lie in its inclusion of in situ and ecological data, its adaptable nature, and its focus on transparent analytical methods, accounting for uncertainty during weighting and integration of the three LoE (Grassi 2022), namely chemical, ecotoxicological and ecological. Another main advantage lies in its three-tiered structure, based on the principle 'simple when possible, complex when needed'. At higher tiers, when justified, the assessment becomes more site-specific, more extensive and time-consuming, and consequently, more reliable and less conservative.

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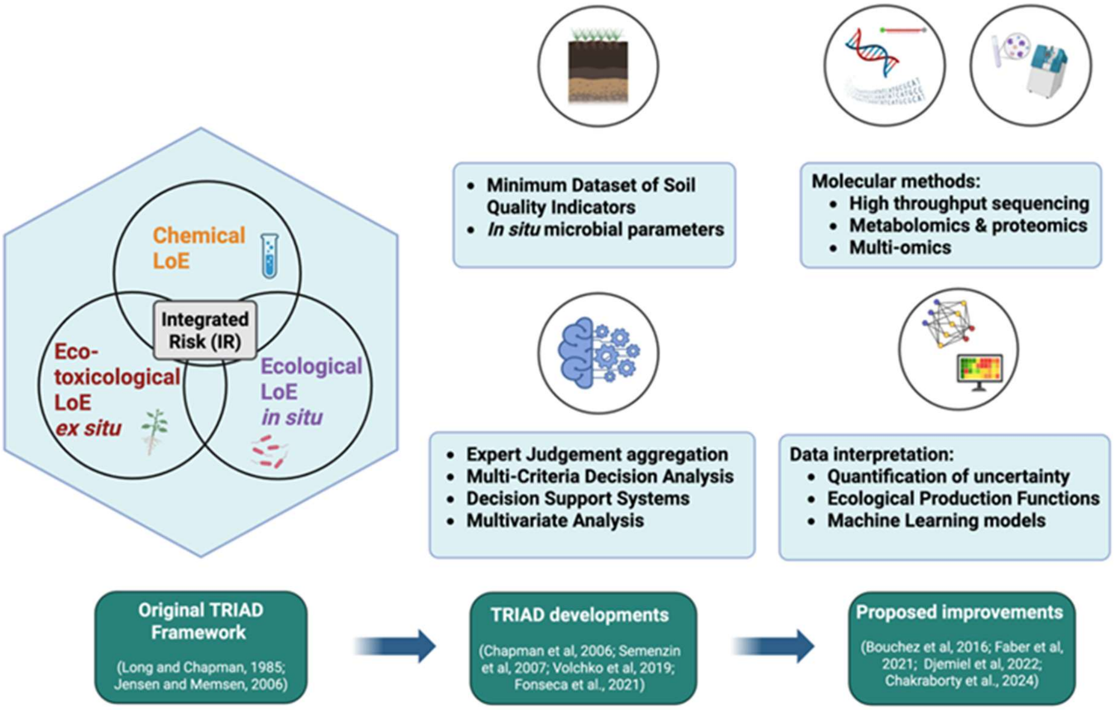

Figure 5. Graphical Abstract depicting the basis of TRIAD-based Environmental Risk Assessment (ERA), current developments, and proposed improvements to update the framework, enhancing ecological relevancy and accuracy.

The TRIAD approach combines three LoE (Figure 6). The first one, Chemical LoE is a site-specific TRIAD assessment that includes testing for bioavailability of contaminants within a field sample through i) reagent extractions, providing insights into readily available fractions, or ii) through sequential extractions, offering a detailed understanding of contaminant partitioning and potential long-term release, vital for assessing bioavailability and informing remediation strategies. In a simpler way, what contaminants are present, in which forms, and how bioavailable they are. The second one, Ecotoxicological LoE analyses how organisms react to contaminated soil under controlled test conditions. Finally, the third one, Ecological LoE, analyses how the real soil community and its functions respond *in situ.*

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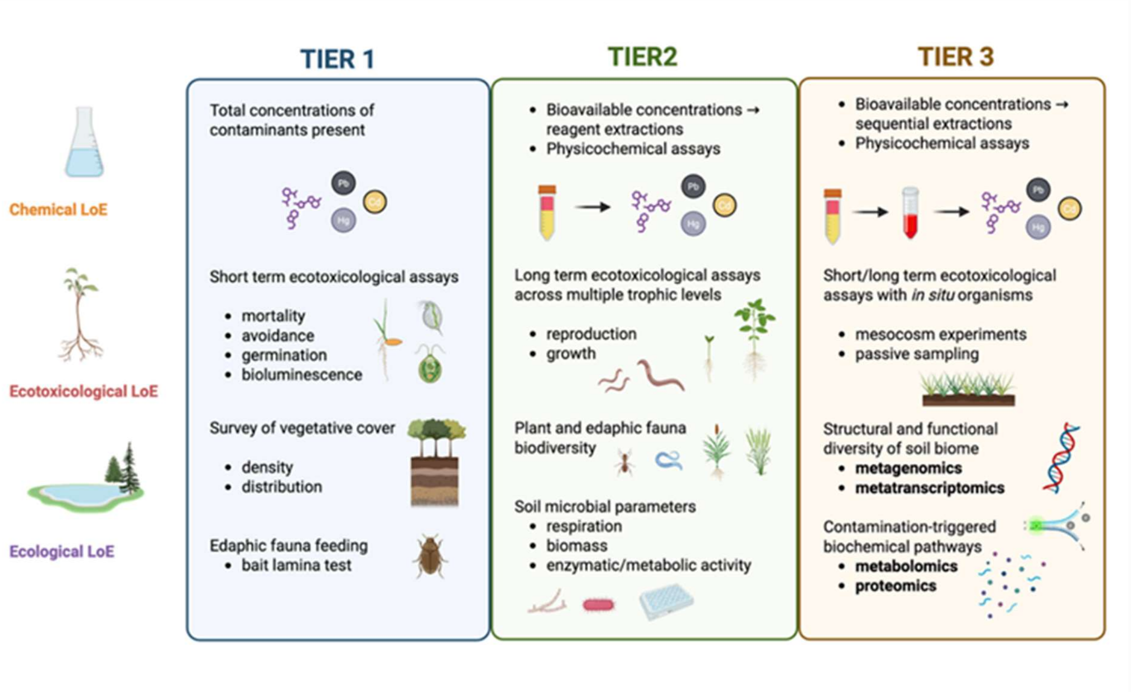

Figure 6. The Tiered TRIAD framework, incorporating soil microbial parameters used in tier 2/3 TRIAD (Niemeyer 2015, Klimkowicz-Pawlas 2023) but not included in the ISO 19204:2017 protocol. Meta-omic techniques, in bold, have been widely used for contaminant assessment; however, thus far, there is only one known case of implementation in tier 3 TRIAD (Gutiérrez 2015, Grassi 2022).

These three LoE are then combined through explicit weighting and integration rules to obtain an Integrated Risk (IR) value for the site. New elements proposed in the updated TRIAD framework include MDS of soil quality indicators, structured expert judgement, meta-omics and machine learning, so that the assessment becomes more site-sensitive and more reproducible.

For that, TRIAD applies different measurement methods. The strategy is to follow the tiered TRIAD logic: start simple and expand the toolbox when risks or uncertainties justify it. Across all tiers, conventional measurements are combined with advanced methods, when justified.

In more detail, in the Chemical line of evidence it is analysed: i) total concentrations of priority contaminants (e.g. heavy metals, PAHs, emerging chemicals); ii) bioavailable fractions, using single or sequential extractions, to capture the fraction that can actually reach organisms; iii) physicochemical assays supporting soil properties (*e.g.* soil acidity (pH), soil organic carbon concentration) that control contaminant mobility and bioavailability. Together, these data allow the estimation of toxic pressure and the comparison with guidelines/benchmark values (having in consideration that chemical thresholds alone are not sufficient to assess risk).

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In the Ecotoxicological line of evidence, standardised bioassays are used to measure short- and long-term effects. These assays deliver clear and quantitative endpoints (e.g. survival, growth, reproduction) that can be directly linked to contaminant exposure.

Finally, in the ecological line of evidence, there's a shift from classical indicators to omics, with a focus on what happens in the field, including soil structure, vegetation, and especially soil biota and functions. Classical indicators include, e.g., simple functional tests (e.g. bait lamina test), soil microbial respiration, biomass and enzyme activities. Since these classical indicators often lack sensitivity, we propose the updated TRIAD framework, which actively promotes omics-based methods as additional tools in higher tiers: i) metagenomics; ii) metatranscriptomics; iii) metabolomics and iv) proteomics.

These methods are particularly useful to determine subtle or early effects (not detected in standard bioassays), distinguish contamination effects from other stressors, identify potential "key taxa" or functional genes that can be used as biomarkers or even as candidates for bioremediation. In practical terms, omics are not used at every site or in every tier. They are targeted to tier 2 or tier 3 assessments where decisions are complex, where multiple contaminants interact, or where we need a high level of ecological detail to support management.

For each LoE, raw data (e.g. concentrations, growth rates) are first transformed into indicator scores that have a comparable scale, typically between 0 (no risk) and 1 (high risk). For omics data, multivariable analyses are used to reduce complexity and to identify patterns, enabling to be summarized into a set of omics-based indicators.

The core of the updated TRIAD framework is how to interpret and integrate the results into a coherent risk statement for the site (Figure 7). One of the main challenges is the role of expert judgement (EJ) and how to decide which indicators to use, how to weight them, how to treat uncertain or conflicting results. The updated TRIAD framework aims to tackle these challenges by proposing the use of structured EJ protocols, applying multi-criteria decision analysis (MCDA) and tracking uncertainty at each stage. These improvements would ease the comparison of assessments between sites and over time.

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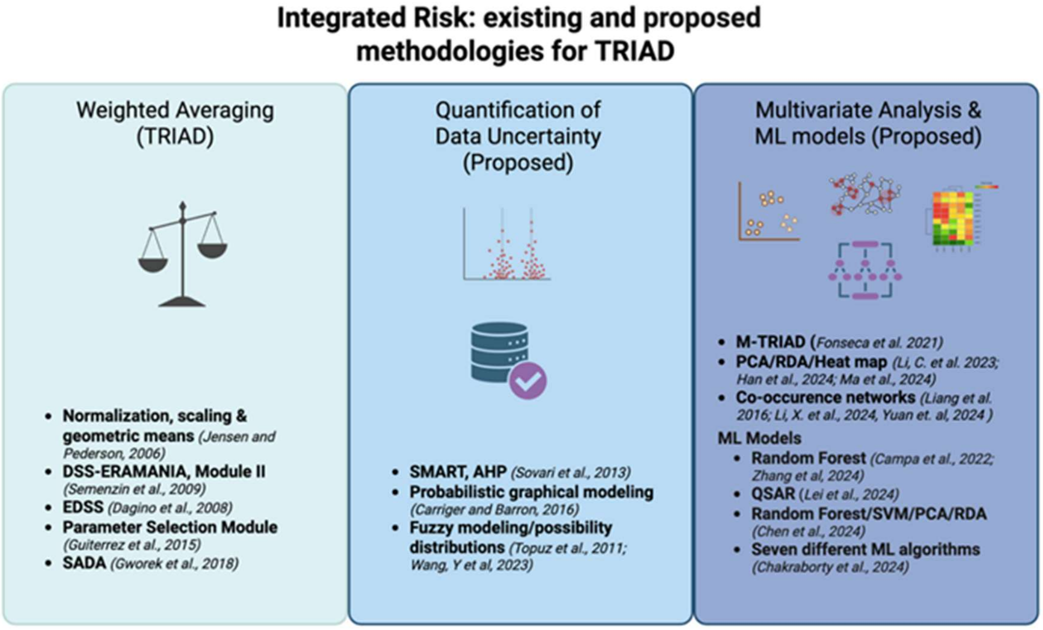

Figure 7. An overview of existing and proposed methodologies for weighting and integrating LoE data and tracking uncertainty for TRIAD IR calculation. Multivariate analyses are widely used in environmental contamination studies; machine learning models are increasingly used- however these mathematically rigorous methods have not yet been developed for TRIAD DSS software, with the exception of the M-TRIAD framework (Fonseca 2021).

Once the indicators are normalised and weighted, the three LoE are combined into an IR score. Within each LoE, individual indicators are combined using mathematically robust methods that preserve relationships between variables and limit the influence of outliers. The ecological LoE often receives higher weight, due to its direct link to ecosystem functioning and soil health. However, different weighting schemes may be tested to check the robustness of conclusions. More advanced implementations use multivariate distance-based approaches and machine learning to integrate the LoE, especially when omics data are included. These tools can identify clusters of sites, response gradients and key predictors of risk.

Ecological risk assessment is not only about declaring a site “safe” or “unsafe”. The goal is to understand how contaminants affect soil functions and ecosystem services, and what this means for the intended future land use. In practice, this assessment should encompass:

- Associating TRIAD indicators to key soil functions (e.g. nutrient cycling, carbon storage, biodiversity).

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- Using omics data to identify sensitive functions (e.g. suppression of microbial networks, disruption of plant–microbe interactions).
- Translating IR and functional impacts into clear management recommendations: no action / monitoring only (where risk is low and soil functions are preserved); targeted management (e.g. organic amendments, vegetation changes; where functions are impaired but remediation is feasible); more intensive remediation or restrictions on land use (when high risks to ecosystem services or human health are identified).

The use of MDS of soil quality indicators and Ecological Production Functions (EPFs) can help quantify how changes in indicators translate into gains or losses in ecosystem services. This improves communication with non-specialists and links ecological risk assessments (ERA) directly to policy and planning.

Overall, the implementation of the updated TRIAD framework brings together classical monitoring, omics technologies and transparent decision tools (Figure 8). It offers a coherent way to evaluate contaminated soils in terms of soil health, ecosystem services and practical land-use decisions.

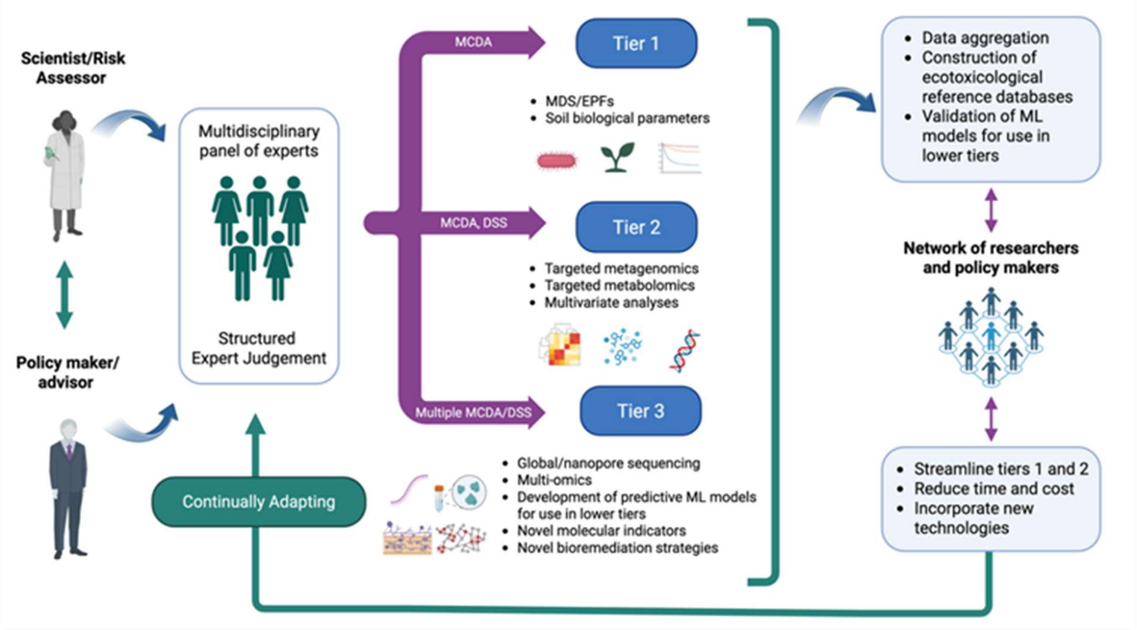

Figure 8. Flowchart for implementing the Updated Triad Framework.

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3.2. The impact of contamination in soil parameters – examples

Soil organic carbon (SOC) and nitrogen cycling are both fundamental components of soil health and contribute to ecosystem functioning, but they do not respond in the same way, or on the same timescales, when soils are exposed to contaminants (e.g. heavy metals, pesticides).

SOC is a core indicator in most soil health frameworks and in the EU SML. It is often described as a relatively robust descriptor as stocks usually change over years to decades, strongly driven by climate, land use, and organic inputs. It underpins several key soil functions as it improves, e.g., structure and aggregate stability, increases water-holding capacity, buffers pH and fuels microbial activity. Distinguishing a pollution-driven change from normal year-to-year variation in SOC is difficult unless pollution is extremely severe or long-lasting. In most regulatory and monitoring contexts, SOC is measured according to ISO 10694, which specifies the determination of organic and total carbon after dry combustion, ensuring all carbon is incinerated. This method is widely validated and applicable to a broad range of soil types (ISO 10694:1995).

Nitrogen cycling, in contrast, is mediated by fast-growing microbial communities and is therefore much more dynamic and sensitive to stressors and are increasingly recognised as sensitive indicators of soil degradation and contamination, enabling them to be point out as a reasonably clear and consistent link between pollution and disruptions in nitrogen cycling. Nitrogen cycling encompasses a suite of microbial processes (e.g. nitrification, biological N fixation) (Velthof 2011). These processes are directly responsible for, e.g., providing plant-available nitrogen.

From a risk-based soil health perspective, SOC is a relatively stable anchor for long-term soil health, and nitrogen cycling is a responsive parameter for diagnosing the functional impacts of pollution.

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4. Matching soil functionality to future land use – indicators and functions

Healthy soils deliver a set of distinct functions such as supporting plant growth, cycling nutrients, storing and regulating water, sequestering carbon, hosting biodiversity, controlling erosion and buffering pH. Which of these functions matters most depends strongly on how the land is (or will be) used.

In this project we link soil functions, land-use types (considering when relevant both past and/or future land use) and measurable indicators through two complementary tools: i) a pyramiding scheme showing a MDS of soil indicators per CORINE land cover type (Figure 9); ii) a colour-coded matrix that matches land use, soil functions as well as relevant descriptors and the associated analytical methods and target values, aligned with the EU SML (Table 3).

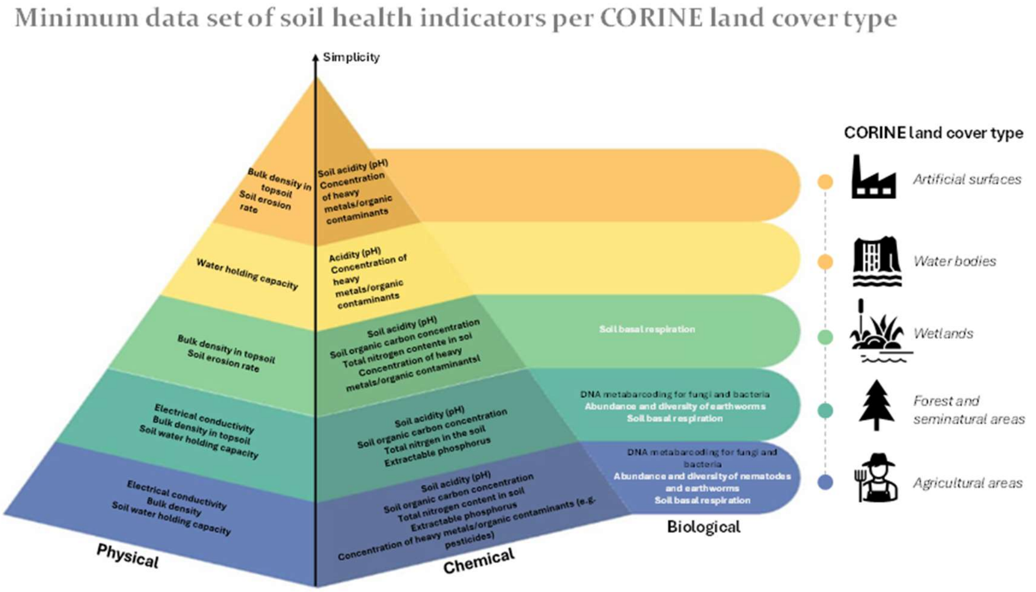

Figure 9. Minimum data set of soil health indicators per CORINE land cover type. Across different land-use types, a coherent core of physical, chemical and biological descriptors is assessed using harmonised methods (based on the SML). This minimum set balances scientific robustness with simplicity, so that monitoring remains feasible in operational contexts. Light gray descriptors in the image are described as optional in the SML.

Together, these elements provide a practical bridge between the concept of soil functionality and concrete monitoring, decision-making and, if needed, remediation.

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Color-coded matrix

The colour-coded matrix (Table 3) is designed as a decision support tool for stakeholders who need to select, for a given site, which soil descriptors are the most relevant to monitor considering the future land use. Rows correspond to broad land-use categories (based on the CORINE land cover type), while columns represent the main soil functions (please see Appendix I for more information).

The colour code assigns a level of relevance to each soil descriptor for a given land use and soil function: Green (high relevance; descriptors that should be monitored as a priority), Yellow (medium relevance; useful where resources allow, or where risks are suspected) and Red (no relevance).

As an example, in agricultural areas, SOC concentration, total nitrogen content in the soil, soil acidity (pH), earthworm abundance and diversity are marked as highly relevant for plant growth and nutrient cycling, while indicators of heavy metals and organic contaminants become relevant under the water filtration function with the means to impact human health and the environment. In artificial surfaces, the focus shifts towards contamination and pH buffering rather than plant production or biodiversity.

In practice, a stakeholder interested in assessing soil health in a particular site should:

- Identify the intended future land-use row in the matrix;
- Start by selecting the green-coded descriptors, particularly for the most relevant soil functions. A value near the threshold value in a green-coded cell for the future land use may deserve higher priority than a similar deviation in a yellow-coded cell.
- Select the recommended methods, compare measured values with the proposed criteria and determine whether the soil can already support the future land use or if any remediation/management is required.

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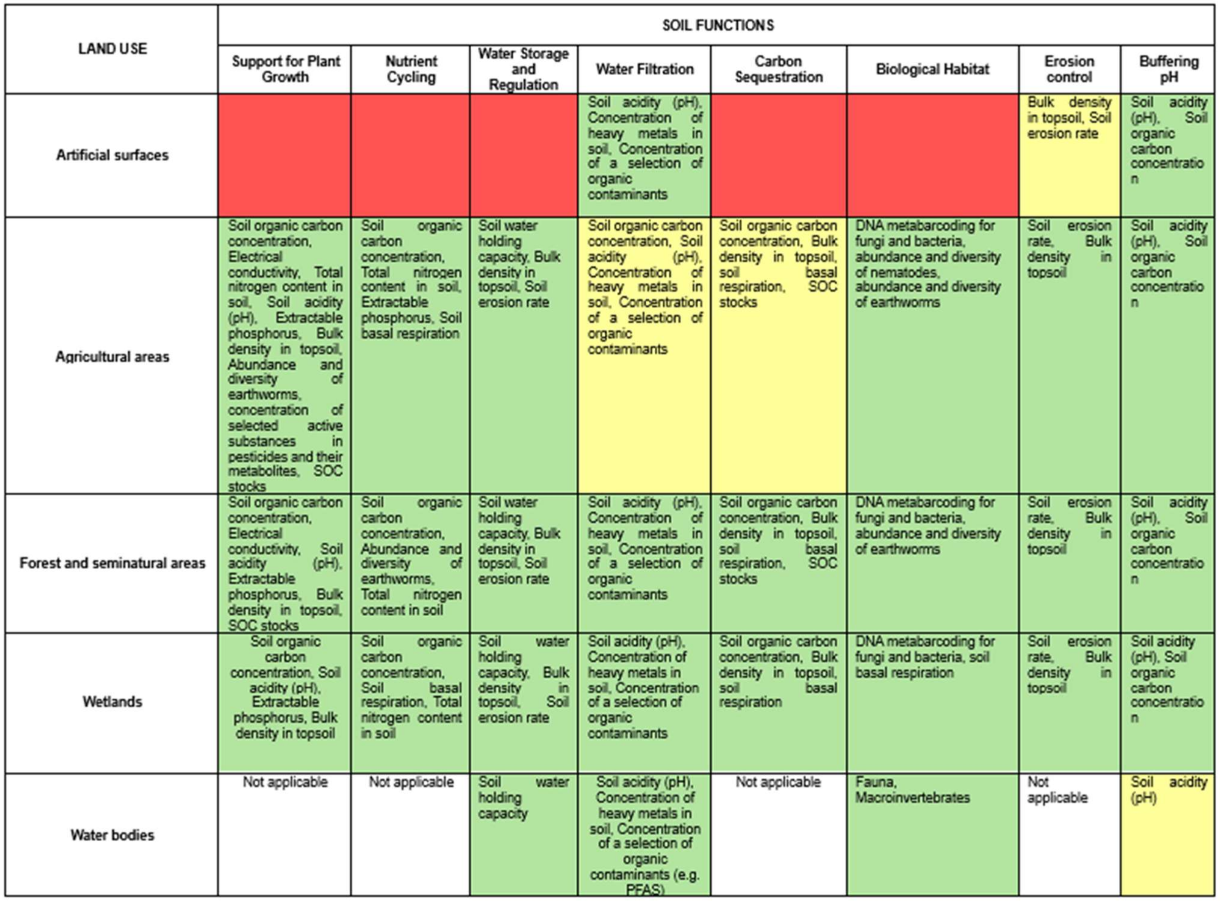
Table 3. Soil descriptors to be assessed to evaluate soil health to each specific land use. The colour code gives the relevance of testing soil descriptors according to the main functions of a specific type of soil (green: high relevance; yellow: medium relevance; red: no relevance; white: not applicable). Stakeholders should address the soil descriptors indicated in green.



LAND USE	SOIL FUNCTIONS							
	Support for Plant Growth	Nutrient Cycling	Water Storage and Regulation	Water Filtration	Carbon Sequestration	Biological Habitat	Erosion control	Buffering pH
Artificial surfaces	🟥	🟥	🟥	🟩 Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	🟥	🟥	🟨 Bulk density in topsoil, Soil erosion rate	🟩 Soil acidity (pH), Soil organic carbon concentration
Agricultural areas	🟩 Soil organic carbon concentration, Electrical conductivity, Total nitrogen content in soil, Soil acidity (pH), Extractable phosphorus, Bulk density in topsoil, Abundance and diversity of earthworms, concentration of selected active substances in pesticides and their metabolites, SOC stocks	🟩 Soil organic carbon concentration, Total nitrogen content in soil, Extractable phosphorus, Soil basal respiration	🟩 Soil water holding capacity, Bulk density in topsoil, Soil erosion rate	🟨 Soil organic carbon concentration, Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	🟨 Soil organic carbon concentration, Bulk density in topsoil, soil basal respiration, SOC stocks	🟩 DNA metabarcoding for fungi and bacteria, abundance and diversity of nematodes, abundance and diversity of earthworms	🟩 Soil erosion rate, Bulk density in topsoil	🟩 Soil acidity (pH), Soil organic carbon concentration
Forest and seminatural areas	🟩 Soil organic carbon concentration, Electrical conductivity, Soil acidity (pH), Extractable phosphorus, Bulk density in topsoil, SOC stocks	🟩 Soil organic carbon concentration, Abundance and diversity of earthworms, Total nitrogen content in soil	🟩 Soil water holding capacity, Bulk density in topsoil, Soil erosion rate	🟩 Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	🟩 Soil organic carbon concentration, Bulk density in topsoil, soil basal respiration, SOC stocks	🟩 DNA metabarcoding for fungi and bacteria, abundance and diversity of earthworms	🟩 Soil erosion rate, Bulk density in topsoil	🟩 Soil acidity (pH), Soil organic carbon concentration
Wetlands	🟩 Soil organic carbon concentration, Soil acidity (pH), Extractable phosphorus, Bulk density in topsoil	🟩 Soil organic carbon concentration, Soil basal respiration, Total nitrogen content in soil	🟩 Soil water holding capacity, Bulk density in topsoil, Soil erosion rate	🟩 Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants	🟩 Soil organic carbon concentration, Bulk density in topsoil, soil basal respiration	🟩 DNA metabarcoding for fungi and bacteria, soil basal respiration	🟩 Soil erosion rate, Bulk density in topsoil	🟩 Soil acidity (pH), Soil organic carbon concentration
Water bodies	Not applicable	Not applicable	🟩 Soil water holding capacity	🟩 Soil acidity (pH), Concentration of heavy metals in soil, Concentration of a selection of organic contaminants (e.g. PFAS)	Not applicable	🟩 Fauna, Macroinvertebrates	Not applicable	🟨 Soil acidity (pH)

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Considering risk and land use sensitivity

Matching soil functionality to land use is ultimately a risk-based exercise. The same measured value for a given descriptor can be acceptable or problematic depending on what the land is used for and how crucial the associated soil functions are.

In line with the SML, many descriptors have sustainable target values or maximum values that serve as reference points for risk assessment. For example, there are indicative limits for electrical conductivity, thresholds for bulk density by texture class, and requirements that contamination levels (either heavy metals, organic pollutants, PFAS or pesticide active substances or their metabolites) do not pose unacceptable risks to human health or the environment. Where natural background concentrations are high, the law explicitly requires that this context be considered before judging a site as “unhealthy” or non-compliant.

Land-use sensitivity is captured in two main ways: i) different functions dominate in different land uses and ii) the acceptability of risk depends on the receptors and exposure pathways. The latter means that a contaminant level or a specific property value (e.g. erosion rate) that might be acceptable under an industrial land use can be unacceptable for food production. If key descriptors for the future land use already meet or exceed healthy thresholds, the soil is functionally suitable, and only maintenance measures may be needed. On the contrary, if several highly relevant descriptors are outside the desirable range, then remediation or a less demanding land use should be considered. In this scenario and guided by the indicators that most strongly limit the desired soil functions, an adequate management or remediation option must be put in place.

This approach allows the project to go beyond a one-size-fits-all notion of “soil health”. Instead, it looks to soil health in an integrated way, as the capacity of a given soil, in a given context, to perform the functions required by its intended land use, without creating unacceptable risks for people or ecosystems.

5. Impacts of remediation on soil functions

While soil remediation can effectively reduce risks from contamination, it also inevitably impacts the inherent soil functions and microbial communities that determine overall soil functionality and can be positive or negative depending on the remediation technique employed (O’Brien 2017b; Volchko 2013). In general, biological approaches (e.g., phytoremediation) generally promote soil health and microbial recovery, albeit often at a slow pace. Conventional physical and chemical methods (e.g., soil washing), which are

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often preferred for rapid and efficient contaminant removal, frequently cause significant and sometimes irreversible damage to soil ecosystems. Remediation techniques are often chosen based on their effectiveness to remove, destroy or contain contaminants; however, there is a notable lack of discussion about the impacts of remediation techniques on soil and what functionality remains following remediation (O'Brien 2017b), with few studies systematically assessing the impacts. Accounting for the impacts of remediation techniques on soil functions is an integral part of considering soil health in contaminated land management that is often neglected during option appraisal. There is need for integrated and carefully monitored remediation strategies that prioritize not only contaminant reduction but also the long-term restoration and preservation of soil's functionality.

This chapter will present the results of literature review carried out to assess the impacts of the most commonly used physical, chemical and biological remediation techniques on soil functions as well as discuss the implication for resulting soil functionality as it relates to future land use, determining the remaining knowledge gaps, and strategies for balancing risk reduction and soil functionality including minimizing impacts and refunctionalizing soils following remediation. With this approach it will be possible to check which indicators are most important for the future land use and then compare the impacts of remediation techniques according to the required soil functionality.

5.1. Assessing the impact of remediation techniques on soil functions

The remediation techniques considered in the review were based on Annex IV of the SML and separated broadly into *conventional remediation techniques* (primarily physical and chemical methods) or *low-impact remediation techniques* (LIRT – primarily biological methods, see (Bardos 2026) and ISLANDR D3.1) to demonstrate the differences between these approaches. A distinction was also made between remediation performed *in-situ* or *ex-situ* since excavation and *ex-situ* treatment is generally considered to have a deleterious effect on soil functions.

Since there is no direct metric of overall 'soil function', the impacts of remediation techniques were assessed for six main aggregated, overarching soil functions that were broken down into the sub-functions and the resulting impacts were assessed according to the expected changes in associated soil quality indicators, or descriptors, for the respective sub-functions and functions. The indicators/descriptors considered and grouping within functions/sub-functions were harmonized with the list of descriptors suggested in the SML:

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i) Organic matter storage, transformation and recycling – consists of the sub-functions decomposition, resource reallocation and biochemical transformation and the primary indicators used to assess these sub-functions include SOC or soil organic matter (SOM) as well as microbial biomass and microbial activity such as organic matter mineralization and catabolic activities (e.g., enzyme activity); **ii) Water regulation, retention and release –** consists of the sub-functions biological retention by plants, water retention, and infiltration and percolation and the primary indicators used to assess these sub-functions include soil texture, SOC, water holding capacity, bulk density, and effects on macrofauna (earthworms); **iii) Nutrient cycling –** consists of the sub-functions nutrient transformation, nutrient reallocation, and nutrient assimilation by plants and the primary indicators used to assess these functions include total and available nutrient (e.g., N and P) content, pH, microbial catabolic activities, soil microbial biomass, cation exchange capacity (CEC), and functional diversity and genes; **iv) Contaminants retention, transformation and degradation –** consists of the sub-functions retention and transformation & degradation and the primary indicators used to assess these functions include SOC, pH, soil texture (clay content), changes in bioavailable concentrations of metals and organics, and microbial activities (this function is considered here as impacts on the soil's inherent capacity to retain, transform and degrade contaminants and manage residual contaminants); **v) Physical stability** – consists of the sub-function of inherent soil stability and evolution and the primary indicators used to assess this function include soil texture, soil microbial biomass, change in pore networks (compaction), aggregation, SOC, effects on macrofauna (earthworms), salinity and bulk density. The geotechnical properties of the soil are also included in this category (see e.g., Rehman 2023); and **vi) Habitat provision** – consists of the sub-functions habitat quality and harboring biodiversity and the primary indicators used to assess these functions include soil texture, pH, SOC, soil microbial biomass, plant biomass production, ecotoxicological quality, and microbial and invertebrate diversity.

A semi-systematic, narrative literature review (Snyder 2019) was performed by searching the Scopus database for scientific studies that have measured the impacts of remediation techniques on specific soil functions or indicators. First, a broad, simple search for combinations of "remediation techniques", "impacts", "soil function", "soil health", and "soil quality" were tested, which resulted in many hits (945) but few relevant papers after a cursory review of titles and abstracts (6). Following this, combinations of primary and secondary keywords were used to collect a representative sample of the literature to make the assessment, which followed the general search strategy for all remediation techniques:1) primary keywords: conventional and low-impact remediation techniques considered in the review including related terms and abbreviations, e.g., "chemical remediation" OR "ISCO" OR "ISCR"; AND 2) search terms related to soil functions and

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specific indicators, e.g., “impacts”, “soil function”, “soil functionality”, “soil health”, “soil quality”, “soil properties”, “organic matter”, “enzyme”, “biodiversity”, etc.

The assessment on whether a remediation technique could be expected to have a generally positive, negative, or no effect on soil functions was carried out by evaluating the results from the relevant collected studies and making an aggregated determination of the expected impact. For each indicator, the expected impact was scored semi-quantitatively according to Table 4. The results are presented in simplified form as average expected impacts on the overall soil function level as well as the more detailed level for each specific indicator (see Appendix II and III).

Table 4. Scoring the impacts on soil functions.

++	clear or highly positive impact
+	somewhat positive impact
+/-	mixed or no impact
—	somewhat negative impact
— —	clear or highly negative impact

5.1.1. Impacts of conventional remediation techniques on soil functions

Table 5 presents the aggregated, average expected impacts of conventional remediation techniques on the six main soil functions. The following sections will provide a summary of the impacts of specific remediation techniques on these soil functions and individual indicators (also connected to contaminatedland.info).

Table 5. Impacts of conventional remediation techniques on soil functions (color coding according to Table 4).

Remediation techniques → **Soil functions ↓**	**Thermal treatment (in-situ/ex-situ*)**	**Soil washing (ex-situ*) or flushing (in-situ)**	**ISCR/ISCO (in-situ)**	**Electrokinetic remediation (in-situ)**	**Multi-phase extraction (in-situ)**	**Air sparging (in-situ)**	**Containment/ capping/barriers (in-situ)**	**Stabilisation/solidiation (S/S, in-situ/ex-situ*)**
Organic matter storage, transformation and recycling	— —	— or +/-	— —	— or +/-		+/-	— —	— —
Water regulation, retention and release	— —	— or +/-	—		+/-	+/-	—	— —
Nutrient cycling	— or +/-	—	—	+/-		+/-	+/-	— —
Contaminants retention, transformation and degradation	—	+/-	—	—	+/-	+/-		+
Physical stability	—	— or +/-	—	+/-		+ or +/-		+
Habitat provision	—	— or +/-	— or +/-	—		+/-	—	— —

++ : clear or highly positive impact; + : somewhat positive impact; +/- : mixed or no impact; — : somewhat negative impact; — — : clear or highly negative impact; grey cells mean that no relevant information was found during literature review.

**Excavation is generally considered to have a deleterious effect on soil functions. Ex-situ treatment and replacement can restore some soil functionality, but most functions will be lost and additional treatment could further reduce functionality.*

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5.1.1. Thermal treatment

Thermal treatments involves heating contaminated soil to volatilize and remove organic contaminants at lower temperatures or destroy contaminants at higher temperatures with the following general pathways according to temperature ranges: i) enhanced mobility, <250°C; ii) thermal desorption, separation, or transformation, 250-500°C; and iii) combustion, >500°C (O'Brien 2017b, 2018). By understanding how soil properties are affected by thermal remediation, costs can be reduced and overall project times can be shorter while minimizing impacts to soil functions (O'Brien 2017b, 2018).

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – thermal treatment of soil likely greatly inhibits most soil functions since it typically results in degradation of SOM, as the temperatures required to remediate contaminants exceed the temperatures at which most components of SOM remain stable (Liao 2025; O'Brien 2017b, 2018). SOM is reduced through thermal remediation by three mechanisms: 1) volatilization of some constituents (distillation); 2) transformation and condensation (charring); and 3) oxidation (combustion) (O'Brien 2018). The combustion or degradation of SOM has cascading effects across many other soil functions. However, the severity of the impacts from thermal treatment are temperature dependent. For instance, mild heating at short duration (<1hour) and lower temperatures (<220°C) may not negatively impact soil functions, and the soil may be expected to recover following treatment (O'Brien 2018; Yi 2016). Short-term heating (ca. 30min) at temperatures exceeding ca. 450°C leads to significant reductions of SOC and reduces enzyme activities that result in significant impacts to soil function and inhibit recovery both in short- and long-term (O'Brien 2018, Pape 2015).

Water regulation, retention and release

Water retention – due to thermal treatment decreasing SOC, the soil's water holding capacity, permeability and optimum moisture content are also negatively impacted (Liao 2025; O'Brien 2017b, 2018). Clayey soils can be highly negatively impacted by thermal treatment due to hardening in the heating process which further reduces water holding capacity if clay minerals are present (Liao 2025; O'Brien 2017b, 2018).

Soil texture – heating at higher temperatures (>450°C) changes soil mineralogy to a particle size distribution predominantly consisting of sand-sized particles (Lee 2021; Liao 2025; O'Brien 2018). A recent meta-analysis showed that soil clay was reduced by 54.2%, while soil sand content was enhanced by 15.2% after thermal treatment, which might be due to the release of cementing agents from clay minerals that resulted in the formation of soil aggregates (Liao 2025). The degradation of clay mineralogy results in lower CEC and lower

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water holding capacity. Additionally, the transformation of SOM to condensed, aromatic structures at lower temperatures results in soil hydrophobicity (O'Brien 2018).

Nutrient cycling

pH – soil pH can change substantially during thermal remediation depending on heating time and temperature, with soils of higher SOM content likely to have greater changes in pH following thermal treatment (O'Brien 2018). In many cases, especially at lower temperatures (<250°C), soil pH is unchanged or slightly decreases with thermal treatment (O'Brien 2018; Yi 2016). However, heating above 250°C leads to the combustion of SOM and subsequent pH increase by destroying organic acids and removing their acidifying influence from the soil solution of soil colloids displaces H^+ ions and replaces them with alkali cations, which are abundant in soil solution following combustion of SOM (O'Brien 2018; Pape 2015).

Plant available nutrients and metals – generally, plant available nutrients decline with thermal treatment, corresponding to the loss of SOM (Liao 2025; O'Brien 2017b, 2018).

Microbial activity – soil microbial activity, as measured by dehydrogenase and beta-glucosidase that are crucial for nutrient transformation, was reduced following low-temperature thermal desorption at 250°C (Yi 2016), though this may be expected to recover after heating at lower temperatures. Heating at higher temperatures (>450°C) increases pH dramatically and available nutrients decrease sharply to create inhospitable conditions for both plants and soil microorganisms (O'Brien 2018).

Contaminants retention, transformation and degradation

Contaminant retention – the resulting change in soil texture, i.e., reduction in clay content (Liao 2025; O'Brien 2018), reduces CEC and can lead to a loss of inherent contaminant retention capability. While metals can potentially be mobilized and genotoxic to organisms following thermal treatment (Bonnard 2010), other studies have shown no remobilization of metals following heating at 500°C, and several metals had increased residual fractionation, indicating that they will be less mobile and less bioavailable (O'Brien 2018). The result depends on the soil type as metals may not necessarily change as organics are destroyed.

Contaminant transformation and degradation – microorganisms are effectively destroyed, or at least significantly impaired, following thermal treatment at higher temperatures (O'Brien 2018), which can result in the inherent capacity of soils to manage contaminants being greatly reduced and not easily recoverable.

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Physical stability

Soil texture, porosity, aggregation and bulk density – thermal treatment can result in significant changes to soil texture and mineralogy because mineral clay lattice structures can become dehydrated and break down under excessive heating resulting in shifts in the particle size distribution (Lee 2021, Liao 2025, O'Brien 2018). These changes alongside reductions in SOM can greatly impact inherent soil stability and evolution and affect pore networks, aggregation and bulk density.

Electrical conductivity – soil electrical conductivity can also be increased by as much as 69.5% after thermal treatment, which might be due to the heating-induced loss of structural hydroxyl groups and the consequent liberation of ions (Liao 2025).

Geotechnical properties – from a geotechnical standpoint, thermal treatment can improve geotechnical properties by solidifying soil and improving mechanical characteristics significantly when heating at high temperatures, such as in vitrification where temperatures can exceed 1500°C (Rehman 2023).

Habitat provision

Microorganisms – generally, thermal treatment is detrimental to soil microorganisms due to the substantial changes in physical and chemical properties that adversely affect the ability of the soil to sustain both microorganisms and vegetation (O'Brien 2018). Microorganisms can persist and recover in time after heating at lower temperatures (up to ca. 300°C), but higher temperature heating will inhibit soil function and delay or even prevent rehabilitation depending on the conditions following treatment (O'Brien 2018, Pape 2015, Yi 2016). The soil biological community composition also changes following heating, where it displays greater diversity and favours heat-tolerant species (O'Brien 2018).

Biomass production – biomass production is dependent by the impacts discussed above, namely reduced SOM, changed soil texture, increased pH, reduced plant available nutrients, and reductions in soil biological communities (O'Brien 2018). Generally, these impacts to soil properties increase with increased heating time and temperature, so vegetative production is lower as heating temperatures increase (O'Brien 2017a, 2018; Pape 2015), though some studies evaluating low-temperature heating have shown little negative impacts (O'Brien 2018, Yi 2016). A recent meta-analysis showed that thermal treatment leads to the reduction of plant germination rate, length, and biomass by 19.4%, 44.8%, and 20.2%, respectively, compared to that of control soil, which might be due to residual contaminants and the loss of soil fertility during the thermal process that inhibited plant germination and growth (Liao 2025).

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Ecotoxicological quality – there are few studies assessing the impacts of thermal remediation on invertebrates and other soil fauna. However, there is an indication that thermal treatment can potentially increase the genotoxicity of residual metal contaminants in soil to organisms such as earthworms (*Eisenia fetida*) due to increased bioavailability and genotoxicity of these contaminants via modification of SOM following thermal treatment (Bonnard 2010).

5.1.2. Soil washing or flushing

Also referred to as “surfactant extraction", soil washing is a remediation technique used to separate contaminants from soil particles through dissolution using surfactants, which is commonly employed in two main ways in soil remediation: by applying low concentrations to enhance bioremediation (increasing contaminant bioavailability) or by applying high concentrations for extracting contaminants in either a washing (ex-situ) or flushing (in-situ) process (O’Brien 2017b).

Most studies have focused on soil washing using the chelating agent ethylenediaminetetraacetic acid (EDTA) due to its common use and high metal removal efficacy; however, it has harmful effects on the soil environment such as inhibiting microbial activity, reducing SOM, and others (Epelde and Hernández-Allica 2008; Jelusic 2014; Lee 2021, Wang 2018). Other types of chemicals such as biodegradable chelators have also been used that show varying removal effectiveness and impact on soil functions (Kaurin 2020, Wang 2018). Most of the negative impacts are linked to the dose or concentration of the chemical chelating agent (e.g., EDTA) used and the residual concentration in the soil in after soil washing, which can have negative impacts on soil functions (Kaurin 2018). These negative impacts can be ameliorated through more efficient washing techniques (Gluhar, Kaurin, Finžgar, 2021), using less toxic, biodegradable chelators (Wang 2018), and using a mix of chelators (Guo 2018). It is recommended that, besides the removal efficiency, the toxicity of residual metals and the effect on the soil microbial characteristics should be taken into account when considering the reuse of washed soils (Wang 2018).

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – soil washing can generally be expected to lead to a loss of SOM (Lee 2021). In one study, SOM was reduced by the EDTA-washing, and was only increased modestly after two crop rotations (Jelusic 2014). Other studies have shown that soil washing slightly but consistently dissolved and reduced SOC and nitrogen (N) and EDTA is known to promote the decomposition of soil organic matter and cause losses of SOC and N (Gluhar, Kaurin, Finžgar, 2021).

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Microbial activity – respiration or organic matter mineralization as an indicator of microbial activity has been shown to have negative impacts in some studies (Wang 2018), though other studies showed no or mixed impacts (Jelusic 2014) or even increases in some cases (Kaurin 2020, 2021). Soil washing may also increase the proportion of easily mineralizable organic matter that can lead to increases in respiration in the short-term (Kaurin 2020, 2021). Soil washing with EDTA can decrease enzyme activities (Epelde and Hernández-Allica 2008), though impacts may differ between enzymes (Kaurin 2018), and these appeared to be short-term impacts that evened out over time (Kaurin 2021). While biodegradable chelating agents still negatively impact soil microorganisms, they are generally noted to have much less impact than EDTA (Epelde and Hernández-Allica 2008, Wang 2018).

Water regulation, retention and release

Water retention – a decrease in water holding capacity is expected as a result of soil washing with EDTA and other chemicals (Gluhar, Kaurin, Vodnik, 2021; Jelusic 2014; Lee 2021). This decrease is attributed to both the loss of SOC as well as a loss of soil structure due to the stringent conditions during the washing process, particularly when combined when mechanical agitation and physical separation, which may increase bulk density, decrease finer pores and the formation of macropores and soil aggregates (Gluhar, Kaurin, Vodnik, 2021; Jelusic 2014; Lee 2021; O'Brien 2017b).

Nutrient cycling

Nutrient retention – soil washing is generally expected to lead to a loss of nutrient holding capacity due to the loss of fine particles in the washing process resulting in a lowered CEC (Lee 2021; O'Brien 2017b). Using gentler, biodegradable chelators (e.g., GLDA), however, can improve nutrient retention thereby maintaining soil fertility (Wang 2016, 2018). Most studies did not report a significant change in soil pH as a result of soil washing.

Microbial activity – soil washing is generally shown to decrease microbial activities, e.g., enzyme activities and respiration, across most studies (Epelde, Hernández-Allica 2008; Jelusic 2014; Kaurin 2021; Kaurin 2018; Wang 2016). However, biodegradable chelates result in higher soil enzyme activity than that of EDTA treatment (Wang 2018). Soil washing has also been shown in one study to reduce the nitrification rate in an acidic soil by 30% and by half in a calcareous soil, which may be due to the higher dose required in calcareous soils and sensitivity of N-cycling microbial communities (Kaurin 2018).

Plant available nutrients and metals – soil washing results in a loss of soil organic matter and micro- and macronutrients including C, P, N and K (Gluhar, Kaurin, Finžgar 2021; Jelusic 2014; Lee 2021).

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Contaminants retention, transformation and degradation

Contaminant retention – EDTA is poorly biodegradable and remains in the environment, which has raised concerns about the leaching of toxic chelates from remediated soil and the risk of groundwater contamination due to residual metal-EDTA complexes (Gluhar, Kaurin, Finžgar 2021; Lee 2021; Wang 2018). Some studies have, however, shown that bioavailable metal fractions and leaching decrease over a period of time after application and shift to more chemically stable forms that are less toxic and available for uptake into plants (Gluhar, Kaurin, Vodnik 2021; Jelusic 2014). Also, washing with some biodegradable chelators (e.g., GLDA, ISA) was shown to dramatically reduce the leachability and mobility of residual Cd, Pb, and Zn compared with the untreated mining soils and EDTA-treated soils in most cases (Wang 2018). The inherent capacity for retention may also be decreased due to the reduced SOC and CEC.

Physical stability

Soil texture – mechanical agitation and screening in ex-situ washing can remove much of the fine particles thereby changing the soil structure and inherent stability (Gluhar, Kaurin, Vodnik 2021; Jelusic 2014; Lee 2021; O'Brien 2017b).

Aggregate stability – the initial loss of natural soil aggregation, which cannot be avoided during soil washing, can result in a lasting reduction in soil stability and as a growth medium for plant growth. The severe physical conditions during washing: soil sieving, slurrying, intensive mixing of soil slurry and soil compaction after dewatering resulted in disaggregation and complete loss of structure (Gluhar, Kaurin, Vodnik 2021).

Geotechnical properties – soil washing may not support geotechnical properties due to deterioration of mechanical characteristics, not being well-suited for fine-grained soils, and that it may cause cavities within ground due to infiltration of water (Rehman 2023).

Habitat provision

Microbial biomass – soil washing is generally expected to lead to a reduction in microbial biomass, especially with more toxic chemicals such as EDTA, but has shown mixed effects across studies depending on the type of microbial biomass measured (C, N or P), soil type and chemicals used (Jelusic 2014; Kaurin 2020; Wang 2018). For instance, Jelusic (2014) showed no change in active microbial biomass after washing with EDTA. Other studies showed that soil washing significantly decreased the amount of extracted DNA compared to the original soil (Jelusic 2013; Kaurin 2018). Also, microbial biomass nitrogen (MBN) and phosphorous (MBP) were reported to decrease by up to 27% and 31%, respectively, upon washing with biodegradable chelators, while MBC increased by up to 40% in the same study (Wang 2018). Other studies, however, have shown significant decreases in soil MBC

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when washing with similar chemicals (Kaurin 2020). Washing with EDTA is expected to have larger negative impacts than washing with biodegradable chelators (Kaurin 2020; Wang 2018). Mycorrhizal fungi colonization may also greatly be reduced following soil washing (Jelusic 2014; Kaurin 2021), but it can be recovered after reinoculation with commercial and native fungal inoculum (Kaurin 2021).

Microbial diversity – studies have reported changes in DNA content and microbial population structure as a result of soil washing (Lee 2021). For instance, T-RFLP fingerprinting showed changes in the microbial community composition 7 weeks after soil washing that varied depending on the type of soil, acidic or calcareous (Kaurin 2018).

Effects on macrofauna (earthworms) – adverse effects have been observed in earthworms after soil washing, which were related to changes in soil pH, EC, TN, and TP (Kwak 2019). The results clearly indicate that, despite the removal of metal contaminants, recently washed soil was not healthy for the earthworms due to changes in soil physical and chemical properties, and remediated soil needs time to recover from the remediation before habitat quality and function are restored (Kwak 2019). There may also be a potential toxicity that impacts such species from residual extractants remaining after washing (Lee 2021), particularly for persistent, non-biodegradable chemicals like EDTA.

Biomass production – soil washing can have mixed effects on the yields of subsequent crops dependent upon the chemical used, soil properties following washing, and the toxicity of the original contaminated soil. Several studies have shown reduced germination and growth rates of crops following soil washing (Jelusic 2014; Kaurin 2018; Lee 2021). This has been explained that while washing reduces toxicity from contaminants, it also removes essential nutrients for plant growth and residual toxicity may also be present from mobilized contaminants and washing chemicals that affect plants. However, other studies have shown that wheat germination rates increased dramatically by 13–40% after soil washing biodegradable chelators, which was higher than both the original soil and soil washed with EDTA (Wang 2018). Importantly, plant uptake of toxic metals from soil has been reported to decrease significantly after washing (Jelusic 2013; Jelusic 2014). In a unique approach, (Gluhar, Kaurin, Vodnik 2021) showed a much improved biomass production in crop yields, though the first year was still suppressed, by washing with a less toxic form of EDTA (Ca-EDTA instead of Na-EDTA), utilizing a more efficient recycling process where less chemical needs to be used that removes residual chelates from the soil, and then fertilizing to replace the lost nutrients by chelation.

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5.1.3. In-situ chemical oxidation (ISCO) or reduction (ISCR)

Chemical remediation methods involve adding chemical agents to contaminated soil or groundwater to degrade or stabilize pollutants and are generally separated into in-situ chemical oxidation (ISCO), using e.g., Fenton's reagent, hydrogen peroxide, permanganate and others, or reduction (ISCR), using e.g., zero valent iron (ZVI) or other iron minerals (Kuppusamy 2017; Lim 2016; Lima 2017; O'Brien 2017b). The impacts on soil function vary depending on the chemical used for remediation and the choice of oxidant in ISCO/ISCR can significantly impact soil properties. For example, permanganate is preferred for its low persistence and relatively low toxicity compared to hydrogen peroxide, and ISCO processes have been generally recognized as more impactful on soil properties than ISCR processes due to their highly reactive and destructive properties (Wu 2021).

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – in general, chemical remediation usually leads to degradation or modification of SOM as part of the non-selective degradation during remediation (O'Brien 2017b). Fenton's reagent and other oxidants are reported to cause a reduction in SOM, which is essential for aggregate stability and porosity, with Fenton's reagent reducing SOM by up to 80% (O'Brien 2017b; Sirguey 2008). As a result of degradation of SOM, there is often a significant increase of dissolved organic carbon (DOC) and an altering the composition of humic and fulvic acids, which may be preferentially degraded over diesel that can delay TPH biodegradation following chemical treatment (O'Brien 2017b, Sutton 2014). The extent of degradation, however, depends on project-specific operational parameters, such as oxidant dosage, temperature, and mode of application as well as the reagent used (O'Brien 2017b). For example, Fenton's reagent using H_2O_2 is often reported to have the largest impact (O'Brien 2017b), but some studies have found that it does not produce any important modification of both SOM content and distribution (Romero 2011). SOM has also been reported to decrease after ISCR using ferrous sulphate (Liao 2014).

Microbial activity – chemical remediation is expected to induce significant reductions in microbial activity, e.g., basal respiration rates. For example, some studies have showed that respiration rates are markedly depressed after Fenton-like treatment but also a prompt recovery, particularly with single or repeated lower doses of H_2O_2 (Polli 2018; Venny, Gan, Ng 2014). The mobilized DOC and increased nutrient availability due to chemical treatment could also lead to a short-term spike in respiration (Sutton 2014).

Water regulation, retention and release

Water retention – chemical remediation is generally expected to decrease water retention due to the loss of SOM and aggregation, which impact soil structure and water movement,

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reducing water holding capacity and that pores can be clogged by residual precipitates such as permanganate, especially in fine-grained soils (O'Brien 2017b). In some studies, however, Fenton oxidation has been reported to improve water retention capacity (Sirguey 2008).

Nutrient cycling

pH – soil pH is likely significantly impacted by chemical remediation with strong changes necessary for reactions to occur though the extent of pH decrease or increase depends on the reagent and dose used as well as oil type (Liu 2019; O'Brien 2017b; Usman 2022). For instance, oxidation reactions like Fenton's reagent typically requires and causes significant drops in pH (around 3), with observed drops from 7.2 to 3.2 in slurries or 7.3 to 4.9 in dry soil (O'Brien 2017b; Usman 2022). Persulfate application can also lead to drops in pH but the effect depends on the dose and activation method (Liu 2019). Permanganate oxidation, in contrast, can cause a pH increase (up to 9.8) due to the generation of free protons (O'Brien 2017b; Sahl 2006). The use of iron minerals in oxidation or reduction reactions can lead to an increase in soil pH and more alkaline conditions, e.g., pH 10 (Usman 2022; Wu 2021).

Microbial activity – studies have indicated that enzyme activities such as dehydrogenase activity, levels of available phosphorus, catalase and polyphenol oxidase were significantly inhibited by chemical remediation, e.g., with ferrous sulfate (Liao 2014). Disruption of (pH-sensitive) microbial communities may impact nutrient cycling; however, microbial communities seem to recover once the oxidant is depleted and studies indicate recovery of activity over time as well as likely recoverable capacity for nutrient cycling and waste management functions (O'Brien 2017b).

Plant available nutrients and metals – chemical remediation can mobilize nutrients such as nitrogen and phosphorous increasing their concentrations in the aqueous phase and availability for plants and microorganisms (O'Brien 2017b, Sutton 2014). However, chemical remediation with ferrous sulphate can result in lower levels of available phosphorus, potentially due to phosphorus immobilization by ferrous salts (Liao 2014).

Contaminants retention, transformation and degradation

Contaminant retention – the large changes in pH, especially the low pH caused by Fenton's reagent, and increased DOC can increase the solubility of some metals (e.g., Zn, Cu, Mn), making them more bioavailable and prone to leaching thus impacting water quality (O'Brien 2017b).

Contaminant transformation and degradation – chemical remediation degrades SOM, increases DOC and negatively impacts the microbial community, with deleterious effects

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on the latter being a major hurdle to coupling ISCO with in-situ bioremediation (Sutton 2014). However, although microbial communities may potentially be adversely affected by chemical oxidation in the short term, a recovery of microbial biomass and/or bioremediation activity can be expected over time and hastened with the addition of amendments and nutrients necessary for biodegradation (Sahl 2006; Sutton 2014).

Physical stability

Soil structure – chemical remediation can alter soil structure by affecting the stability of aggregates and the distribution of pore spaces alongside changes in soil chemistry and SOM content, potentially impacting porosity and permeability (O'Brien 2017b, Romero 2011, Usman 2022).

Electrical conductivity (EC) – chemical remediation does not seem to significantly impact EC, with values after chemical hydrogen peroxide propagation (CHP) treatment ranging from 0.47–0.58 dS/m, which is within acceptable limits for growing crops (<2 dS/m) (Venny, Gan, Ng 2014).

Geotechnical properties – chemical remediation has mixed impacts on geotechnical properties and could be positive or negative depending on the application. For instance, the injection or thrusting methods used could change the physico-mechanical characteristics of soil and deteriorate the mechanical response of treated soil (Rehman 2023). Also, oxidation reactions could reduce the long-term serviceability of soils by removing SOM without proper compaction alongside other chemical reactions occurring in the soil that affect the soil's physico-chemical and geotechnical properties (Liu 2021, Rehman 2023). However, a separate study showed that chemical remediation with persulfate could improve some geotechnical properties such as the undrained shear strength (Liu 2019).

Habitat provision

Soil microbial biomass and diversity – chemical remediation methods generally adversely impact microbial diversity and abundance due to a combination of direct chemical toxicity and strong changes in soil pH and SOM (Huang 2024; Polli 2018; Usman 2022). Fenton-like treatment causes a dramatic decrease in bacterial density, diversity, and functionality immediately after treatment (Polli 2018; Usman 2022). For instance, hydrogen peroxide is an antiseptic and will inhibit/kill microorganisms even at low doses (Polli 2018). One study suggests, however, that comprehensive spatial and temporal PLFA screening data showed that chemical remediation with a more gentle chemical like permanganate did not significantly alter the site's microbial community structure (Azadpour-Keeley 2004). In general, shift in community composition can be expected due to changing conditions and some species are more sensitive than others (e.g., Pseudomonas) and nitrogen-cycling

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bacteria may be especially vulnerable (Huang 2024, Wu 2021). However, in many cases, the habitat quality can be expected to improve over time once the chemical is depleted leading to a recovery over microbial biomass and activity, though this depends on the dose of chemical, chemical type and soil type (O'Brien 2017b; Sahl 2006; Usman 2022).

Biomass production – many studies have showed a generally diminished capacity for biomass production following chemical remediation due to residual toxicity, especially at high doses, and lower soil fertility that delays or reduces germination as well as decreasing root and shoot biomass (O'Brien 2017b, Usman 2022). However, some studies have showed a positive impact on seed germination and ryegrass growth following Fention oxidation that was linked to increased water availability (Sirguey 2008).

5.1.4. Electrokinetic remediation

Electrokinetic remediation methods are based on applying low-intensity, direct electric current between the cathode and anode electrodes distributed in the contaminated soil through which heavy metal ions are transported in a guiding pore liquid and precipitate at the reverse electrode by electroosmosis, electromigration, and electrophoresis, resulting in metal dissolution and removal (Hamdi 2025, Kuppusamy 2017, Lima 2017, O'Brien 2017b). Electrokinetic remediation can alter soil properties (Guedes 2019), including pH, moisture content, and electric conductivity, which can impact the effectiveness of the treatment and the overall soil function. These changes are largely due to the application of an electric field, which can drive ion movement, water flow (electroosmosis), and potentially affect the soil's chemical and biological characteristics (O'Brien 2017b, Pazos 2012). The redistribution of soil resources, typified by the pH gradient between anode and cathode, may be expected to create a spectrum of soil function across the treated area with functions surrounding the anode particularly negatively impacted (O'Brien 2017b). The impacts on soil functions vary with the intensity of the electric current where a higher voltage induces larger changes.

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – no significant impacts to SOM from electrokinetic remediation were detected across the reviewed studies.

Microbial activity – electrokinetic remediation can both stimulate and suppress microbial respiration and carbon substrate utilization (i.e., functional diversity), with effects that are highly spatially heterogeneous and dependent on electric field intensity, electrolyte composition, and pH gradients (Lear 2004, 2007). Electrolyte choice further influences outcomes, with EDTA exhibiting detrimental impacts on microbial activity, particularly

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near the cathode, while enhanced dehydrogenase activity and increases in some microbial populations have been observed near the anode (Kim 2010). Similarly, in a Cr-contaminated soil, the elevated pH and introduction of NaClO in the soil resulted in a significantly adverse impact on the functional diversity of the soil microbial community (Cang 2007).

Water regulation, retention and release

Water retention – while electrokinetic remediation can potentially alter water movement via electroosmosis, there are limited studies evaluating the impacts on this function. For instance, Kim et al., (2010) report that electrokinetic treatment can cause a decrease in soil moisture content, particularly near the anode, due to electroosmosis and the movement of water towards the cathode which can increase moisture content near the cathode. There may be a risk of compaction and reduced permeability due to temperature increases and moisture changes.

Nutrient cycling

pH – a ubiquitous consequence of electrokinetic remediation is the creation of a pH gradient between the anode and cathode in the soil (O'Brien 2017b). For example, studies have shown a pH gradient developing across the length of the electrokinetic chambers from pH 3.8 close to the anode (ca. 2.2 cm) to pH 7.9 close to the cathode (Lear 2004, 2007) and 3.5 near the anode to pH 10.8 near the cathode (Kim 2010). There is strong evidence to suggest that the significant impact on the soil microbial community and activity that was detected across multiple studies adjacent to the anode was attributable to the low pH generated by the electrokinetic process (Lear 2004). However, a more recent study shows that the application of an alternating current direction can prevent the formation of strong pH gradients (Johansson 2025).

Microbial activity – multiple studies have shown that the electric field used in electrokinetic remediation can significantly inhibit microbial enzyme activities such as urease and invertase, phosphatase (Cang 2012, Pazos 2012), with impacts increasing at higher voltages. The decrease of enzyme activity is suspected to coincide with the release of available nutrients (N and P) (Pazos 2012). When combined with phytoremediation, basal soil respiration and microbial biomass carbon have been reported to increase near both electrodes, indicating that biological interactions may partially offset electrokinetic-induced stress (Cang 2012). In general, the spatial distribution of microbial activity is highly uneven, with decreases expected in more acidic soil due to pH changes, that may lead to hotspots of nutrient cycling and SOM degradation (O'Brien 2017b).

Plant available nutrients and metals – metals and plant nutrients become more mobile and accumulate towards the anode or cathode depending on the element's charge leading to

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a redistribution of nutrients, with N and P accumulating at the anode and K migrating towards the cathode (O'Brien 2017b; Pazos 2012). For instance, after 60h of electrokinetic remediation, the available N, P, and K in soil were increased by an average of 0.44, 3.31, and 1.25 fold, respectively, which showed a clear increase in the bioavailability of nutrients after treatment (Chen 2006).

Contaminants retention, transformation and degradation

Contaminant retention – electrokinetic remediation can be highly effective for mobilising and removing metals and contaminants, particularly at high voltages for low-permeability soils. However, the increased mobility can potentially lead to leaching or increased ecotoxicity of metals due to pH changes. Degradation of contaminants may also be highly spatially variable due to strong differences in soil properties across the electric gradient (O'Brien 2017b).

Physical stability

Soil structure – electrokinetic remediation can potentially lead to soil compaction due to induced changes in soil moisture and ion accumulation around the electrodes, but there is little published information about the impacts of electrokinetic remediation on soil structure.

Geotechnical properties – electrokinetic remediation can have positive impacts on the geotechnical properties of soils. It can, for example, improve the permeability of textured soils and stimulate chemical processes and precipitation in the pores to stabilize the mechanical characteristics of soil, but control of the electrochemical process is vital for desirable geotechnical results (Rehman 2023). Electrokinetic remediation has also been shown to improve the unconfined compression strength by 30-100% in saline soils, thereby improving soil structure and other mechanical properties such as the stress-strain characteristics (Jayasekera 2007).

Habitat provision

Soil microbial biomass and diversity – the impacts of electrokinetic remediation on soil microorganisms can vary considerably depending on the study, but many show that the only obvious change in the microbial community occurred in soil right next to the anode. For example, the electric current (3.14 A/m^2) used in electrokinetic remediation did not significantly harm soil microbes by itself in a study performed without soil contaminants (Lear 2004). However, another study looked at electrokinetic remediation on soil contaminated with PCP and found contrasting results where the counts of culturable bacteria and fungi were significantly lowered (by 17%, and 30%, respectively), as well as decreased microbial respiration and carbon substrate utilization, particularly near the

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acidic anode where PCP accumulated due to the increased toxicity (Lear 2007). The soil pH change by electrokinetic remediation is generally expected to reduce microbial cell number and microbial diversity (Kim 2010, Lear 2007). The negative impacts on soil microbiota are, however, reversible by applying various bioremediation approaches following electrokinetic remediation (Crognale 2020).

Biomass production - despite the increased availability of nutrients in some areas, electrokinetic remediation can have direct adverse impacts on plant growth, e.g., decreased root elongation by up to 25% in *Brassica juncea* when exposed to a charge potential difference above $2Vm^{-1}$ (O'Brien 2017b). Other studies, however, have shown that lower-intensity electrical current combined with phytoremediation can improve remediation effectiveness and plant growth while mitigating some of the negative impacts on soil properties (Cang 2012, Hamdi 2025).

5.1.5. Multi-phase extraction

Multi-phase extraction (MPE) is also termed bioslurping or vacuum-enhanced extraction or dual-phase extraction (DPE) (Kuppusamy 2016). In MPE, vacuum-assisted free product and/or groundwater recovery is paired with bioventing and soil vapor extraction to simultaneously recover free product (if present) and remediate the vadose and capillary/smear zones and shallow saturated zone (FRTR 2025, Kuppusamy 2016). There is very little information regarding the impacts of this treatment technology on soil functions.

Organic matter storage, transformation and recycling

Impacts of MPE on SOM, microbial activities, and related indicators are not directly addressed in the literature but there is likely a minimal impact on SOM.

Water regulation, retention and release

Impacts of MPE on water retention and infiltration are not directly addressed in the literature but there is a possibility that the high-pressure vacuum extraction can lead to changes in soil moisture levels as well compaction that could reduce permeability and infiltration.

Nutrient cycling

No relevant information was found during literature review.

Contaminants retention, transformation and degradation

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Impacts of MPE on inherent contaminant retention or degradation is not directly addressed in the literature but, by lowering the water table, MPE may expose previously saturated soil to air, thereby increasing oxygen levels and potentially stimulating aerobic biodegradation of organic contaminants such as PAHs.

Physical provision

Not relevant information was found during literature review.

Habitat provision

No relevant information was found during literature review.

5.1.6. Air sparging

Air sparging (also known as soil venting or vacuum extraction) is an in-situ technique where atmospheric air is injected into soil promoting volatilization of organic contaminants. Air injection enhances the transfer of aqueous phase contaminants into vapour phase, and at the same time the injected oxygen promotes biodegradation of organic contaminants, meaning the remediation supports both physical and biological removal of contaminants from the soil. (Bass 2000, Lim 2016). Air can be injected either to saturated or unsaturated zone, the latter being more common. Injection wells can be either horizontal or vertical depending on the site conditions. In addition to injection wells, air extraction wells (Soil Vapour Extraction, SVE) are installed, that draw the injected air and the vaporised contaminants from the soil for subsequent treatment. Parameters that affect the remediation planning are soil moisture and organic matter content, air flow rate and temperature. Typically, this method is used in high porosity soils. (Lim 2016). There is some literature available on the effects of air sparging on the soil functions.

Organic matter storage, transformation and recycling

Addition of oxygen to soil along the injected air increases biodegradation rates. While the contaminants are transformed into forms where carbon may be accessible to other biota as well, the increased oxygen levels may also increase other organic matter degradation on one hand making it available to other organisms than microbes, but on the other hand also losing it into the atmosphere in gaseous form through respiration.

Water regulation, retention and release

If the air sparging is conducted using heated air, it understandably dries the soil and vaporizes some of the moisture present in the soil. The effect is dependent on the temperature of the injected air and duration of the remediation. The soil moisture

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conditions return to those predating the remediation when it ends. The air sparging method does not have a long lasting effect on water regulation, retention nor release.

Nutrient cycling

Nitrification is an aerobic process, meaning air sparging can enhance the rate of nitrogen fixation in the soil, but depends on other factors too (available nutrients for microbes, water content, pH). Denitrification occurs mainly in anaerobic conditions, meaning air injection decreases nitrogen loss in gaseous form. Nitrogenase enzymes are sensitive to oxygen as oxygen inactivates the enzyme, meaning increased oxygen concentrations may decrease the rate on nitrogen loss for the duration of the remediation. Carbon cycling and degradation may be enhanced for the duration of the remediation, by accelerated breakdown of organic substances.

Contaminants retention, transformation and degradation

The oxygen present in the injected air may chemically oxidate the contaminant and lead to chemical degradation and transformation into another compound but also enable its transition from aqueous phase to gaseous phase leading to its volatilisation from the soil. High SOC content results in increased sorption of organic contaminants, which reduces their concentration in groundwater and retards their transport (Benner 2002). Organic compound degradation may offer more sources of sustenance to microbes leading to increased degradation rates. Injecting air to saturated zone may lead to precipitation of dissolved iron and manganese if they are present, which may form oxides and cause blocking of pores. This may in turn lead to slower groundwater flow and decrease contaminant transport.

Physical stability

No relevant information was found during literature review. Air sparging is not expected to cause notable or permanent changes in soil stability.

Habitat provision

When air is injected into soil, the oxygen the air contains increases microbiological activity in the soils leading to increased biodegradation. (Lim 2016) The air is injected with some pressure, which displaces water and increases air-filled porosity making more contaminants available for consumption as well as offer more pore space as habitat for microbes. (Bass 2000) This effect would last only the duration of air injection, after which the water table returns to previous level.

5.1.7. Containment, capping or barrier techniques

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Containment, capping, and barrier techniques are in-situ soil remediation methods used to prevent the spread of contaminants and minimize exposure risks, often employed when other means of remediation are not feasible or cost-effective. These techniques isolate polluted soil using physical barriers, such as slurry walls or geosynthetic liners and capping systems, including clay or synthetic caps, to stop water infiltration and contaminant migration along the flow (Padhye 2023). They also block the contaminant transport along wind from the contaminated soil surface (Meuser 2013). There are several ways to construct these structures, and therefore the effect on the soil functions largely depends on the chosen approach and technique.

Key containment and capping techniques include surface capping completely or partially, using concrete, asphalt, geotextiles or selected soil materials among the soil sealing layers, or ensuring the cover stays vegetated, whereas vertical barriers are typically constructed of geotextiles, clays or permeable reactive barriers of selected material.

Surface capping involves placing layers of low-permeability materials (clay, geomembranes, or asphalt) over contaminated soil to stop water infiltration, prevent leachate generation, and reduce direct contact risks.

Vertical barriers are subsurface walls, such as slurry walls (bentonite/soil) or grout curtains, that are installed to stop the lateral migration of contaminated groundwater (Meuser 2013). Permeable reactive barriers (PRBs) are also used for water quality improvement (Valhondo 2020). Liners and geomembranes are used as physical barriers for encapsulation, and they may be either impermeable or permeable.

Sand or other clean material to cover underwater sediments has been used for stabilizing contaminated area and preventing re-suspension of pollutants from the sediments.

Organic matter storage, transformation and recycling

No relevant information was found during literature review. Vertical barriers affect only a small area in comparison to the soil surface sealing by capping (concrete, asphalt), allowing large part of the area to maintain the original soil structure, meaning their significance on the organic matter storage, transformation and cycling is small. Roy et al. (2023) found that geotextiles can be used effectively to prevent soil erosion in agricultural use, and subsequently to increase carbon sequestration, that was found to correlate with the amount of soil erosion.

Water regulation, retention and release

Vertical permeable reactive barriers do not have a notable effect on the water regulation on site, as they do not block the infiltration horizontally from the soil surface and the

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vertical barriers let water flow through changing the chemistry in some way depending on the used barrier material. Geomembranes can, however, be clogged due to fine particles in soil and their permeability may decrease over time (Meuser 2013). Soil capping on the other hand can be related to soil sealing, and is usually done to diminish water infiltration (Meuser 2013). This leads to drying of the underlaying soil which makes the soil environment suboptimal for microbes and plants leading to fragmented soil habitat (Tobias 2018).

Nutrient cycling

Vertical barriers or containment structures under contaminated soil material have little effect to nutrient cycling, other than blocking their transportation at that site if they are impermeable. Permeable barriers may allow their transport depending on the barrier material. Capping the soil with completely impenetrable materials may cause soil drying directly underneath the structure, in which case the soil is not optimal habitat anymore for microbes responsible for nutrient cycling.

Contaminants retention, transformation and degradation

Vertical barriers made of organic material or calcareous stone are effective in removing contaminating metals from water. Capping is mainly used when the contaminants cannot be removed or are not easily biodegradable. Capping does not affect much on the transformation or degradation but is effective in retaining of contaminants.

Physical stability

Geotextiles can be used to reduce soil erosion (Bhattacharyya 2010, Meuser 2013, Roy 2023). Soil capping with cement or asphalt may be a suitable option, if the future use of the site demands physical stability, like a road or other area with heavy traffic (Meuser 2023).

Habitat provision

No relevant information was found during literature review.

5.1.8. Stabilisation / Solidification (S/S)

Soil stabilisation / solidification (S/S) is done to modify the physical and chemical properties of soft or easily wetted soil to improve its mechanical strength and often to optimise the quality suitable for construction purposes (Zhou 2024). Soil stabilisation can be done also to decrease contaminant leaching from a contaminated site. (Dermatas

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2003), and it is excellent method to prevent hazardous waste from leaching (Paria 2006). Stabilisation / solidification is caused by adding and mixing a suitable amendment to soil; commonly used products for stabilisation are cementitious, e.g. cement, lime, fly ash or different industrial by-products. Strength development as well as chemical and physical binding in soil is mainly caused by cementation between soil particles (Dermatas 2003; Zhou 2024). Contaminants are bound in the S/S process either to the structure of the cement, to the surface of the cement, or especially in the case of many organic contaminants, in the pore space inside the cement (Paria 2006).

Organic matter storage, transformation and recycling

Cementitious treatment often increases apparent SOM stability, but this should not be confused with natural sequestration. Encapsulation and physical isolation of organic matter within cement hydration products (C–S–H gels, ettringite) reduces accessibility to microbes and enzymes (Zhao 2025). S/S reduces soil water permeability and pore connectivity (Paria 2006), which limits oxygen diffusion and substrate transport, and so reduces the quality of the habitat for microbes preventing their access to energy sources and sustenance. Organic matter can basically persist for long periods in S/S treated soil, but in a functionally unavailable pool, disconnected from natural soil processes.

Fresh cement raises soil pH, even as high as above 12 (Zhou 2024) and in a study by Mao et al. (2023), pH value correlated negatively with total nitrogen, phosphorus, potassium and available nitrogen concentrations in soil. High amount of cement added to soil was found to limit soil fertility by limiting N mineralization and release, which reduces plant growth (Caracava 2016).

Water regulation, retention and release

Stabilisation affects the soil structure by making it often poorly penetrable to water and thus affects highly negatively to water balance from the soil functions point of view. Often the primary objective of geotechnical solidification is to increase the impermeability compared to natural soil (Zhou 2024). The binding substances, e.g. Portland cement, slag and fly ash undergo hydration and pozzolanic reactions, that create expansive products filling especially the larger pores, shifting the soil quality towards smaller pores (Zhou 2024) Low water and substrate availability reduce microbial activity leading to organic matter no longer being transformed via biologically mediated pathways but instead follows abiotic ageing and carbonation processes.

Nutrient cycling

From a soil and carbon cycle perspective, S/S is negative remediation method for nutrient cycling. As the cementitious materials considerably reduce the pore space, the nutrients

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cannot move deeper to soil from the topsoil along infiltration from precipitation as it is considerably reduced (Zhou 2024). S/S treated soil pH is not optimal for microbes to live (Mao 2023), so they do not cycle nutrients by mineralizing them nor incorporate them to larger nutrient cycles anymore. Plant roots cannot penetrate into hard cement, unless there are cracks, so nutrient uptake does not occur optimally either. All in all S/S in detrimental to nutrient cycling.

Contaminants retention, transformation and degradation

Contaminants are bound to the soil chemically and physically when cementitious substances are used for stabilisation / solidification, which increases the retention considerably (Dermatas 2003). Stabilisation / solidification can be used to remediate several kinds of contaminants, from metals to organic substances. Cementitious matrices are effective at the physical encapsulation and chemical fixation of organic pollutants. (Haghseno 2024) For example, cement-fly ash mixtures are specifically noted for their ability to adsorb organic pollutants, preventing them from leaching into the surrounding ecosystem.

Physical stability

From a geotechnical perspective, S/S by cementing is regarded as a fundamental technique for ground improvement (Zhao 2025) and is used to improve the physical stability of soil by engineering.

Habitat provision

Stabilization / solidification effectively destroys soil ecosystem functioning, no more providing habitat for microbes, macrofauna nor plants. Cement S/S causes a sharp decline or near-elimination of microbial biomass and long-term suppression of microbial recolonisation due to high pH and cementitious mineralogy. The minimized pore space reduces water conductivity or blocks it completely. S/S binds, in addition to the contaminants, the organic matter in the stabilized soil structure, making it inaccessible to microbes and other organisms that would consume it. When cemented, the soil is poorly accessible to plant roots either.

5.2. Impacts of low-impact remediation techniques (LIRT) on soil functions

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Table 6 presents the aggregated, average expected impacts of low-impact remediation techniques on the six main soil functions. The following sections will provide a summary of the impacts of specific remediation techniques on these soil functions and individual indicators.

5.2.1. Bioremediation

In general, bioremediation is a process wherein soil organisms reduce contaminant concentration through degradation, detoxification, stabilization, or transformation, and includes both in-situ (e.g., biostimulation, bioaugmentation, composting and phytoremediation) and ex-situ (e.g., land farming, biopiles) approaches (Kuppusamy 2016, 2017; O'Brien 2017b). The principle of this technique is to optimise soil parameters that govern the rate of biodegradation (e.g., pH, redox potential, microbial populations) for either an indigenous microbial community (biostimulation) or for an introduced contaminant-degrading community (bioaugmentation) (O'Brien 2017b). Depending on the choice of technique and usage of soil amendments, bioremediation can have variable impacts on soil functions. Mycoremediation and vermiremediation could also be included within the umbrella of bioremediation, but since they are more novel, experimental methods, they will not be covered in more detail.

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – biostimulation often involves the addition of organic soil amendments (e.g., compost, manure), which increase SOM (Lacalle 2020; O'Brien 2017b). Bioremediation processes generally have been shown lead to an initial spike in TOC then a decrease over time as contaminants are degraded (Polyak 2018).

Microbial activity – bioremediation also influences organic matter transformation and recycling by enhancing microbial biomass growth and activity through the addition of organic matter and nutrients as well as promoting decomposition of organic contaminants such as petroleum hydrocarbons (O'Brien 2017b). Organic matter mineralization, as measured by microbial respiration rates, should generally increase with bioremediation (Lacalle 2020). One study showed that aeration stimulates microbial community activities, including those involved in degrading various organic contaminants, and may facilitate the interactions between the pollutants and the microbial community (Militon 2010). However, some studies have shown that the short-term increases in basal respiration resulting from biostimulation or bioaugmentation may flatten out over time (Polyak 2018). Various enzyme activities have also been shown to increase due to bioremediation, with dehydrogenase highlighted as being sensitive to contamination and responsive to bioremediation treatment (Polyak 2018). For instance, activities of enzymes

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associated with the transformation and cycling of carbon, such as lipase and hydrolysis of fluorescein diacetate, were significantly increased by biostimulation and bioaugmentation compared to natural attenuation in one study (Cui 2020).

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Table 6. Impacts of low-input remediation techniques (LIRT) on soil functions (color coding according to Table 4).

Impacts of remediation techniques → on soil functions ↓	**Bioremediation (in-situ/ex-situ?*)**	**Phytoremediation (all, in-situ)**	**Monitored natural attenuation/NSZD (in-situ)**	**Immobilisation with amendments (organic, in-situ)**	**Immobilisation with amendments (inorganic, in-situ)**
Organic matter storage, transformation and recycling	+ or +/-	++	+	++	+/-
Water regulation, retention and release	+	++	+/-	+	+/-
Nutrient cycling	+/-	+	+/-	+	+/-
Contaminants retention, transformation and degradation	+/-	+	+/-	+	+
Physical stability	+ or +/-	+	+/-	+	+
Habitat provision	+ or +/-	+	+	+	+/-

++ : clear or highly positive impact; + : somewhat positive impact; +/- : mixed or no impact; — : somewhat negative impact; — — : clear or highly negative impact

**Excavation is generally considered to have a deleterious effect on soil functions. Ex-situ treatment and replacement can restore some soil functionality, but most functions will be lost and additional treatment could further reduce functionality.*

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Bioremediation (cont)

Water regulation, retention and release

Water retention – addition of organic soil amendments as part of a biostimulation strategy usually increases SOM and improves water holding capacity and porosity (O'Brien 2017b). Also, in a study evaluating bioremediation of an oil-contaminated, highly plastic clayey soil, bioaugmentation based on the addition of a bacterial inoculum and nutrients reduced the maximum dry density and increased the optimum moisture content. It was shown that bioremediation resulted in the formation of quasi-fibrous textures and porous and agglomerated structures, which increased soil porosity and void ratio, due to the stimulated bacterial activity and secretions (Salimnezhad 2021).

Nutrient cycling

pH – soil pH is likely minimally impacted by bioremediation with potentially some small initial decreases (Polyak 2018). The changes can affect the availability of nutrients or microbial activity, but are highly variable depending on the bioremediation strategy, amendments used, and soil conditions.

Plant available nutrients and metals – bioremediation promotes nutrient decomposition and retention due to increased microbial activity as well as through addition of organic soil amendments (O'Brien 2017b). Nutrient availability is a key factor in biodegradation effectiveness that often limits degradation, and biostimulation through nutrient addition can be as effective in breaking down contaminants as bioaugmentation. In general, available nutrients (N, P, K) are likely to increase initially following amendment or nutrient addition and increased microbial activity but are utilized by microbes for biodegradation leading to a decrease over time (Polyak 2018). For instance, in a long-term, 9-year experiment, sharp increases of available P, N-NO_3 and N-NO_4 were observed in both biostimulation and bioaugmentation treatment but these values were shown to decrease over time to be indistinguishable from the control soil (Polyak 2018). The depletion of nutrients during biodegradation can potentially lead to less availability for plants.

Microbial activity – several studies show that enzyme activity relating to nutrient cycling (e.g., urease, catalase, dehydrogenase) can increase with bioremediation (Cui 2020, Polyak 2018, Shen 2016). However, the response varies on the enzyme, and the increases may be rapid, initial increases that flatten out over time as part of the slower recovery phase (Polyak 2018). Results also differ depending on whether the bioremediation is based on biostimulation or bioaugmentation, with biostimulation being the preferred strategy according to one comparative study (Polyak 2018).

Contaminants retention, transformation and degradation

Contaminant transformation and degradation – bioremediation often has a positive impact on microbial activity and soil physicochemical properties, particularly through biostimulation, which can favour indigenous microorganisms and improve their capacity for biodegradation of organic contaminants (Polyak 2018). However, the most common inadvertent consequence of bioremediation is the accumulation of toxic compounds formed by incomplete degradation of organic contaminants (O'Brien 2017b).

Physical stability

Soil structure - addition of organic soil amendments as part of a biostimulation strategy usually increases SOM and improves soil structure through better soil aggregate stability and porosity (O'Brien 2017b). Bioremediation is generally expected to maintain or improve soil structure.

Geotechnical properties – in a study evaluating bioremediation of an oil-contaminated, highly plastic clayey soil, bioaugmentation based on the addition of a bacterial inoculum and nutrients was shown to improve geotechnical properties such as shear strength, cohesion, and internal friction as well as decreasing free swelling and swelling pressure due to the formation of quasi-fibrous textures and porous and agglomerated soil structures (Salimnezhad 2021).

Habitat provision

Soil microbial biomass and diversity - The addition of nutrients and organic matter from composting, aeration, irrigation, and fertilization generally increases soil microbial abundance and diversity (O'Brien 2017b). However, contaminant degrading microorganisms may be overrepresented, which could entail instead a decrease in biodiversity amongst microorganisms. For instance, one study investigating the shifts in microbial community composition during oxygen biostimulation has shown a dominance of a small number of phylotypes (e.g., shifting from *Gammaproteobacteria* to *Actinobacteria*), including some rare phylotypes, that more easily adapted to the changed conditions with aeration (Militon 2010). In another study testing bioremediation strategies for a petroleum hydrocarbon contaminated soil, both biostimulation and bioaugmentation significantly increased bacterial alpha-diversity, with the combined strategy resulting in the highest diversity, while favouring petroleum hydrocarbon degraders such as *Proteobacteria* that can adapt to polluted environments (Cui 2020). The dominance of degrading species also has implications for functional gene diversity, which may be reduced in favour of increased abundance of functional genes utilized in contaminant degradation such as PAHs (Cui 2020; Wolf 2019) and lindane (Lacalle 2020). In general, many studies show that bioremediation may favour organisms that thrive in

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more extreme environments (e.g., gram-positive bacteria) and degrading species, but the impacts to other soil functions may still be unclear (O'Brien 2017b).

Ecotoxicological quality – the formation of toxic, intermediate products from incomplete degradation of organic contaminants is a significant concern in bioremediation (O'Brien 2017b), which can cause residual ecotoxicity and negatively impact soil organisms. For example, the formation of toxic, bioavailable metabolites during petroleum hydrocarbon biodegradation led to an increased ecotoxicity that negatively impacted plant growth and microorganisms (Shen 2016). Ecotoxicological assays are highly recommended for evaluating the effectiveness of bioremediation versus only using the total contaminant concentrations (Shen 2016). Upon successful bioremediation, however, bioremediation using an *Actinobacteria* consortium has been shown to significantly alleviate soil ecotoxicity to earthworms (*Eisenia fetida*) in Cr(VI) and lindane co-contaminated soils and improve earthworm survival rate and growth (Lacalle 2020).

5.2.2. Phytoremediation

Phytoremediation employs plants and their associated microorganisms to reduce, stabilize, degrade, or extract contaminants from soil, including different mechanisms for managing contaminants such as phytoextraction, phytostabilization, phyto- and rhizodegradation, phytovolatilization, and rhizofiltration (Cundy 2016, Drenning 2022). Phytoremediation is typically included within the umbrella term gentle remediation options (GRO) and are considered a vital part of a sustainable contaminated land management, or phytomanagement, strategy to achieve a net gain in soil function while providing numerous wider benefits like ecosystem services (Burges 2018; Cundy 2016). Phytoremediation, especially when combined with organic amendments like compost, significantly increases SOM content, improves soil structure, enhances nutrient retention, and boosts carbon storage, which leads to improved soil fertility and supports overall ecosystem services (Fiorentino 2018; Lacalle 2018a). An important note is that while phytoremediation may sometimes fail to achieve a significant reduction in total contaminant concentrations, it often leads to a significant improvement in soil health (Anza 2019).

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – phytoremediation, especially when aided by organic amendments like compost, cow slurry, or biochar, significantly increase soil organic matter (SOM) content (Adl 2008; Ciadamidaro 2014; O'Brien 2017b). In addition, perennial crop cultivation, a typical component of phytomanagement, minimizes soil disturbance

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and promotes carbon storage in the soil (carbon sequestration) by converting crop residues, litter and root exudates into SOM (Adl 2008).

Microbial activity - overall, phytoremediation has been shown to increase soil microbial biomass and activity, e.g., respiration (organic matter mineralization) and enzyme activities, contributing directly to nutrient and carbon cycling and storage (Ciadamidaro 2014; Epelde, Becerril, 2008; Epelde 2009; Gómez-Sagasti 2012; Kumpiene 2009; Lacalle 2018a; Míguez 2020; Touceda-González, Prieto-Fernández 2017; Touceda-González, Álvarez-López 2017).

Water regulation, retention and release

Water retention – phytoremediation and addition of organic amendments lead to an increase in SOM, which also improves soil water-holding capacity (WHC) (Marchand 2016). Phytoremediation improves water regulation generally through root development as plant roots improve water retention and improving soil structure and aggregation through increasing SOM that improves WHC and porosity (O'Brien 2017b). Several studies have shown that phytomanagement in combination with organic amendments improves ecosystem services such as water flow regulation by increasing WHC (Burges 2016, 2017, 2018; Mench 2023).

Water infiltration – water infiltration is also expected to improve due to plant root growth by increasing soil porosity (Míguez 2020; O'Brien 2017b), which is an important aspect in flood mitigation.

Nutrient cycling

pH – soil pH will generally trend towards neutral during phytoremediation but the increase of SOM can lower soil pH (O'Brien 2017b). The addition of soil amendments, e.g., lime, can significantly influence the result.

Microbial activity – soil enzyme activities involved in C, N, P and S cycling (e.g., urease, acid/alkaline phosphatase, arylsulfatase, β-glucosidase, and dehydrogenase) are consistently highlighted as key indicators of soil quality and functioning that can be improved by phytoremediation (Gómez-Sagasti 2012). For instance, some studies have shown increases in enzyme activities involved in the biogeochemical cycles of C, N, P, and S by up to 164% during phytoextraction with *Thlaspi caerulescens* (Epelde, Becerril 2008) 675% during aided phytostablisation with *Lolium perenne* (Epelde 2009), with similar results across many other studies, particularly in combination with amendments like compost (Burges 2016, 2017; Garaiyurrebaso 2017; Gómez-Sagasti 2012; Kumpiene 2009; Macci 2013, 2016; Touceda-González, Álvarez-López 2017). Mycorrhizal-assisted phytoremediation and intercropping with leguminous plants has also been highlighting

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as a key strategy in phytomanagement that enhances the activity of soil enzymes involved in nutrient cycling (Gómez-Sagasti 2021).

Functional diversity **–** some studies have shown that phytoremediation can increase carbon substrate utilization (i.e., functional diversity) based on community-level physiological profiles (Epelde, Becerril 2008; Gómez-Sagasti 2021).

Plant available nutrients and metals – the addition of organic amendments during phytomanagement is often crucial for providing beneficial macro- and micronutrients, thereby improving nutrient availability for plant establishment and growth (Anza 2019; Gómez-Sagasti 2018; Lacalle 2018a; Mench 2023). For example, phytomanagement of Cu-contaminated soils, which are often characterized by low nutrient availability, with compost and dolomitic limestone improved overall soil nutrient availability and plant growth (Burges 2021, Mench 2023). Rhizobial and mycorrhizal symbioses through intercropping with leguminous plants like alfalfa and inoculation can also improve plant growth and stimulate microbial activity more than plants alone, indirectly enhancing nutrient cycling and other processes (Gómez-Sagasti 2021, Marchand 2016). Inoculation with plant growth-promoting rhizobacteria (PGPR) have also been shown to increase nutrient (N, P, and K) availability in soil and content in plant tissues (Ju 2019).

Contaminants retention, transformation and degradation

Contaminant retention - the establishment of a vegetation cover plays a critical role in reducing water percolation and controlling contaminant leaching towards groundwater through increased root development and water uptake. Poplar plantations, for example, can reduce the leaching of contaminants by influencing water balance through transpiration and achieve hydraulic control (El-Gendy 2009; Fiorentino 2018). Also, plant roots, often together with soil amendments, can stabilize contaminants to reduce their bioavailability and solubility as well as spreading through pathways such as erosion and dust emission (Drenning 2022). However, migration of contaminants during phytoremediation, which typically takes a long time, is variable and a primary concern for phytoremediation (O'Brien 2017b).

Contaminant transformation and degradation – phytoremediation often has a positive impact on microbial activity and soil physicochemical properties to promote biological degradation of organic contaminants, which is the main objective of phyto- and rhizodegradation (Gómez-Sagasti 2021; Lacalle 2018a; Macci 2016). Sustained contaminant degradation can be expected in a successful phytoremediation project, typified by an increase in vegetation production and improvement in soil properties leading, in turn, to improved contaminant degradation (O'Brien 2017b).

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Physical stability

Soil structure – improving SOM through phytoremediation and organic amendments directly promotes soil structure and stability (Adl 2008; Anza 2019; Fagnano 2020; Fiorentino 2018; Marchand 2016; Míguez 2020). Phytoremediation can positively influence physical properties like bulk density and porosity, although large, rapid improvements often require the addition of soil amendments. Plant root growth and exudates can stimulate aggregate formation (O'Brien 2017b).

Erosion reduction – through the development of roots and establishment of a vegetation cover (e.g., turfgrass, dense tree rows, or other plants), phytoremediation can significantly reduce soil erosion via wind and water, which is a key aspect of phytostabilization to protects against offsite movement of contaminants (Cundy 2016; Drenning 2022; Fiorentino 2018).

Geotechnical properties – phytoremediation reinforces soil to improve geotechnical properties such as shear strength and slope stability through root development. However, it may cause other problems that limit geotechnical serviceability due to increased SOM and decaying roots that will require removal or improvement before any construction on such ground (Rehman 2023).

Habitat provision

Soil microbial biomass and diversity – phytoremediation is a key part of soil rehabilitation that generally restores and enhances soil biodiversity, including microbial, faunal, and floral communities (Adl 2008; Garaiyurrebaso 2017; Touceda-González, Prieto-Fernández, 2017). For instance, spontaneous vegetation establishment has been shown to lead to greater plant and soil microbial diversity (Gómez-Sagasti 2021). The enhancement of soil microbial biomass, activity, and functional diversity is consistently reported and often attributed to the input of labile organic carbon from amendments and root exudates (Epelde, Becerril 2008; Lacalle 2018a; Míguez 2020). Phytoremediation can induce shifts in microbial community composition, promoting groups involved in, for example, N cycling such as Alphaproteobacteria and an increased abundance of genes involved in the N cycle (nirK, nirS, nosZ, amoA) (Burges 2020; Touceda-González, Prieto-Fernández 2017). Organic fertilization has been linked to increased activity of N-cycling bacteria (Fagnano 2020). While an overall increase in microbial diversity might not always be immediately evident in long-term phytomanagement, significant structural shifts have been shown to occur (Burges 2020). Overall, many studies show that phytoremediation increases soil microbial biomass and activity (Burges 2016, 2017; Ciadamidaro 2014; Kumpiene 2009; Lacalle 2018a; Míguez 2020; Touceda-González, Álvarez-López 2017; Gomez-Sagasti 2012; Touceda-Gonzalez 2017; Lacalle 2018; Epelde 2008, 2009).

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Ecotoxicological quality – several studies have shown that phytoremediation can reduce ecotoxicity, e.g., to plants and soil organisms such as nematodes and earthworms, from residual contaminants following treatment (Enell 2016; Foucault 2013; Marchand 2016; Quintela-Sabarís 2017).

Effects on macrofauna (earthworms) – while studies are limited, phytoremediation is generally expected to have positive impacts on soil fauna such as earthworms, particularly when organic amendments like compost are used (Marchand 2016).

5.2.3. Monitored natural attenuation or natural source zone depletion

The terms monitored natural attenuation (MNA) or natural source zone depletion (NSZD) refer to the reliance on natural physical, chemical, and biological processes to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil and groundwater (Wozney 2022, Song 2023). Unlike active engineering interventions, MNA is a passive remediation strategy that utilizes naturally occurring mechanisms such as biodegradation, sorption, volatilization, radioactive decay, and chemical stabilization to achieve site-specific cleanup objectives within a reasonable timeframe. Biodegradation is frequently considered the primary destructive mechanism, as it results in the actual reduction of contaminant mass through microbial activity. (Declercq 2012) Other "non-destructive" processes, such as dispersion, dilution, and sorption, reduce pollutant concentrations by spreading the mass or binding it to soil particles but do not destroy the chemical itself. MNA / NSZD are not new techniques and have been in use for decades.

MNA / NSZD are not a "no action" or "do nothing" approach; they require comprehensive site characterization and a planned monitoring strategy to verify that natural processes are effective enough and protect human health and the environment (Chapelle 2007). Typically, implementation requires source control or is used in addition to another method for treating the hot spot, meaning the removal or stabilization of the primary contamination source to ensure that natural processes are not overwhelmed (Rügner 2006). The strategy is generally deemed appropriate only for stable or shrinking contaminant plumes.

Organic matter storage, transformation and recycling

When compared with many other remediation techniques, MNA/NSZD conserves the site conditions well. The effect on organic matter storage on the site is positive, as the microbes on site use the contaminant as an energy source (in addition to other organic matter present) consuming it and transforming it into their own biomass. When there is

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oxygen present, microbes convert the organic matter and contaminant into carbon dioxide, water and biomass. Biodegradation consumes oxygen and in anaerobic conditions the organic matter that already exists in the soil degrades more slowly on its own, as microbes use also other energy sources, e.g. iron, nitrate or sulfate, to degrade organic compounds (Declercq 2012). The resulting compounds from biodegradation can be recycled and used by other organisms on site (Smith 2022), and the organic contaminant enters the carbon cycle.

Water regulation, retention and release

As the organic contaminant degradation by microbes results finally to release of water and carbon dioxide, the site water balance can be expected to remain its state. On the other hand, the degradation of a hydrophobic contaminant, like oil, may improve the water balance as oily substances may prevent precipitation infiltration (Al-Esawi 2020). As the contaminant degrades it frees continuously more pore space for water and air, and a part of it is removed in gaseous form. No large shifts to either direction in water regulation or retention capacity are expected. In soil with fine particle size the organic compounds left from the degradation processes may retain more water, as they are not migrated away from the site as fast e.g. along with infiltrating precipitation or groundwater as in coarser soils.

Nutrient cycling

MNA and NSZD effectively incorporate the organic contaminant into the carbon cycle by transforming it into microbes' biomass and further on along the food chain (Balland-Bolou-Bi 2023). The degradation chain of a complex contaminant can serve as a resource to consume for several different species.

Contaminants retention, transformation and degradation

The contaminant consumption on site retains the contaminant, leading to slower migration of the contaminant plume. When choosing the MNA/NSZD as the remediation method for the site, the suitability of the method must be ensured prior to use. The retention and degradation rates must be monitored and ensured to be on a suitable level to not cause a risk of exposure further from the site to the direction of plume travel.

Physical stability

No expected changes, or small positive change when organic contaminants are removed possibly improving the friction between mineral grains on site. The plants that may grow on the site lessen the topsoil erosion, as they are not removed from the site or damaged during the remediation.

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Habitat provision

As the MNA / NSZD does not interfere with the soil conditions, habitats are conserved as they are for the macrofauna and flora, and contaminant consumption may offer an additional energy source for microbes. If the contaminant concentration is high enough to cause harmful exposure to biota, MNA/NSZD could be considered to deteriorate the habitat if the remediation rate is not enough to reduce the risk to an acceptable level.

5.2.4. Immobilization with organic amendments

Immobilization, or in-situ chemical stabilization, with organic amendments entails the use of amendments such as compost, biochar, manure, biosolids, or other organic substances to reduce the solubility and mobility of contaminants, by increased metal complexation, precipitation, redox reaction, and/or sorption, thereby decreasing bioavailability for biota and leaching (Drenning 2022, Kumpiene 2019, Lwin 2018). Organic amendments also have the added benefit of enabling the establishment of vegetation in poor soils by significantly improving many soil properties such as soil organic matter, bulk density and pore structure, water retention, soil fertility, and supporting communities of soil invertebrates and microorganisms (Bai 2018, Gómez-Sagasti 2018, Kidd 2015). The addition of organic amendments is especially impactful for revegetation via aided-phytostabilization of heavily degraded post-mining soils and tailings (Galende 2014, Garaiyurrebaso 2017, Gómez-Sagasti 2018; Kidd 2015). However, the specific impacts on soil properties vary between the different types of amendments (see e.g., (Schröder 2018)). Also, the specific substrate and production of the amendment, e.g., biochar feedstock and pyrolysis temperature, makes a large difference in the composition and projected impacts on different soil functions (see e.g., (Handiso 2024, Lehmann 2011)). Since the literature on organic amendment application for contaminant immobilization and soil improvement is vast and the impacts can vary widely, this section will provide a broad overview of the general trends that can be expected for the various indicators and soil functions.

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – addition of organic amendments, which is a standard agronomic practice in organic agriculture and soil restoration, has been broadly demonstrated to increase SOM content (Bai 2018; Gómez-Sagasti 2018).

Microbial activity – overall, organic amendment addition is expected to increase soil microbial biomass and activity, since adding organic matter increases the nutrient supply for microorganisms, thus improving nutrient and carbon cycling and storage (Epelde 2009;

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Gómez-Sagasti 2018; Kidd 2015; Kumpiene 2009; Míguez 2020; Touceda-González, Álvarez-López, 2017).

Water regulation, retention and release

Water retention – addition of organic amendments leads to an increase in SOM, which improves soil water-holding capacity (WHC), and improved soil aggregation for water retention (Bai 2018; Gómez-Sagasti 2018; Marchand 2016). As previously noted, phytomanagement in combination with organic amendments improves ecosystem services related to water flow regulation (Burges 2016, 2017, 2018; Mench 2023).

Water infiltration – water infiltration is also expected to improve with organic amendment addition due to an increased soil porosity and reduced bulk density (Gómez-Sagasti 2018; Míguez 2020; O'Brien 2017b).

Nutrient cycling

pH – some organic soil amendments such as biochar and digestate will increase soil pH, especially in acidic soils thus making the soil more suitable for certain crops, while certain types of compost have been shown to lower pH (Schröder 2018). However, the change in soil pH can be transient depending on the amendment used and type of soil (Epelde 2014).

Microbial activity – soil enzyme activities involved in C, N, P and S cycling are often significantly improved through organic amendment addition, which has been shown in many phytomanagement studies applying plants together with amendments like compost (Burges 2016, 2017; Gómez-Sagasti 2012; Kumpiene 2009; Macci 2016; Macci 2013; Touceda-González, Álvarez-López, 2017). Other studies have shown that amendments applied without plants can also a stimulating effect on microorganisms thus increasing enzyme activities when applying, for example, biochar (Abou Jaoude 2020; Bera 2016) and lime-treated sewage sludge (Epelde 2014) for chemical stabilization.

Functional diversity – some studies have shown that organic amendment addition can increase carbon substrate utilization (i.e., functional diversity) based on community-level physiological profiles (Abou Jaoude 2020; Galende 2014). For instance, increased C-substrate utilization has been shown using Biolog community-level physiological for the application of 3% biochar (Abou Jaoude 2020), different doses of lime-treated sewage sludge (Epelde 2014), and different organic amendments where results varied significantly (Galende 2014).

Plant available nutrients and metals – the addition of organic amendments is often crucial for providing beneficial macro- and micronutrients to improve nutrient availability for plant establishment and growth (Anza 2019; Gómez-Sagasti 2018). Biochar can also

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enhance nutrient acquisition and has a high cation exchange capacity (CEC) (Schröder 2018). However, biochar has also been shown to immobilize plant-available forms of inorganic nitrogen (Brtnicky 2021; Drenning 2024; Rijk 2024), which can become a limiting growth factor for biomass production.

Contaminants retention, transformation and degradation

Contaminant retention – in general, the addition of organic soil amendments can stabilize contaminants to reduce their bioavailability and mobility through mechanisms like complex formation with humic acids or adsorption onto the organic matrix (Drenning 2022, Epelde 2009, Garaiyurrebaso 2017, Kumpiene 2019). However, some organic amendments may also increase mobility in risks of leaching, e.g., dissolved organic carbon from non-stabilised organic amendments or 'green waste compost' may increase metal mobility, there is a risk of adding contaminants to soil if the source material is contaminated when using, for example, sewage sludge or municipal biosolids (Gómez-Sagasti 2018, Kidd 2015, Lwin 2018). Also, pH changes may selectively mobilize or immobilize certain contaminants such as metal(loid)s such as for biochar which decreases mobility of cations but may increase mobility of anions like arsenic (Bolan 2014).

Contaminant transformation and degradation – since organic amendment addition is shown to increase microbial biomass and activity, it is likely that transformation and degradation of organic contaminants is also increased by providing supplemental nutrients and a carbon source for degrading microorganisms (Gómez-Sagasti 2018, Lacalle 2018a).

Physical stability

Soil structure – improving SOM through addition of organic amendments directly promotes soil structure and stability (Adl 2008, Anza 2019, Fagnano 2020, Fiorentino 2018, Marchand 2016, Míguez 2020). For example, combining organic matter amendments with calcium-carbonate rich materials was shown to stimulate soil formation at acidic mine tailing deposits by building SOM and accelerating the establishment of a functional ecosystem (Zanuzzi 2009). Incorporating organic matter can also reduce soil bulk density thereby improving soil aeration and root penetration (Schröder 2018). Compost addition, in particular, has also been shown to improve the stability of soil aggregates (Fagnano 2020)

Erosion reduction – significant additions of SOM likely also prevents erosion by improving or stabilizing the bulk soil structure, porosity, and water holding capacity (Gómez-Sagasti 2018).

Geotechnical properties – organic amendments such as biochar may improve the mechanical characteristics of the soil, e.g., cohesion and compressive strength, and

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decrease volume change tendency upon wetting and drying (Rehman 2023). However, a complete geotechnical evaluation is required for each amendment, and the substantial addition of SOM may reduce geotechnical properties.

Habitat provision

Soil microbial biomass and diversity – addition of organic amendments is a key part of soil rehabilitation that generally restores and enhances soil biodiversity, including microbial, faunal, and floral communities (Adl 2008; Touceda-González, Prieto-Fernández 2017). The enhancement of soil microbial biomass, activity, and functional diversity is consistently reported and often attributed to the input of labile organic carbon from amendments and root exudates (Epelde, Becerril 2008; Lacalle 2018a; Míguez 2020). Organic fertilization has been linked to increased activity of N-cycling bacteria (Fagnano 2020). Overall, many studies show that phytoremediation increases soil microbial biomass and activity (Burges 2016, 2017; Ciadamidaro 2014; Kumpiene 2009; Lacalle 2018a; Míguez 2020; Touceda-González, Álvarez-López 2017, Gomez-Sagasti 2012; Touceda-Gonzalez 2017; Epelde 2008, 2009).

Ecotoxicological quality – in general, addition of organic amendments can improve the soil habitat by reducing contaminant bioavailability and ecotoxicity for plants, soil fauna and microorganisms (Gómez-Sagasti 2018; Marchand 2016; Quintela-Sabarís 2017). However, reduce studies have shown that certain types of biochar may have adverse, toxic effects on groups of soil organisms such as earthworms due to the presence of potentially harmful substances, ash, or changes in pH, with specific impacts dependent on the dose, feedstock and pyrolysis temperature (Bielská 2018, Brtnicky 2021, Godlewska 2021).

Effects on macrofauna (earthworms) – overall, global reviews have shown that addition of organic amendments that increase SOM is generally expected to have positive impacts on soil fauna such as earthworms and increase their abundance (Bai 2018; Gómez-Sagasti 2018).

5.2.5. Immobilization with inorganic amendments

Immobilization, or in-situ chemical stabilization, with inorganic amendments entails the use of lime, gypsum, zero-valent iron (ZVI), iron slag, fly ash, bentonite, zeolites or other inorganic substances to reduce the solubility and mobility of contaminants, by increased metal complexation, precipitation, redox reaction, and/or sorption, thereby decreasing bioavailability for biota and leaching (Cui 2023, Kumpiene 2019, Lwin 2018). Similar to organic amendments, the addition of inorganic amendments can also have positive impacts on many soil properties; however, the specific impacts vary substantially. When selecting an appropriate immobilizing agent, both the contaminant immobilization effectiveness and its impacts on soil functions should be considered (Lwin 2018). For

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instance, iron-based amendments such as iron slag or ZVI alone likely have largely negative impacts on many soil parameters but several studies show that combination with organic amendments such as compost and biochar can mitigate the potential negative impacts while maintaining effective stabilization (Baragaño 2020, Lebrun 2019).

Organic matter storage, transformation and recycling

Soil organic matter (SOM) – addition of inorganic amendments can have a small positive impact on SOM, but significant improvements depend on their addition together with organic amendments. For example, the addition of iron grit alone to a technosol increased SOM content compared to the unamended soil, though much greater improvement were seen when applied together with compost or biochar (Lebrun 2019). Treatment with magnesite showed lowered total carbon content compared to treatment with biochar, suggesting that magnesite does not significantly enhance carbon content (Baragaño 2021).

Microbial activity – generally, inorganic amendment addition seems to have little to no impact on microbial activity though liming materials and gypsum can lead to soil improvements and increased nutrient availability that increase microbial activity in some soils (Lwin 2018). Other studies have shown, however, that amendments like nZVI did not have any significant effect on soil microbial parameters such as basal respiration or substrate-induced respiration (Lacalle 2018b, 2018a).

Water regulation, retention and release

Water retention – addition of inorganic amendments (e.g., gypsum, clay minerals and some industrial wastes) can lead an increase in water retention due to an increase in fine particulates and improved soil structure linked to reduced bulk density, increased soil aggregate stability and water holding capacity (Cui 2023, Lwin 2018). However, other studies have shown that addition of iron grit without other organic amendments led to a slight but significant decrease in soil water holding capacity compared to unamended technosols, which may be due to iron grit being unable to retain water (Lebrun 2019, Nandillon 2019).

Water infiltration – water infiltration may be improved with inorganic amendment addition using, for example, gypsum or clay minerals due to improvements in soil structure and porosity in a degraded soil (Cui 2023, Lwin 2018), but there is little direct evidence in the literature.

Nutrient cycling

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pH – inorganic soil amendments such as liming materials and gypsum will lead to an increase in soil pH, especially in acidic soils (Cui 2023, Lwin 2018). However, other amendments such as iron grit and nZVI, zero-valent iron nanoparticles, have limited or negligible impacts on soil pH (Baragaño 2020; Lebrun 2019; Nandillon 2019) and adding ferrous sulfate as the source of Fe-oxides may even decrease soil pH (Kumpiene 2019).

Microbial activity – there are limited studies assessing the impact of inorganic soil amendments on soil enzyme activities involved in C, N, P and S cycling. One study indicated that in soils amended with hydroxyapatite and composite additions, the activities of soil catalase, urease, and acid phosphatase are significantly elevated (Cui 2017). The addition of 0.5% nano-montmorillonite to a Cd-contaminated agricultural soil was also shown to improve soil enzyme activity by reducing Cd toxicity to microorganisms (Liu 2022).

Functional diversity – there are limited studies assessing the impact of inorganic amendment addition on functional diversity. One study determined that nZVI application did not have any significant effect on soil microbial parameters related to carbon substrate utilization (Lacalle 2018b, 2018a).

Plant available nutrients and metals – the addition of some inorganic amendments such as gypsum and phosphates can provide crucial macro- and micronutrients to degraded soils that may otherwise be lacking (Lwin 2018). Liming may also indirectly induce increased plant nutrient mobilization, though application of gypsum may lead to leaching of exchangeable cations as it replaces them in the soil matrix (Lwin 2018). nZVI has been shown to reduce the concentration of plant-available P, though this did not seem to cause any phytotoxic effects (Baragaño 2020).

Contaminants retention, transformation and degradation

Contaminant retention – in general, the addition of inorganic soil amendments should lead to a significant immobilization of contaminants in the soil matrix to reduce bioavailability and (Cui 2023, Kumpiene 2019, Lwin 2018). Indeed, the application of inorganic amendments such as nZVI may be necessary to immobilize anions such as As, which may be mobilized by organic amendments like compost and biochar (Baragaño 2020). Addition of nZVI alone, however, led to a slight increase in Cu availability (Baragaño 2020).

Physical stability

Soil structure – the addition of inorganic amendments to degraded soils can lead to significant improvements in soil structure such as reducing bulk density, increasing soil aggregate stability and water holding capacity (Lwin 2018). Liming and gypsum addition, through increasing Ca saturation, can reduce dispersion of soil particles and promote

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flocculation to facilitate soil structure development and formation of soil aggregates and stability (Lwin 2018).

Geotechnical properties – inorganic amendments such as cement, lime, fly ash, and other types of cementing additives may improve the mechanical characteristics of the soil, e.g., cohesion and compressive strength, and decrease volume change tendency upon wetting and drying (Rehman 2023). Addition of nZVI has also been shown to induce significant changes to the microstructure of soil, such as increased particle size, bubble prints, and porosity, which led to an increase in vane shear strength, stiffness, friction angle, and plasticity index of clay soil, as well as a decrease in the compression index (Liu 2021).

Habitat provision

Soil microbial biomass and diversity – there are limited studies assessing the impacts of inorganic amendments on soil microbial biomass and diversity and the results are highly variable. For instance, studies assessing nZVI application showed that it did not have any significant effect on active soil microbial biomass as measured using substrate-induced respiration (Lacalle 2018b, 2018a) while another showed that Thomas basic slag significantly improved the growth of the total bacterial population (Bert 2012). Another study assessing the change in microbial biodiversity after addition of 0.5% nano-montmorillonite to a Cd-contaminated agricultural soil showed a significant improvement in the microbial alpha diversity index and enhancement of the relative abundance of Bacteroidetes and Planctomycetes (Liu 2022).

Biomass production – the impacts of inorganic amendments on biomass production are highly variable and depend on the specific amendment used. For example, gypsum and phosphates are highly likely to improve biomass production, particularly for degraded, nutrient-poor soils, since provide many essential plant nutrients (Lwin 2018). In one study, hydroxylaptite and Thomas basic slag were shown to promote plant production in a highly contaminated sediment by improving nutrient availability for plants and ameliorating potential phytotoxicity (Bert 2012). Compared to Thomas basic slag and the untreated soil, hydroxylaptite showed a greater reduction in oxidative stress and higher plant species richness and diversity (Bert 2012). In another study, magnesite treatment was shown to inhibit the growth of Brassica juncea plants entirely, making it unsuitable to sites where revegetation is a priority (Baragaño 2021). Amendment with iron grit alone was also shown to prevent the germination of Trifolium repens seeds, likely due to high soluble Fe concentrations and increased acidity in the soil pore water (Nandillon 2019).

Ecotoxicological quality – while reducing contaminant bioavailability, some inorganic amendments may still be toxic for plants and soil organisms depending on the dose. For instance, 1.5% w/w iron grit amendment alone increased soil pore water (SPW) toxicity

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compared to the unamended control (Lebrun 2019). In one study 1g nZVI kg^{-1} dw soil had no toxic effect on soil microbial communities but caused an indirect toxic effect on plant root elongation due to its interaction with soil organic matter (Lacalle 2018b, 2018a), which was confirmed in a different study where 2% dose of nZVI was not toxic to plants. Certain organic components of bone meal (e.g. various proteins), along with their degradation products (e.g. ammonia and nitrate), may be toxic to soil organisms and have implicated as the reason for earthworm toxicity following bone meal amendment (Kumpiene 2019). However, a separate study showed that Thomas basic slag and hydroxylaptite significantly reduced the acute ecotoxicity in a highly contaminated sediment as compared to the untreated soil (Bert 2012). Although, neither of these amendments caused significant differences in the abundance or diversity of soil fauna (Collembola communities) compared to untreated soil (Bert 2012).

5.3. Balancing risk reduction and soil functionality

Finding the balance between the need for risk reduction to mitigate health and environmental risks and required soil functionality must be done on a project-by-project basis, in accordance with site-specific conditions and project goals. In most cases, risk reduction takes first priority because of regulatory requirements and liability concerns. However, the impacts to soil function should not be ignored when screening potentially suitable remediation techniques, as they are important factors in overall sustainability and subsequent reclamation or restoration efforts can be much be difficult and expensive following high-impact remediation (O'Brien 2017b; Volchko 2013). Indeed, in some cases, remediation may exert a greater effect on ecological receptors than leaving the limited contamination in place (Burger 2016). These results highlight that some techniques have clear negative impacts on soil functions, particularly conventional, physical and chemical methods, but for many techniques the impacts are mixed and depend on site-specific conditions and technique specifications. In many cases, the specific application can be adapted to mitigate negative impacts. Also, in-situ methods are preferred where maintaining soil functionality is an important project objective. Excavation and ex-situ treatment is generally considered to have a deleterious effect on soil functions and even if treatment and replacement can restore some soil functionality much of what was lost can only be recreated at great cost.

The impacts on soil health indicators and soil functions are provided here as general, qualitative trends to give an indication of what can be expected from conventional or low-impact remediation techniques. One challenge in finding the balance between risk reduction and soil functionality is that quantitative thresholds for indicators showing when the impacts exceed the point of no recovery are difficult to determine. Given this

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challenge, as well as the variability in post-remediation land uses, the best approach is to compare pre-remediation soil metrics with post-remediation metrics to determine the actual changes in each situation and whether the achieved function is fit for the use. Even with this approach, the balance remains subjective and must be determined by each specific project manager (O'Brien 2017b). Indeed, while some techniques may not favour ecological soil functions for a soft reuse they can improve geotechnical properties for a hard land use (Rehman 2023). In addition to impacts on soil functions, many studies addressed risks and residual contamination that may result from the use of specific techniques that impact both environmental risks and soil properties. For instance, thermal treatment can result in the release of metals and increased residual ecotoxicity that can inhibit recovery of soil functions. Also, some techniques like soil washing, ISCO/ISCR, and electrokinetic remediation that induce strong chemical changes in the soil, e.g., large changes in soil pH, may increase contaminant solubility and the risk of leaching. In the case of organics, there is a risk in bioremediation of the generation of toxic byproducts which may be toxic for microorganisms and other soil organisms (O'Brien 2017b).

While there are many studies performed in recent years that have evaluated the impacts of remediation techniques on specific soil health indicators, there are still many knowledge gaps regarding both individual techniques and indicators. For instance, there was very little information that could be found about the impacts of multi-phase extraction air sparging. In addition, more novel, experimental techniques such mycoremediation likely have great potential for both managing contamination and improving soil functionality; however, there are yet few studies showing successful field application and impacts on soil properties. Regarding indicators, most studies evaluating impacts to soil properties include physical and chemical parameters, but impacts to biological parameters tend to be lacking. For example, very few studies considered the impacts from remediation on soil fauna such as earthworms, which are an important determinant of soil health. There remain challenges in both assessing the impacts to soil functions and aggregating this information to provide an overall assessment that can be generalized to different contexts. Due to differing site conditions, technique specifications, contamination, etc., the studies could occasionally contrast or indicate mixed results where impacts could be either positive or negative depending on the context.

5.4. Minimizing impacts on soil functions from remediation and refunctionalizing soil

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For the conventional remediation techniques discussed above (Table 5), minimizing impacts on soil functions requires process optimization and a shift from single-method application towards adaptive, hybrid strategies that combine techniques, e.g., as treatment chains, to balance contaminant removal with soil function preservation. Integrating low-impact and nature-based methods such as soil amendments and phytomanagement into these remediation strategies can substantially reduce long-term functional degradation and improve the prospects for sustainable soil reuse. Understanding the soil functions that can be disrupted during the remediation process provides information for the establishment of remediation strategies and restoration plans that minimize disturbance (Lee 2021). These findings underscore the importance of integrating rehabilitation and refunctionalisation measures into remediation planning from the outset, rather than treating them as optional post-remediation add-ons.

In thermal remediation, excessive temperatures and prolonged heating may provide limited additional contaminant removal while accelerating losses of soil organic matter, microbial biomass, and aggregate stability, which inhibit plant growth as well as ecological restoration (Liao 2025, O'Brien 2018). Evidence indicates that lower-temperature treatments can preserve sufficient soil functionality for agricultural reuse while reducing energy consumption by up to 35% compared to conventional high-temperature thermal desorption (Rehman 2023). Similarly, soil washing is effective for contaminant removal but often results in persistent degradation of soil physicochemical and biological properties. Recent studies emphasise the importance of selecting lower toxicity or biodegradable washing agents and dosages, controlling contaminant mobilisation, and prioritising post-treatment soil health recovery alongside removal efficiency. Biodegradable chelators such as GLDA and ISA that can effectively extract metals are highlighted as having lower impacts, but may still alter metal mobility and bioaccessibility, posing potential risks for soil reuse (Kaurin 2020; Wang 2018). However, chelator choice and dose remain critical, as some biodegradable agents may still lead to nutrient losses and structural degradation, while conventional chelators such as EDTA raise concerns regarding persistence and residual ecotoxicity. Notably, modified soil washing approaches using reduced and recycled EDTA doses (e.g. in the ReSoil® process) have demonstrated comparatively low impacts on soil properties, particularly when combined with post-remediation rehabilitation measures such as compost addition, microbial inoculation, and phytoremediation (Gluhar, Kaurin, Finžgar 2021; Gluhar, Kaurin, Vodnik 2021; Kaurin 2020, 2021). ISCO/ISCR often leads to losses of SOM, reduced aggregation, and increased leaching of dissolved organic carbon, nutrients, and mobilised metals, particularly under acidic conditions. Several studies suggest first applying ISCO to reduce contaminant concentrations then following with in-situ bioremediation as a strategy to both mitigate negative impacts and enhance overall remediation effectiveness (O'Brien 2017b; Polli 2018; Sahl 2006). However, the chemical treatment may have negative impacts on soil

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microorganisms thus impairing the biodegradation and mobilised DOC and nutrients may also delay contaminant biodegradation as they are preferred substrates (Sutton 2014). Electrokinetic remediation may induce strong pH gradients and transient reductions in microbial abundance; however, these effects are often reversible when EK is followed by or combined with bioremediation, biostimulation, bioaugmentation, or phytoremediation. In several hybrid systems, microbial abundance and activity have recovered to levels exceeding those of untreated contaminated soils, indicating that biological processes can compensate for short-term electrochemical stress while improving overall remediation effectiveness (Crognale 2020; Kim 2010; Lima 2017). Similarly, immobilisation with Fe-based nanoparticles or iron grit combined with organic amendments such as compost or biochar have shown promise for remediating metal-contaminated soils while mitigating negative effects associated with inorganic amendments alone (Baragaño 2020; Lebrun 2019; Nandillon 2019).

While soil functions may recover slowly over time following remediation, in many cases, rehabilitation of the soil to restore soil functionality will be required following remediation, especially where high-intensity conventional treatment has been applied. The soil health recovery trajectory is strongly dependent on post-treatment soil conditions and the implemented rehabilitation measures. The recovery of soil biota and associated functions depends strongly on the SOM content, nutrient availability, and water content, as well as the reintroduction or recolonisation of microorganisms following treatment (O’Brien 2017b). Indeed, without restoration of SOM and favourable soil conditions, recovery of soil biodiversity may take decades, even where contaminant concentrations have been reduced to acceptable levels (Adl 2008). This is especially relevant for intensive remediation methods such as thermal remediation, where most soil organisms are destroyed during heating, but post-treatment recovery can be hastened through microbial inoculation, amendment addition, natural recolonisation and mixing with uncontaminated agricultural soil (O’Brien 2017b, 2018; Rehman 2023). Low-impact and nature-based remediation approaches, such as organic amendment addition, phytoremediation and bioremediation, are a key part of the rehabilitation process that can be integrated as part of the treatment chain. For instance, soil washing can substantially harm soil microorganisms and inhibit their functions, but these effects are often reversible by, for example, following up with phytomanagement to “polish” washed soils thereby mitigating residual ecotoxicity and supporting recovery of soil microbial activities (Gluhar, Kaurin, Finžgar 2021; Kaurin 2021). Also, the addition of a combination of organic amendments such as vermicompost, compost, biochar, manure, uncontaminated soil, and soil organisms such as earthworms or microorganisms can promote the recovery of soil following chemical washing (Gluhar, Kaurin, Finžgar 2021; Jelusic 2014; Kaurin 2020; Kaurin 2018). Various bioremediation approaches, often in combination with organic amendment addition, should also be considered as part of the

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rehabilitation process. For instance, a common application of mycoremediation is the addition of spent mushroom substrate (SMS), which functions as a fungal inoculum and organic amendment rich in organic matter and nutrients that can improve soil properties as well as biodegradation of residual organic contaminants such as PAHs, pesticides and chlorinated compounds (Antón-Herrero 2023, Hidalgo 2023).

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6. Demonstration

6.1. Integration of soil health concept into regional-scale risk assessment approaches

In addition to the indicators considered in regional risk assessment frameworks (see deliverable D2.2), the concept of soil health deserves specific attention when addressing diffuse contamination at large spatial scales. Integrating soil health into a regional risk assessment perspective allows soil degradation processes to be analysed in a spatially explicit manner, supporting preventive and management-oriented decision-making. The relevance of considering soil health within the ISLANDR risk assessment framework was also discussed during the WP2 workshop hold in January 2026, highlighting the need to explore its integration.

The integration of soil health into diffuse contamination regional-scale risk assessment could aim to assess the risk of degradation of the soil itself.

Soil health, in the regional risk assessment (RRA) methodology, can be described using indicators related to key soil functions in line with the SML, such as pH, SOC content, texture and soil structure, land use, conductivity (water infiltration potential), biological activity. To apply the framework in a GIS-based procedure, those attributes must be georeferenced. Moreover, the expected soil functionality can be evaluated according to the current land use, recognising that different land-use contexts require different soil functions. Since direct measurements of soil health and biological functions are rarely available at regional scale, proxy indicators can be used to approximate soil functionality (e.g., soil quality or soil biota indices such as *Indice de Qualité Biologique des Sols* or *Indice de Qualité des Sols Wallons*.

During the WP2 workshop on Soil Health, participants identified a key priority for integrating soil health into the regional risk assessment framework: enabling the prioritisation of areas where contamination-related risk coincides with high soil functional value.

In line with the relative RRA approach, this integration aims to identify areas that are more susceptible to unacceptable impacts due to direct diffuse contamination. If a high-risk area is located near to this high-quality soil health area, this area should be prioritised for investigation and remediation, since the impairment of high-quality soil health and associated soil functions should be avoided.

Since balancing risk reduction with the preservation of soil functionality is essential, this integrated approach supports the spatial identification (and visualization) of areas where a high/low contamination risk coincide with high soil functional value. This enables an initial screening to guide future actions, including remediation or restoration. This approach remains scalable and applicable at both European Union and Member State level within a risk-based and fit-for-purpose management strategy.

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6.2. Demonstration: inclusion of soil health concept into the Large-Scale Risk assessment of diffuse contamination and demonstration in the Toulouse ITA

The integration of soil health into the regional risk assessment framework is here presented with example maps of the Toulouse Metropolitan Area, with the objective of illustrating how soil health considerations can be operationally incorporated into a large-scale risk-based methodology.

The hazard component was defined in alignment with the diffuse contamination methodology described in D2.2. Interpolated concentration maps of selected contaminants were compared against land-use-specific Contamination Threshold Concentrations (CSCs), derived from Italian legislation (see also D.2.2 for additional details) and used as conservative proxies in the absence of harmonised European soil quality standards. Areas where measured concentrations exceeded ten times the relevant CSCs were identified as zones of main potential concern. In parallel, SOC was included as an additional soil property to support the interpretation of spatial patterns.

As a second step, the same distinction according to the land use can also be applied for soil health, as it is expressed through different soil functions relevant for each specific land use (e.g. agricultural or urban).

A few indicators are here shown; these values should be classified into value ranges and associated with relative scores, representing increasing levels of vulnerability or functional importance. Soil health can be included in the RRA methodology, while other risk receptors may remain consistent within this methodology, namely groundwater, surface water, human health, and protected areas.

A key limitation in the practical implementation of soil health at regional scale is the availability of harmonised, georeferenced datasets for the selected indicators (Figure 10). As it is often the case in large-scale assessments, data availability constrained the level of detail that could be achieved. For this reason, the Toulouse application should be regarded as an illustrative example. The dataset has been obtained from a national database, and it include sparse data.

Despite these limitations, the application provides a proof of concept for the integration of soil health into regional risk assessment, highlighting its potential role in supporting prioritisation and preventive management strategies in the context of diffuse soil contamination.

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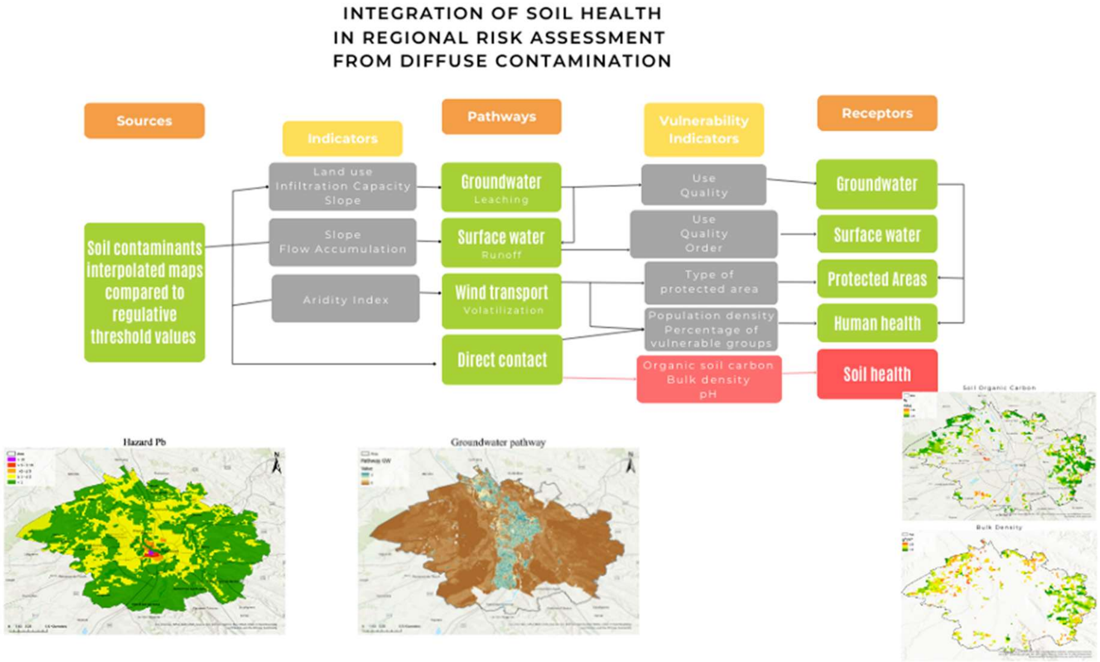

Figure 10. Integration of soil health in regional risk assessment; example maps in GIS application from Toulouse ITA area. Two indicators were taken as an example for soil health: soil organic carbon and bulk density.

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7. Conclusions

The work conducted within ISLANDR demonstrates that integrating soil health considerations into the management of contaminated land requires additional input at every stage of the process. A key challenge is ensuring that these additions remain coherent and aligned with the core objectives of contaminated land management, namely risk and contaminant reduction, throughout soil management. Soil health is integrated into an already complex decision-making context in which contaminated land management must address risks to human health, ecosystems, and site rehabilitation.

This deliverable highlights the need for in-depth assessment of soil functions through appropriate indicators, and to evaluate the impact of remediation on these functions. It also emphasises the importance of adapting Environmental Risk Assessment frameworks to explicitly include soil health.

Within this context, this deliverable focused on the conceptual development and large-scale demonstration of soil health integration into contaminated land management, extending risk-based approaches to explicitly consider soil functionality.

Beyond quantitative data, there is also a clear need to provide perspective and purpose to soil health inputs so that soil functionality and risk assessments are guided by meaningful site-use objectives within the stepwise approach recommended by the SML. It provides an overarching framework and protocol to support the integrated assessment of soil functionality, environmental risk, and contaminated land management through a soil-use-oriented perspective.

A key takeaway is that both remediation strategies and land-use planning can benefit from a soil health perspective by explicitly considering the soil trajectories envisaged for a site.

The recently adopted SML distinguishes between soil health monitoring (Chapter 2) and contaminated land management (Chapter 4). However, this work highlights important overlaps between these domains, particularly regarding contaminants managed in Chapter 4 and monitored in Chapter 2, as well as environmental risk assessments in Chapter 4 that require input from soil data monitored in Chapter 2. In this respect, soil health trends identified at soil unit level may provide useful contextual guidance; however, remediation decisions at contaminated sites should remain grounded in site-specific risk assessment, reflecting local conditions and exposure pathways.

Building on past and ongoing research, future work should ensure that soil health monitoring and the management of contaminated land evolve in a coordinated and

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integrated manner, supporting more sustainable, resilient, and function-oriented soil and land management practices within holistic SRBLM frameworks..

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Appendix I – Soil descriptors

Table A 1 links each descriptor in the matrix to i) the recommended analytical or observational technique (preferably ISO or other internationally recognised standards); and ii) indicative target or threshold values for “healthy soil” conditions, as defined in the Soil Monitoring Law.

Table A 1. Soil descriptor, technique used to assess the descriptor, defined criteria for a healthy soil condition and land areas exempted from meeting the related criterion, as described in the Soil Monitoring Law Annex.

	Soil descriptor[1]	**Technique***	**Criteria for healthy soil condition – non-binding sustainable target values**[2]	**Land areas exempted from meeting the related criterion**
Soil Health Law Annex -part A	Electrical conductivity (deci-Siemens per meter)	Option 1: ISO 11265 Determination of the specific electrical conductivity Option 2: saturated soil paste extract (eEC) measurement method (FAO SOP: GLOSOLAN-SOP-08**)	< 4 dS m^{-1} when using saturated soil paste extract (eEC) measurement method, or equivalent criterion if using another measurement method	Naturally saline land areas, areas with regular flooding from marine submersion and areas subject to sea spray
	Soil organic carbon concentration (g per kg)	ISO 10694 Determination of organic and total carbon after dry combustion, ensuring all carbon is incinerated SOC shall be calculated by determining the total carbon content and subtracting the carbon present as carbonate, which shall be determined in accordance with ISO 10693	- For organic soils: respect targets set for such soils at national level in accordance with Article 4(2) and (4), and Article 11(4) of Regulation (EU) 2024/1991 - For mineral soils: SOC/Clay ratio > 1/13 (that is the ratio of SOC content to the content of the clay fraction (fraction with a diameter of less than 0,002 mm)) Member States are expected to apply corrective factors to the ratio where specific soil types or climatic conditions	No exemption Non-managed soils in natural land areas

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			justify it, considering the link to structural stability		
	Bulk density in subsoil (g per cm^3)	ISO 11272 for determination of dry bulk density Where an equivalent parameter is chosen, the methodology shall be either a European or international standard where available; if such standard is not available, the methodology chosen shall either be available in the scientific literature or publicly available	Soil texture[3]	range	Non-managed soils in natural land areas and areas with naturally compacted soils
			Sand, loamy sand, sandy loam, loam	<1,80	
			Sandy clay loam, loam, clay loam, silt, silt loam	<1,75	
			Silt loam, silty clay loam	<1,65	
			Sandy clay, silty clay, clay loam with 35-45 % clay	<1,58	
			Clay	<1,47	
			Member States may apply different texture classes or values corresponding to the levels considered problematic for plant rooting system development		
	Optional: – saturated hydraulic conductivity, Ksat (cm per day)		≥ 10 cm/day[4] Member States may adapt this value according to their local soil conditions		

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	- air capacity (%)		≥ 5 %[5] Member States may adapt this value according to their local soil conditions	
Soil Health Law Annex -part B	Extractable phosphorus (mg per kg)	Preferred: ISO 11263 for spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution (P-Olsen) Other methods may be used as an alternative	< "maximum value" Member States shall lay down their own maximum value, at a level that would not entail damage to human health and the environment	Non-managed soils in natural land areas
	Soil erosion rate (tonnes per hectare per year)		< 'maximum value' Member States shall lay down their own maximum value, at a level that would not entail damage to human health and the environment	Badlands and natural land areas, except if they represent a significant disaster risk
	Concentration of heavy metals in soil: As, Sb, Cd, Co, Cr (total), Cu, Hg, Pb, Ni, Tl, V, Zn (mg per kg) Concentration of a selection of organic contaminants established by Member States and considering existing concentration limits in Union law, e.g. for water quality and air emissions	For heavy metals: ISO 54321: Aqua Regia Optional: bioavailable fractions of contaminants, such as ISO 17586 using dilute nitric acid	Reasonable assurance, obtained from soil point sampling, identification and investigation of potentially contaminated sites and any other relevant information, that an unacceptable risk to human health and the environment from soil contamination does not exist Natural and anthropogenic background levels shall be considered in the risk assessment If natural background is the only reason leading to unacceptable risks, then the relevant soil shall be deemed to meet the healthy soil criteria if it is managed in such a way that an unacceptable risk to human health does not exist Habitats with a naturally high concentration of heavy metals that are included in Annex I to Directive 92/43/EEC shall remain protected	No exemption

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	Water retention: – soil water holding capacity of the soil sample (% of water per total soil (volume or mass)) Water infiltration: – saturated hydraulic conductivity, Ksat (cm per day) – air capacity (%)	Methodology to determine the value for one sample point: (2) (1) Soil water holding capacity and air capacity: Option 1: LABORATORY: ISO 11274 for determination of the water-retention characteristic Option 2: ESTIMATION: apply pedotransfer functions requiring input variables such as particle size distribution, bulk density, soil organic carbon concentration (2) Saturated hydraulic conductivity: Option 1: LABORATORY: ISO 17313: Determination of hydraulic conductivity of saturated porous materials Option 2: ESTIMATION: apply pedotransfer functions requiring input variables such as particle size distribution, bulk density, soil organic carbon concentration	The estimated value for the total water holding capacity, the saturated hydraulic conductivity and the air capacity of a soil unit is above the minimal threshold and may also be assessed by river basin or sub-basin, considering water processes occurring at that scale The minimal threshold shall be set (in tonnes) by the Member State at the relevant scale, at such a value that the impacts of flooding following intense rain events or of periods of low soil moisture due to drought events are mitigated	No exemption
	SOC stocks (tC ha^{-1}) Optional: – soil organic carbon content (g per kg)	Methodology as set out in Annex V to Regulation (EU) 2018/1999 in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories	Contribute to national targets for net greenhouse gas removals in the LULUCF sector as referred to in Article 4(3) of Regulation (EU) 2018/841 > ‘minimum value’ Member States shall lay down the minimum value by soil texture	No exemption

	Total nitrogen content in soil (mg g^{-1}) SOC to nitrogen ratio	Option 1: ISO 11261 for determination of total soil nitrogen using a modified Kjeldahl method Option 2: ISO 13878 for determination of total nitrogen by dry combustion	Without criteria	
Soil Health Law Annex -part C	Soil acidity (pH) Member States may also select the optional descriptor: – Topsoil compaction base saturation (i.e. (Ca + Mg + K)/effective cation exchange capacity (CEC))	ISO 10390 for determination of pH in H_2O, KCl and $CaCl_2$ extract	Without criteria	
	Bulk density in topsoil (A-horizon[6]) (g cm^{-3}) Optional: – saturated hydraulic conductivity (cm per day) – air capacity (%)	ISO 11272 for determination of dry bulk density	Without criteria (A-horizon[6])	
	DNA metabarcoding for fungi and bacteria Member States may also select at least one optional soil descriptor for biodiversity, such as: - metabarcoding of archaea, protists and animals phospholipid fatty acid analysis (PLFA) abundance and diversity of nematodes	Use European or international standards where available; if such standard is not available, the methodology chosen shall either be available in the scientific literature or publicly available **Basal Respiration**	Without criteria	

	abundance and diversity of earthworms abundance and diversity of springtails abundance and diversity of native ants soil biological quality based on arthropods (QBS-ar) presence of invasive alien species and plant pests soil basal respiration	Follow indications described in the scientific article “Microbial biomass and activities in soil as affected by frozen and cold storage”		
	Concentrations of PFAS-21[7] or concentrations of PFAS-43[8] or selected PFAS set by Member States in accordance with Article 7(4) Concentrations of selected active substances in pesticides and their metabolites set by Member States in accordance with Article 7(4) Optional: - concentrations or presence of a selection of other emerging soil contaminants set by Member States in accordance with Article 7(4)			
Soil Health Law Annex - part D	Soil sealing and soil removal indicators	The methodologies used shall comply with the definitions set out in Article 3 and Annex I. Such methodologies shall make use of at least the Copernicus services or,		

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		preferably, best available data including remote-sensing images, which shall be supplemented with relevant national inventories.		
	Total sealed soils and areas that underwent soil removal (km^2 and % of Member State surface) Soil sealing and soil removal, de-sealing and net-sealing (average per year – in km^2 and % of Member State surface) Total settlement area (km^2 and % of Member State surface) Land use change to and from settlement area (average per year – in km^2 and % of Member State surface) Member States may also measure other related optional indicators, such as: – soil artificialisation – land fragmentation – land recycling rate – land taken for commercial activities, logistic hubs, renewable energies, surfaces such as airports, roads, mines, – consequences of soil sealing and soil removal, such as quantification of loss of ecosystem services, change in the intensity of floods			

[1] The minimum criteria for the methodology for in-situ sampling of soil descriptors are provided for in Annex II, Part A, and further details are to be provided pursuant to Article 24.

[2] Further details on the methodology on setting non-binding sustainable target values and operational trigger values for soil descriptors listed in Annex I, Parts A, B and, when possible, Part C, are to be provided pursuant to Article 24.

[3] As defined in IUSS Working Group WRB. 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

[4] Lebert, M., Böken, H., Glante, F. 2007. Soil compaction—indicators for the assessment of harmful changes to the soil in the context of the German Federal Soil Protection Act. Journal of Environmental Management 82(3): 388-397.

[5] Lebert, M., Böken, H., Glante, F. 2007. Soil compaction—indicators for the assessment of harmful changes to the soil in the context of the German Federal Soil Protection Act. Journal of Environmental Management 82(3): 388-397.

[6] As defined in the FAO Guidelines for Soil Description, Chapter 5 (https://www.fao.org/3/a0541e/a0541e.pdf).

[7] 6:2 FTS, PFBA, PFBS, PFDA, PFDoDA, PFDoDS, PFDS, PFHpA, PFHpS, PFHxA, PFHxS, PFNA, PFNS, PFOA, PFOS, PFPeA, PFPeS, PFTrDA, PFTrDS, PFUnDA, PFUnDS or other 21 PFAS, as available in the laboratories.

[8] PFOS, PFOA, PFHxS, PFNA, PFBS, PFPeS, PFHpS, PFNS, PFDS, PFUnDS, PFDoDS, PFTrDS, PFBA, PFPeA, PFHxA, PFHpA, PFDA, PFUnDA, PFDoDA, PFTrDA, PFTeDA, PFOSA, N-EtFOSA, N-MeFOSA, FOSAA, N-EtFOSAA, N-MeFOSAA, FHxSA, N-EtFHxSA, N-MeFHxSA, FHxSAA, N-EtFHxSAA, N-MeFHxSAA, FBSA, N-EtFBSA, N-MeFBSA, FBSAA, N-EtFBSAA, N-MeFBSAA, 6:2 FTS, 8:2 FTS, 5:3 FTCA, 7:3 FTCA or other 43 PFAS, as available in the laboratories.

* Soil texture (clay, silt and sand content – needed for the determination of other descriptors and related ranges) should be determined using ISO 11277 (Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation)

** https://www.fao.org/3/cb3355en/cb3355en.pdf

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Appendix II– Impacts of conventional remediation techniques on soil functions

Table A 2. Expected impacts of conventional remediation techniques on the six main soil functions, sub-functions and indicators/descriptors.

Impacts of remediation techniques → on soil functions ↓		***Conventional remediation techniques***							
Function	**Sub-functions & -** *indicators/descriptors*	**Thermal treatment (in-situ/ex-situ*)**	**Soil washing (ex-situ*) or flushing (in-situ)**	**ISCR/ISCO (in-situ)**	**Electrokinetic remediation (in-situ)**	**Multi-phase extraction (in-situ)**	**Air sparging (in-situ)**	**Containment/ capping/barriers (in-situ)**	**Stabilisation/ solidification (S/S, in-situ/ex-situ*)**
Organic matter storage, transformation and recycling	**Decomposition**								
	-soil microbial biomass	— or +/-	— or +/-	— —	— or +/-		+ or +/-	— —	— —
	-invertebrate feeding activity						+	— —	— —
	-organic matter mineralization in soil	+/-			— or +/-		-	— —	— —
	Resource reallocation								
	-soil organic carbon (SOC)	— —	—	— —	+/-		— or +/-	— —	— —
	Biochemical transformation								
	-soil organic carbon (SOC)	— —	—	— —	+/-		— or +/-	— —	— —
	-microbial basal respiration (carbon mineralization)		— or +/-	— or +/-	— or +/-			— —	— —
	-microbial catabolic activities (MSIR, enzymes)	— or +/-	— —	—	— or +/-		+	— —	— —

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	-functional diversity/genes				— or +/-			— —	— —
Water regulation, retention and release	**Water retention**								
	-soil texture	— —	— or +/-	+/-			+ or -	— or +/-	+ or -
	-water holding capacity (retention)	— —	—	—			-	— or +/-	— —
	-soil organic carbon (SOC)	— —	—	— —			— or +/-	--	— —
	Infiltration and percolation								
	-infiltration/permeability	—				+/-	+ or +/-	--	— —
	-bulk density	+/-	+/-			+/-	+ / -	+ / -	+ / -
	-effects on macrofauna (earthworms)	— or +/-		— —			+ / -	--	
Nutrient cycling	**Nutrient transformation**								
	-total nitrogen content	— or +/-	—	—	+/-		+/-	+/-	
	-Assimilable/extractable phosphorous content	+ or +/-	—	+ or +/-	+ or +/-			+/-	
	-pH	+/-	+/-	— —	— —		-	+/-	+/-
	-microbial catabolic activities (MSIR, enzymes) - and respiration?	—	— —	—	+/-		-		
	-soil microbial biomass	— or +/-	— or +/-	— —	—		+ or +/-		
	Nutrient reallocation								
	-CEC		+/-	—					
	-microbial catabolic activities (MSIR, enzymes)	— or +/-	— —				+		
	Nutrient assimilation (plants)								
	-available nitrogen (NO2, NO3)			+ or +/-	+ or +/-		—		
	-microbial activities (denitrification)	— —					—		

	-functional diversity/genes				——				
Contaminants retention, transformation and degradation	**Retention**								
	-soil organic carbon (SOC)	——	—				— or +/-		
	-pH	+/-	+/-	——	——				+/-
	-soil texture (clay content)	——		+/-					+/-
	-total/bioavailable concentrations of metals and organics	+/-	+/-	—	—		—		
	Transformation & Degradation								
	-microbial catabolic activities (respiration, enzymes)	— or +/-	— or +/-		—				
	-soil microbial diversity								
	-biodegradation of organic chemicals					+	++		——
Physical stability	**Inherent soil stability and evolution**								
	-soil texture	——	— or +/-						
	-soil microbial biomass	— or +/-	— or +/-	——	—		+		
	-change in pore networks (compaction, etc.)	— or +/-	— or +/-	—			— or +/-		
	-aggregation	— or +/-	— or +/-				+ / -		
	-soil organic carbon (SOC)	——	—	——			— or +/-		
	-effects on macrofauna (earthworms)	— or +/-	+/-	——			+ / -		
	-salinity (electrical conductivity)	—	+/-	+/-					
	-CEC		+/-						
	-soil erosion rate	—					+ / -		

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	-bulk density (plant rooting)	—	+/-			— or +/-	
	-geotechnical properties	+	— or +/-	— or +/-	+	+ / -	
Habitat provision	**Habitat quality**						
	-soil texture	—	— or +/-			— or +/-	— or +/-
	-pH	+/-	+/-	— —	— —	— or +/-	— or +/-
	-soil organic carbon (SOC)	— —	—	— —			— or +/-
	-soil microbial biomass	— or +/-	— or +/-	— —	—	+	— —
	-plant biomass production	—	+/-	— or +/-			
	-ecotoxicological quality (effects on macro-/meso-/microfauna and microbes) - density, abundance, reproduction, etc.	— or +/-	— or +/-	— —	—		— —
	Harbouring biodiversity						
	-microbial diversity (indices, genetic sequencing)	— or +/-	— or +/-	—	—		— —
	-invertebrate diversity (indices, genetic sequencing)	— or +/-					--

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Appendix III – Impacts of low-impact remediation techniques on soil functions

Table A 3. Expected impacts of low-impact remediation techniques on the six main soil functions, sub-functions and indicators/descriptors.

Impacts of remediation techniques → on soil functions ↓		***Low-impact remediation techniques***				
Function	**Sub-functions &** **-***indicators/descriptors*	**Bioremediation (in-situ/ex-situ)**	**Phytoremediation (all, in-situ)**	**Monitored natural attenuation (in-situ)**	**Immobilisation with amendments (organic, in-situ)**	**Immobilisation with amendments (inorganic, in-situ)**
Organic matter storage, transformation and recycling	**Decomposition**					
	-soil microbial biomass	+ or +/-	++	+	+	+ or +/-
	-invertebrate feeding activity		+	+	+	
	-organic matter mineralization in soil	+	+	+/-	+	
	Resource reallocation					
	-soil organic carbon (SOC)	+ or +/-	++	+	++	+ or +/-
	Biochemical transformation					
	-soil organic carbon (SOC)		++	+	++	
	-microbial basal respiration (carbon mineralization)	+ or +/-	+	+	+	+/-
	-microbial catabolic activities (MSIR, enzymes)	+ or +/-	+	++	++	
	-functional diversity/genes	—	+		+	+/-
	Water retention					

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Water regulation, retention and release	*-soil texture*		+/-	– or +/-		
	-water holding capacity (retention)	+	+	+ or +/-	+	+/-
	-soil organic carbon (SOC)		++		++	
	Infiltration and percolation					
	-infiltration/permeability	+	+		+	+/-
	-bulk density	+	+/-		+	+
	-effects on macrofauna (earthworms)		+	-	+	+/-
Nutrient cycling	**Nutrient transformation**					
	-total nitrogen content	+/-	+/-	+/-	+	
	-Assimilable/extractable phosphorous content	+/-	+/-	+/-	+	+/-
	-pH	+/-	+/-		+/-	+/-
	-microbial catabolic activities (MSIR, enzymes) - and respiration?		+		++	+/-
	-soil microbial biomass		+	+	+	
	Nutrient reallocation					
	-CEC		+/-		+	+
	-microbial catabolic activities (MSIR, enzymes)		+	+	+	
	Nutrient assimilation (plants)					
	-available nitrogen (NO2, NO3)	+/-	+/-	+/-	+ or +/-	
	-microbial activities (denitrification)		+	+/-	+	

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	-functional diversity/genes	—	+	+	+	
Contaminants retention, transformation and degradation	**Retention**					
	-soil organic carbon (SOC)		+		+	
	-pH	— or +/-	+/-		+	+
	-soil texture (clay content)			+ / -		
	-total/bioavailable concentrations of metals and organics	+/-	+	— or +/-	+/-	++
	Transformation & Degradation					
	-microbial catabolic activities (respiration, enzymes)	+ +	+	++	+	
	-soil microbial diversity		+	++	+	
	-biodegradation of organic chemicals	++	+	++	+	+/-
Physical stability	**Inherent soil stability and evolution**					
	-soil texture			+/-		+
	-soil microbial biomass		+	+	+	
	-change in pore networks (compaction, etc.)	+	+	+/-	+	+
	-aggregation	+	+	+/-	+	+
	-soil organic carbon (SOC)	+ or +/-	+	+/-	++	
	-effects on macrofauna (earthworms)		+	+/-	+	
	-salinity (electrical conductivity)			+/-	+	+/-
	-CEC			+/-	+	+
	-soil erosion rate?		+	+/-		
	-bulk density (plant rooting)		+	+/-	+	+
	-geotechnical properties	+ or +/-	— or +/-	+/-	+/-	+

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Habitat provision	**Habitat quality**					
	-soil texture		+/-	+/-		
	-pH	+/-	+/-	+/-	+/-	+/-
	-soil organic carbon (SOC)	+ or +/-	+		++	
	-soil microbial biomass	+ or +/-	+	+	++	
	-plant biomass production				++	+/-
	-ecotoxicological quality (effects on macro-/meso-/microfauna and microbes) - density, abundance, reproduction, etc.	+/-	+		+	+/-
	Harbouring biodiversity					
	-microbial diversity (indices, genetic sequencing)	+ or +/-	+	+	+	+/-
	-invertebrate diversity (indices, genetic sequencing)		+		+	

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