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Scoping document

Outlook on the knowledge gaps to reduce land degradation in Europe

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1. Introduction

One of the primary processes jeopardizing soil health at a global scale is Land Degradation (LD). More precisely, according to the United Nations (UN), Land Degradation means "reduction or loss of biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and, (iii) long-term loss of natural vegetation. Land degradation, therefore, includes processes that lead to surface salt accumulation and waterlogging associated with salt-affected areas." (United Nations 2007).

Notably, in the realm of soil conservation, there is often confusion between the terms soil degradation and land degradation, with soil erosion mistakenly considered synonymous with both. Furthermore, soil degradation encompasses more than just erosion, Soil degradation can involve: water erosion (includes sheet, rill and gully erosion); wind erosion; salinity (includes dryland, irrigation and urban salinity); loss of organic matter; fertility decline; soil acidity or alkalinity; structure decline (includes soil compaction and surface sealing); mass movement; and soil contamination (NSW Department of Planning, Industry and Environment, 2019). However, land degradation covers a broader scope beyond soil alone. Referring to its usage in land evaluation (FAO 1976), the term "land" contains all natural resources contributing to agricultural production, including forestry and livestock production. This definition includes landforms, climate, water resources, soils, and vegetation (both forests and grasslands) (FAO 1999). Several interconnected components of land degradation exist, all of which may lead to a decrease in agricultural production (Douglas 1994), as cited by the Food and Agriculture Organization (FAO) (FAO 1999). Land degradation generally also includes processes other than soil degradation, such as alterations of superficial and groundwater resources, reduction of quantity and quality of plant production, biodiversity degradation (e.g. species extinction), or climate deterioration (FAO 1999).

In the context of the Soils for Europe (SOLO) project, and also in this document, which aligns with the Soil Mission Implementation Plan of the EU, the term "Land Degradation" primarily refers to “Soil Degradation”. This stems from the fact that according to the Soil Mission, the objective (Specific Objective 1) “Reduce Land degradation relating to desertification”, is linked solely to soil health indicators, such as soil organic carbon stock, presence of soil pollutants and excess of salts (European Commission 2019a).

The imperative to combat Land degradation on both European and global scales arises from the close association of Land Degradation with critical losses of biodiversity and key ecosystem services (Keesstra et al. 2018, Panagos and Katsoyiannis 2019). Furthermore, a substantial consensus within reports and assessments indicates that a significant segment of the Earth's land surface faces degradation, estimated at between 20% and 40% of the total global land area (UN Convention to Combat Desertification

2019a, UN Economic and Social Council 2019, United Nations Convention to Combat Desertification 2022). In this light, according to Wischnewski 2015, 169 out of 194 countries, participating in the United Nations Convention to Combat Desertification (UNCCD), are affected by Land Degradation. Thenceforth, the degree of global land degradation today is considered to be negatively affecting 3.2 billion people worldwide (Brooks et al. 2006, Cardinale et al. 2012, Haddad et al. 2015, UNDP 2019, Panagos and Katsoyiannis 2019, Li et al. 2021).

As for the evolution of Land Degradation, it is essential to highlight that the Global Land Outlook report (United Nations Convention to Combat Desertification 2022) warns that without immediate actions, the problem of land degradation will persist and escalate. By the year 2050, if the current rates continue, an expanse equivalent in size to South America is projected to experience degradation (United Nations Convention to Combat Desertification 2022). Moreover, according to the Global Risk Report of the World Economic Forum 2025, natural resource shortages, including soil, represents the 4th most important long-term financial risk. This emphasizes the pressing need to address land degradation urgently in order to avert further environmental, economic and societal deterioration.

Specific concerns related to land degradation are also prominent within the European Union (EU). More precisely, data drawn from all EU Member States, as outlined in the Soil Mission Implementation Plan (European Commission 2019a), highlight several alarming issues. Notably, it reveals that 83% of agricultural soils within the EU contain residual pesticides. In addition, a substantial number of potentially contaminated sites, amounting to 2.8 million, exist, with a mere 65,000 having undergone remediation efforts by 2018 (European Commission 2019a). Within the EU, issues related to soil erosion by water, compaction, soil sealing and excavation also persist. Approximately 24% of EU land is marked by unsustainable water erosion rates, 23% experiences compaction, soil sealing affected about 2.7 % of EU land, and a staggering 520 million tonnes of soil are excavated and treated as waste, despite the majority of it not being contaminated (European Commission 2019a). Relevant findings are also addressed in the recently published State of Soils for Europe report and the EUSO Soil Degradation Dashboard (European Comission and European Environment Agency 2024).

In addition, the aforementioned Soil Mission Implementation Plan (European Commission 2019a) underscores the pressing imperative to address land degradation and desertification*[1]. This urgency is reflected in the inclusion of the 'Reduction of land degradation relating to desertification' within the Specific Objectives (more precisely, SO1) of the Soil Mission. In particular, the SO1 is intricately linked to the Mission’s Target 1.1, which aims to 'Halt desertification to help achieve land degradation neutrality and initiate restoration'—a commitment aligned with Sustainable Development Goal (SDG) target 15.3 (Combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation neutral world). The SO1 works as a catalyst for the attainment of other SDGs (European Commission 2006b, IPCC (Inter-Governmental Panel on Climate Change) 2001, United Nations Convention to Combat Desertification 2022), as well as key initiatives such as the EU Soil Strategy, the Green Deal, the Soil Monitoring Law, the 2030 Biodiversity Strategy, the Zero Pollution Action Plan, the Farm to Fork Strategy, the Circular Economy Action Plan, the Nature Restoration Law, and the EU Climate Law.

Mitigating land degradation necessitates a comprehensive approach encompassing sustainable land management practices, support to the farmers and land managers, multiple stakeholders working together, soil conservation, reforestation efforts, and initiatives to curb e.g., soil pollution and contamination. Moreover, despite the EU focus of the SOLO project, international collaboration, as exemplified by the UNCCD, also holds significant importance in tackling this challenge and safeguarding the integrity of our land resources for the benefit of future generations. The upcoming decades will be decisive in shaping and implementing a fresh and transformative EU and global land management and conservation strategy.

To support these efforts, the Land Degradation Think Tank forges a vibrant and transdisciplinary cluster through the active collaboration and engagement of key stakeholders and a diverse network of partners from various fields of knowledge, brought together by their commitment to soil health. This collaborative effort, along with an extensive literature review, aims to intricately weave together a roadmap that transcends traditional boundaries, seeking to pinpoint and address critical knowledge gaps, navigate through bottlenecks, and uncover cutting-edge technological innovations (Fig. 1). The ultimate goal is to craft a comprehensive strategy that effectively propels the mission to enhance soil health.

Figure 1. doi

Land Degradation Think Tank methodology.

The Land Degradation Think Tank's main objectives are to:

- Identify and enumerate key knowledge gaps related to land degradation in the EU, through a transdisciplinary approach.
- Identify and delineate drivers and obstacles (Bottlenecks) that hinder soil health in the EU.
- Identify the needs and priorities of the EU to achieve Land Degradation Neutrality by 2050.
- Identify and describe pioneering actions and activities that are crucial to overcoming the barriers that affect land health.
- Co-develop a research and innovation roadmap for the EU Soil Mission in relation to land degradation and integrate it into an overarching roadmap tackling the specific mission objective. Integral to this roadmap is the establishment of science-based guidelines for defining threshold values for soil health, which will serve as critical benchmarks for monitoring progress, guiding restoration efforts, and fostering sustainable land management practices across the EU.

Given the above, the Land Degradation Think Tank adds value by uniting experts across disciplines to identify knowledge gaps, overcome obstacles, and co-develop a science/ stakeholders-based roadmap that guides EU efforts toward achieving land degradation neutrality by 2050 and improving soil health.

2. State-of-the-Art

2.1. Current state of the knowledge on Land Degradation

In the field of soil quality monitoring, the EU has adopted the definition of the FAO for Sustainable Soil Management (SSM) (FAO - ITPS 2020). According to the FAO, SSM includes the prevention, minimization, or combating of soil quality deteriorations which, in their extreme expression, might potentially lead to land degradation and desertification. At the same time, the United Nations Convention to Combat Desertification (UNCCD) has set a specific goal to achieve Land Degradation Neutrality (LDN) by 2030 (United Nations Convention to Combat Desertification 2017). In particular, the UNCCD’s target is to stop the ongoing loss of healthy soils due to degradation, and promotes for the first time a two-pronged approach, with measures to prevent or reduce land degradation combined with other compensational measures for land degradation of the past. Implementing such effective measures requires a better understanding of Land Degradation drivers (e.g. aridity, unsustainable agricultural practices, forest fires, urbanization, mining and quarrying, drought), and processes (e.g. erosion, flooding, soil structure deterioration, pollution, soil sealing, compaction, loss of biodiversity).

Considering the above, Land Degradation represents an essential "wicked problem" - a multifaced challenge - characterized by interconnected environmental, societal, economic and policy dimensions (Fig. 2).

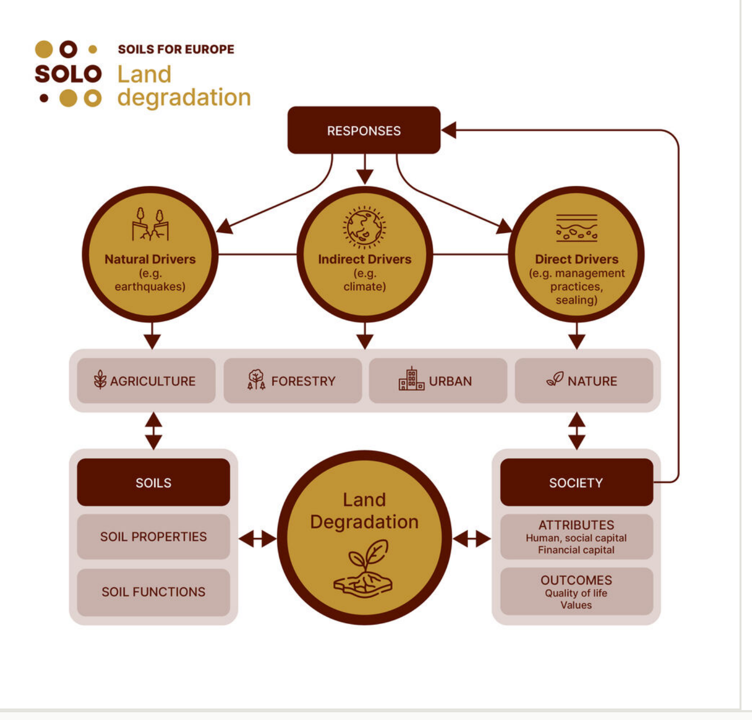

Figure 2. doi

Land Degradation: A transdisciplinary challenge

Land Degradation poses significant challenges. Therefore, in recent decades, several methods, approaches and datasets have been developed and used to assess the status of the complex and dynamic processes of Land Degradation in Europe at different scales. More precisely, examples of datasets that provide information about Land Degradation components are the Soil Organic Carbon Dataset*[2] and the Salt Affected Soils Dataset*[3] of the FAO. The FAO also provides a plethora of relevant complementary datasets, such as the Map of Agreement on Global Cropland*[4] and networks. An example network refers to the Global Soil Laboratory Network (GLOSOLAN), established in 2017, and aims to enhance the capabilities of soil laboratories worldwide by standardizing analytical methods and data. This harmonization is essential to: i) Provide consistent and comparable information across countries and projects, ii) Facilitate the creation of unified soil datasets, and iii) support informed decision-making for sustainable soil management.

Moreover, in 2023, the Joint Research Center's soil team (JRC D3), developed the EU Soil Observatory (EUSO) dashboard that integrates several soil related datasets. In particular, the EUSO Dashboard offers insights into potential locations (spatial resolution of 500 meters) of unhealthy soils within the EU, with plans for regular updates based on emerging scientific findings. As for the datasets that synthesize the EUSO Dashboard, they refer to but are not limited to erosion related datasets, such as the Soil Erosion by Water Dataset*[5] (based on the RUSLE model) and the Soil Erosion by Wind Dataset*[6] (based on the RWEQ model), soil pollution relevant datasets, e.g. the Copper Excess Dataset*[7] and the Mercury Excess Dataset*[8], and soil nutrient datasets, such as the Phosphorous Deficiency and the Phosphorous Excess Dataset*[9]. Additional datasets of the EUSO Dashboard refer to the Potential Threats to Soil Biodiversity Dataset*[10], the Soil Compaction Dataset*[11] and the Soil Sealing Dataset*[12].

Furthermore, over the recent decades, various concepts and methodologies have emerged to establish schemes for monitoring and assessing Land Degradation. More precisely, Gianoli et al. 2023, evaluated Land Degradation status at the EU level by applying the Convergence of Evidence (CoE) conceptual framework, originally developed for the World Atlas of Desertification (WAD), and incorporating additional indicators of land status and trends. CoE entails the idea that evidence from disparate and independent sources can converge to form robust conclusions (Gianoli et al. 2023). This conceptual framework has been employed in environmental science, particularly in conjunction with satellite remote sensing data (Cherlet et al. 2018, Ivits et al. 2013, Martínez-Valderrama et al. 2022). In the study by Gianoli et al. 2023 the additional indicators encompassed data such as population density and change, groundwater table decline, acidification, and eutrophication. These were complemented by variables aligned with those used in the WAD, such as soil erosion by water and wind, land cover, land productivity dynamics, baseline water stress, and biodiversity loss.

Similarly, another continental (EU-scale) study by Schillaci et al. 2022 evaluated the United Nations Sustainable Development Goal 15.3.1 indicator of Land Degradation across Europe. This study applied the UNCCD methodology and utilized the *Trends.Earth**[13] software, while also assessing the influence of alternative datasets, such as NDVI time series at varying spatial resolutions, alongside policy-relevant data sources for land cover (e.g., CORINE) and soil organic carbon (SOC) stocks (e.g., LUCAS dataset).

At the country scale, examples of applications employing the UNCCD approach, supplemented by Earth Observation (EO) and soil monitoring data, include the work of Wunder and Bodle 2019, who developed a land use change-based indicator for Germany. However, this approach may be affected by declines in land productivity (LP) due to decoupling strategies within the Common Agricultural Policy, such as reduced agricultural intensity (Schillaci et al. 2022). Another example is a high-resolution (20 m) assessment conducted for Italy, which incorporated additional variables, such as loss of habitat quality, burnt areas (2008–2018), and the density of artificial land cover (Assennato et al. 2020).

Despite these advancements, the baseline assessment procedure, as outlined in the UNCCD Good Practice Guidance (UNCCD 2021), faces challenges in some parts of the EU. These challenges include limited data availability due to small land-use parcel sizes, land suitability issues, resilience constraints, and socio-cultural and economic factors. As a result, monitoring land degradation using the three UNCCD land-based global indicators may lead to false positive classifications or an underestimation of the extent of degraded land (Schillaci et al. 2022).

In this light, assessing the indicator 15.3.1, which measures the proportion of degraded land over the total land area, necessitates ongoing data collection by countries to monitor changes spatially and temporally. Earth Observation can significantly contribute to both generating this indicator in countries lacking data and enhancing existing national data sources (Dubovyk 2017). To address this challenge, Giuliani et al. 2020 introduced an innovative, adaptable, and scalable approach for monitoring land degradation across different scales (national, regional, and global) by utilizing various components of the Global Earth Observation System of Systems (GEOSS) platform to harness Earth Observation resources for informing SDG 15.3.1. The proposed approach adheres to the Data-Information-Knowledge pattern, leveraging the Trends.Earth model (http://trends.earth) along with diverse data sources to compute the indicator (Giuliani et al. 2020).

Other essential examples of these concepts and approaches are the usage of the MEDALUS method, where the Climate Quality Index (CQI), the Soil Quality Index (SQI), the Vegetation Quality Index (VQI), the Management Quality Index (MQI) and the Social Quality Index (SoQI) were integrated under several climate change scenarios (Perović et al. 2021, Prăvălie et al. 2020). Besides, other components that describe Land Degradation in the literature refer to

- Biophysical components (e.g. plant cover and agricultural productivity trends, net primary productivity, soil erosion etc.) (European Commission 2006aAyalew et al. 2020, Dubovyk 2017, European Commission 2006b, Panagos et al. 2020Giuliani et al. 2020, Jucker Riva et al. 2017),
- Environmental ClientEarth 2022, Gholizadeh et al. 2018, Giuliani et al. 2020, Gorji et al. 2019, Prăvălie et al. 2017, Taghadosi et al. 2019, Žížala et al. 2018) and/or
- Socio-economic factors (e.g. poverty, migration and population density) (Reed and Stringer 2016Akhtar-Schuster et al. 2017, Barbier and Hochard 2018, Keesstra et al. 2018European Commission 2020c, European Commission 2020b, Ustaoglu and Collier 2018Blaikie and Brookfield 2015, Istanbuly et al. 2022, Panagos et al. 2024, Sartori et al. 2019) as well as the
- Utilization of long-term satellite observations (e.g. Sentinel-2 optical satellite constellation) (ClientEarth 2022, European Commission 2020c, United Nations 2023) which provide a practical way of generating a monitoring system that can derive cost effective and widely applicable indicators of Land Degradation.

In addition, Land Degradation is also assessed by fine-scale field-based and modeling techniques, Geographic Information Systems (GIS), informatics (Machine-Learning and Artificial Intelligence models), time-series and residual trends (European Commission 2020c, Žížala et al. 2018, European Commission 2020b, United Nations 2023, European Commission 2019b, European Commission 2021b, Dahal et al. 2024, European Commission 2021a, Gholizadeh et al. 2018, Perpiña Castillo et al. 2021, Xie et al. 2020, Petropoulou et al. 2023). However, throughout the lifespan of the Soils for Europe project, it is important to first clarify *what information* should be used to assess Land Degradation, rather than focusing on *how* this information is processed. By identifying the key data sources and indicators—such as soil health metrics, land cover changes, or productivity trends—a clear and consistent framework for soil degradation assessments can be established. Once the essential information is defined, then the most effective methods (e.g., GIS, AI, or modeling techniques) to process and analyze this data can be explored. This approach could ensure a streamlined and actionable take-home message from the Land Degradation Think Tank to the relevant stakeholders, emphasizing the critical indicators to include in soil degradation assessments before delving into the technicalities of data processing.

Considering the above, it can be concluded that there have been significant advancements in scientific research, datasets, policies, and strategies aimed at addressing land degradation. Nevertheless, critical knowledge (application) gaps persist, hindering comprehensive solutions and effective knowledge transfer regarding this multifaceted issue. Land degradation is a complex, transitional problem with multiple drivers, scales, and perspectives, requiring integrated monitoring and assessment schemes (UN Convention to Combat Desertification 2019b, Reynolds et al. 2007, Vogt et al. 2011, Hessel et al. 2014, European Commission 2015, European Environment Agency 2019). While efforts have been made, challenges remain in understanding the full scope of land degradation, its drivers, and its socio-economic and ecological impacts.

For instance, while restorative practices like biochar and integrated nutrient management show promise, there is insufficient research on trade-offs, cost-effectiveness, and scalability across diverse land uses and pedo-climatic zones (Maroušek and Trakal 2022 Lal 2015, Keesstra et al. 2024). Additionally, gaps and limitations in data availability, quality and monitoring, along with the integration of cultural and socio-economic values into land management decisions further complicate efforts to achieve Land Degradation Neutrality (LDN) and understand LD effects and drivers (Dubovyk 2017, Jucker Riva et al. 2017, Žížala et al. 2018, Gholizadeh et al. 2018, Taghadosi et al. 2019, Giuliani et al. 2020, Ayalew et al. 2020Bardgett et al. 2021, Jones et al. 2021, Silva et al. 2023). The lack of comprehensive, standardized data and the underrepresentation of certain ecosystems, such as grasslands, mountainous regions, and urban soils, highlight the need for more inclusive and context-specific research (Löbmann et al. 2022, Chowdhury et al. 2024).

As such, while participatory approaches and stakeholder engagement are vital for sustainable land management, empirical evidence on their effectiveness and knowledge transfer remains controversial (Knierim et al. 2015, Löbmann et al. 2022). Economic assessments of land degradation and restoration efforts also face challenges, including inconsistent methodologies and the exclusion of non-monetary considerations, which hinder the development of robust, site-specific solutions (Panagos et al. 2018, Tepes et al. 2021).

In a nutshell, while progress has been made in understanding LD, the trajectory of future research must embrace a diverse array of topics, spanning from the exploration of the processes, mechanisms, and impacts of land degradation to the nuanced examination of the environmental, climatic, political, social, cultural and financial aspects of Land Degradation as driving forces behind its persistence (European Commission 2021c).

Embracing cutting-edge technologies and monitoring methodologies, advancing theoretical frameworks, and refining ecological restoration approaches are imperative for fostering sustainable land management practices (European Commission 2021c). Moreover, interdisciplinary collaboration is essential for unraveling the complex dynamics inherent in land degradation phenomena and the formulation of robust policy frameworks is crucial to guide sustainable land management initiatives (European Commission 2021c).

2.2 Prioritization of knowledge gaps

The approach of the Land Degradation Think Tank (refer to Fig. 1) is designed to identify Knowledge Gaps, Actions, and Bottlenecks (see Section 3) throughout the SOLO project. Once a set of Knowledge Gaps was identified, the next step involved prioritizing these Knowledge Gaps to determine the most critical areas requiring research and funding within the EU.

The resulting prioritized (Top 10) Knowledge Gaps for the Land Degradation Think Tank can be found in Table 1 (Suppl. material 4) and are addressed in detail in Section 3.1. It is noteworthy that a complete list (and a short description) of all identified knowledge gaps is given in section 3.3.

Table 1. Top 10 Knowledge Gaps

Suppl. material 4

3. Roadmap for the Land Degradation Think Tank

Despite the recent surge in scientific publications, policies, and strategies dedicated to addressing land degradation, it is widely recognized that significant knowledge gaps persist. Furthermore, even with maximum utilization of these various policies and strategies, it remains challenging to comprehensively address all aspects of land and its associated threats (European Commission 2022, Xie et al. 2020)

In this regard, the complex issue of Land Degradation needs a combination of the above-mentioned monitoring and assessment schemes (UN Convention to Combat Desertification 2019b) as Land Degradation is considered a complex issue with multiple dimensions, scales and perspectives, it is transitional and has multiple drivers and actors. This conclusion is also supported by other scientists such as Reynolds et al. 2007, Vogt et al. 2011, Hessel et al. 2014, European Commission 2015, and the European Environment Agency 2019.

Considering the above, it can be concluded that there are various knowledge gaps, and therefore, activities but also associated bottlenecks that should be considered regarding Land Degradation and the achievement of the aim of a LDN Europe in the upcoming years. These gaps highlight critical areas where research, innovation, and policy interventions are urgently needed.

The identified Knowledge Gaps are detailed in the following subsections:

- **Section 3.1** focuses on the **Key Knowledge Gaps**, which represent the top three priorities (Top 3 KGs) as outlined in Table 1.
- **Section 3.2** covers the remaining prioritized Knowledge Gaps, ranked from the Top 4 to the Top 10.
- **Section 3.3** provides an overview of all identified Knowledge Gaps, Actions, and Bottlenecks, which collectively form the foundational elements of the Roadmap.

By organizing these elements into a structured framework, the Roadmap aims to provide a clear and actionable pathway for addressing Land Degradation and advancing toward LDN in Europe.

3.1 Key Knowledge Gaps

The **Key Knowledge Gaps**, representing the top three priorities as determined by stakeholder voting, are outlined below:

Knowledge Gap 1

Identification of the most efficient and cost-effective Land Degradation prevention and restoration measures, incorporating an assessment of trade-offs between different land uses and pedo-climatic zones.

As the EU grapples with soil degradation, scientists and practitioners have identified various land use and restoration measures to prevent and reverse degradation. These efforts span from traditional to modern knowledge and try to address the specific needs of different regions and land types. Among the promising restorative and sustainable practices are biochar (Maroušek and Trakal 2022, Kalu et al. 2022, Fišarová et al. 2024), organic matter, and nutrient-integrated management (Lal 2015, Keesstra et al. 2024). These measures are designed to minimize losses and maximize the efficiency of soil, water, and nutrient use, which is the guiding principle of achieving "more from less" in land management (Lal 2015). However, much of the EU research funding and literature on sustainable land management (SLM) practices has predominantly focused on agricultural soils, with insufficient attention given to other land uses, such as urban soils or industrial and post-mining soils (e.g., Farrell et al. 2020, Table 1 of Löbmann et al. 2022, Psarraki et al. 2023, Figure 7 to 10 of Chowdhury et al. 2024, Zoka et al. 2024). Despite the growing work in land degradation prevention and restoration, challenges persist (European Commision 2020). Limited studies on trade-offs between different land uses and pedo-climatic zones, cost-benefit analyses, and the applicability of restoration techniques across various scales and socio-ecological contexts hinder the widespread adoption of effective solutions. As such, there is an urgent need for more comprehensive research that integrates diverse land uses, such as grasslands, urban areas, forested lands, and agricultural spaces, alongside other areas with various activities (industrial, mining, etc.). Some example studies that display such limitations can be found below:

Addressing Trade-offs in Restoration: Insights from Grassland Studies

A notable contribution to understanding these challenges is the study by Bardgett et al. 2021, which examined limited awareness and research on grassland degradation, at a global, and European scale. Their study emphasized the importance of grasslands in ecosystem functioning and biodiversity maintenance but pointed out that restoration efforts for these ecosystems remain underfunded and fragmented. Bardgett et al. 2021 applied a multi-criteria decision analysis (MCDA) model to identify sufficient solutions, addressing complex trade-offs among conservation practices (e.g. conventional and organic) and incorporating socio-economic factors, such as access rights and power dynamics between stakeholder groups (Martín-López et al. 2019). However, to achieve better outcomes from decision-making tools like MCDA, it is crucial to focus on the optimal allocation and prioritization of limited resources, especially since funding for grassland restoration is often scarce (Bardgett et al. 2021). In addition, they highlighted the necessity for new approaches that allow for the standardized assessment of grassland conditions, considering various environmental and climatic contexts. These approaches should evaluate the extent of grassland degradation, its impacts on biodiversity and ecosystem services, and the effectiveness of restoration initiatives. Moreover, the fragmentation of restoration efforts across regions and organizations further complicates these challenges, as data often remains incompatible or inaccessible, hindering knowledge sharing (Bardgett et al. 2021). Thus, the scaling up of restoration initiatives, particularly in grassland and other sensitive ecosystems, demands significantly more resources and concerted effort to maximize benefits and minimize trade-offs (IPBES 2018, Roe et al. 2021).

Cost-Effectiveness in Large-Scale Restoration: A Participatory Approach

Another example of innovative restoration planning is found in the study by Silva et al. 2023, who developed a participatory cost-effectiveness model to identify high-priority areas for landscape restoration. Their work, conducted in Southeastern Spain, a semi-arid region severely impacted by human activity, highlights the importance of considering both the financial costs and the potential improvements in ecosystem service delivery. The model they created not only accounts for the costs of restoration but also integrates stakeholder perspectives, offering a more holistic view of the restoration process. In their study, Silva et al. 2023 found that while restoration costs are generally lower than the costs of degradation, securing sufficient funding for restoration efforts in the short term remains a significant barrier. This underlines the importance of cost-optimization strategies and effective prioritization to make the most of available resources (Molin et al. 2018). The study also emphasized the need to improve the representativeness of stakeholder groups by including underrepresented sectors such as youth, women, and those with lower education levels (Silva et al. 2023). Such inclusiveness can help address imbalances in power dynamics and ensure that all perspectives are considered in decision-making processes. Furthermore, Silva et al. 2023 suggested that future restoration projects should focus on enhancing long-term stakeholder engagement through improved communication, clear modeling approaches, and real-time modeling tools that help stakeholders visualize restoration outcomes (Green et al. 2019, Hooftman et al. 2022). These measures would foster greater involvement in decision-making and ensure that restoration plans align with the needs of diverse communities.

In conclusion, achieving effective and cost-efficient land degradation prevention and restoration requires a multifaceted approach. While the application of restorative practices such as biochar and crop rotation show promise, scaling these efforts across diverse land types and regions presents considerable challenges. The integration of socio-economic factors, stakeholder engagement, and cost-effectiveness analysis tools, such as MCDA and participatory models, can help address these challenges. Additionally, there is a need for standardized, European, national and local approaches to assess land degradation and guide restoration efforts, particularly in regions, where restoration is often underfunded. As research and case studies continue to evolve, it will be crucial to refine these strategies, improve stakeholder participation, and better understand the trade-offs of soil management practices between land uses and pedo-climatic zones.

Knowledge Gap 2

Lack of thorough understanding of the interactions between Land Degradation and Ecosystem Services. Land degradation continues to be a significant concern, with profound implications for ecosystems and the services (ES) they provide (Guerra et al. 2022). However, there are considerable knowledge gaps and limitations in understanding the interactions between land degradation and the delivery of ES. These gaps hinder effective policymaking and the development of sustainable management strategies. Some limitations that can be found in the literature are discussed below:

To begin with, accurate and reliable data on land degradation and ES is crucial for understanding their interactions. Empirical evidence obtained through field and landscape indicators is vital for assessing soil health and the services provided by ecosystems (Petrosillo et al. 2023). However, the scarcity of region-specific measurements remains a significant barrier to advancing research in this field (Petrosillo et al. 2023). The lack of comprehensive and standardized data across different landscapes, combined with fragmented knowledge, often limits the ability to draw broad conclusions (Petrosillo et al. 2023). To effectively assess and monitor land degradation, there is a growing need for innovative tools and technologies. One of the most promising approaches is the use of remote sensing data, which can provide valuable insights into the type, extent, and severity of land degradation. By leveraging satellite imagery and aerial data, remote sensing allows for large-scale, precise monitoring of land conditions over time, enabling more accurate identification of degradation patterns. This technology plays a crucial role in understanding how land is changing and can guide targeted interventions to mitigate and reverse degradation (Prokop 2020, de Oliveira et al. 2022). However, challenges remain in integrating this data with on-the-ground field assessments (Prokop 2020, de Oliveira et al. 2022, Tziolas et al. 2024). Furthermore, despite the progress in using remote sensing for monitoring, the complexity of soil and ecosystem dynamics, including the role of soil biodiversity and its contribution to ES, remains insufficiently understood. More precisely, according to the study of Ferreira et al.

2022, associated with soil degradation in the Mediterranean region, local research has mapped soil heterogeneity and degradation through monitoring sites and long-term experiments at relatively small scales (e.g., Barão et al. 2019). However, this information is seldom collected or inventoried (FAO 2019). While all EU countries are required to produce state-of-the-environment reports, most Mediterranean countries do not regularly assess their soil resources (Solomun et al. 2020).

Moreover, one significant limitation in ES research is the difficulty in understanding, quantifying and integrating cultural ecosystem services (CES) into land management decisions. In particular, cultural services, including aesthetic, spiritual, and recreational values, are vital to human well-being but are often difficult to define and measure (Jones et al. 2021). This is primarily due to the challenge of understanding what motivates individuals to engage with nature and how these motivations relate to various cultural, social, economic, and psychological factors (Jones et al. 2021). In this light, several studies on soil degradation tend to focus predominantly on the natural dimensions, leaving insufficient attention to the cultural and social factors; however, a similar investment could lead to a similar degree of understanding.

To address these limitations, the study of Jones et al. 2021 proposed a framework that integrates cultural, social, and human capital, offering a promising approach to understanding the role of these factors in CES. While their trans-disciplinary study demonstrated that cultural capital, measured through EcoCentrism, was a strong predictor of environmental engagement, it also revealed that a significant portion of the variation in people's perceptions of natural spaces, such as urban meadows, remained unexplained. This points to a need for new metrics and frameworks that can capture the full range of motivations and values associated with cultural interactions with the environment. The incorporation of variables like intergenerational knowledge and indigenous relationships with land could further enrich this framework and provide a more nuanced understanding of CES (Jones et al. 2021).

Another study that investigated the research gap between soil biodiversity and the the delivery of soil ecosystem services, from Oberreich et al. 2024, with a focus on Germany, highlighted that soil and soil biodiversity are often overlooked in ecosystem assessments. Additionally, the social awareness of the term "ecosystem services" remains limited (Oberreich et al. 2024). Moreover, the findings suggest that the studies in the reviewed papers primarily focused on smaller spatial scales, emphasizing local and regional contexts. This is especially relevant for soil biodiversity, which, as the literature reviewed, varies due to several locally specific factors (e.g., Köhler et al. 2020).

Furthermore, land degradation and its impact on ES must be understood within broader socio-economic and policy contexts. While the role of soil-related ES in supporting human well-being is widely recognized, the interactions between ES and land use policies, particularly in terms of mitigating land degradation, need further exploration (Wei et al. 2018, Mengist et al. 2020). The principle of "Avoid > Reduce > Reverse" land degradation, which emphasizes avoiding further degradation as the most cost-effective strategy, is gaining traction in the context of land degradation neutrality (UNCCD 2017, Petrosillo et al. 2023). However, examples that depict a lack of policy integration in land degradation and ES research remain a major limitation. A notable example refers to the mountainous regions, where just a few studies link ecosystem service outcomes to actionable policy recommendations (Wei et al. 2018, Mengist et al. 2020). This gap in literature points to the need for more research on the role of policy in managing trade-offs and synergies between ES, land degradation, and human activities. In addition, there is a gap in research related to soil governance, particularly regarding the interactions between different governance mechanisms and their effects on soil management (Mason et al. 2023). This suggests a need for further exploration into institutions, policy support, and training in soil governance (Helming et al. 2018, Mason et al. 2023).

One other significant aspect is the valorization of ES which remains a significant barrier to understand the interactions between ecosystem services and land degradation. While valuable progress has been made in estimating the economic value of ES, particularly in the context of sustainable land management (SLM), the lack of reliable, comprehensive datasets hinders the full assessment of ecosystem service costs and benefits (Kieslich and Salles 2021, Mirici 2022). For instance, in landscape restoration projects, where benefits such as water regulation, drought resistance, and soil erosion control are critical, the incomplete data on these services, limits their effective inclusion in restoration planning (Almagro et al. 2013, de Groot et al. 2022). This data scarcity is a widespread issue in ecosystem and landscape restoration. However, two key initiatives— the TEER-initiative (The Economics of Ecosystem Restoration, led by FAO, CIFOR, and WRI) and the Ecosystem Services Valuation Database—may help address this issue (de Groot et al. 2022). Nevertheless, there still remains a pressing need for more accessible and reliable data to inform land management decisions.

Further research is needed to develop innovative methodologies, improve data collection and valuation practices, and strengthen the integration of policy recommendations into ES research. Addressing these gaps is essential for advancing sustainable land management practices and ensuring the effective delivery of ecosystem services in the face of land degradation.

Knowledge Gap 3

What are the historical, current, and future social and economic interactions with Land Degradation?

Land degradation presents significant challenges across multiple domains, including social and economic spheres. Understanding the intricate connections between land degradation, social vulnerability and structure, along with financial implications is critical to addressing its causes and impacts effectively. Although substantial research has been conducted on these topics, several knowledge gaps persist, particularly regarding the historical, current, and future socio-economic interactions with land degradation within the European Union (EU) (The Economics of Land Degradation 2015). Below, we separate the social and economic components of land degradation to highlight their respective limitations.

Social Impacts of Land Degradation

Land degradation directly affects communities, particularly in regions with intensive agricultural practices or vulnerable ecosystems. The social aspects of land degradation have been studied extensively, but several critical knowledge gaps remain. First, there is a need to understand the long-term societal consequences of land degradation (Johnson et al. 2024). Research has examined the immediate effects on agricultural productivity and rural livelihoods, but the total social cost, including health, migration, unemployment, inequality and displacement, is still poorly understood (Johnson et al. 2024). A key aspect is that land degradation can lead to social vulnerability by eroding community resilience and forcing vulnerable populations to migrate. Yet, the impacts of this environmental migration remain underexplored, with most studies focusing on climate change migration (IPBES 2018).

Second, there is a gap in understanding the role of indigenous and local knowledge in coping with land degradation. The integration of these traditional insights into modern land management practices could provide valuable solutions for more sustainable land recovery. Indigenous practices often emphasize ecosystem health and holistic land exploitation, offering an important counterpoint to contemporary methods of land degradation mitigation (Johnson et al. 2024). Yet, the validation and systematic integration of such knowledge remain insufficient and often overlooked in favor of purely scientific or technological solutions (Teuber et al. 2022).

Moreover, the socio-economic benefits of suitable land management practices have not been fully explored (examples were also discussed in the Knowledge Gap 1). Effective land restoration practices can yield long-term socio-economic returns, including improved food security, rural employment, and ecosystem services (Löbmann et al. 2022). However, a comprehensive understanding of how these practices contribute to community well-being, particularly in the context of varying socio-economic conditions across the EU, remains challenging (Visser et al. 2019, Amin et al. 2020, Löbmann et al. 2022). There is a need for integrated research to assess these benefits within diverse socio-economic contexts to facilitate the design of context-specific solutions.

Finally, the importance of participatory approaches in addressing land degradation has been recognized, particularly in the framework of the Agricultural Knowledge and Innovation System (AKIS), which fosters joint learning and co-creation (Knierim et al. 2015, Löbmann et al. 2022). Participatory approaches to data gathering and research, which engage farmers, amateur soil scientists, community members, or school students, have gained attention for both advancing scientific progress and achieving social and educational outcomes (Löbmann et al. 2022). As defined by von Korff et al. 2012, "participatory" refers to the involvement of not only trained professionals but also a broader range of interested parties, including non-experts and local community members. However, there is a lack of empirical evidence on the effectiveness of these participatory approaches, which limits their potential to generate actionable insights (Hallinger and Nguyen 2020). Future research should explore the value of participatory methods in creating more inclusive, adaptive, and sustainable land management practices.

Economic Impacts of Land Degradation

According to the study by Panagos et al. 2018, 12 million hectares of agricultural land in the EU that are affected by severe soil erosion by water annually lose around 0.43% of their crop productivity, which translates to a cost of approximately €1.25 billion. The agricultural sector incurs a direct cost of €300 million, while the GDP loss amounts to €155 million. Italy is identified as the country with the highest economic impact, while most Northern and Central European countries experience only marginal losses Panagos et al. 2018. More recent and relevant financial information can be found in the State of Soils in Europe Report (European Comission and European Environment Agency 2024).

As seen from an economic perspective, the costs of land degradation and the financial viability of soil protection measures are critical areas where some knowledge gaps and limitations still exist. More precisely, land degradation has significant economic consequences, as in agriculture, which is often one of the most directly affected sectors. Despite this, there remains a lack of comprehensive economic assessments of soil protection practices, especially at the farm level (Tepes et al. 2021). For example, many existing studies on the cost-effectiveness of soil protection measures rely on secondary data and assume that the benefits of these practices consistently exceed their costs. However, this assumption is frequently challenged by evidence that indicates such benefits do not always outweigh the costs, especially in heterogeneous areas (Tim Chamen et al. 2015, Tepes et al. 2021).

Another major limitation in economic research on land degradation is the lack of consistent and comparable data. Much of the existing literature focuses on specific regions, using varied methodologies, and often excludes non-monetary considerations, which leads to gaps in understanding the full economic value of soil health (Kenter et al. 2016, Löbmann et al. 2022). For instance, many studies omit the broader economic implications of off-site impacts, such as soil erosion, which can have far-reaching effects on local economies, beyond just the immediate agricultural sector. These impacts are difficult to quantify and remain underexplored in many studies (Kubiszewski et al. 2013, Romanazzi et al. 2024).

Furthermore, economic models that assess the costs and benefits of land degradation and remediation often rely on overly simplified assumptions, such as the uniform distribution of soil degradation across different agricultural systems. These assumptions can lead to inaccurate estimations of the actual costs of land degradation. For example, studies conducted in regions like the UK and Germany suggest that economic outcomes can vary significantly depending on local agro-economic conditions, meaning that cost analyses should be conducted at more localized scales (Intergovernmental Panel on Climate Change 2019).

While progress has been made in understanding the social and economic dimensions of land degradation, significant gaps remain in both areas. From a social perspective, more research is needed on the long-term impacts of land degradation on communities, including migration, vulnerability, and the role of indigenous knowledge. A more integrated and participatory approach to land management is necessary to address the complex and context-specific nature of land degradation.

Economically, there is a need for more robust, site-specific studies on the costs and benefits of soil protection and remediation measures. Economic assessments should move beyond generalized assumptions and account for the diverse agro-economic conditions that influence land management decisions, while also accounting for off-site effects. Additionally, future research should explore innovative policy instruments that integrate both financial and social aspects of land degradation.

Ultimately, addressing these knowledge gaps will contribute to a more comprehensive understanding of land degradation, enabling the development of more effective policies and interventions. As the EU works toward its land degradation neutrality targets, these insights will be crucial in ensuring that both social and economic factors are accounted for in the sustainable management of land resources.

3.2 Prioritized Knowledge Gaps

As far as the remaining **Prioritized Knowledge Gaps** are concerned, they can be found below:

Knowledge Gap 4

Lack of comprehensive understanding of Land Degradation (effects and drivers)

There is a lack of comprehensive and detailed understanding of the causes, processes, and impacts of Land Degradation across different regions and soil types (Reynolds et al. 2007, Saljnikov et al. 2022, Daliakopoulos et al. 2016, FAO 2015, Ravi et al. 2010, Xie et al. 2020). Some relative examples refer to the difficulties that arise due to the diversity of perspectives on land degradation, limited studies regarding soil compaction, and complexities in revealing the intricate nature of interactions between Soil Organic Matter (SOM) fractions (Gianoli et al. 2023). More precisely, despite the existence of numerous case studies at a European and global level, applying such findings on a continental scale remains a challenge, as understanding the precise dynamics of driver interactions and their plausible impacts on specific sites requires detailed case-specific examination (Gianoli et al. 2023). Moreover, while there are some studies offering estimates of the areas affected by compaction, there are only a handful of field studies that actively monitor the impacts of soil compaction and the subsequent alterations in the soil structure and functions after a compaction event (Keller et al. 2017, Saljnikov et al. 2022). As for the gaps in understanding SOM fractions interactions, challenges can be found in understanding the relationships between aboveground and belowground biota (Orgiazzi and Panagos 2018), and the impact of drivers on the accumulation/decomposition of

SOM (Jia et al. 2019). Consequently, more research is needed to fill these knowledge gaps and develop a better understanding of the complexities involved and the interlinkages between various drivers and processes concerning Land Degradation.

Knowledge Gap 5

How can we enhance regional planning regarding reducing Land Degradation?

One of the key challenges in enhancing regional planning to reduce land degradation is the fragmented nature of policies and the lack of coordination among various stakeholders (Saik et al. 2024). Research indicates that a unified political environment is essential for integrating LDN objectives across governance levels—from local to national authorities (Kust et al. 2017, Saik et al. 2024). Another limitation is the insufficient data on land resources and soil, which impedes accurate assessments of land degradation risks and restoration potential (Oliveira et al. 2018). To address these gaps, there is a need for improved data collection and monitoring mechanisms. Current research suggests that spatial planning tools and models, which assess land degradation risks and track restoration progress, could help align LDN efforts with broader climate resilience and economic development goals (Briassoulis 2019, UNCCD/Science-Policy Interface 2023). These tools are essential for developing integrated strategies that promote sustainable land management. Additionally, the integration of ecosystem services into land-use planning remains a significant challenge (Oliveira et al. 2018). While studies highlight the importance of incorporating ecosystem services into land management (Zhang et al. 2022), methods for assessing and quantifying these services in the context of LDN are still underdeveloped. Ecosystem services, such as soil fertility, water regulation, and carbon sequestration, must be accounted for in regional planning to ensure the sustainability of land-use decisions. As noted by Cowie et al. 2018, achieving LDN requires careful consideration of the balance between land degradation and restoration, which depends on reliable indicators for monitoring changes in land condition. Furthermore, a central knowledge gap in the current discourse is the lack of attention given to land degradation in strategic spatial planning (Oliveira et al. 2018). Although environmental issues are often acknowledged in land-use planning, few studies address how strategic spatial planning can effectively contribute to the reduction of land degradation, particularly in urban regions (Gomiero 2016, Albrechts 2016). As highlighted by recent reviews, strategic spatial planning has been increasingly recognized as an important way for managing land transformation, yet its potential to mitigate land degradation has not been fully explored (Briassoulis 2019, Cowie et al. 2019). In this context, there is a need to expand the role of strategic spatial planning in addressing land degradation. For regional planning to effectively contribute to land degradation reduction, it must move beyond the general recognition of environmental concerns and implement concrete strategies to protect and restore land (Oliveira et al. 2018). This requires the inclusion of all sectors of society, from land managers to local communities, in the planning process. Furthermore, it is essential that spatial plans are developed with clear objectives for sustainable land use and LDN implementation.

Knowledge Gap 6

Lack of Land Degradation data and limited monitoring at different scales

Comprehensive data on land degradation (LD) is essential for understanding its causes, extent, and impacts, yet significant gaps exist across various spatial and temporal scales. Without accurate, high-resolution data on land and soil health, the development of targeted solutions and the implementation of effective policies remain a challenge (European Commission 2019a, European Commission 2020a, Saljnikov et al. 2022, United Nations to Combat Desertification 2016, Lunik 2022, Ontel et al. 2023). One notable example is highlighted by Panagos et al. 2020, where the uncertainty in soil erosion estimates arises from the lack of georeferenced data, specifically data on crop types and soil management practices implemented annually. This data gap makes it difficult to accurately assess the spatial distribution of land degradation and complicates the monitoring of restoration efforts.

Another example study that provides a flexible and valid starting point for assessing land degradation is not without its challenges (Manna et al. 2024). In particular, the study of Manna et al. 2024 highlighted that one of the significant issues is the difficulty of obtaining up-to-date databases for land cover and soil organic carbon (SOC) data. The lack of timely data can result in the underestimation of critical land degradation indicators, particularly in areas with irregular spatial distributions. These variations can often only be detected through in situ sampling or the use of very high-resolution multispectral images.

In addition to the technical limitations in data collection and analysis, there are conceptual challenges related to the measurement and classification of land degradation. A recurring issue in land degradation studies is the lack of clear differentiation between processes and drivers, cause and effect, as well as hazard and vulnerability (von Keyserlingk et al. 2023). This ambiguity complicates the development of quantitative risk projections and impedes the connection between research findings and decision-making processes (Akbari et al. 2016 Martínez-Valderrama et al. 2020b, Martínez-Valderrama et al. 2020a).

In many studies, land degradation is either treated as a permanent condition or as a discrete hazard, with limited consideration of its temporal dynamics. While some studies (Masoudi and Jokar 2018, Martínez-Valderrama et al. 2020) include probabilistic elements of risk, such as scenario analyses based on state and transition models, such approaches are not universally adopted (von Keyserlingk et al. 2023). The absence of a consistent framework for integrating temporal dynamics into land degradation assessments further limits the ability to predict future degradation trends and develop adaptive management strategies. Incorporating a more nuanced understanding of the processes, drivers, and risks associated with land degradation is essential to inform more effective policymaking and land management practices.

In conclusion, accurate data plays a pivotal role in several key processes related to land degradation, including monitoring and assessing land health, designing evidence-based policies, securing funding, and fostering collaboration among stakeholders. These processes rely on the availability of high-quality, comprehensive datasets. Therefore, it is crucial to prioritize data collection, the digital transformation of data systems, and dedicated research efforts aimed at addressing land degradation through enhanced research and innovation (R&I) initiatives.

Knowledge Gap 7

How do we support the farmers to make the turning point towards sustainable land and soil management soil practices?

Farmers often use management practices like ploughing, believing they will increase crop production. However, these practices can degrade soil and reduce yields in the long run (Quinton et al. 2022). Although several farmers recognize the challenges they face, they often lack the knowledge, means and/or motivation to adopt and implement sustainable practices and make the turning point towards sustainable soil practices. Tillage, common in crop production across 15.5 million km² of soil at a global scale, has been shown to cause soil thinning, reduce yields, and increase erosion, especially on sloping land (Quinton et al. 2022). Over time, mechanized farming accelerates this erosion, further diminishing productivity. To counteract these effects, adopting non-tillage practices is essential.

In addition, volatile agricultural markets can make it difficult for farmers to plan for the future. Access to accurate market data can help farmers make better decisions and improve profitability.

To support the transition to sustainable practices, farmers need better knowledge, training, funding and access to tools, such as reliable business models, that demonstrate the benefits of non-tillage, appropriate fertilization practices, and other sustainable farming methods. Consumers, on the other hand, need information (such as those recently developed for certified biodiversity-friendly practices: https://www.olivaresvivos.com/en/certification/) in order to compensate farmers and produce a better market value to support such practices. By addressing both the knowledge gaps and economic challenges, farmers can be empowered to adopt sustainable land management, benefiting soil health in the long term.

Utilizing the Voluntary Carbon Market to Enhance Liquidity in the Agri-Food Value Chain

One compelling approach to enhancing liquidity in the agri-food value chain is through the voluntary carbon market, which offers a financial incentive for farmers who adopt regenerative farming practices and provide ecosystem services to society. By sequestering carbon in soil and adopting nature-based solutions (NbS), farmers can generate high-quality carbon credits that can be sold in the market (Stofferis et al. 2025). As described in the Taskforce on Nature Markets (https://www.naturemarkets.net/), in addition to carbon credits, other types of credits are emerging, such as biodiversity credits and resilience credits. While carbon and resilience credits aim to bolster systems' ability to cope with climate impacts, biodiversity credits are specifically designed to protect and enhance biodiversity. These credits can complement each other within broader environmental and sustainability strategies. Resilience credits, in particular, monetize the benefits of risk reduction. They present a promising solution by providing a financial mechanism for investing in practices that enhance ecosystem resilience. The integration of resilience credits with insurance models could significantly boost global investments in NbS, offering a synergistic approach that combines financial risk management with ecological sustainability (https://www.nature.org/). Both resilience and nature-based carbon credits can play a crucial role in supporting adaptive management strategies in agriculture, helping farmers transition to sustainable practices while maintaining financial stability (Stofferis et al. 2025). Biodiversity credits, on the other hand, focus on conserving and restoring natural habitats, ensuring long-term ecological health. At this point in time, the voluntary market for carbon credits remains the most liquid. This liquidity provides farmers with an immediate financial return for their efforts in carbon sequestration, making it an attractive option. However, as markets for resilience and biodiversity credits develop, they too could offer substantial opportunities for farmers to gain financial rewards for their contributions to environmental health (Stofferis et al. 2025). Overall, leveraging these various credit systems can create a more sustainable and economically viable agricultural sector. By aligning financial incentives with environmental stewardship, we can ensure that farmers are rewarded for their role in enhancing ecosystem services, contributing to greater resilience and biodiversity, and ultimately supporting global sustainability goals.

Knowledge Gap 8

Limited mitigation Land Degradation strategies

There is a need for further research to optimize soil management practices, strategies and techniques that can help mitigate and prevent Land Degradation (Vanino et al. 2023). More emphasis should be placed on developing innovative and sustainable soil management practices that are suitable for different regions, scales and cases (European Commission 2020a, FAO 2015). In particular, there is a pressing demand for the establishment of systematic and validated methodologies to select/develop practices that will enhance our comprehension and facilitate the advancement and adoption of appropriate Sustainable Land Management (SLM) practices to diverse conditions (Giger et al. 2018, Gonzalez-Roglich et al. 2019, Liniger et al. 2019, Haregeweyn et al. 2023). In this regard, Liniger et al. 2019), highlighted the "insufficient attention to monitoring" at the field level and identified the "involvement of land users" in SLM and monitoring tasks as ongoing challenges. Demonstrating both on- and off-site impacts, as well as assessing both monetary and non-monetary "costs and benefits of SLM" are essential to provide evidence for informed decision-making (Giger et al. 2018, Schwilch et al. 2014). Moreover, dissemination and training activities for the farmers are essential to support the application of sustainable soil management practices. More relevant studies are also discussed in Section 3.1 (Knowledge Gap 1).

Knowledge Gap 9

How do we educate and inform the population more effectively about the value of natural resources, including soil?

Effective education and engagement of the public on the value of natural resources, such as soil, is essential for achieving sustainable land management and environmental conservation. A key aspect of fostering this awareness is promoting meaningful dialogue between science, policy, and society. A notable example is the recent developments within the European Union (EU) that have highlighted the growing momentum involving citizens in biodiversity policy development. Initiatives like citizen science have been leveraged to encourage public participation, allowing citizens to contribute to knowledge production. At the EU level, online mechanisms have been employed to spread information and promote public deliberation, although participation remains inconsistent (Varumo et al. 2020). To strengthen this engagement, tools such as online science cafés have been explored in the study of Varumo et al. 2020 , to facilitate dialogue between scientific communities, policymakers, and the public. These platforms are particularly valuable when addressing complex, multi-scalar challenges like soil degradation and natural resource management. Findings from research on such dialogues stress the importance of iterative communication processes that allow for continuous feedback and engagement (Varumo et al. 2020) . This approach ensures that discussions are inclusive and that a diverse range of voices is heard, ultimately helping to inform and influence policy.

Moreover, to effectively address the environmental crisis, it is evident that neither traditional methods of education nor business-as-usual approaches are sufficient (Wals and Benavot 2017). Education for sustainability must be expansive and collaborative, involving multiple sectors, actors, and levels of governance. Schools and educational institutions must be integrated into their communities to influence not just students, but also decision-makers in government and business. This broader approach is critical for ensuring that long-term environmental concerns, such as soil health and natural resource preservation, are incorporated into decisions at all levels (Wals and Benavot 2017).

In summary, educating and informing the population about the value of natural resources like soil requires a shift toward more inclusive, participatory models of engagement. By incorporating iterative dialogues, fostering collaboration across sectors, and ensuring that sustainability education is embedded within communities, we can cultivate a more informed and proactive society that supports policies for the protection and sustainable use of natural resources.

Knowledge Gap 10

Is the concept of Land Degradation Neutrality enough to ensure healthy land and soils in the future?

Land degradation remains a significant EU and global challenge, with far-reaching implications for agricultural productivity, ecosystem services, biodiversity, and human well-being. As soil health continues to decline, effective strategies are essential to address this pressing issue. One such strategy that has gained increasing attention is the concept of Land Degradation Neutrality (LDN), which has gradually materialized into concrete guidelines, thanks to the advice of the Science-Policy Interface of the UNCCD (United Nations Convention to Combat Desertification 2017, Cowie et al. 2018, Chasek et al. 2019). LDN promotes a balanced approach to land management, focusing on maintaining or restoring land productivity by integrating both degradation prevention and restoration efforts (Feng et al. 2022). By incorporating ecosystem services into land-use planning, LDN aims to safeguard natural capital and ensure long-term sustainability (Mikhailova et al. 2024). However, there is still a long way to go before LDN becomes an effective instrument. The proposal involves developing a plan that integrates the various sectoral plans already in place within each country, taking into account the National Irrigation Plans, the Forestry Plans, the Water Management Plans, the Strategic Plan for the Common Agricultural Policy, and several sectoral plans currently implemented at different administrative levels. Moreover, it is crucial to evaluate whether the concept of LDN alone is sufficient to ensure the health of land and soils in the future (Mikhailova et al. 2024).

For example, LDN analysis should not only be accomplished in an overall approach but also disaggregated by administrative units and LD type (e.g., agriculture) (Mikhailova et al. 2024). An overall LDN at the country or region scale can falsely imply overall LDN when there are ongoing LD increases in different types of LD (Mikhailova et al. 2024).

In addition, substantial challenges remain in translating LDN concepts into actionable strategies that effectively reduce land degradation at local and regional scales. One key challenge is the incorporation of LDN into land-use practices, particularly in regions with fragmented land ownership and insecure land tenure systems (Feng et al. 2022).

In Eastern Europe and Central Asia, for example, land reforms in the 1990s aimed at transitioning from centrally planned economies to market-driven systems (Sutton et al. 2016, FAO 2021). These reforms involved land restitution and distribution, resulting in a shift from large collective farms to individual family farms. While many of these countries have formalized land rights in registries, land fragmentation remains an issue in several European countries, often hindering agricultural productivity and contributing to unsustainable land management practices (Hartvigsen and Gorgan 2020). This fragmentation and insecure land tenure, particularly for women and girls, further exacerbate challenges related to land degradation (FAO 2021).

Furthermore, LDN must be integrated into broader land-use policies that consider both environmental and socio-economic factors to effectively ensure healthy land and soil for the future (Mikhailova et al. 2024). This integration could include estimates of the social costs of GHG emissions based on the concept of avoided vs. realized social costs (Mikhailova et al. 2024)

In conclusion, while the concept of Land Degradation Neutrality offers a promising framework for addressing land degradation, it is not sufficient by itself to guarantee healthy land and soil. Achieving sustainable land management requires a multi-faceted approach that includes addressing land tenure insecurity, land fragmentation, and incorporating social and financial dimensions into land-use planning. Moreover, continued research, data collection, systematic monitoring, and policy development are necessary to close the knowledge gaps and improve the effectiveness of LDN in combating land degradation globally.

3.3 Overview

The subsection 3.3 displays three tables and one list of Knowledge Gaps. More precisely, Table 2 represents an overview of all identified Knowledge Gaps, Table 3 the Actions, and Table 4 the Bottlenecks, which collectively form the foundational elements of the Roadmap.

Table 2

Suppl. material 1

Table 3

Suppl. material 2

Table 4

Suppl. material 3

Lastly, a slightly more extensive description of the **Knowledge Gaps**, starting from number 11 onwards, is provided in the following paragraphs. These gaps, while not ranked among the top priorities, represent additional critical areas that require attention and further exploration to address Land Degradation effectively.

- **Current and future climate change interactions with Land Degradation in the EU**: Land Degradation and climate change are interconnected processes. However, there is still limited understanding of the exact interactions and feedback mechanisms between Land Degradation and climate change (European Commission 2015, IPCC (Inter-Governmental Panel on Climate Change) 2001Intergovernmental Panel on Climate Change 2019, Odebiri et al. 2023). An example of some related knowledge gaps can be found in the following questions (Reed and Stringer 2016): Which variables play a crucial role in monitoring the interactions and feedback loops between climate change and land degradation? What role do climatic factors play in either mitigating or accelerating land degradation, and how can emerging opportunities be harnessed to achieve Land Degradation Neutrality (LDN) within the framework of a changing climate? What is the impact of Land Degradation on Climate? Furthermore, there is a strong focus on climate change on climate change impacts almost solely on agricultural crops and food production, overlooking livestock, forest farming and pests, as well as disregarding components of the food system and security

(Farooq et al. 2022). As such, research is needed to assess the impacts of climate change on LD, as well as the potential of degraded land to contribute to climate change.

- **Current and future biodiversity loss interactions with Land Degradation in the EU**: Land Degradation and biodiversity loss are interlinked processes. Despite this fact, there are several limitations in understanding the causal relationships and feedback loops between biodiversity loss and land degradation. Examples of relevant knowledge gaps can be found in the effects of climate adaptation options on soil's role as a habitat and genetic reservoir. More precisely, according to the study of Hamidov et al. 2018, among the 20 EU case studies that they examined regarding the impacts of climate change adaption options on soil functions, solely a few consider the impacts on soil biodiversity. The evident neglect of soil biodiversity issues in the majority of case studies contradicts the growing recognition of the crucial functional role of soil organisms in soil processes (Cluzeau et al. 2012). This represents a significant knowledge gap that requires attention in future research endeavors (Hamidov et al. 2018). Additionally, there is a need for standardized, comprehensive approaches for measuring the compaction, diversity, and function of soil biota (Saljnikov et al. 2022, Thiele-Bruhn et al. 2020).
- **Absence of well-established and interlinked policies and legislations concerning Land Degradation and its components**: Lack of well-established and/or Land Degradation-related policy frameworks leads to unclear guidelines for soil management, resulting in a lack of standardisation in R&I methodologies (European Environment Agency 2019, Guerra et al. 2016). While this can be mainly seen as a bottleneck, it can also be characterised as a lack of knowledge when interlinkages between drivers affect the process of establishing clear policies. A relevant example refers to the study of Paleari 2017, where it was noted that despite the existence of several policies to address and regulate some soil threats, others, such as salinization, receive only limited consideration and lack a comprehensive framework for soil protection.
- **Knowledge gaps on the quantification of off-site Land Degradation effects and costs**: The contemporary understanding of land degradation is marked by a significant gap in knowledge, particularly concerning the quantification of off-site effects and costs associated with Land Degradation (Boardman et al. 2019, Saljnikov et al. 2022). This refers to the impacts that extend beyond the immediate area of degradation and affect surrounding regions or ecosystems. The existing knowledge deficit in this specific aspect underscores the need for up-to-date research efforts to address and quantify these off-site effects and costs comprehensively.
- **Insufficient knowledge for accessing funds related to Land Degradation and soil projects and initiatives**: Insufficient knowledge to navigate the administrative procedures for accessing funds related to Land Degradation and soils (European Commission 2021c, EU Soil Observatory 2019). Are Land Degradation related funds and efforts sufficient to stop it?

- **Land Degradation models' limitations, uncertainties and capabilities**: Despite the existence of several models and methodologies to assess the Land Degradation status or components, there is a limitation in understanding their capabilities and uncertainties due to the lack of validation data and long-term measurements (Hessel et al. 2014Saljnikov et al. 2022, Aouragh et al. 2023, European Commission 2020a, Li et al. 2021, Prăvălie et al. 2021, Xu et al. 2023).
- **Lack of sufficient understanding of urban soils in relation to Land Degradation**: As indicated in the Soil Mission Implementation Plan (European Commission 2019a), the scope of land/soil degradation knowledge predominantly revolves around agricultural soils, with limited attention given to other land uses. It is necessary to bridge this gap and enhance our capabilities for supporting and rejuvenating land and soil health, both in urban and rural areas.
- **Difficulties in understanding the drivers of individual and collective decisions associated with Land Degradation**: Understanding the drivers behind individual and collective decisions is crucial for addressing land degradation effectively. Individual or collective decisions made by land users, such as farmers or landowners, play a significant role in shaping land management practices (Boardman and Evans 2019, European Commission 2019a, EU Soil Observatory 2019). Despite advancements in research, there are still difficulties in understanding individuals' decisions as decision-making is dynamic (it evolves over time in response to changing conditions), is represented by an inherent diversity (decision-making heterogeneity) and there is a lack of data to capture the behavioural factors (EJP Soil 2018).
- **Lack of understanding of subsurface processes related to Land Degradation**: The insufficient comprehension of subsurface processes associated with land// soil degradation underscores a notable gap in current research and data acquisition efforts. In comparison to topsoil, subsurface processes have not received a proportionate level of scrutiny. This incompatibility is further exacerbated by the fact that a predominant portion of existing Land Degradation and soil datasets (e.g. Soil Organic Carbon), as well as research projects and initiatives, predominantly concentrates on the topsoil layer (European Commission 2019a).
- **How can we sufficiently control water resources to avoid provoking issues in soils? How could the water directive be adjusted**?
  Water and land degradation are interconnected, with one often exacerbating the other. For example, deforestation can lead to increased soil erosion, which in turn reduces water infiltration and increases runoff, further accelerating land degradation (Borrelli et al. 2020). Water plays a significant role in land degradation, both as a cause and a consequence, as highlighted by the following key insights:

  <u>Water as a cause of land degradation:</u>

  Erosion: Water erosion is a major contributor to land degradation, particularly in areas with heavy rainfall, steep slopes, or poor vegetation cover. The force of moving water dislodges and carries away soil particles, leading to the loss of fertile topsoil and the formation of gullies and ravines (García-Ruiz et al. 2015).

Salinization: In arid and semi-arid regions, excessive irrigation can lead to the buildup of salts in the soil, making it unsuitable for plant growth. This process, known as salinization, is exacerbated by poor drainage and the use of saline water for irrigation (Mohanavelu et al. 2021).

Waterlogging: Over-irrigation or poor drainage can lead to waterlogging, where the soil becomes saturated with water, depriving plant roots of oxygen and causing their death (Ritzema et al. 2008).

Flooding: Floods can cause significant land degradation by eroding soil, depositing sediments, and damaging infrastructure (IPCC 2021).

<u>Water as a consequence of land degradation:</u>

Reduced water availability: Land degradation reduces the soil's ability to absorb and retain water, leading to decreased water availability for plants and humans (Lal 2015).

Increased runoff: Degraded land is less able to absorb rainfall, leading to increased runoff and a higher risk of floods (Montanarella et al. 2016).

Contamination of water resources: Land degradation can contaminate water resources with sediments, nutrients, and pesticides, harming aquatic ecosystems and human health (United Nations Convention to Combat Desertification 2022).

Despite the evident interlinkages between the two natural resources, current regulatory frameworks and policies often fail to address this nexus to bridge soil and water resources management, perpetuating fragmented governance. An example is how disjointed policies fail to address feedback loops like salinization from poor irrigation practices.

- **How to ensure land restoration is an integral part of social structures and actions at all scales**? Engaging local communities and tapping into their traditional knowledge and innovations plays a vital role in achieving effective conservation endeavors (Economics of Land Degradation 2016). This principle aligns with the Aichi Biodiversity Target 8, which underscores the importance of respecting and leveraging traditional knowledge, innovations, and practices of indigeneous people while involving local communities in conservation efforts (Convention of Biological Diversity (CBD) 2014). Their active participation not only ensures that they benefit from and are rewarded for their conservation efforts but also contributes to addressing land degradation. However, the limited capacity of local communities to address technical aspects of natural resource management poses a significant constraint that undermines SLM (Economics of Land Degradation 2016). More specifically, a challenge arises when attempting to integrate land restoration into social structures that drive social actions, particularly in the context of indigenous knowledge (Santini and Miquelajauregui 2022). In this light, despite the existence of studies exploring the benefits of indigenous knowledge in enhancing land restoration, involving local communities in restoration activities does not consistently result in successful ecosystem restoration or benefits for those communities (Tellez et al. 2019). Moreover, the social aspects related to land restoration are not thoroughly explored and there is not sufficient participation from local rural communities (Reyes-García et al. 2018, Van Noordwijk et al. 2020, Wehi and Lord 2017). There is still much work to be done in identifying the factors that contribute to successful restoration efforts that also bring advantages to local communities.

- **How to build commons-based land governance systems**? Contemplating land-based commons allows us to delve into the intricate dynamics of how individuals, communities, and humanity navigate interconnected natural and social environments (Giraud et al. 2016). From there, we can assess which organizational levels hold the greatest significance in understanding the interaction among customary, informal, and formal rules and practices. By incorporating these insights, we can craft adaptive approaches to natural resources management and delve into how territorial development strategies and organizational structures might impact the future of highly coveted land, such as arable and irrigable areas, as well as vulnerable territories like grazing and wildlife zones, forests, mountain tops, sacred sites, lakes and rivers - areas often targeted for land grabbing (International Land Coalition 2016). However, there are still existing challenges in establishing transparent and effective land governance systems (Giraud et al. 2016).
- **How do we shift from the current trend of intensification of agricultural production and overexploitation to land conservation**? More precisely, during the last decades, the EU has placed increasing demands on essential resources like food and fiber, necessitating a substantial boost in agricultural production. Modern agricultural technologies, such as machinery, fertilizers, and advanced irrigation, are crucial to meet this demand. However, large-scale construction and environmental challenges like climate change also stress European resources, particularly agricultural land (F.A.O. 2015). Soil, a non-renewable resource formed over millennia, is central to food, energy, and water security, as it supports over 95% of global food production (Saljnikov et al. 2022). Yet, the pursuit of higher agricultural output through technology can accelerate soil degradation to a critical point where further advancements can't compensate for inherent soil limitations (Saljnikov et al. 2022).
- **How can we support a land workers-led research on Land Degradation and how can we integrate the outputs of such endeavors**? Citizen science is an untapped resource for European soil and land research. In this light, the recent years the EU has been investing in a cornucopia of actions and projects to engage citizens in soil science and support them to preserve soil health (Panagos et al. 2024). Such actions and projects refer to but are not limited to the Soil funDamentals project, the UKSO Soil Observatory, the Grow observatory, the

ECHO project, the Soil Plastics monitoring application, and the Heavy Metal City Zen project. Despite the significance and achievements of these efforts, there is a need to better communicate soil science to the plausible citizen scientists and a need to integrate the outputs of these projects (Wadoux and McBratney 2023).

- **How can we overcome the challenges in the land regulatory framework introduced by land ownerships**? As land is not a common good.
- **Lack of an early warning system related to soil degradation dynamics**, e.g. in case of a landslide (Dang et al. 2025, Yarahmadi et al. 2024).
- **Lack of knowledge on how to address the EU's competitiveness challenges in the global market.** These challenges include, but are not limited to, knowledge gaps in closing the European innovation gap—particularly in advancing the technology sector—and bridging the EU's financial shortfalls, as described in the Draghi report (European Commission 2024).
- **Lack of understanding Nature Based Solutions**: Not well studied yet (Dunlop et al. 2024).
- **Is it possible to identify sets of adaptation options that complement each other, mitigating trade-offs and fostering mutually beneficial outcomes for both climate change and land degradation (Reed and Stringer 2016)**?
- **At what spatial scale do Land Degradation vulnerability maps offer the most valuable insights to decision-makers while maintaining a rich level of information and detail (Reed and Stringer 2016)**?
- **What resources are required for studying Land Degradation , and how do the monitoring (action) costs compare with the costs of not monitoring (inaction) across short, medium, and long time frames (Reed and Stringer 2016)**?
- **How do we pinpoint the thresholds, both in terms of time and space, at which Land Degradation adaptive practices and technologies may turn counterproductive, warranting discouragement of their widespread adoption (Reed and Stringer 2016)**?
- **What is the optimal resolution and frequency of monitoring to provide decision-makers with crucial information on key variables associated with climate change and land degradation (Reed and Stringer 2016)**?
- **How can we harmonize findings from monitoring both slow and fast Land Degradation-related variables (Reed and Stringer 2016)**?

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Supplementary materials

Suppl. material 1: Table 2 Knowledge gaps doi

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Endnotes

*1 Particularly as 25% of land in Eastern, Southern, and Central Europe faces the risk of desertification (European Commission 2019a).
*2 The dataset can be found at: http://54.229.242.119/GSOCmap/
*3 The dataset can be found at: http://54.229.242.119/GloSIS/
*4 The dataset can be found at: https://data.apps.fao.org/catalog/iso/c790f7c9-23ac-4578-b4bf-a8c0137f0fea
*5 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015
*6 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/Soil_erosion_by_wind
*7 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/copper-distribution-topsoils
*8 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/mercury-content-european-union-topsoil
*9 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data
*10 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/potential-threats-soil-biodiversity-europe
*11 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/natural-susceptibility-soil-compaction-europe
*12 The dataset can be found at: https://land.copernicus.eu/en/products/high-resolution-layer-impervious-built-up/impervious-built-up-2018
*13 For more information, please visit the following link: http://trends.earth/