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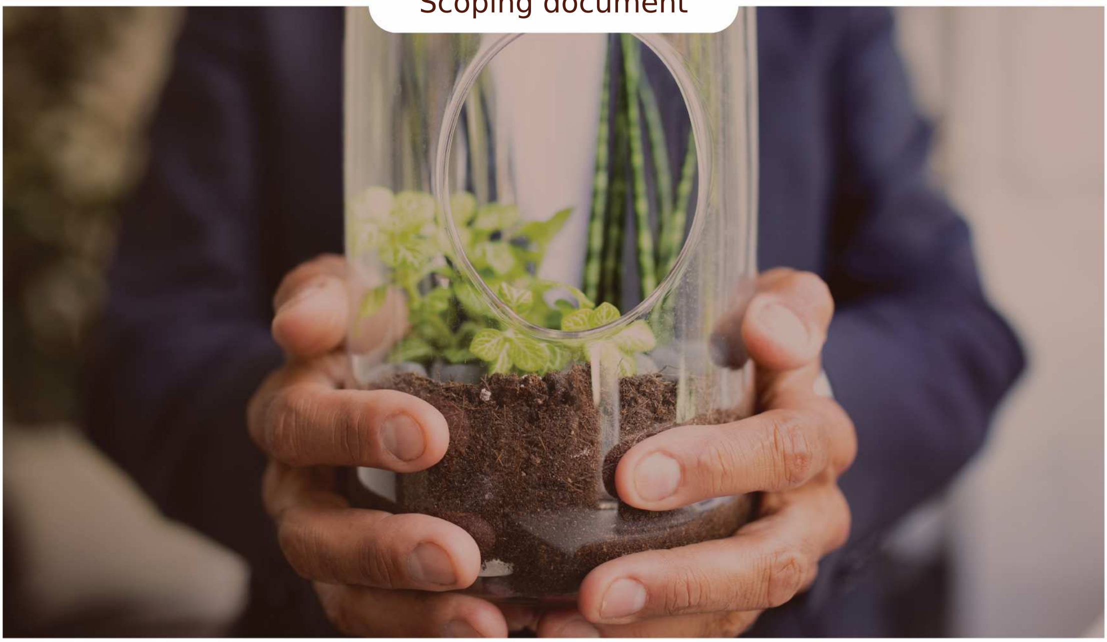
SOLO Land degradation

Scoping document



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Scoping Document

Preliminary assessment of the knowledge gaps to reduce land degradation in Europe

Melpomeni Zoka[‡], Salvador Lladó[§], Nikolaos Stathopoulos[‡], Martha Kokkalidou[‡], Ana Maria Ventura[|,¶,#], Lindsay C Stringer[¤], Barbara Baarsma[«], Lukáš Trakal[»], Markus Gorfer[˄], Santiago Soliveres Codina[˅]

‡ National Observatory of Athens (NOA), Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing (IAASARS), Operational Unit "BEYOND Center of Earth Observation Research and Satellite Remote Sensing", Athens, Greece
§ Department of Genetics, Microbiology and Statistics, University of Barcelona, Barcelona, Spain
| Centre for Ecology, Evolution and Environmental Changes, University of Lisbon, Lisbon, Portugal
¶ Department of Environment, University of Ghent, Ghent, Belgium
# Solutopus- Recursos e Desenvolvimento, Lda, Santiago do Cacém, Portugal
¤ University of Leeds, Leeds, United Kingdom
« University of Amsterdam, Amsterdam, Netherlands
» Department of Environmental Geosciences, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic
˄ Austrian Institute Of Technology, Vienna, Austria
˅ University of Alicante, Alicante, Spain

Corresponding author: Melpomeni Zoka (zoka@noa.gr)

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Introduction

One of the major processes that affect land is Land Degradation. More precisely, according to the United Nations, 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 from 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).

It is noteworthy that in the realm of soil conservation, there's often confusion between the terms soil degradation and land degradation, with soil erosion mistakenly considered synonymous with both. However, soil degradation encompasses more than just erosion, and land 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). There exist several interconnected components of land degradation, all of which may lead to a decrease in agricultural production. According to Douglas (Douglas 1994), as cited by FAO (FAO 1999), the most significant elements are:

- Soil degradation: “This refers to the decrease in the soil's productive capacity due to erosion and changes in its hydrological, chemical, biological, and physical properties”.
- Vegetation degradation: “This entails a reduction in the quality and/or quantity of natural biomass and a decline in vegetative ground cover”.
- Water degradation: “This involves a decrease in the quality and/or quantity of both surface and groundwater resources”.
- Climate deterioration: “This refers to alterations in the macro- and micro-climatic conditions that escalate the likelihood of crop failure”.
- Losses to urban/industrial development: "This involves a reduction in the total area of land that is available, or with the potential, of use for agricultural production due to the conversion of arable land to urban, industrial, and infrastructural purposes" (FAO 1999).

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

Regarding the imperative to combat Land degradation on both European and global scales, it 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 confronts 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 important 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). This emphasises the pressing need to address land degradation urgently in order to avert further environmental 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 erosion by water, compaction, and soil sealing and excavation also persist. Approximately 24% of EU land is marked by unsustainable water erosion rates, 23% experiences compaction, 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).

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), which works as a catalyst for the attainment of other SDGs according to the United Nations Convention to Combat Desertification (UNCCD) (European Commission 2006b, IPCC (Inter-Governmental Panel on Climate Change) 2001).

Mitigating land degradation necessitates a comprehensive approach that encompasses sustainable land management practices, multiple stakeholders working together,, soil conservation, reforestation efforts, and initiatives aimed at curbing pollution and contamination. Moreover, despite the EU focus of this project, international collaboration, as exemplified by the UNCCD, holds also 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 strategy for land management and conservation.

Considering the above, the Soils for Europe - SOLO project has created a network of knowledge where various stakeholders from different fields (e.g. social and economics) are organized in Think Tanks. The Think Tanks serve as vital components within the framework of the Soils for Europe initiative, playing a pivotal role in co-developing the European Union

Mission known as A Soil Deal for Europe. Led by different SOLO partners, each Think Tank aligns with a specific Soil Mission objective, working in tandem to support its aims and aspirations. This Scoping Document refers to the aforementioned SO1 regarding Land Degradation and aims to assist the Soil Mission through a multi-actor approach.

More precisely, through the active collaboration and engagement of key stakeholders and a diverse network of partners related directly or indirectly to the soil science community, a vibrant and multidisciplinary cluster is being forged. This collaborative effort 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. The ultimate goal is to craft a comprehensive strategy that effectively propels the mission to enhance soil health.

Thenceforth, the Land Degradation Think Tank main objectives are to:

- Identify and enumerate key knowledge gaps related to land degradation in the EU, through a multidisciplinary approach.
- Identify and delineate drivers and obstacles (Bottlenecks) that hinder land 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, crucial to overcome 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 in an overarching roadmap tackling the eight mission objectives.

State-of-the-Art

Evaluating Land Degradation (LD), which comprises a combination of processes impacting land resources in the EU and globally, poses significant challenges. As such, the latest decades, several methods, approaches and datasets are being 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 Food and Agriculture Organization of the United Nations (FAO). 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 withing EU, with plans for regurlar updates based on emerging scientific findings. As for the datasets that synthesize the EUSO Dashboard, they refer to but not limited to erosion related datasets, such as the Soil Erosion by Water Dataset*[4] (based on the RUSLE model) and the Soil Erosion by Wind Dataset (based on the RWEQ model)*[5] , soil pollution relevant datasets, e.g. the Copper Excess Dataset*[6] and the Mercury Excess Dataset*[7], and soil nutrient datasets, such as the Phosphorous

Deficiency and the Phosphorous Excess Dataset*[8]. Additional datasets of the EUSO Dashboard refer to the Potential Threats to Soil Biodiversity Dataset*[9], the Soil Compaction Dataset*[10] and the Soil Sealing Dataset*[11].

It is notewothy that the JRC's soil team (JRC D3) is currently working on establishing the EUSO Soil Policy Dashboard which will serve as an ongoing evaluation of advancements in formal policy commitements regarding soil. It will be regularly updated three times per year to demonstrate the evolution of policy developpment. The dashboard will primarly track progress related to key initiatives such as the EU Soil Strategy, the Soil Health 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.

Furthermore, over the last decade, various concepts and approaches have emerged for establishing schemes regarding Land Degradation monitoring and assessments. To elaborate further, in the study of Gianoli et. al., 2023 (Gianoli et al. 2023), the Land Degradation status was assessed at an EU level by utilizing the Convergence of Evidence (CoE) conceptual framework of the World Atlas of Desertification and incorporating additional indicators of land status and trends when evaluating Land Degradation. 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 (Ivits et al. 2013, Cherlet et al. 2018, Martínez-Valderrama et al. 2022). As for the additional indicators of the study, they refer to but are not limited to population density and change, groundwater table decline, acidification and eutrophication (Gianoli et al. 2023).

Moreover, another continental (EU-scale) study refers to the publication of Schillaci et. al., 2020 (Schillaci et al. 2022), where they evaluated the United Nations Sustainable Devlopment Goal 15.3.1 indicator of Land Degradation in Europe by following the UNCCD methodology and the Trends.Earth Software, while simultaneously evaluating the influence of alternative datasets (e.g. NDVI time series) at varying spatial resolution, as well as policy-relevant data sources for land cover (CORINE) and soil organic carbon (SOC) stock (LUCAS dataset).

As for examples of country-scale applications employing the UNCCD approach, supplemented by additional Earth Oobservation (EO) and soil monitoring data, include the work of Wunder and Bodle, 2019 (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). Additionally, a 20 m spatial resolution assessment was conducted for Italy, incorporating several additional variables, such as loss of habitat quality, burnt areas (2008–2018), and the density of artificial land cover (Assennato et al. 2020). However, according to the continuous learning approach advocated by the UNCCD Good Practice Guidance (UNCCD 2021), the baseline assessment procedure may encounter constraints in some parts of the EU due to factors such as limited data availability stemming from the relatively small size of land use parcels, land suitability issues, resilience challenges, and socio-cultural and economic factors.

Consequently, monitoring potential land degradation using the three UNCCD land-based global indicators may result in 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 (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 EO 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). Additionally, it incorporates supplementary components for model execution and coordination, knowledge management, and visualization (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 (Prăvălie et al. 2020, Perović et al. 2021). Besides, other components that describe Land Degradation in the literature refer to biophysical (e.g. plant cover and agricultural productivity trends, net primary productivity, soil erosion etc.) (European Commission 2006a, European Commission 2006b, Dubovyk 2017, Ayalew et al. 2020, Panagos et al. 2020, Jucker Riva et al. 2017, Giuliani et al. 2020), environmental (ClientEarth 2022, Gholizadeh et al. 2018, Gorji et al. 2019, Prăvălie et al. 2017, Taghadosi et al. 2019, Žížala et al. 2018, Giuliani et al. 2020) and/or socio-economic factors (e.g. poverty, migration and population density) (Reed and Stringer 2016, Akhtar-Schuster et al. 2017, Keesstra et al. 2018, Barbier and Hochard 2018, European Commission 2020c, European Commission 2020b, Ustaoglu and Collier 2018, Sartori et al. 2019, Istanbuly et al. 2022, Blaikie and Brookfield 2015, Panagos et al. 2024) as well as the utilisation of long-term satellite observations (e.g. Sentinel-2 optical satellite constellation) (ClientEarth 2022, European Commission 2020c, United Nations 2023) which provides 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 modelling 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, European Commission 2021a, Gholizadeh et al. 2018, Xie et al. 2020, Perpiña Castillo et al. 2021, Dahal et al. 2024).

In spite of the aforementioned scientific endeavors (e.g. modelling, frameworks) and the abundance of free of charge accessible Earth Observation and geospatial data, currently, there are no established procedures that produce systematic, precise and reliable information regarding Land Degradation (Giuliani et al. 2020). More precisely, challenges and limitations persist in several aspects, such as data limitations and data acquisition conditions (Gholizadeh et al. 2018, Giuliani et al. 2020), the need for integration of additional data (Ayalew et al. 2020, Taghadosi et al. 2019), lack of validation of the EO data and modeling outputs against in situ data and limitations of the EO-based variables (Dubovyk 2017, Giuliani et al. 2020, Žížala et al. 2018, Jucker Riva et al. 2017).

In conclusion, the trajectory of future research in the realm of land degradation 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).

Knowledge Gaps

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; European Commission, 2022).

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).

By taking into account 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. Some of the major knowledge gaps, can be summarized below:

Knowledge Gaps

- **Lack of comprehensive understanding of Land Degradation**: 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, Reynolds et al. 2007, FAO 2015, Ravi et al. 2010, Daliakopoulos et al. 2016, 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, in spite of 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.

- **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) 2001, Intergovernmental 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.
- **Historical, current and future social-economical interactions with Land Degradation within the EU**: The interactions between land degradation and socio-economic aspects represent a complex and multifaceted field of study. While there has been significant research in this area, several knowledge gaps still exist, such as understanding the long-term socio-economic consequences of land degradation, the factors that enable or hinder communities in coping with land recovering from land degradation, understanding the potential socio-economic benefits of suitable land management practices and integrating and validating indigenous and local knowledge (The Economics of Land Degradation 2015, Economics of Land Degradation 2016). Addressing these knowledge gaps will contribute to a more comprehensive understanding of the intricate relationship between land degradation and socio-economic pathways, ultimately enabling more effective policies and interventions to mitigate and adapt to the impacts of land degradation.
- **Current and future biodiversity loss interactions with Land Degrdation 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 habotat and genetic reservoir. More precisely, according to the study of Hamidov et. al., 2018 (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). Additionaly, there is a need for standarized, comprehensive approaches for measuring the compaction, diversity, and function of soil biota (Thiele et al. 2020, Saljnikov et al. 2022).

- **Lack of Land Degradation-related data at different scales**: Without comprehensive Land Degradation data at different scales, our understanding of the causes and extent of land/soil degradation remains incomplete, making it difficult to develop targeted solutions and implement effective initiatives (Saljnikov et al. 2022, European Commission 2019a, European Commission 2020a, United Nations to Combat Desertification 2016, Lunik 2022). One relevant example that was mentioned in the study of Panagos et. al., 2020 (Panagos et al. 2020), is the uncertainty in the soil erosion by water estimates, that arises from the absence of georeferenced data that provide information on the crop type and the soil managment practices implemented in the field in an annual basis. Monitoring and assessing land and soil health, advocating for evidence-based policies, securing funding, and fostering collaboration all rely on the availability of accurate data. It is essential to prioritise data collection, digital transformation and research efforts to support R&I initiatives aimed at addressing and mitigating Land Degradation.
- **Limited Land Degradation mitigation strategies**: There is a need for further research to optimise 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, according to Haregeweyn et. al., 2023 (Haregeweyn et al. 2023), there is a pressing demand for the establishment of systematic and validated methodologies 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). In this regard, Linger et. al., 2019 (Liniger et al. 2019), highlighted the "insufficient attention to monitoring" at the field level and identified the "involvement of land user" 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 (Schwilch et al. 2014, Giger et al. 2018).
- **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 lead 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 lack of knowledge when interlinkages between drivers affects the process of establishing clear policies. A relevant example refer to the study of Paleari, 2017 (Paleari 2017), where it was noted that despite the existence of several policies to address and regulate some

soil threats, otheres, 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 (Saljnikov et al. 2022, Boardman et al. 2019). 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. 2014, Saljnikov et al. 2022, European Commission 2020a, Aouragh et al. 2023, Li et al. 2021, Prăvălie et al. 2021, Xu et al. 2023).
- **Land/soil health and Ecosystem Services interactions**: The concepts of land/soil health and the ecosystem services provided by land/soil need to be supported by empirical evidence obtained through field and landscape indicators and measurements (Petrosillo et al. 2023). It is worth mentioning that these measurements should be region or case specific. Furthermore, ES include also cultural and aesthetic values, and thence it is important to investigate the connection between human well-being and all the variables that contribute to it. Moreover, collaborative methods are indispensable for resolving conflicts among stakeholders and gaining a comprehensive understanding of land and soil functioning and its sustainable use over time. This necessitates the development of an advanced field diagnostic system that relies on dependable on-site measurement technology, complemented by expert-driven knowledge and assessment methodologies. Enhancing the field of soil science is crucial for making strides in the effort to mitigate and reverse land degradation. Additionally, the economic valorization of ES, which is currently lacking, is a key point for their effective delivery (Kieslich and Salles 2021, Mirici 2022).
- **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 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 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 for achieving effective conservation endeavors (Economics of Land Degradation 2016). This principle alligns 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 undermine 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 (Wehi and Lord 2017, Reyes-García et al. 2018, Van Noordwijk et al. 2020). 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's rapidly expanding population 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 environmetal 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 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 observatoy, the ECHO project, the Soil Plastics monitoring application, and the Heavy Metal City Zen project. Despite the significance and the 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 land regulatory framework introduced by land ownerships**? As land is not a common good.
- **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)**?
- **Is the concept of Land Degradation Neutrality enough to ensure healthy land and soils in the future (Mikhailova et al. 2024)**?

Knowledge Implementation Gaps - Stakeholders insights during the Consortium Meeting

- **Administering arable agriculture and agroforestry systems with a focus on organic carbon poses a challenge** , as the decline in organic carbon is linked to the difficulty of implementing existing knowledge into practice/practical policies.
- **There is insufficient awareness and recognition of the risk of arable land loss.** How can we effectively convey knowledge about this risk?
- **How do we educate and inform the population about the value of natural resources, including soil**?
- **How can we enhance regional planning in regards to Land Degradation** ?
- **What are the green investments for Land Degradation**? Green investments for Land Degradation will facilitate EU actions concerning climate change and will result in much quicker reactions. However, there are gaps in terms of resource allocation (how can government budget and private sector investements tackle Land Degradation?) and the strengthening of political will to face the issue.
- **How do we support the farmers to make the turning point towards sustainable land and soil management practices**? Sometimes farmers might use management practices (e.g. ploughing) assuming that this will lead to an increase in their production. However, this is contradicting the reality as it actually decreases their production. While there is willingness to change as they can realize the current and plausible future production issues, there is a lack of knowledge on how to start changing and how to make the turning point.
- **How can farmers manage their animals more effectively in regards to Land Degradation** ?

- **How can we alter the thinking-behaviour of farmers, consumers, markets and society towards Land Degradation Neutrality**?
- **What are the solutions, awarding-motivation schemes, and policies to revive farmers' hope**?
- **What are the means to further educate policy makers so they can support better practices towards sustainability and Land Degradation Neutrality**?
- **How can we tackle the existing issues in policy implementation and how can we better align all the Land Degradation related policies with each other**?
- **How can we enhance knowledge transfer**?
- **How do we deal with the markets**? There is a need to create a balance between Land Degradation and markets/ecological economics (European Commission 2020a).
- **How can we sufficiently control water resources to avoid provoking issues in soils? How could the water directive be adjusted**?
- **What is considered a sustainable treatment for land and soil**?
- **What are the risks associated with Land Degradation and ice caps? What will happen and why**?
- **What are 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**?
- **What are the most reliable thresholds, monitoring systems and indicators to estimate soil and land degradation in the EU**?

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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://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015

*5 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/Soil_erosion_by_wind

*6 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/copper-distribution-topsoils

*7 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/mercury-content-european-union-topsoil

*8 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data

*9 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/potential-threats-soil-biodiversity-europe

*10 The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/natural-susceptibility-soil-compaction-europe

*11 The dataset can be found at: https://land.copernicus.eu/en/products/high-resolution-layer-impervious-built-up/impervious-built-up-2018