The state of soils in Europe

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The State of SOILS in Europe

Fully evidenced, spatially organised assessment of the pressures driving soil degradation.

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Contents

Abstract

This report investigates the intricate interplay between drivers of changes in soil health and pressures and impacts on soil in the 32 European Environment Agency (EEA) member countries, along with six cooperating countries from the West Balkans, Ukraine and UK, shedding light on the multifaceted challenges facing soil conservation efforts. Our analysis shows the complex interactions among various factors, both anthropogenic and natural, shaping soil degradation processes and their subsequent consequences. We highlight key findings, including the significant impacts of soil degradation on agriculture, ecosystem resilience, water quality, biodiversity, and human health, underscoring the urgent need for comprehensive soil management strategies. Moreover, our examination of citizen science initiatives underlines the importance of engaging the public in soil monitoring and conservation efforts. This work emphasises the policy relevance of promoting sustainable soil governance frameworks, supported by research, innovation, and robust soil monitoring schemes, to safeguard soil health and ensure the long-term resilience of ecosystems.

The State of Soils in Europe

Foreword

The sustainable management of soils is a formidable challenge, but crucial if we are to truly meet the aspirations and objectives of a European green transition. Healthy soils, and the diverse lifeforms that live within them, provide us with food, biomass and raw materials, while regulating climate, water and nutrient cycles. Soil is a unique habitat in its own right, hosting almost 60% of all biodiversity on terrestrial land; it also underpins aboveground ecosystems.

Unfortunately, Europe's soils are deteriorating. Taking centuries or millennia to form, they can be destroyed or damaged in minutes. According to the analysis of the Joint Research Centre's EU Soil Observatory, degradation processes affect at least 63% of soils in the European Union.

Together with the European Environment Agency, the Joint Research Centre has assembled a rich scientific community to assess soil degradation and communicate the need to protect soils to the wider society. This is in line with the vision and objectives of the European Union's Soil Strategy 2030 and Horizon Europe's Mission "A Soil Deal for Europe" to enhance soil literacy.

Building on a previous JRC and EEA assessment on the state of soils from 2012, this updated report provides new insights and highlights a number of key issues. Among the main findings in the report, it is worth mentioning that many soils are experiencing carbon loss – this could pose a threat to the EU's climate targets if left unaddressed. About 1 billion tonnes of soil are washed away by erosion every year with concerns of increasing losses of erosion as a result of more extreme weather events. Between 2012 and 2018, more than 400km^2 of land was lost per year to soil sealing in the European Union (EU). Worryingly, about 74% of agricultural land in the EU+UK faces excessive nitrogen inputs, while extensive areas exhibit phosphorus surpluses. Moreover, pesticide residues and other pollutants are prevalent in agricultural soils, further exacerbating environmental concerns.

However, many countries still lack comprehensive data on soil health, especially on diffuse pollution. The proposed Soil Monitoring Law, supported by research and innovation initiatives such as the Horizon Europe mission, 'A soil deal for Europe', aims to address this gap while supporting the transition towards a more sustainable future. Future versions of this report will be able to benefit from the increased volume of data from the Law in order to provide a more comprehensive picture of the state of soils.

This publication marks an important milestone towards a better understanding of the role of soil in Europe and beyond. We encourage readers to share and promote this rich knowledge base.

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Soil assessments in the EU are made possible thanks to Europe's Land Use / Cover Area Frame Survey (LUCAS), and we therefore express our gratitude to all involved in its implementation. The coordination of LUCAS is facilitated by Unit E4 of Eurostat, the statistical office of the EU. In addition, soil sample collection and laboratory analyses are supported by the Directorate-General for Environment, the Directorate-General for Agriculture and Rural Development and the Directorate-General for Climate Action.

While the related work is currently in the very early stages, we hope that future revisions of this report will be underpinned by the EU soil monitoring and resilience directive and the advances in understanding and monitoring techniques brought about by the Horizon Europe mission 'A soil deal for Europe'.

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Executive summary

Policy context

Healthy soils need to be at the heart of the European Green Deal. In this respect, this report is aligned with several key EU policy initiatives, such as the EU's soil strategy for 2030, part of the EU biodiversity strategy for 2030; the zero pollution action plan; and the European Climate Law. With over 90 authors, it offers diverse expertise, reflecting the latest scientific insights on the topic of soil degradation in Europe. With over 60 % of soils in the EU undergoing degradation processes, the stakes are high, with impacts on food security, ecosystem services and human health. This report synthesises current research and highlights the issues that need to be addressed through sustainable soil management. Offering comprehensive analyses and recommendations, the report aims to increase understanding of this crucial area. Its relevance is critical amid ongoing debates on environmental sustainability and agricultural policies. Moreover, its findings extend beyond soil health, potentially influencing policies on biodiversity conservation, climate change mitigation and land use planning, and stressing the need for multistakeholder cooperation to ensure environmental, social and economic sustainability in Europe.

Key conclusions

The report confirms the magnitude of soil degradation in Europe and highlights the challenges arising from the impact of warfare on soils, particularly in conflict-affected regions such as Ukraine. New policy measures may need to be considered to address these emerging issues and ensure the resilience of European soils.

Despite significant progress, knowledge gaps persist, particularly regarding diffuse pollution, the social impacts of soil degradation and the effects of warfare on soil health. Bridging these gaps will require further research and greater public engagement to raise awareness and foster collective action.

The findings presented in the report highlight several key policy-relevant consequences of soil degradation and recommendations for addressing this issue in Europe. Firstly, it is evident that existing policy frameworks need to be strengthened to effectively monitor and mitigate soil degradation processes. This will involve, for example, implementing legislative mechanisms such as the proposed soil monitoring and resilience directive, which would provide a framework for comprehensive soil health assessments that could in turn support targeted interventions.

In addition, there is a clear need for cross-sectoral coordination and collaboration to tackle soil degradation comprehensively. Policy measures already in place could be strengthened to incentivise farmers to adopt soil-friendly agricultural practices (e.g. reducing tillage and planting cover crops) and to promote sustainable land management practices through support schemes and capacity-building initiatives.

Overall, the findings of the report emphasise the urgency of addressing soil degradation in Europe through targeted policy interventions, collaborative approaches and continued investment in research and innovation.

Main findings

This assessment offers a comprehensive examination of soil degradation in the 32 European Environment Agency member countries and in 6 collaborating nations in the western Balkans, Ukraine and the United Kingdom. With contributions from over 90 authors, the report draws on the latest research, case studies and soil monitoring data, providing a thorough analysis of soil threats and their implications.

Europe’s soils serve as the foundation for a multitude of ecosystem services that are crucial for human well-being and environmental sustainability. However, nutrient imbalances, acidification, organic carbon loss, peatland degradation, erosion, compaction, pollution and salinisation jeopardise their essential functions. Addressing these challenges requires a coordinated effort to understand the underlying drivers and implement effective management strategies.

Soil monitoring programmes, such as the Land Use / Cover Area Frame Survey, that provide data to the EU Soil Observatory’s Soil Degradation Dashboard play pivotal roles in making it possible to assess soil condition, guiding policy formulation and promoting sustainable land management practices. In addition, they provide valuable insights into trends in soil condition and help in identifying areas in which intervention is needed. There is a lack of comprehensive soil data in the EU’s neighbouring countries and regions affected by conflict, such as Ukraine. This highlights the need for international collaboration and data-sharing initiatives.

To effectively address soil degradation, policy frameworks need to be strengthened, neighbouring countries need to be supported in transitioning to sustainable practices and incentives for soil-friendly agriculture need to be provided. Furthermore, improving soil restoration techniques and making soil more resilient to climate change will require investment in research and innovation and in cross-sectoral cooperation.

By implementing these recommendations and prioritising soil health, policymakers can safeguard the long-term productivity and sustainability of Europe’s soils, ensuring their ability to continue providing essential ecosystem services for generations to come.

Related and future JRC work

The Joint Research Centre provides scientific support to the European Commission in the development and implementation of policies aimed at protecting soil resources. Future efforts of the centre will include supporting the implementation of the soil monitoring and resilience directive by providing scientific evidence and recommendations for soil health assessments. The Joint Research Centre remains dedicated to incorporating soil-related considerations into wider environmental policies and partnerships, in line with the objectives of the ‘Science for the Global Gateway and International Green Deal’ initiative.

Quick guide

The report offers a comprehensive assessment of soil degradation across Europe, focusing on key challenges and policy recommendations.

Chapter 1 provides a regional overview, highlighting the diversity of Europe's soils and the specific challenges faced in different regions. **Chapter 2** discusses the vital role soils play in providing ecosystem services, such as climate regulation, water filtration, and biodiversity support. **Chapter 3** identifies the main drivers of soil degradation, including climate change, land use practices, and pollution. The core of the report, **Chapter 4**, presents the status and trends of soil degradation across Europe, with detailed insights at regional and national levels. **Chapter 5** synthesises evidence from national soil monitoring programs and the EU Soil Observatory to provide a comprehensive view of soil degradation across Europe. **Chapter 6** explores the interplay between different drivers and impacts of soil health, emphasising the complex nature of soil degradation processes. **Chapter 7** highlights the role of citizen science in soil monitoring, showcasing how public participation can complement scientific efforts. **Chapter 8** reviews current soil policies and suggests pathways for strengthening soil governance and protection. **Chapter 9** addresses the challenge of balancing land use demands with the need to protect soil health and ensure ecosystem resilience.

Introduction

Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans. While traditional assessments of soil have primarily focused on crop productivity, contemporary perspectives on soil health encompass its impact on water quality, contributions to climate change dynamics and implications for human health (Lehmann *et al.*, 2020).

The health of soil ecosystems, covering their physical, chemical and biological condition, determines their capacity to function as vital living systems and provide essential ecosystem services. In recent years, concerns about the status of soil health in Europe have escalated due to various anthropogenic pressures such as intensification of agriculture, urbanisation, industrial activities and climate change. Recognising the urgency of addressing these challenges, policymakers have increasingly turned their attention to understanding the current state of soils and implementing measures to ensure their long-term viability.

The primary purpose of this report is to assess the state of soil in Europe, by examining key indicators, trends and drivers of change. The geographical scope of the assessment covers the 32 European Environment Agency (EEA) countries, along with 6 cooperating countries in the western Balkans([1]), Ukraine and the United Kingdom. Drawing on existing and recent evidence from research, case studies and soil monitoring, the report discusses various soil threats in its core chapters.

By synthesising existing research and data, the report aims to provide policymakers, stakeholders and the public with a comprehensive overview of the current state of soil degradation in the region. In addition, it seeks to identify gaps in knowledge and propose recommendations for enhancing soil management practices and on policy interventions.

The central policy problem addressed in this report is soil degradation in Europe, which has implications for agricultural productivity, environmental sustainability and human well- being. As soil degradation continues to accelerate due to human activities, policymakers are confronted with the challenge of developing effective strategies to conserve and restore soil ecosystems. The overarching issue is determining how to reconcile competing demands for land use while safeguarding soil health and ensuring the long-term resilience of European agriculture and ecosystems.

The importance of prioritising soil health cannot be overstated. Healthy soils are fundamental to sustaining agricultural productivity, supporting biodiversity, regulating water resources, mitigating and adapting to climate change, and preserving cultural heritage. Furthermore, soil degradation poses significant economic costs, including reduced crop yields, increased input costs and the loss of ecosystem services. By prioritising soil health, policymakers can promote sustainable land management practices, enhance resilience to environmental stresses and safeguard the well-being of current and future generations.

The main objectives of this report are multifaceted. Firstly, it aims to assess the current state of soils in Europe, including using key indicators such as carbon level, pollution, nutrient availability, compaction, erosion, salinisation and biodiversity. Secondly, the report seeks to identify the drivers of soil degradation and pressures on soil health, ranging from land use changes and agricultural intensification to urbanisation and climate variability. Thirdly, the research aims to evaluate

1 The 32 member countries are the 27 European Union Member States, together with Iceland, Liechtenstein, Norway, Switzerland and Türkiye. The six cooperating countries are Albania, Bosnia and Herzegovina, Kosovo*, Montenegro, North Macedonia and Serbia.

existing policies and initiatives focused on soil conservation and sustainable land management practices. Finally, the report aims to propose evidence-based recommendations on enhancing soil monitoring and on policy development and implementation at the European and national levels. Ultimately, the report is designed to inform decision-making processes and support the development of holistic and integrated approaches to soil management and conservation.

In summary, this report provides a comprehensive overview of the state of soils in Europe, highlighting its significance for agriculture, the environment and society. By addressing key policy questions and objectives, the report aims to inform evidence-based policymaking and promote sustainable soil management practices across the region.

#01 Regional overview

01 Regional overview

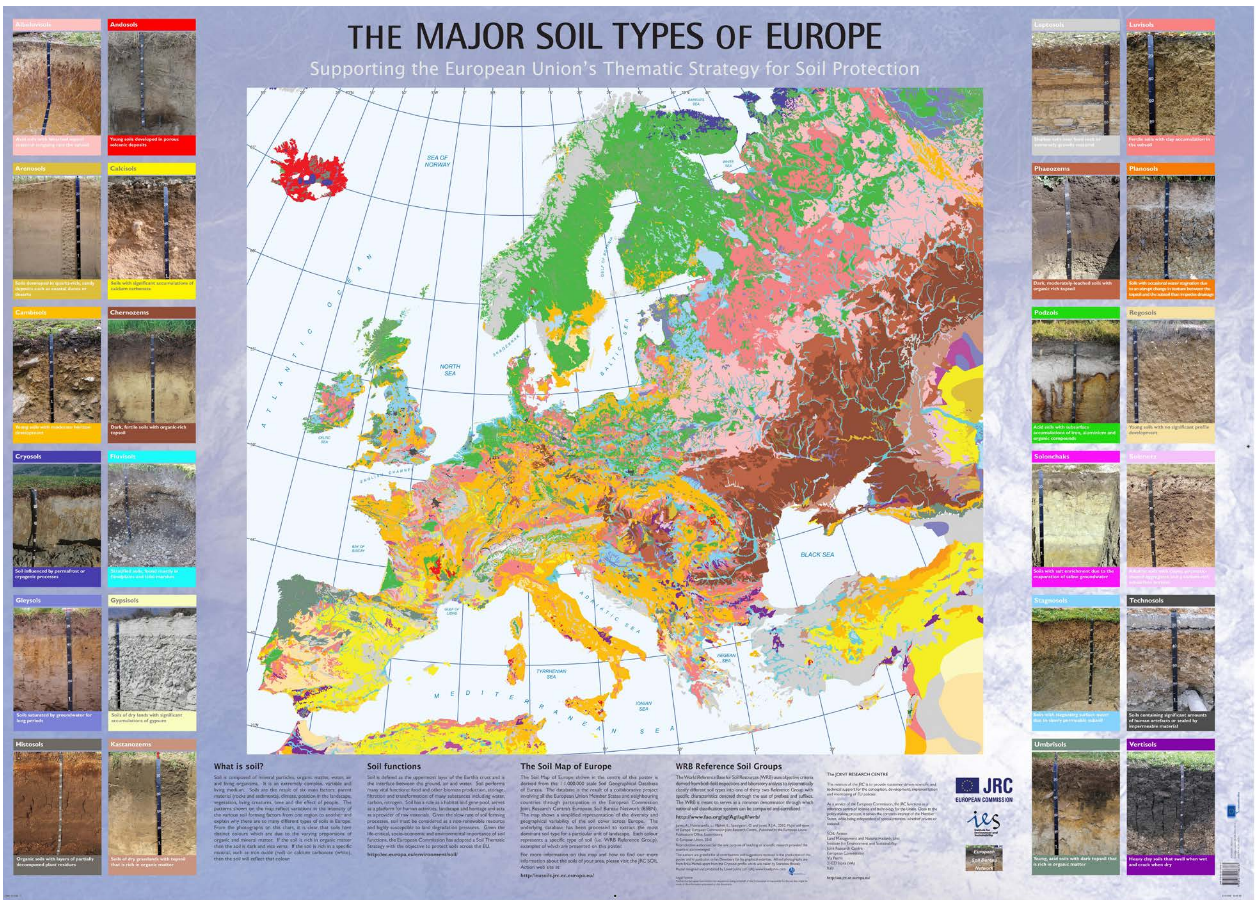
A regional overview of soils in Europe (European Commission, 2005; Tóth *et al.*, 2011) reveals a diverse landscape characterised by more than 20 soil types, according to the World Reference Base for Soil Resources classification system. Across the continent, soils exhibit a wide range of features, including in terms of texture, structure and chemical properties. These are influenced by factors such as parent material, climate, topography and vegetation cover (Figure 1).

In northern Europe, soils are predominantly Histosols, which are soils formed from organic material, and Podzols, which are soils typical of boreal and temperate zones, with cool summers and cold winters. Podzols are characterised by an acidic pH, a low level of moisture and a low nutrient content. These soils are therefore often found in forested areas and have limited agricultural potential.

Moving towards western Europe, soils vary widely depending on the local parent material and climate. The dominant soil types are Cambisols, Luvisols and Albeluvisols. Luvisols are soils typical of (sub)humid temperate climates and are generally productive soils suitable for a wide range of agricultural uses. Cambisols are relatively young soils, often being highly suitable for agricultural land use.

In southern Europe, typical soils are Calcisols, Cambisols and Leptosols. The Mediterranean

Figure 1. Major soil types in Europe, based on the World Reference Base for Soil Resources classification.



Source: European Commission, 2005.

climate, with hot and dry summers and mild winters with short periods of rain, favours the development of Calcisols, with a high pH and low organic matter content, and the poorly developed Cambisols. The steep topography in mountainous areas gives rise to very shallow Leptosols. Regosols are typical of the mountain areas in Albania, Greece, Italy, Spain and Türkiye. These soils are poorly developed mineral soils, and often occur in eroded land, for example in mismanaged orchards and vineyards.

Eastern Europe exhibits a mix of soil types, influenced by both continental and maritime climates. Chernozems, Phaeozems, and Kastanozems are typical soil types in the steppic region. These soils are characterised by moderate to high soil organic carbon content and are highly suitable for arable cropping. The climate varies from temperate continental in the north to more continental and semi-arid in the south-east, which explains the sequence of Phaeozem - Chernozem – Kastanozem, characterised by the high accumulation of organic matter in the superficial mineral horizon, with dark colors, and high base saturation.

Azonal soils, not confined to any specific European region, are Fluvisols, Stagnosols and Gleysols. Fluvisols are stratified soils found along rivers and lakes, having developed in alluvial deposits. While Gleysols develop mainly in a low landscape position, under the influence of excess water at depth, Stagnosols form in areas prone to surface waterlogging.

Despite the diversity of European soils, they face common threats, such as erosion, compaction, contamination and loss of organic matter (Jones *et al.*, 2012; FAO and ITPS, 2015; EEA, 2019a; IPCC, 2019; European Commission, 2021). In light of the ongoing changes in soil health and ecosystem dynamics, it is important to incorporate new findings and insights into the existing knowledge base in order to develop effective strategies for soil conservation and management tailored to diverse European contexts.

#02

The role of soils as providers of vital ecosystem services

02 The role of soils as providers of vital ecosystem services

Europe's diverse soils form the bedrock of ecosystems, providing a myriad of essential services vital for human well-being and environmental sustainability. From supporting biodiversity and regulating climate to purifying water and sustaining agriculture, soils play a multifaceted role in maintaining the balance of our planet. Recognising the intrinsic value of soils, including their cultural heritage, is imperative for safeguarding these vital resources and fostering a resilient and inclusive society, in alignment with the UN sustainable development goals.

Europe's diverse landscapes are home to a rich tapestry of soils, each playing a vital role in supporting ecosystems and providing a myriad of essential services. Ecosystem Services (ES) are "the benefits people obtain from ecosystems" or the direct and indirect benefits that human societies receive from Natural Capital (Millennium Ecosystem Assessment, 2005).

Soil health (2) encompasses the overall condition and functionality of a soil ecosystem, reflecting its ability to support plant growth, maintain ecosystem biodiversity, regulate nutrient cycles, and provide other essential ecosystem services. Healthy soils exhibit attributes such as adequate nutrient availability, balanced soil structure, diverse microbial and faunal activity, good water retention capacity, and resilience to environmental stresses (Lehmann *et al.*, 2020). Nevertheless, it is crucial to acknowledge that certain soils, such as Podzols that are characterised by low nutrient availability, may naturally lack some of these attributes. This absence, however, does not necessarily imply an unhealthy soil condition.

European soils contribute significantly to biodiversity by providing a habitat for a vast array of organisms (Orgiazzi *et al.*, 2022; Labouyrie *et al.*, 2023). From microorganisms to fauna, soils support a complex web of life. The diverse soil types and climates across the continent (Figure 1) fosters a wide range of plant species (Deharveng *et al.*, 2019). This biodiversity, in turn, supports ecosystem resilience, making it more adaptable to environmental changes and disturbances.

Soils play a crucial role in regulating the climate by acting as a carbon sink (Lal *et al.*, 2021). European soils store vast amounts of carbon, helping to mitigate climate change by reducing atmospheric carbon dioxide (CO_2) levels.However, unsustainable land use practices, such as deforestation and intensive agriculture, lead to soil degradation and the release of stored carbon, exacerbating climate change (Cotrufo *et al.*, 2019; Poeplau and Dechow, 2023).

Soils act as natural filters, purifying water as it passes through them. This process helps to maintain water quality by removing impurities and pollutants, reducing the contamination of groundwater and surface water bodies. In addition, soils play a vital role in water regulation, influencing the balance of water availability in ecosystems. Well-managed soils contribute to flood prevention and sustainable water supply (Erdogan *et al.*, 2021; Keesstra *et al.*, 2021).

Soils are key to sustaining life, as they provide the foundations for food and biomass production, essential for agriculture and forestry. Europe's agricultural success is closely tied to its diverse

2 'Soil health' means the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services.

soils. Different regions support different crops due to variations in soil properties, texture and fertility (Tóth *et al.*, 2020; Fendrich *et al.*, 2023).

As the global population continues to grow, the role of soils in ensuring food security becomes increasingly critical (Pozza and Field, 2020). Beyond sustaining crops and forests, soils serve as a vital source of raw materials necessary for various industries and processes (Tóth *et al.*, 2013). In light of historical and ongoing urbanisation dynamics, natural ecosystems, including soils, have undergone substantial modifications. With approximately 38 % of the European population residing in urban areas as of 2021 (Eurostat, 2023), the significance of ecosystem services derived from urban landscapes cannot be overstated. Urban soils present many challenges and opportunities for human populations in cities (Rate, 2022).

Protecting soil cultural heritage is crucial for enhancing soil security, as it strengthens the connection between soil and society (Montanarella and Panagos, 2021). The EU's soil strategy for 2030 acknowledges the diverse range of services offered by soils, going beyond traditional agricultural, forestry and environmental perspectives to include social and cultural dimensions, notably soil cultural heritage. This recognition aligns with the perspectives of various researchers (Morgan and McBratney, 2020; Friedrichsen *et al.*, 2021; Costantini, 2023), who advocate for a comprehensive evaluation of soil health. They emphasise the importance of assessing not only the material value of soil but also its non-commercial value, which encompasses cultural ecosystem services such as spiritual significance, heritage and recreation. These non-commercial values of soils contribute to human well-being, supporting the achievement of targets included in the UN's sustainable development goals by promoting health, education, environmental conservation and inclusive societies (Keesstra *et al.*, 2016). Recognising the importance of soil's social value in influencing physical and mental health, education, diversity and cultural identity, underscores the significance of the cultural and natural heritage services it provides (Field, 2017; Friedrichsen *et al.*, 2021).

As Europe faces ongoing environmental challenges (EEA, 2019b), such as air and water pollution, biodiversity loss, climate change impacts and habitat destruction, the wise stewardship of its soils will be key to maintaining the health and resilience of its ecosystems.

Photo 1. Food and Futures.

Source: Created through the Joint Research Centre art and science programme by artists in residence Sonja Stummerer and Martin Hablesreiter to highlight the importance of a fair, healthy and environmentally friendly food system fulfilling the UN sustainable development goals as part of the European Green Deal.

#03

Drivers of changes in soil health

03 Drivers of changes in soil health

Drivers of changes in soil health are the various factors and processes that influence the condition, quality and functionality of soil ecosystems over time (Berhe, 2019). These drivers can originate from natural processes, such as climate variability and geological dynamics, and from human activities, including land use practices, industrial activities and urbanisation (Berhe, 2019). Drivers of change exert pressure on soils, leading to alterations in their properties, biological composition and functions. This can have significant implications for agricultural productivity, environmental sustainability and ecosystem resilience (Smith *et al.*, 2016). Understanding the key drivers of soil change is essential for identifying threats to ecosystems and assessing their impacts, and implementing strategies to mitigate soil degradation and promote sustainable soil management practices.

3.1 Climate change

Climate change is one of the primary drivers of soil degradation (Banerjee and van der Heijden, 2023), exerting significant influence through various mechanisms. Prolonged periods of drought and rising temperatures exert significant pressure on soil resources such as water and nutrients. Rising temperatures affect soil condition by altering heterotrophic activity, organic matter decomposition rates and nutrient cycling processes. Warmer temperatures can accelerate soil organic matter decomposition, leading to carbon loss and reduced soil fertility (Wang *et al.*, 2021). In addition, extreme temperature fluctuations can affect soil structure and stability, increasing the risk of soil erosion, compaction and salinisation (Daliakopoulos *et al.*, 2016; Kelishadi *et al.*, 2018; Panagos *et al.*, 2021; Kaushal *et al.*, 2023). Changes in precipitation patterns, including the frequency, intensity and distribution of rainfall events, can have a profound impact on soil (Meng *et al.*, 2021). Excessive rainfall can cause soil erosion, nutrient leaching and waterlogging, while drought can lead to soil moisture depletion, increasing susceptibility to erosion and desertification (Ferreira *et al.*, 2022).

The EU's ambitious climate targets hinge on preserving vegetation and soils to prevent further carbon losses, especially in organic soils, and to foster carbon sequestration. However, gains from prolonged growing seasons may be offset by soil organic carbon (SOC) losses due to climate-related hazards such as temperature extremes, heavy precipitation and droughts (Searchinger *et al.*, 2022). Between 2000 and 2022, an average of 4.2 % of the EU's land area (approximately 167 000 km^2) was affected annually by droughts, attributed to low precipitation, high evaporation and heatwaves driven by climate change (EEA, 2023a). In high-latitude regions, climate-change-induced permafrost thaw can release stored carbon and methane, leading to soil subsidence, land instability and altered hydrological regimes, hence exacerbating climate change feedback loops (Jin *et al.*, 2021).

3.2 Land use and land cover change

Between 2011 and 2021, the proportion of protected land in the 32 EEA member countries and 6 cooperating countries increased from 24 % to 26 % (EEA, 2023). However, this is juxtaposed with forecasts predicting a significant rise, of 15 %, in global demand for agricultural products by 2028 (OECD/FAO, 2023). This surge in demand is poised to impact natural resources such as land and water, and biodiversity, underscoring the importance of sustainable land management practices. The management of cropland, pasture and agroforestry is particularly critical in this context. Concurrently, forest and tree plantation management, grazing land management and

Photo 2. Soil sealing through urban expansion.

Source: A. Jones.

extractive industry development influence land use dynamics. In the last few years, we have started to observe that the mountains of Europe are being re-explored by the mining industry, with the expansion of open pit and underground mines (Eurostat, 2018; del Mármol and Vaccaro, 2020).

Urbanisation and infrastructure development have also left a tangible mark on land use patterns. Between 2012 and 2018, land take in the EU-27 and the United Kingdom expanded by 3 581 km^2. In addition, soil sealing increased by 1 467 km^2, representing 23 % of the territory and affecting 75 % of the population, mainly at the expense of croplands and pastures (EEA, 2021). Notably, nearly 80 % of land take occurred in commuting zones, which, unlike city centres, provide valuable wildlife habitats, support carbon sequestration, offer flood protection and serve as sources of food and fibres (EEA, 2021). Despite these trends, land recycling, including constructing in or rehabilitating previously built-up areas, only accounted for 13.5 % of urban development in the EU between 2006 and 2012 (Nicolau and Condessa, 2022). This signals the need for more sustainable land use practices to mitigate adverse impacts on soils and ecosystems.

3.3 Socioeconomic drivers

Socioeconomic factors play a crucial role in driving soil degradation, reflecting complex interactions between human activities and environmental dynamics (Gambella *et al.*, 2021). Rapid population growth and urbanisation exert pressure on agricultural land, leading to intensified farming practices and expansion into marginal areas (Beckers *et al.*, 2020). Intensive agriculture, driven by the demand for food and commodities, often involves the excessive use of chemical inputs, extensive tillage and monoculture cropping, which degrade soil and reduce biodiversity (Emmerson *et al.*, 2016). Land use changes, driven by economic incentives and policies, such as deforestation for agriculture or infrastructure development, further exacerbate soil degradation by disrupting natural ecosystems and increasing erosion rates (Olsson *et al.*, 2019). In addition, socioeconomic inequalities and lack of access to resources and knowledge can limit sustainable land management practices, leading to land degradation and loss of livelihoods (Schuh *et al.*, 2022).

In 2020, according to The Third Clean Air Outlook, produced by the European Commission (2022), 75 % of the total area of the EU-27 exceeded critical loads for nitrogen (N) deposition. The Po Valley in Italy, the Dutch–German–Danish border areas and north-eastern Spain were characterised by significant exceedances, affecting the ecological quality of natural areas (Zhang *et al.*, 2021). N deposition decreased by 12 % between 2005 and 2020. The zero pollution action plan aims for a 25 % reduction from 2005 levels by 2030. Forest ecosystem properties in Europe, such as soil pH buffer potential and plant biodiversity, are expected to respond with varying delays to the current trend of decreasing N deposition (Gilliam *et al.*, 2019; Schmitz *et al.*, 2019).

3.4 Soil water

Owing to the recognition of the interconnectivity between water, energy, food security and ecosystems, whereby any limitation in one of the inputs will disturb the availability of the others, it is important to understand water as a key element in soil degradation (FAO, 2014; Carmona-Moreno *et al.*, 2019). Almost all chemical and biological activities in soil are dependent on its water content, which ultimately influences plant growth (Sharma and Kumar, 2023). Soil water balance determines soil health, irrigation needs and crop productivity, and is intimately connected with degradation processes such as drought, salinisation and flooding. Water scarcity (drought stress) is an important driver of soil degradation, as it inhibits the biological functioning of soil and soil organic matter development (Védère *et al.*, 2022), which impacts other ecosystem services. While water excess due to poor drainage conditions can induce oxygen deficiency in soils (Védère *et al.*, 2022; Sharma and Kumar, 2023), it can also increase soil erosion due to saturation-excess run-off (Landemaine *et al.*, 2023) or flooding (Merz *et al.*, 2021). It is crucial to note that changes in the water content of soil also have profound implications for the greenhouse effect, particularly in sensitive ecosystems such as peatlands and rice crops, and in many natural or semi-natural humid ecosystems. These environments play critical roles in global carbon cycles and biodiversity conservation, making them particularly vulnerable to fluctuations in water availability (Vereecken *et al.*, 2022).

Despite the importance of climate in controlling the water content of soil, the implementation of appropriate soil management practices (Ferreira *et al.*, 2022), combined with the boosting of soil organic matter and soil biodiversity (Philippot *et al.*, 2023), has been shown to improve soil water conditions, such as water-holding capacity and water infiltration, and overall to improve the soil's resilience to changes in water content (Falkenmark and Wang-Erlandsson, 2021).

box **1**

War-induced soil degradation.

The effects of the First World War on soils are still evident today (Williams and Rintoul-Hynes, 2022). The ongoing war in Europe has resulted in much more significant impacts on soil. Scientists at Ukraine's Institute for Soil Science and Agrochemistry Research have estimated that the war has degraded more 10 million hectares of agricultural land across Ukraine so far. Military actions have led to a wide array of soil degradation issues, including pollution, compaction, loss of organic matter and nutrients, reduced biodiversity, soil sealing and other, less well understood, issues (Dmytruk et al., 2023). The ongoing conflict in Ukraine involves the utilisation of state-of-the-art military weaponry, including aircraft bombs weighing between 1 500 kg and 3 000 kg, ballistic missiles, massive fire and toxic chemicals. Consequently, the environmental impact of the military activities is set to be significantly more severe than ever witnessed in history. Experiences in other conflict-affected areas indicate that soils in areas where there are intense hostilities, such as Bakhmut and Avdiivka, will take decades (or even centuries) to be restored. While conducting a thorough survey of soils impacted by military activities remains unfeasible at present, it is evident that addressing the repercussions of the war will pose a substantial challenge in tackling global issues.

Photos box 1: Soil desgradation caused by the war in Ukraine. *Source: Y. Dmytruk.*

3.5 Disturbances (wildfires, droughts and windstorms)

Fire activity in Europe has undergone significant changes in recent decades (1980–2020), which have been marked by the emergence of summers with unprecedented fire-facilitating weather conditions (Jolly *et al.*, 2015; Abatzoglou *et al.*, 2018; Carnicer *et al.*, 2022). To understand the extent of the damage, in 2022 nearly 900 000 ha of natural land were affected by fires, and 43 % of the total burned land was within Natura 2000 sites (San-Miguel-Ayanz *et al.*, 2023). Climate change is expected to further disrupt fire patterns, increasing fire season duration and risks globally, especially in Europe.

Southern Europe, already a hotspot for climate-related risks such as fires, droughts and heatwaves, faces heightened challenges (Andela *et al.*, 2017; Dupuy *et al.*, 2020). Europe's record-breaking summer of 2022, the second-warmest year on record, resulted in the largest drought-affected area ever recorded: over 630 000 km^{2}, far exceeding the annual average of 167 000 km^2 between 2000 and 2022. This trend is alarming, given projections of increased heatwave frequency and intensity by 2030, along with decreased summer precipitation in continental and Mediterranean regions.

Soil degradation can significantly influence fire activity. Degraded soils are often less able to retain moisture, leading to drier conditions that can contribute to the flammability of vegetation (O *et al.*, 2020). Conversely, fires themselves can exacerbate soil degradation by reducing organic matter, altering soil structure and increasing erosion risk (McGuire *et al.*, 2024). In doing so, they create a feedback loop originating from multiple disturbances, leading to further soil degradation, limited ecosystem recovery and eventually desertification (Neary, 2009). To mitigate these impacts, adjusting land management practices is crucial. Therefore, the implementation of effective adaptation strategies by the EU and its Member States is vital.

The *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC), published in 2021 (Ranasinghe *et al.*, 2021), states that northern and central Europe are likely to experience an increased frequency and intensity of storms, including strong winds and extra-tropical storms. In southern Europe, the intensity of storms is predicted to rise, while their frequency may decrease. Agricultural soils, especially bare surfaces, face severe threats from heavy rainfall and accompanying winds (Marzen *et al.*, 2017).

In summary, disturbances such as wildfires, droughts and windstorms are key factors to consider in assessing soil degradation in Europe. These events can greatly influence soil properties and functions, underscoring the need for effective strategies to manage these impacts and protect soils from them. Addressing these challenges is therefore essential for maintaining good soil condition and ensuring the long-term sustainability of European ecosystems.

Photo 3. Impacts of fire on the landscape in Serra da Estrela, Portugal.

Source: D. Vieira.

#04 Regional status and trend of soil degradation

The State of Soils in Europe

04 Regional status and trend of soil degradation

Assessing soil condition involves evaluating a range of physical, chemical and biological indicators. Soil degradation is defined as a change in soil health resulting in the diminished capacity of the ecosystem to provide goods and services for its beneficiaries (FAO, 2024). Drawing from existing and recent evidence, including research findings, case studies and soil monitoring data, our assessment focuses on various soil degradation indicators. These include:

- soil acidification
- soil carbon change
- soil erosion
- soil compaction
- soil pollution
- soil salinisation and sodification
- soil biodiversity change
- soil sealing and land take.

4.1 Excess and deficiencies in soil nutrients

Soil nutrient status in Europe, particularly regarding nitrogen (N) and phosphorus (P), exhibits significant spatial variations, influenced by factors such as agricultural practices, climate, and soil properties. Despite efforts to manage nutrient inputs, high N and P surpluses persist in many regions, posing risks to soil and water quality. Addressing the drivers of nutrient excesses and deficiencies, including fertilizer application, land use practices, soil erosion, and climate patterns, is crucial for mitigating environmental pollution, soil acidification, and economic costs, while safeguarding human health and agricultural productivity. Effective soil management strategies are essential to balance nutrient inputs and outputs, ensuring sustainable land use and ecosystem resilience in the face of ongoing environmental challenges.

Soil nutrients are essential for plant biomass production and quality, and other ecosystem services (Li *et al.*, 2016; Ros *et al.*, 2022). These other services includes the major biogeochemical cycles and related soil functions, notably carbon sequestration (Van Groenigen *et al.*, 2017).

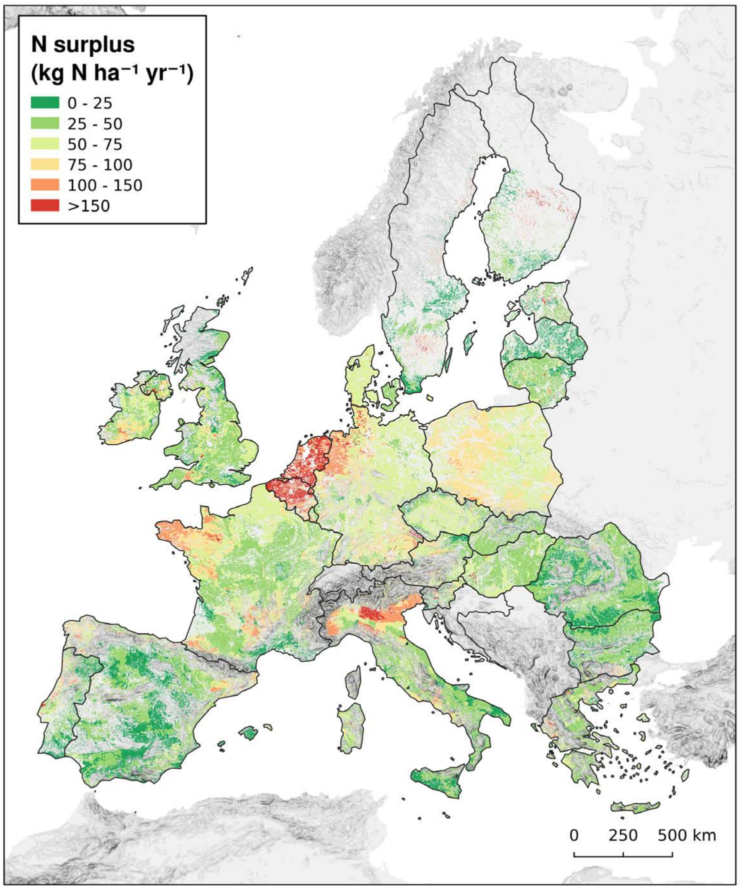
Nutrient management is therefore essential to maintain soils in good chemical, biological and physical conditions. Nutrients are managed to achieve agronomic and economic objectives (i.e. yields and yields versus costs) while minimising environmental impacts (avoiding losses to air and water and the introduction of contaminants) (Beegle *et al.*, 2000; Hou *et al.*, 2023).

4.1.1 Status and trends

Soil N content ranges mostly from 1 g and 2 g kg^{-1} in EU topsoils (Ballabio *et al.*, 2019). Due to the high mobility of nitrate, N losses from the soil are highly correlated with N surpluses (input minus crop uptake). There is a large variation in N surpluses across the EU and the United Kingdom (Figure 2), from nearly 0 kgN ha^{-1} yr^{-1} to more than 150 kgN ha^{-1} yr^{-1}.

A high N surplus mostly occurs in areas with high N inputs, especially in intensive livestock areas, except for some regions with low (Poland) or high (Massif Central in France, Ireland and the United Kingdom) N use efficiency (De Vries *et al.*, 2021).

Figure 2. The N surpluses (inputs minus offtake by crops) for agricultural land across the EU and the United Kingdom.



Source: *De Vries et al. (2021)*

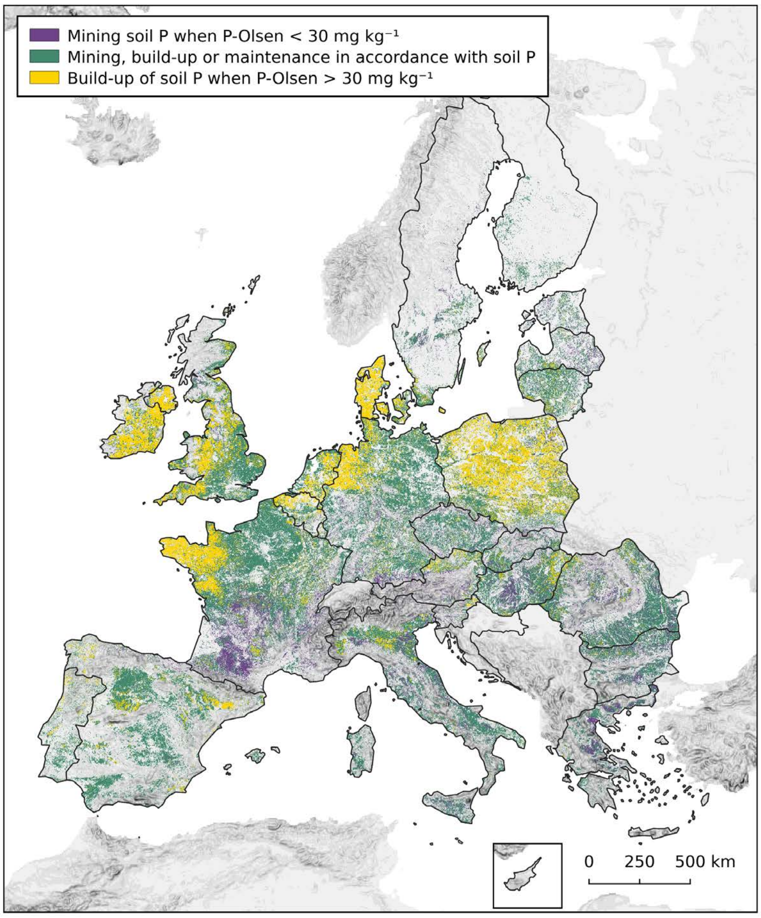
About 74 %, 66 % and 18 % of all agricultural land in the EU and the United Kingdom has excessively high N inputs when considering the regional variation in ecosystem sensitivity for N loss by run-off to surface water, ammonia (NH3) emissions and N loss through leaching to groundwater, respectively (De Vries *et al.*, 2021).

Between 1930 and 1990, N surplus increased by a factor of 2–3 (Batool *et al.,* 2022), reaching its highest value around 1990 because of a peak in N inputs. The surplus declined in subsequent years. Since 1990, total N inputs in cropland have been relatively stable, with a slight increase from 138 kgN ha^{-1} yr^{-1} to 145 kgN ha^{-1} yr^{-1} in 2021 (Einarsson *et al.,* 2021).

Available phosphorus (P) concentrations in topsoils vary considerably across the EU and the United Kingdom, with most areas having concentrations around 20–25 mg kg^{-1} (based on P-Olsen). Higher levels occur in northern Germany, northern France and northern Italy, and in Belgium, Denmark, Ireland, the Netherlands, Poland and the United Kingdom. Despite these high soil P levels, balance calculations have shown an average surplus of P in the EU and United Kingdom of 0.11–0.80 kg P ha^{-1} yr^{-1} (Panagos *et al.*, 2022b; Muntwyler *et al.*, 2024) or higher (De Vries *et al.,* 2014; Einarsson *et al.,* 2020). However, there is considerable variation among countries, and extensive areas in the EU and the United Kingdom are currently experiencing surpluses of more than 10 kg P ha^{-1} yr^{-1}, despite the generally high soil P concentrations in these regions.

The current P management practices were evaluated by comparing the P balance with the available concentration of P in the soil (P-Olsen) (Ballabio *et al.*, 2019). The P balance is defined as organic and mineral fertilizer inputs minus outputs due to removal by crops and loss by erosion (Muntwyler *et al.*, 2024). When the P-Olsen concentration is less than 30 mg kg^{-1}, negative P balances increase the potential risk of P deficiency for agricultural production (Jordan-Meille *et al.*, 2012; Steinfurth *et al.*, 2022). This occurs in 13 % of EU and UK agricultural land. When P-Olsen concentrations are greater than 30 mg kg^{-1} (Jordan-Meille *et al.*, 2012; Steinfurth *et al.*, 2022), positive P balances increase the

Figure 3. Current P inputs for a P-Olsen threshold of 30 mg kg^{-1}.



Source: EUSO, based on Ballabio et al., (2019) and Muntwyler et al., (2024).

risk of P environmental losses which is the case in 33 % of EU and UK agricultural land (Figure 3). Many Member States have experienced much more imbalanced P management in recent decades: P inputs peaked above 30 kg ha^{-1} in around 1980 (Sattari *et al.*, 2012), while P inputs are nowadays, on average, 16 kg ha^{-1} in the EU and the United Kingdom (Panagos *et al.*, 2022b). Due to the low mobility and high retention of P in soils, the positive P balance of the past have resulted in high soil P legacy (Sattari *et al.*, 2012). When 30 mg kg^{-1} of P-Olsen is used as threshold values for excess (Jordan- Meille *et al.*, 2012; Steinfurth *et al.*, 2022), about 60 % of agricultural soils in the EU and the UK can be defined as P-rich soils, with possible adverse impacts on water quality. The threshold of 30 mg kg^{-1} is the lowest value of the range proposed by the European Commission in the proposed Soil Monitoring Law to define P excess in soils (European Commission, 2023b). When taking the upper range value of 50 mg kg^{-1}, 10 % of agricultural soils in the EU and UK has excess of P.

In non-EU countries such as Norway, P surpluses reduced from 1985 to 1990, and have remained relatively stable since (OECD, 2024). The P surpluses in Norway are similar to those in the United Kingdom, contributing to the eutrophication of water bodies in the region (Ulén *et al.*, 2007). P surpluses reduced in Switzerland between 1990 and 2000, and have since fluctuated between 2 kg ha^{-1} and 5 kg ha^{-1} (OECD, 2024).

The N and P budgets in Iceland are generally low and have been stable over the years (OECD, 2024). Ukraine has seen the largest decrease in N and P budgets since 1990 of all non-EU countries considered (OECD, 2024), with a P budget of – 2.4 kg ha^{-1} yr^{-1} in 2020. This drastic reduction in fertiliser input after the 1990s can be attributed to the political transformations in post-Soviet countries. Political changes have also affected the nutrient balances in the western Balkans (Zdruli *et al.*, 2022). In this region, about 5.2 % of total agricultural land could have relatively large N surpluses, as this area consists of greenhouses and open field horticulture crops, which receive the largest N fertiliser doses. However, generally fertiliser application in these countries happens to be far below the average EU level; they therefore have a higher chance of having negative N and P budgets (as found in Ukraine (OECD, 2024)), contributing to nutrient mining and a decrease in soil fertility (Zdruli *et al.*, 2022).

In Türkiye, both the N balance and the P balance have increased in the last 5 years (OECD, 2024). N fertiliser use on crops fluctuated between approximately 46 kg N ha^{-1} yr^{-1} and 89 kgN ha^{-1} yr^{-1} from 2004 to 2022; the application of P fertiliserfluctuated between 6 kg P ha^{-1} yr^{-1} and 15 kg P ha^{-1} yr^{-1}; and the application of potassium (K) in agricultural production varied from approximately 2 kg ha^{-1} to 6 kg ha^{-1} from 2004 to 2022 (MoAF, 2022).

Available K concentrations, determined using ammonium acetate, vary across the EU and the United Kingdom depending on parent material, soil clay content and manuring history, with higher concentrations in clay-rich soils (Ballabio *et al.*, 2019). K inputs are usually higher in countries or regions with intensive animal husbandry. For example, in France, the exchangeable K thresholds (ARVALIS, 2020) defining the risk of K deficiency vary from 49 mg kg^{-1} to 247 mg kg^{-1} (with an average of 123 mg kg^{-1}) depending on soil type (Comifer, 2019). Using these threshold values, 16 % and 68 % of EU and UK agricultural soils have exchangeable K concentrations of below 123 mg kg^{-1} and 247 mg kg^{-1}, respectively. They can therefore be considered soils with low K levels for biomass production.

Secondary macronutrients (e.g. sulphur (S), calcium and magnesium) and micronutrients (e.g. iron, zinc (Zn), copper (Cu), manganese (Mn), molybdenum, boron and cobalt) have a fundamental role in sustaining terrestrial ecosystems, which is partly related to their contribution to sustaining biomass development. In addition, these elements are divalent cations, which control aggregate stability, soil water retention and supply, resistance to wind erosion, topsoil sealing, subsoil compaction, and drought and wetness stresses (Ros *et al.*, 2022). However, at the EU level, there is limited information on the levels of these nutrients in soil and their input to correct deficiencies. In the EU, there is information on the total amounts of some micronutrients in soils (Ballabio *et al.*, 2018; Van Eynde *et al.*, 2023), but these have low agro-environmental relevance (Alloway, 2009). Micronutrients are typically applied in the form of salts and chelates, but there is no spatial information regarding the quantity of micronutrient fertilisers used in the EU to correct deficiencies. Soils at risk of micronutrient deficiencies are generally those characterised by a high pH and low organic matter content (Moreno- Jiménez *et al.*, 2022), while intense cropping can exacerbate micronutrient depletion in specific soils (Jones *et al.*, 2013). Budget calculations underscore the significance of manure as a source of Cu and Zn for agricultural soils in the EU (De Vries *et al.*, 2014), alongside sewage sludge (Yunta *et al.*, 2024) and fungicides (El Hadri *et al.*, 2012).

4.1.2 Drivers

The main drivers of soil nutrient excesses and deficiencies are multifaceted and can vary depending on the specific context. However, some common drivers include the following.

- Fertiliser and manure application. Since the 1950s, the increased use of fertilisers has boosted crop and forest production, but their excessive and inefficient use has led to nutrient excesses and losses (Townsend *et al.*, 2003). Gaseous emissions from industry and agriculture, as well as natural processes, also lead to the deposition of nutrients in terrestrial ecosystems.

- Land use and management practices. Agricultural systems have become specialised, resulting in the decoupling of crop and livestock production. On the one hand, there are systems relying on both internally and externally produced feed, resulting in significant amounts of nutrient-rich waste such as manure. Applying this nutrient source inappropriately often leads to substantial losses. On the other hand, some arable fields depend on external fertiliser inputs to manage their nutrient needs. In addition, agricultural practices such as tillage, irrigation and pesticide use can impact soil nutrient levels (Edlinger *et al.*, 2022).

- Soil erosion and leaching. Erosion results in the loss of nutrients such as P to lower areas and to surface water (Alewell *et al.*, 2020), while leaching can result in the loss of nutrients such as N and S to groundwater (De Vries *et al.*, 2021). The loss of nutrients leads to a decline in soil fertility, while sedimentation and leaching can result in an excess of nutrients elsewhere.

- Soil properties. Soil types and related characteristics, such as mineralogy (e.g. clays, carbonates, oxides) control the release and retention of carbon and nutrients such as K and P in soils (e.g. van Doorn *et al.*, 2023). Furthermore, soil pH influences the solubility, concentration in soil solution, ionic form, and adsorption and mobility of many elements (Moreno-Jiménez *et al.*, 2022; Hartemink and Barrow, 2023). Organic matter affects nutrient content, retention and release in soils (Moreno-Jiménez *et al.*, 2022).

- Climate and weather patterns. Weather events such as heavy rainfall can accelerate nutrient leaching and nitrous oxide (N_2O) emission to the atmosphere, while drought conditions can concentrate salts in the soil, potentially leading to nutrient imbalances. In addition, climatic conditions control crop yield and nutrient use efficiencies (Young *et al.,* 2021).

4.1.3 Impacts

Soil nutrient excesses and deficiencies can greatly influence agricultural productivity, and environmental, ecosystem and human health. Some of the key consequences are as follows.

- Environmental pollution. Excess nutrients, particularly N and P, can leach into groundwater or move to surface water bodies in run-off and by erosion. This results in eutrophication, with the loss of biodiversity, the depletion of subaquatic vegetation, a decline in coral reef health, the occurrence of algal blooms and the creation of oxygen-depleted or hypoxic waters (Carpenter *et al.*, 1998; Smith, 2003; Smith and Schindler, 2009; Lundin and Nilsson, 2021). An excess of N can also result in increased N losses into the atmosphere. The subsequent deposition of N is a major driver of plant biodiversity loss through N enrichment and soil acidification in natural areas (Bobbink *et al.*, 2010).

- Climate change. Excess N in soil can lead to the increased emission of N_2O, a potent greenhouse gas (GHG). N_2O is released from soils through denitrification, whose rate increases with N input (Butterbach-Bahl *et al.*, 2013; Arias-Navarro *et al.*, 2017; McDonald *et al.*, 2022; Pan *et al.*, 2022).

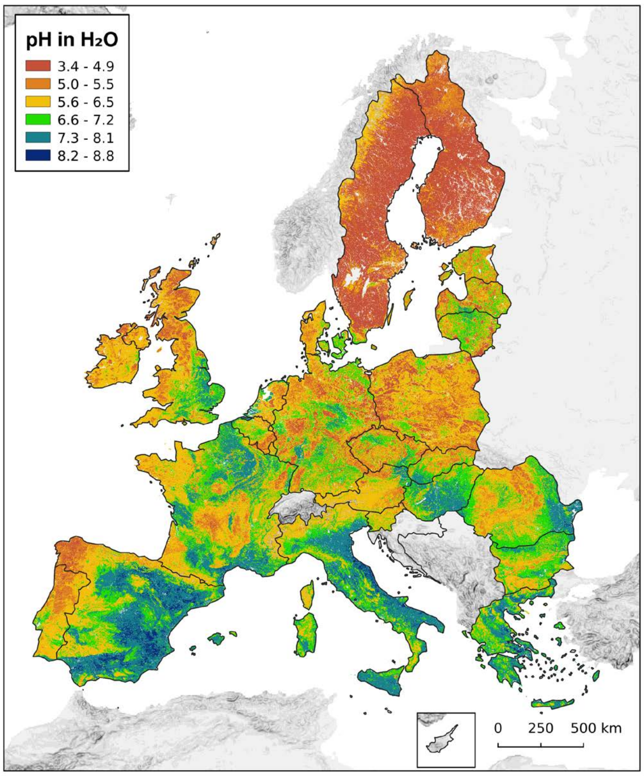
- Soil acidification and salinisation. Excessive nitrate in soils due to N fertilisation causes acidification due to the release of hydrogen ions during the process of nitrification, affecting the availability of other nutrients, and contaminants (Zhang *et al.*, 2023). Finally, excess N fertilisation in dry and sub-dry regions can lead to soil salinisation (Han *et al.*, 2015).

- Soil pollution. The excessive use of P fertilisers (Nziguheba and Smolders, 2008), as well as organic fertilisers and amendments, may introduce heavy metals and other soil pollutants (Mantovi *et al.*, 2003; Pan and Chu, 2017). The application of synthetic chelates to correct micronutrient deficiencies in Mediterranean soils may also lead to the introduction of recalcitrant products, with negative environmental impacts (Yunta *et al.*, 2013).

- Economic costs. Soil nutrient deficiencies can lead to reduced crop yields (Schils *et al.*, 2018) and crop nutritional quality (Dimkpa and Bindraban, 2016), and increase the susceptibility of plants to disease (Dordas *et al.*, 2000). These impacts reduce farmers' incomes, and increase the costs of inputs. Excess nutrients can also lead to serious losses to the environment, requiring environmental mitigation measures, with associated costs.

- Human health risks. Gaseous N emission contributes to the formation of aerosol and particulate matter air pollutants, affecting human health (Pozzer *et al.*, 2017). Nutrient losses to aquatic ecosystems also affect human health, as they can compromise the safety of drinking water (Lundin and Nilsson, 2021). Finally, nutrient deficiencies or imbalances reduce crop nutritional quality, compromising livestock production, as well as food security and food quality for humans (Ishfaq *et al.*, 2023). For instance, a deficiency of Zn in semi-arid and arid regions is very common and is a growing concern, as this nutritional disorder causes almost 116 000 deaths per year worldwide (Galetti, 2018).

Figure 4. Soil pH, measured in H_2O, in EU and UK soils.



Source: EUSO, based on Ballabio et al. (2019).

4.2 Soil acidification

Soil acidification, a global concern, impacts soil quality, ecosystem integrity and human well-being. It predominantly affects non-calcareous soils, with low buffer capacity, leading to a decline in pH. This decline can impair nutrient availability and increase the mobility and availability of toxic elements. While some countries have seen improvements, acidification remains a significant issue in Ukraine and Türkiye, affecting agricultural productivity and environmental quality. Drivers of soil acidification include natural processes, industrial emissions and agricultural practices. The excessive use of ammonium-based fertilizers may lead to soil acidification.

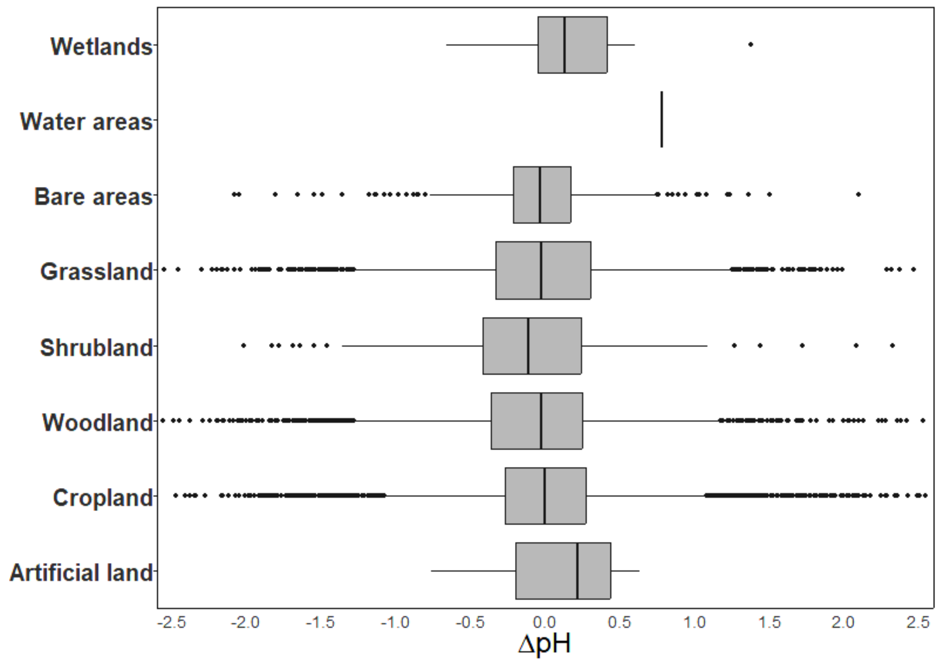
Soil acidification, defined as a decrease in the acid neutralisation capacity of the soil (De Vries and Breeuwsma, 1987; Guo *et al.*, 2010) is a major issue all around the world. In calcareous soils with a high natural buffer capacity, there is little concern, as the pH remains stable and slightly alkaline until all carbonates are depleted. This depletion depends on their dissolution rate. However, in non-calcareous soils, with a low buffer capacity, especially sandy soils with low organic matter content, soil acidification may cause a relatively fast decline in soil pH and base saturation. Soil pH is an important indicator of soil health, as it affects the availability and mobility of nutrients and toxic elements (e.g. aluminium, cadmium and other heavy metals). As a consequence, it affects primary productivity (Bolan *et al.*, 2003; Pagani and Mallarino, 2012; Hartemink and Barrow, 2023), the quality of surrounding water bodies (Haynes and Swift, 1986; Dijkstra *et al.*, 2004), and the functioning of soil as a habitat for organisms and hence biodiversity (Siciliano *et al.*, 2014).

4.2.1 Status and trends

Soil pH differs across the EU (Figure 4). The differences mainly reflect the soil type, which is a result of climatic conditions (Ballabio *et al.*, 2019), parent material, vegetation and past management practices, such as liming.

Soils with a relative low pH (< 5.5) are present in 10 % of the agricultural land across Europe (Figure 4), with possible adverse effects on plants and soil microor-

Figure 5. Difference in soil pH (ΔpH) measured in H2O for LUCAS topsoil samples collected in 2009 and 2018.



Source: EUSO, based on LUCAS 2009 and 2018 topsoil databases.

ganisms as toxic elements (e.g. aluminium) become increasingly available (Kunhikrishnan *et al.*, 2016).

A preliminary analysis of the Land Use / Cover Area Frame Survey (LUCAS) topsoil samples from 2009 and 2018 shows that pH both increased and decreased (Figure 5). Positive values reflect an increase in soil pH from 2009 to 2018, while negative values show a decrease in soil pH. In some land cover classes, the trend is an increase rather than a decrease. Further analysis should assess which factors explain the change in pH. Given the negative impact of soil acidification and low soil pH on primary productivity, as mentioned above, a typical management strategy is liming. However, there are currently no regulations on the application of lime to agricultural or forest soils at the EU level, nor are there any data about the application of lime to agricultural soils.

Historically, acidification has impacted various land uses, including forest, agricultural land and semi- natural ecosystems (Bolan *et al.*, 2003). In recent decades, a slight improvement in upper soil horizons has been observed, with pH values rising (Achilles *et al.*, 2021). However, recovery from past acidification appears to vary depending on soil depth. While some research indicates increasing pH values over time in forest floor soil and topsoil (Navrátil *et al.*, 2007; Schmitz *et al.*, 2019; Wellbrock and Andreas, 2019), deeper mineral soil remains acidified due to historical exposure to acidifying air pollutants (Berger *et al.*, 2006). In the United Kingdom, reduced sulphate deposition has facilitated the recovery of topsoil from acidification (Thomas *et al.*, 2020). Several monitoring schemes have reported an increase in soil pH across all UK habitats, with national-level data showing a mean increase in pH from 5.4 to 5.9 (Reynolds *et al.*, 2013). In Switzerland, soil acidification remains a significant concern in forests in terms of both extent and ongoing progression (Braun *et al.*, 2020). In Ukraine, approximately 24 % of soils are acidic. Acidic soils are predominantly found in the Polissya zone, while alkaline soils (18.4 %) are more prevalent in the steppe zone. Soil acidification, particularly in the natural areas of the Polissya zone, has been identified as a significant issue (Institute of Soil Protection of Ukraine, 2023).

Soil acidity is important for sustaining soil health, particularly in the East Black Sea Region of Türkiye. As a result of natural processes, the high annual rainfall results in leaching, which increases the presence of hydrogen and aluminium cations, ultimately leading to soil acidity.

4.2.2 Drivers

The drivers of soil acidification are diverse and can vary depending on regional and local factors. Some of the main drivers include the following.

- Natural processes. Soil acidification is a natural process. It is mainly caused by the dissociation of carbonic and organic acids, which leads to the leaching of bicarbonate and non-acidic cations (Zamanian *et al.*, 2024). The weathering of particular mineral rocks containing sulphide minerals (e.g. pyrite) can naturally generate acidic conditions in soils.

- Acid deposition and waste. Mining activities and industrial processes can release acidic substances into the environment, either directly through emissions or indirectly through the disposal of acidic waste materials. Ammonia (NH_3), nitrogen oxide (NOx) and sulphur oxide (SOx) emissions and air pollution have been major drivers of forest soil acidification in recent decades (through increasing the deposition of mainly N and S compounds), thereby hampering tree growth and affecting forest composition (EEA, 2014). However, regulatory controls have reduced emissions and consequently the deposition of compounds causing acidification (Engardt *et al.*, 2017), especially S compounds. This has resulted in the re-alkalinisation of several European forest soils in which acid deposition had decreased (Berger *et al.*, 2016; Prietzel *et al.*, 2020). N deposition is now identified as the main cause of acidification in many European regions (Michel *et al.*, 2022). Critical loads of acidity are currently rarely exceeded, except for in the Netherlands (De Vries *et al.*, 2024).

- Agricultural practices. In agricultural soils, acidification is caused by the application of acidifying fertilisers, nitrate leaching, nutrient uptake (affecting cation/anion balance) by plants, N fixation in legumes, plant root exudates and the mineralisation of soil organic matter (Debreczeni and Kismányoky, 2005; Goulding, 2016; Xu *et al.*, 2019). Agronomic measures such as the addition of manure and lime mitigate the impact of soil acidification, thereby preventing a decline in soil pH.

4.2.3 Impacts

Soil acidification can have various impacts on soil, ecosystem functioning and human health.
Some of the main impacts are as follows.

- Reduced nutrient availability. Soil pH influences the solubility, concentration in soil solution, ionic form and adsorption of most nutrients, as well as their mobility (Hartemink and Barrow, 2023). The availability of some nutrients (calcium, P, magnesium and K) can be reduced in acidic soils, reducing primary productivity (Pagani and Mallarino, 2012).

- Contamination and human health. Soil acidification can increase the solubility and mobility of toxic elements such as aluminium, cadmium and other heavy metals (Bolan *et al.*, 2003), affecting primary productivity. Due to the increased mobility of pollutants upon acidification, the quality of surrounding surface water and groundwater is reduced (Haynes and Swift, 1986; Dijkstra *et al.*, 2004). This has negative consequences for aquatic biodiversity (Soveri, 1992) and human health (due to contamination of drinking water) (Steffan *et al.*, 2018).

- Altered soil biota activity. Soil acidification can influence the composition and activity of microbial communities in soil (De Vries *et al.*, 2006; Siciliano *et al.*, 2014). Studies have found that acidification results in a reduction in nematode and rotifer abundance and earthworm biomass, and a change in microbial composition, thereby affecting microbe-mediated processes such as SOC cycling (Tibbett *et al.*, 2019).

- Ecosystem disturbance. Soil acidification can disrupt ecosystem dynamics and alter the composition of plant communities. Acid-sensitive plant species may become less abundant, while acid- tolerant species may become more predominant, leading to shifts and reductions in biodiversity (Bobbink *et al.*, 2010).

Overall, soil acidification poses significant challenges to agriculture, forestry, ecosystem management and human health, reinforcing the importance of implementing strategies to mitigate its impacts and restore soil condition. Various practices can be employed to address soil acidification, such as the application of agricultural lime to neutralise acidity. On the other hand, soil alkalinisation, especially common in agricultural fields through liming activities, can enhance the volatilisation of ammonia, so the application of ammonium-based fertilisers at the same time as lime is not recommended (Adams, 1986).

4.3 Soil carbon change (in mineral soils, organic soils and inorganic carbon)

Soil hosts the largest carbon pool in the terrestrial ecosystem, playing an essential role in the global carbon cycle and the regulation of climate change. Soil carbon is solid carbon stored in soils, existing in organic and inorganic forms. An important distinction between these two forms is that inorganic carbon has a much higher potential for permanence in soils than organic carbon. Soils are characterised as mineral or organic based on their organic matter content.

Mineral soils form most of the world's cultivated land and may contain a trace of or up to 20 % organic matter. Organic soils are naturally rich in organic matter, principally due to vegetation and climate, and are distinguished from mineral soils by meeting specific criteria outlined in the IPCC guidelines for national GHG inventories (Drösler *et al.*, 2014) and Food and Agriculture Organization (FAO) guidelines (FAO, 2006). These criteria include a thick organic horizon, a high organic carbon content, and the possibility of water saturation episodes.

4.3.1 Mineral soils

The SOC content of mineral soils varies across Europe, with the highest levels in woodlands. Croplands exhibit the lowest SOC content, posing challenges to achieving EU climate targets due to ongoing carbon loss. Land use changes, includingthe conversion of grasslands to croplands, have a significant impact on SOC stocks, highlighting the need for sustainable land management practices. Climate change and land use change are major drivers of SOC change, influencing soil fertility, water dynamics, GHG emissions, biodiversity and resilience to climate change. Mitigating SOC loss is essential for maintaining soil health, agricultural productivity, and ecosystem stability, highlighting the importance of implementing strategies to enhance soil carbon sequestration and minimise soil degradation.

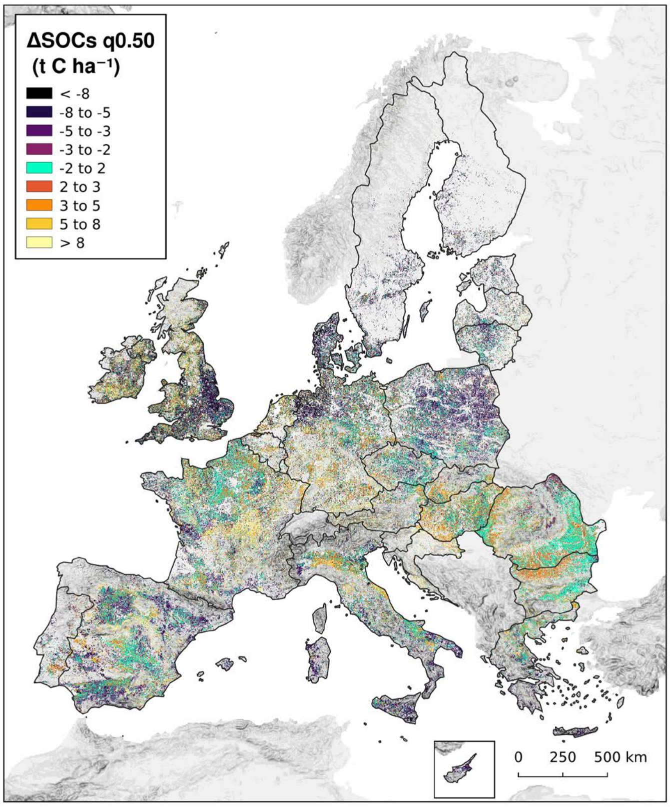
4.3.1.1 Status and trends

Europe exhibits considerable spatial variability in soil types, climates and land uses, leading to diverse patterns in SOC content across regions. Based on the soil measurements from LUCAS, SOC content increases from south-eastern to north-western climatic zones (Fernandez-Ugalde *et al.*, 2022). The highest SOC levels (EU mean = 318 g kg^{-1}) are found in the wetlands of the boreal and Atlantic zones (peatlands). SOC content is also high in woodlands (EU mean = 88 g kg^{-1}), especially in north-western climatic zones (boreal, Atlantic, suboceanic and northern subcontinental). The mean SOC content of grasslands is 40 g kg^{-1}, rising slightly to 55 g kg^{-1} in shrubland. Organic carbon content is the lowest in croplands (EU mean = 18.3 g kg^{-1}) and, unsurprisingly, in bare land (EU mean = 17.3 g kg^{-1}).

Overall, soils are losing carbon as CO_2 (EEA, 2022a), which could hamper the achievement of EU climate targets. SOC changes in agricultural soils across the EU and the United Kingdom from 2009 to 2018 have been comprehensively assessed, showing varied impacts depending on land use and management practices (De Rosa *et al.*, 2023). The total SOC loss from croplands is moderate, representing 0.75 % of their initial stocks and amounting to 70 Mt of carbon from the initial 9.3 Gt of carbon within the first 20 cm of soil. Spatial analysis reveals different changes in SOC across the continent (Figure 6). The median change in SOC content indicates an average decrease of 0.4 t C ha^{-1} for the EU and the United Kingdom combined, with some countries, such as Austria and Slovenia, experiencing increases of up to 3 t C ha^{-1}. The most significant losses, up to – 4.9 t C ha^{-1}, occur in the higher latitudes of northern Europe, where a lower soil clay content correlates with decreased carbon retention capacity.

In contrast, central European regions mostly maintained stable SOC levels over the period studied. The Mediterranean area, characterised by warmer temperatures and less rainfall, showed a broader range of change, from –5 t C ha^{-1} to 1.5 t C ha^{-1}, with the initial SOC levels also being the lowest in the EU. Notably, grasslands in this region played a beneficial role in carbon sequestration, with continuous grassland or conversion from cropland contributing to an increase in SOC. Conversely,

Figure 6. Spatial distribution of the median change in SOC content (ΔSOCs q0.50) at 0–20 cm soil depth, 2009–2018



Source: EUSO, based on De Rosa et al. (2023).

continuous cropland had a net negative impact on SOC levels, attributed to practices such as monoculture and tillage. In addition, soils with a high initial SOC content tended to lose more carbon than soils with lower initial SOC contents.

Overall, SOC trends observed using soil data from LUCAS is approximately confirmed by observations from several national soil monitoring networks (Heikkinen *et al.*, 2013). However, Swedish cropland soils constitute an exception: their SOC content has increased in most parts of the country due to a steadily increasing proportion of ley in rotations (Bellamy *et al.*, 2005; Poeplau and Don, 2015; Knotters *et al.*, 2022).

In the United Kingdom, some studies suggest that there has been a decrease in SOC (which could be linked to changes in the climate (Thomas *et al.*, 2020)), especially in agricultural soils in England and Wales (Bellamy *et al.*, 2005); however, this finding was challenged by a subsequent study (Smith *et al.*, 2007).

Twenty-five years of SOC observations in Swiss croplands show stability overall but some divergent trends (Gubler *et al.*, 2019). The Norwegian Ministry of Agriculture and Food is funding the national programme for monitoring SOC in forests and intensive grasslands. Soil sampling started in July 2023, and these samples will provide information about the levels of, and eventually changes in, soil carbon stores in Norwegian forests and grasslands.

In the western Balkans, it is estimated that the area of land affected by low and declining management in the western Balkans, the loss of SOC is evident in most agricultural soils (Vidojevic *et al.*, 2022). Albanian soils have a relatively low SOC content (≤ 2 %) (Ministry of Tourism and Environment, 2019). Certain research in Bosnia and Herzegovina shows that the SOC content is mostly at a moderate level (3–4 %). SOC content in Kosovo ranges from 0.02 % to 2.79 %, depending on soil type, soil depth, land use, slope, soil cover, etc. There are no data for Montenegro on SOC change. An analysis conducted on many soil samples to monitor the fertility of agricultural land in Serbia shows that most samples had an organic carbon content of between 1 % and 2 %. A major cause of the degradation of agricultural land in the Serbia is a loss of organic matter due to intensive agricultural production, intensive tillage, a lack of organic fertilisation, irrigation, the removal of crop residues or their burning and other SOC stocks is less than 5 % of the total land area and about 10 % of agricultural land (Zdruli *et al.*, 2022). According to a report discussing the state of the art of soil unsuitable cultivation practices.

The soil organic (or total) carbon content is not determined as part of the monitoring and surveying of Ukrainian agricultural land, but the humus content (%) is measured. The weighted average humus content in soils decreased from 3.16 % in the 2015 survey round to 3.07 % in the 2020 round. According to survey results, the lowest humus content was observed in the Polissya zone (2.43 %), while in the forest of the steppe zone it was 3.2 % and in the steppe zone overall it was 3.31 % (Institute of Soil Protection of Ukraine, 2023).

The most recent SOC data for Türkiye, published in 2018 (ÇEM, 2018), indicate that the average SOC content was 47.04 t ha^{-1}. Most carbon reservoirs are located in forests, followed by pastures, which are mostly degraded. After bare and artificial areas, cultivated land has the lowest SOC content. According to FAO's land degradation neutrality decision support system, the SOC content in Türkiye is projected to decline by 2040.

However, the system has reported that SOC levels in agricultural soils are rising due to the increasing use of organic fertilisers and the expansion of drip-irrigated agriculture, compared with the period when re-irrigation practices were intensively used.

4.3.1.2 Drivers

Numerous experiments have investigated the impact of drivers of SOC change, and the findings are being consolidated in an increasing number of meta-analyses (Xu *et al.*, 2020; Beillouin *et al.*, 2023). The main drivers include the following.

- Climate change. Soils will release more carbon into the atmosphere under future warmer climatic conditions (i.e. resulting in positive feedback loops of soil carbon loss causing climate warming) (Wang *et al.*, 2022; Lugato, 2024). The impact of climate change is not solely confined to direct effects; rather, indirect consequences such as wildfires and changes in snow cover may have a more substantial influence on SOC. With a notable increase in the occurrence of forest fires in Europe, as evidenced by the alarming statistic that 2022 was the second worst year on record in the EU in terms of area burned by wildfires (San-Miguel-Ayanz *et al.*, 2023), it becomes imperative not to underestimate the indirect effects of climate change. While phenomena such as flooding, drought and alterations in snow cover have received limited attention in existing meta-analyses (Koven *et al.*, 2017) there is a noticeable absence of synthesised results on indirect effects (Beillouin *et al.*, 2023). Further investigations are needed to enhance our understanding of the individual and collective impacts of climate change on SOC, particularly across diverse land use types and varying climatic conditions (Beillouin *et al.*, 2023).

- Land use change. The overall effects of land use change and land management on SOC are 7–10 times larger than the direct effects of climate change (Beillouin *et al.*, 2023). Reducing the conversion of grassland to cropland could provide significant climate change mitigation by retaining soil carbon stocks that may otherwise be lost (De Rosa *et al.*, 2023). Conversion of grasslands to croplands typically results in a loss of approximately 36 % of SOC stocks within a 20-year period (Poeplau *et al.*, 2011). Preventing this conversion is crucial for averting soil carbon losses. However, it is essential to acknowledge that the conversion of grassland to cropland often occurs in response to food security challenges. This poses a dilemma, as food security could be compromised, given that more land is required to produce human food from livestock on grasslands than crops on croplands (Lal, 2001; de Ruiter *et al.*, 2017; Clark and Tilman, 2017; Poore and Nemecek, 2018; De Rosa *et al.*, 2023). Future changes in land use and climate have broader implications for land degradation, including effects on vegetation, fire and coastal erosion (IPBES, 2018; IPCC, 2019; Smith *et al.*, 2019). For instance, by 2080, extreme climate change could lead to carbon losses from mineral topsoil in the order of 2.5 ± 1.2 Pg in the EU and the United Kingdom (Lugato *et al.*, 2021).

- Soil erosion. Due to on-site soil losses and off-site sediment transfer and deposition, soil erosion has multiple environmental impacts, with significant negative effects over time (Panagos *et al.*, 2018a; Borrelli *et al.*, 2023). This has implications for biogeochemical processes such as SOC cycling, by increasing CO_2 emissions through enhancing mineralisation and decreasing carbon sinks and sediment burial (Lugato *et al.*, 2016; Borrelli *et al.*, 2017; Panagos *et al.*, 2018a).

4.3.1.3 Impacts

Soil carbon losses have significant and multicausal impacts on the environment, agricultural productivity and overall ecosystem health in Europe. Some of the main impacts include the following.

- Reduced soil fertility. SOC is a key component of organic matter, which provides essential nutrients. Its decline can therefore affect nutrient availability for plant growth. Declining soil fertility can lead to decreased crop yields, reduced agricultural productivity and affecting overall forest health, in particular when organic matter declines below 2 %. There is some evidence that crop yields and yield stability enhance with increasing organic matter content, though some studies show equivocal impacts (Lal, 2006).

- Impaired water retention and drainage. SOC plays a crucial role in regulating soil water dynamics. The loss of carbon can reduce the infiltration and water retention capacity of soils, making them more prone to waterlogging or, conversely, decreasing water availability during dry periods. This can reduce the efficiency of water use by crops, increase the risk of soil erosion and affect the overall functioning of the forest ecosystem (Niu *et al.*, 2008; Schindlbacher *et al.*, 2012).

- Increased GHG emissions. Soil carbon losses contribute to the increased emission of GHGs, particularly CO_2. When organic matter decomposes, carbon is released into the atmosphere. This process not only reduces soil carbon stocks but also contributes to climate change, exacerbating global warming (Bispo *et al.*, 2017; Lugato *et al.*, 2021; Le Noë *et al.*, 2023).

- Loss of biodiversity. Soil organic matter is a habitat and food source for various microorganisms, fungi and fauna. A decrease in soil carbon can lead to a loss of biodiversity inthe soil ecosystem, affecting soil functions and services. This can have cascading effects on the entire ecosystem, including above-ground plant communities (Geisen *et al.*, 2019).

- Soil erosion. Soil carbon loss is often associated with soil erosion, as it weakens the soils' structural stability and reduces infiltration rates, and thereby soils' ability to resist erosion. Erosion leads to the removal of topsoil, which is rich in organic matter. This, in turn, exacerbates the loss of soil fertility and hinders sustainable agricultural practices (Pimentel, 2006; Borrelli *et al.*, 2017).

- Increased vulnerability to climate change. Agricultural soils with lower organic carbon content are generally more vulnerable to the impacts of climate change, such as extreme weather events, droughts and temperature fluctuations, than those with higher carbon contents. Increasing SOC levels can enhance soil's resilience to these climate stressors (Wang *et al.*, 2023).

4.3.2 Organic soils

European peatlands are facing significant degradation due to agriculture, drainage and peat extraction, leading to significant carbon loss, biodiversity decline and environmental damage. New land use change policies under the common agricultural policy (CAP) reform aim to reduce drainage and implement the rewetting of drained peat soils. The EU Regulation on Nature Restoration, aims to restore degraded peatlands to achieve climate and biodiversity objectives and enhance food security. Restoring drained peatlands is identified as one of the most cost-effective ways to reduce greenhouse gas emissions in the agricultural sector.

4.3.2.1 Status and trends

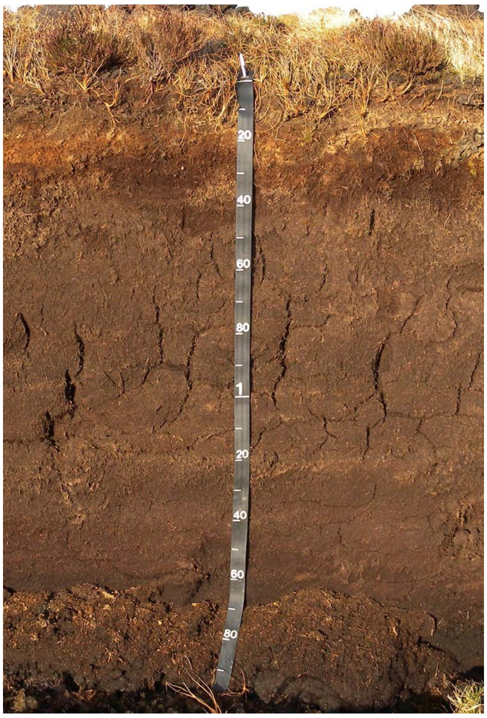
Peatlands are unique ecosystems that store significant amounts of carbon. In Europe, peatlands store approximately five times more carbon than forests (Limpens *et al.*, 2008) and about half of Europe's total SOC. The corresponding organic soils, also known as Histosols, are important SOC stores.

Organic soils store much more carbon per unit area than mineral soils. The amount could be more than 10 times the carbon stored in mineral soils, depending on peat thickness. As acidic and waterlogged conditions restrict decomposition (low temperature can also be a factor), peatlands hold more carbon per hectare on average than all other ecosystems, making them the largest carbon stock of the entire terrestrial biosphere (Temmink *et al.*, 2022).

A map of peatlands in Europe (Tanneberger *et al.*, 2017) reveals a strong northern bias in the distribution of organic soils across Europe, generally reflecting climatic conditions. Peatlands cover a large portion of the land area in the Nordic countries. Almost one third of European peatland is in Finland, and more than a quarter is in Sweden. The remainder is in Iceland, Poland, the United Kingdom, Norway, Germany, Ireland, Estonia, Latvia, the Netherlands and France. Small areas of peat and peat-topped soils occur in Lithuania, Hungary, Denmark, Czechia, Belgium, Italy, Austria and Spain (Kløve *et al.*, 2017; Tanneberger *et al.*, 2022).

Data from peatlands, particularly heavily degraded ones, are relatively limited (Evans *et al.*, 2022). Measuring the depth of the organic horizon helps quantify the amount of carbon stored in the soil, which is essential for understanding the role of peatlands in climate regulation and carbon sequestration (Beaulne *et al.*, 2021). The depth of the organic horizon was measured at 1 050 sites as part of the soil data collected in the 2018 LUCAS soil module (Fernandez-Ugalde *et al.*, 2022), with 30 % recording a depth of 40 cm or more. However, most of the sites selected for depth assessments appear not to fulfil the depth criteria for Histosols. The assessment failed to analyse the very shallow organic soils, such as those found on bedrock. The implication could be either that many of these locations are mineral soils with well-developed organic horizons, or that peatlands have been eroded back to the underlying mineral base (Fernandez-Ugalde *et al.*, 2022).

Photo 4. Peat profile.



Source: A. Jones.

Monitoring changes in the depth of the organic horizon over time can help assess the extent of peatland degradation due to factors such as drainage, land use change and climate change. Germany has initiated a peatland monitoring programme (implemented from October 2020 to May 2025) utilising a standardised approach aimed at the long-term investigation of site-specific and land-use-related influences on peatland development. The programme aims to fulfil existing reporting obligations concerning peatlands, containing peat and other organic soils, within the land use, land use change and forestry sectors and the agricultural sector. It seeks to achieve this by providing measurements and enhancing methods for regionalising the primary factors determining emissions.

European peatlands are facing significant degradation. Some 48 % are already degraded (excluding European Russia), primarily due to agriculture, drainage and peat extraction, leading to significant carbon loss, biodiversity decline and environmental damage. Within the EU, the proportion is 50 % (120 000 km^2) (Tanneberger *et al.*, 2021a). The EUSO Soil Degradation Dashboard shows EU peatlands that are likely to be degraded due to agriculture-related pressures (2 % of the total area of the EU) based on the United Nations Environment Programme's Global Peatlands Assessment , whose data are retrieved from the Global Peatland Database compiled by the Greifswald Mire Centre.

In Europe, the degree of peatland degradation clearly increases from Arctic to temperate regions. In central Europe, more than 90 % of all peatlands have been utilised for agriculture, forestry or peat extraction for centuries (Joosten, 2010).

Drained peatlands in the EU emit around 220 Mt-CO_2eq per year (around 5 % of EU emissions), mainly from agriculture on drained peat soils. This land makes up only 2.5 % of the total agricultural area but generates around 25 % of the total agricultural GHG emissions in the EU (including CH_4 from enteric fermentation and N_2O from fertilisation). The contribution is even larger in peatland-rich countries such as Finland (62 %), Poland (42 %) and Germany (37 %), based on national inventory reports data for 2019 (Tanneberger *et al.*, 2021b). In 2019, Member States reported a loss of carbon from 17.8 million hectares of land with organic soil (4.2 % of the total land area), corresponding to emissions of 108 Mt CO_2 (EEA, 2022a).

Ukrainian peat soils are situated in the southernmost region of eastern Europe's peat soil expanse. Shaped by warmer climates, they boast an age surpassing their northern counterparts. These soils previously achieved an equilibrium, including a carbon balance, under natural conditions (Truskavetskii, 2014). However, human intervention has disrupted this equilibrium, resulting in a negative carbon balance. Various researchers (Bradis *et al.*, 1973; Tanovitskii, 1980; Succow and Jeschke, 1986; Bambalov and Rakovich, 2005; Truskavetskii, 2014) highlight the disappearance of valuable flora and fauna, a reduction in biodiversity, and a trend towards the desertification of areas adjacent to extensive peatlands.

4.3.2.2 Drivers

The main factors driving peat loss are intricately connected, each influencing and exacerbating the effects of the others. These vary depending on the type of peatlands involved. Certain threats are more relevant to specific peatland types; for example, arable agriculture poses a particular risk to lowland peat.

- Land use change. The impact of humans on northern peatlands dates back centuries, to well before the industrial revolution (Holden *et al.*, 2004). Since then, there has been evidence of changes stemming from agricultural cultivation, the expansion of grazing pastures, forestry activities and the extraction of peat for fuel. The population growth from the 1700s to the 1900s increased the need for more arable land. In the early 1800s, the pressure for land resulted in its reclamation for agriculture or other uses, which continued with many large drainage projects at the end of the century (Kløve *et al.*, 2017). In Finland, a lack of coherence in forest, agricultural and environmental policies has led to increased drainage activity on peat soils since the beginning of the 20th century, which is linked to targets of increasing farm size and productivity and to developments in the CAP. The area of cultivated peat soils has grown, although fields cleared since 2004 have not been eligible for area- based subsidies (Regina *et al.*, 2016).

- Drainage. Drainage is the key driver of the degradation of peat soils (Swindles *et al.*, 2019). In the Nordic countries, between 3 % and 40 % of the original peatland area has been drained for agricultural purposes (Kløve *et al.*, 2017; Szajdak *et al.*, 2020). In countries such as Denmark, Germany, the Netherlands, Poland and Ireland, more than 80 % of peatlands have been drained for these reasons (Tanneberger *et al.*, 2021a). Agricultural uses vary from extensive pastures to intensive cultivation, for example vegetable production in Switzerland and the United Kingdom; the growth of maize for fodder and biogas generation in Germany; and dairy farming on grassland in the Netherlands.

- Peat extraction. Peat extraction for horticultural and energy purposes directly removes carbon-rich peat from organic soils, leading to the irreversible loss of soil carbon. Peatlands have always been important for farmers as a source of fuel (Runefeldt, 2010). Peat extraction for electricity production and heating continues in a small number of northern European countries, while the mining of peat to provide growing media (e.g. potting composts sold globally) occurs mainly in Ireland and some Baltic states (Girkin *et al.*, 2023).

- Climate change. Climate-driven drying of European peatlands is likely to have been exacerbated by direct human impacts in recent centuries (Swindles *et al.*, 2019). During a period of significant population growth throughout Europe (McEvedy and Jones, 1978), coupled with the expansion of cropland and intensified land use (Ramankutty and Foley, 1999), hydrological shifts took place. Distinguishing between the impacts of climate change and direct human influences becomes challenging, as these factors overlap and interact with each other.

- Fire. Wildfires on peatlands are becoming a common phenomenon during summer throughout Europe, because dry peat is a fossil fuel. When peatlands are drained, prolonged droughts turn peat into highly combustible matter that can easily be ignited through carelessness. Increased wildfire frequency and severity are expected to increase carbon loss from peatlands, contributing to a shift from carbon sink to carbon source (Nelson *et al.*, 2021). Changes to the structure of vegetation can increase the amount of wildland fire fuels available and can alter the hydrological connectivity of the landscape (Thompson *et al.*, 2019), thereby increasing fire risk and post-fire burn severity (Wilkinson *et al.*, 2018).

4.3.2.3 Impacts

Loss of soil carbon from organic soils, particularly in peatlands, in Europe can have profound impacts on the environment, ecosystems and society. Peatlands provide a wide range of ecosystem services, including carbon sequestration, water regulation, biodiversity conservation and recreational opportunities. Loss of soil carbon in peatlands diminishes their capacity to provide these services, compromising their ecological and socioeconomic value to society (Fluet-Chouinard *et al.*, 2023).

- Climate change. Loss of carbon through drainage, degradation and fires accelerates climate change in a positive feedback loop. Changes in temperature and precipitation patterns associated with climate change can alter soil carbon dynamics. Warmer temperatures can enhance heterotrophic activity and accelerate decomposition rates (Briones *et al.*, 2022), while changes in precipitation patterns can influence soil moisture levels, affecting decomposition rates and carbon storage. Drainage of wetlands and peatlands for agriculture, forestry or development purposes accelerates decomposition of organic matter by increasing oxygen availability. This process enhances biological activity, leading to increased decomposition rates and loss of soil carbon (Ma, Zhu *et al.*, 2022). Without rewetting, drained peatlands will continue to lose SOC and climate change will induce further peat loss from undrained peatlands (Tanneberger *et al.*, 2022).

- Biodiversity loss. Peatlands are unique ecosystems that support a rich diversity of plant and animal species, many of which are specially adapted to these environments. The loss of carbon from soil in peatlands can disrupt these ecosystems, leading to the loss of habitat and decreased biodiversity. Rare and specialised species, such as bog mosses, are particularly vulnerable to habitat degradation. Indeed, many European peatlands have already undergone shifts in vegetation composition over the last 300 years, including changes in Sphagnum communities (Gałka *et al.*, 2015), andincreases in grass, sedge (Gogo *et al.*, 2011) and shrub (e.g. Calluna vulgaris) cover (Turner *et al.*, 2014) . Typical peatland biodiversity, in particular that of groundwater-fed fens in temperate Europe, has been devastated by drainage (Hans *et al.*, 2017; van Diggelen, 2018).

- Reduced water quality. Peatlands play a crucial role in regulating water flow, filtering pollutants and maintaining water quality (Holden *et al.*, 2004; Millennium Ecosystem Assessment, 2005; Zedler and Kercher, 2005). The loss of carbon from soil in peatlands can degrade water quality by increasing sedimentation, nutrient run-off and contamination from agricultural chemicals (Clutterbuck and Yallop, 2010). Drained peatlands with agricultural uses in the EU are also a source of 1–5 Mt of NO_3 annually (Tanneberger *et al.*, 2021b). This can harm aquatic ecosystems, reduce water quality for human consumption and increase treatment costs for water utilities. Further negative consequences of drainage are a reduction in water quality through the discharge of nutrients to ground and surface water (Tanneberger *et al.*, 2021b), and increasing water acidity in the case of sulphide-bearing peat drainage (Saarinen *et al.*, 2013).

- Increased flooding and erosion. Peatlands act as natural sponges, absorbing and storing water during periods of heavy rainfall and releasing it slowly over time. Loss of carbon from soil in peatlands reduces their ability to retain water, increasing the risk of flooding and soil erosion. This can lead to damage to infrastructure, the loss of arable land and the degradation of aquatic habitats (Lieffers and Macdonald, 1990; Cleary *et al.*, 2005; Rooney *et al.*, 2012; Nieminen *et al.*, 2018).

- Cultural and archaeological losses. Peatlands contain valuable cultural and archaeological sites, including ancient human settlements, artefacts and well-preserved organic materials. The loss of carbon from soil due to drainage, degradation and extraction activities can damage or destroy these sites, resulting in the loss of important cultural heritage and historical information (Bain Bonn *et al.*, 2011; Flint and Jennings, 2020; Historic England, 2021).

- Economic costs. The impacts of peatland degradation and loss of carbon from soil impose significant economic costs on societies. These costs include the loss of ecosystem services, increased flood damage, reduced agricultural productivity and expenditure on restoration and conservation efforts. Drainage of peatlands also leads to land subsidence (1–2 cm yearly), which increases drainage costs and flooding risk, and results in the loss of productive land (Joosten *et al.*, 2012; Bonn *et al.*, 2016) and damage to infrastructure.

New land use change policies under the CAP reform aim to reduce drainage and the implement of rewetting of drained peat soils (Anon, 2020). Restoration also offers potential gains with respect to water quality, flood management, habitats and biodiversity, the protection of buried paleo-archaeological features and recreational enjoyment (Moxey and Moran, 2014). The EU Regulation on Nature Restoration (EU, 2024) aims to enable the restoration of degraded ecosystems, helping to achieve the EU's climate and biodiversity objectives and enhance food security. As restoring drained peatlands is one of the most cost-effective ways to reduce emissions in the agricultural sector, EU countries must restore at least 30 % of drained peatlands by 2030 (at least a quarter should be rewetted), 40 % by 2040 and 50 % by 2050 (when at least one third should be rewetted). However, rewetting will remain voluntary for farmers and private landowners. Successful peatland restoration in Europe requires knowledge transfer among academics, practitioners and policymakers (Zak and McInnes, 2022).

4.3.3 Inorganic carbon

The distribution of Soil Inorganic Carbon (SIC) in Europe varies geographically, concentrating in areas with Mediterranean climates and calcareous parent materials. Human activities such as fertilization, irrigation, management of soil organic matter, and reclamation practices impact SIC levels. Loss of SIC can have wide-ranging impacts, including reduced carbon sequestration capacity, soil fertility decline, land degradation, desertification, changes in water resources, and biodiversity loss. Research on SIC dynamics is essential to develop management strategies for carbon sequestration and soil condition improvement, in particular in the areas with Mediterranean climates.

4.3.3.1 Status and trends

SIC distribution in Europe varies geographically, concentrating in regions with Mediterranean climates and calcareous parent materials. Consequently, large areas of southern Europe, particularly those with Mediterranean climates, are characterised by carbonate-rich soils with pH values exceeding 7.5. Other areas located on calcareous lithology also show relevant concentrations in the soil profile in humid and subhumid temperate areas, such as the French regions of Champagne and Charente. Recent research (Lu *et al.*, 2023) has compiled the data from LUCAS 2015 regarding SIC concentrations in European topsoils, presenting them in digital maps. There is high variability in the values observed, ranging from 0 g kg^{-1} to more than 300 g kg^{-1}. No information is available on the trends in SIC concentration or storage in European soils, although data from the more recent rounds of LUCAS could be used to estimate such changes.

4.3.3.2 Drivers

The most relevant natural factors contributing to SIC concentration are soil parent material and climate. However, some other factors, such as position in the landscape and even vegetation can also play a role in the final allocation and typology of soil carbonates. As a result, SIC can be present in soils in varying amounts, vertical distribution in the profile, size distribution and pedofeatures (infillings, coatings, pendants, etc.). Carbonates can also be present as cementing agents, forming petrocalcic horizons. In addition, SIC is known to be affected by different factors in soil management. The most relevant ones are as follows.

- Fertilisation. Mostly as a source of acidity, mineral fertilisation with N salts can induce the dissolution and progressive loss of soil carbonates, while releasing CO_2 (Zamanian *et al.*, 2016). Fertilisation can also result in changes in the proportion of pedogenic compared with lithogenic carbonates (Bughio *et al.*, 2016).

- Irrigation. By changing the soil water regime, affecting primary productivity and biological activity, and acting as a source of calcium and/or bicarbonate, irrigation interferes with many aspects of SIC cycling. In addition, the partial pressure of CO_2 in soil solution is affected by irrigation, which influences bicarbonate leaching (Greenway *et al.*, 2006). Thus, irrigation has been observed to increase the emission of CO_2 from soils (Hannam *et al.*, 2016), and to reduce the amount of carbonates in the silt and clay fractions, while increasing the proportion of pedogenic carbonates (de Soto *et al.*, 2017).

- Management of soil organic matter. Some forms of organic matter added to agricultural soils can be sources of acidity, and therefore enhance natural acidification processes (Raza *et al.*, 2021). However, organic fertilisation has also been observed to induce carbonate neoformation in some soils (Liu *et al.*, 2023).

- Reclamation of sodic calcareous soils. The use of gypsum for reclamation of this type of soil can result in the formation of calcium carbonate, while the use of S to dissolve carbonates in sodic soils can result in the loss of carbonates by acidification (Virto *et al.*, 2022).

4.3.3.3 Impacts

- Carbon sequestration. The retention of SIC helps maintain the soil's capacity to sequester carbon, potentially mitigating increases in atmospheric CO_2 levels and alleviating the effects of global warming. In addition, because of the role of SIC in organic matter stabilisation, changes in SIC concentration, typology and physical distribution in soils can have consequences for SOC storage and protection in agricultural soils (Raza *et al.*, 2021). Fertiliser-induced soil acidity and leaching loss in agricultural ecosystems may cause irreversible changes in soil carbon (e.g. organic and inorganic) levels, and SIC stocks could be lost entirely as CO_2 (Zamanian *et al.*, 2018; Zamanian and Kuzyakov, 2019).

- Climate change. SIC levels can change with the climate, and the consequences are crucial for crop production, soil quality and land management practices (Lal, 2004, 2011; Rasmussen, 2006; Banger *et al.*, 2009; Bughio *et al.*, 2016; Gao *et al.*, 2017). However, the acknowledgement of changes in SIC in response to changes in temperature and CO_2 concentrations, and the corresponding influence on soil characteristics and SOC, are minimal (Ferdush and Paul, 2021).

- Soil fertility decline. Inorganic carbon contributes to soil pH regulation and nutrient availability. The loss of SIC can lead to soil acidification, or have the opposite effect, which can reduce soil fertility by reducing the availability of essential nutrients such as calcium and magnesium. This can impair plant growth and productivity, ultimately reducing agricultural yields (Ferdush and Paul, 2021). Furthermore, the pH range of calcareous soils (7.5–8.5) limits the availability of some other nutrients, for example iron and P, although various crop and fertilisation strategies can be used to counteract these effects (Ahmad *et al.*, 2022; Ahmadi *et al.*, 2023).

- Land degradation and desertification. SIC can act as a substantial carbon reservoir in dryland soils, especially those derived from sedimentary parent material (Deane McKenna *et al.*, 2022). Continued loss of SIC can contribute to land degradation processes such as desertification, particularly in arid and semi-arid regions. Given the overall increase in aridity in a warming world, drought may exacerbate loss of SIC from dryland soil under warming conditions (Li *et al.*, 2024). The dissolution of SIC is more important than previously thought in regulating atmospheric CO_2 concentrations (Zamanian and Kuzyakov, 2019), and if future climate change accelerates aridity in drylands (Dai, 2013), the contribution of SIC-derived CO_2 to total CO_2 emissions may become even more substantial (Li *et al.*, 2024).

- Impacts on water resources. SIC loss can affect soil water dynamics, leading to changes in groundwater (Kim *et al.*, 2020). From a wider geographical perspective, changes in SIC associated with increased fertilisation can also result in changes in riverine alkalinity at the watershed level (Perrin *et al.*, 2008).

- Biodiversity loss. As plants and soil organism distribution is known to be pH-dependent (Lauber *et al.*, 2009; Rousk *et al.*, 2010), changes in soil properties due to the loss of SIC can impact microbial communities, fauna and plant species composition in soil. This could disrupt ecosystem functioning and reduce habitats' suitability for various organisms, leading to biodiversity loss and ecological imbalances. Research on the dynamics of carbonates in soils is still much below the level that will allow practitioners to implement strategies to manage CO_2 sequestration as SIC. Some of the possible research paths are using non-acidifying fertilisers on calcareous soils, developing practices other than liming to combat acidification and to use calcifying or oxalogenic plants (Hirt *et al.*, 2023) or soil organisms using calcium from sources other than carbonates, such as gypsum (Laudicina *et al.*, 2021).

4.4 Soil erosion

Soil erosion poses a significant threat to soil health and agricultural sustainability in Europe. Water erosion is particularly prevalent, affecting 24 % of EU land at unsustainable rates, surpassing soil formation rates and impacting soil quality and land productivity. Projections of future trends in soil erosion in Europe are emerging, as the increase in rainfall erosivity may lead to an increase of up to 25 % in soil loss. Soil erosion in Europe, driven by factors such as poor land management, deforestation, climate change and wildfires, poses significant threats. It leads to loss of soil fertility and agricultural productivity, while also causing sedimentation, flooding and landslides, affecting water quality and causing economic losses. Loss of soil fertility, sedimentation and agricultural production losses are among the most obvious impacts of soil erosion, but other off-site impacts such as risks to cultural heritage sites, land abandonment, desertification and biodiversity loss should not be neglected. Addressing soil erosion necessitates holistic approaches integrating policy interventions and sustainable land management practices tailored to regional conditions.

Erosion is considered one of the most significant threats to European soils and the ecosystem services they provide. It threatens all major functions of soils, leading to a decline in land productivity and multiple off-site effects (Lal, 1998; Patault *et al.*, 2021; Panagos *et al.*, 2024a). More specifically, soil erosion reduces the fertility of soil, alters its structure, changes its biological activity and reduces its water holding capacity. In addition, it causes nutrient loss to water, and can reduce SOC pools (Quinton and Fiener, 2024). The spatially distributed and ephemeral nature of erosion makes its prediction and monitoring challenging, hindering proper risk assessment and policy mitigation. Worldwide, very few national survey programmes for soil erosion exist. Notable exceptions are the United States National Resources Inventory and the Chinese national general survey programme on soil and water conservation. No coordinated monitoring efforts exist across the EU. While recent modelling has been transformative in informing policy, it has been restricted to single processes, whereas often several natural and anthropogenic erosion processes operate in the same area simultaneously or subsequently (Poesen, 2018; Borrelli *et al.*, 2023).

The processes of soil erosion include water erosion through sheet, rill, gully and piping erosion; wind erosion; tillage erosion; and soil loss due to crop harvesting (SLCH). The co- occurrence or exclusivity of these different erosion processes determine the total risk from soil erosion (Borrelli *et al.*, 2023). Given the wide diversity of landscapes in Europe, the occurrence of all aforementioned erosion processes has been documented in various European countries (Boardman and Poesen, 2006). Erosion processes are notoriously ephemeral, as they depend on the nexus of susceptible soil, mechanical disturbance, antecedent moisture conditions, land use and weather conditions (especially the occurrence of meteorological extremes, such as intense rainfall events, snow and frost or the coincidence of droughts with wind).

4.4.1 Status and trends

Soil erosion by water is one of the most prominent soil degradation processes in the EU, with an estimated 24 % of land exhibiting unsustainable erosion rates (> 2 t ha^{-1} yr^{-1}) (Panagos *et al.*, 2015a). It is important to note that this rate only considers the loss of topsoil through sheet and rill erosion and does not include other water- related processes such as gully or piping erosion or landslides, which cause soil loss at lower depths. Nevertheless, this value exceeds estimated average soil formation rates (Panagos *et al.*, 2020). These rates vary quite significantly, with some studies reporting 0.05–0.5 mm yr^{-1} (1–1.4 t ha^{-1} yr^{-1}) (Verheijen *et al.*, 2009). To give spatially continuous estimations of soil erosion by water in Europe in 2000, 2010 and 2016, a modified (hybrid) version of the revised universal soil loss equation (RUSLE) was applied (Panagos *et al.*, 2020). The mean soil loss by water erosion in the EU was estimated to be around 2.4 t ha^{-1} yr^{-1}. This value is well above the aforementioned soil formation rates, and there is high variability between rates for different land uses. An area twice the size of Belgium is estimated to experience a 1 cm yearly displacement of soil throughout the EU and the United Kingdom. A major benefit of the approach adopted compared with past models implemented is that it incorporates the effects of policy scenarios based on land use changes and support (Panagos *et al.*, 2015a, 2015b; Borrelli and Panagos, 2020). These inputs to the model are linked to the Good Agricultural and Environmental Conditions requirements of the CAP and the EU's guidelines for soil protection, which can be grouped into the areas of land management (with methods including reduced/no-till farming, and the use of plant residues and cover crops), enhanced conditionality (through crop rotation and the designation of ecological focus areas) and supporting practices (contour farming, the maintenance of stone walls and the use of grass margins).

Wind erosion primarily occurs in dry conditions when the soil is exposed to strong winds. The finest particles, in particular, are removed and potentially transported over long distances before being redeposited (Webb *et al.*, 2006). To gain a better understanding of the wind erosion situation in Europe, the European Commission's Joint Research Centre (JRC) carried out the first assessment of land susceptibility to wind erosion in the EU (Borrelli *et al.*, 2014, 2016) using the revised wind erosion equation (Fryrear *et al.*, 2000).

The results of the application of the equation suggest that wind erosion in croplands may have a mean rate of 0.53 t ha^{-1} yr^{-1}, with the second and fourth quantiles placed at 0.3 t ha^{-1} yr^{-1} and 1.9 t ha^{-1} yr^{-1}, respectively (Borrelli *et al.*, 2017b).

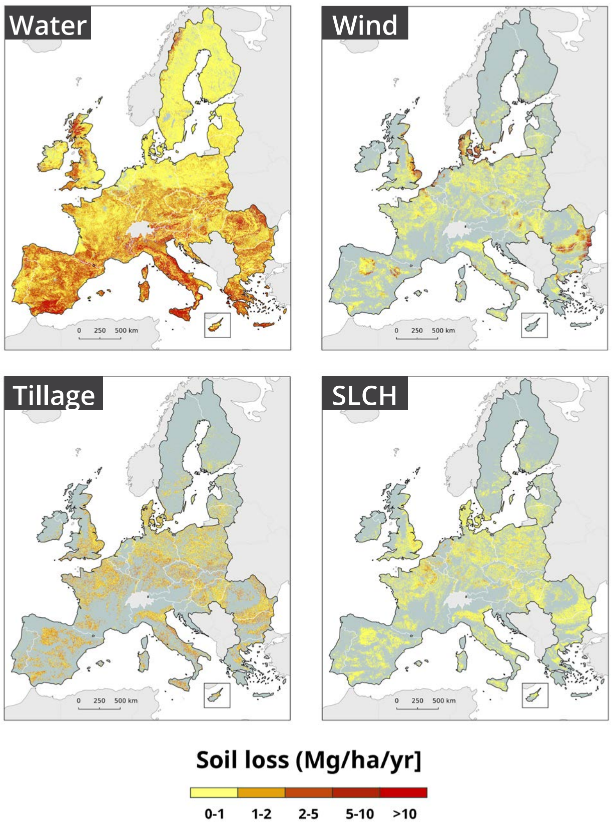
Tillage erosion occurs in cultivated fields through the net downhill movement of soil due to tillage operations (Lindstrom *et al.*, 1992). While tillage is a soil degradation process in its own right, it also makes the soil more sensitive to other forms of erosion (Govers *et al.*, 1994). In specific locations, such as hillslope convexities and land parcel borders, tillage erosion can result in greatly decreased soil depths, with direct negative impacts such as reduced crop yields. Soil erosion due to tillage has been modelled at the pan-EU scale as a function of the erosivity of tillage operations and the erodibility of the cultivated landscape (Van Oost *et al.*, 2009). The basis for this assessment is a modified version of the tillage erosion model constructed by Lobb and Gary Kachanoski (1999). The estimates derived show that the gross total erosion rate is 7.2 t ha^{-1} yr^{-1} for the EU and the United Kingdom, corresponding to a total soil mobilisation rate of 0.76 Pg yr^{-1} (Van Oost *et al.*, 2009).

SLCH is defined as the removal of topsoil from arable land during the harvesting of root and tuber crops, such as potatoes, sugar beets, carrots and chicory roots (Poesen *et al.*, 2001; Kuhwald *et al.*, 2022). During a harvest (be it done manually or by machinery), loose soil, soil clods and rock fragments that are attached to crop components are uplifted from the soil. While a small amount of the soil is redistributed on the surface of the field, most of the adhering soil is completely removed from the field with the crop (Ruysschaert *et al.*, 2004; Parlak and Blanco-Canqui, 2015). In 2019, 8.4 % of all global arable land was cultivated with root and tuber crops and therefore affected by SLCH (Kuhwald *et al.*, 2022). In Europe, sugar beets and potatoes hold particular significance for SLCH due to their high annual cultivation volumes. This is especially true in central Europe (e.g. Belgium, Germany and France), where production rates are high and harvest is frequently conducted under unfavourable soil conditions (high soil moisture content). In such cases, SLCH can be up to 30.1 t ha^{-1} per harvest (Ruysschaert *et al.*, 2007; Kuhwald *et al.*, 2022). During 2000–2016, SLCH associated with sugar beet and potato harvesting in the EU was estimated to be around 0.13 t ha^{-1} yr^{-1}, equal to 14.7 million tons of soil per year (Panagos *et al.*, 2020).

Gully erosion occurs when concentrated water flowing at the soil surface has enough energy to incise a larger channel into the soil. A typically accepted minimum threshold for defining a channel as a gully is a cross-sectional area of 900 cm² (Poesen *et al.*, 2003). However, many gullies are several metres wide and deep and lead to enormous soil losses. Gully erosion, leading to ephemeral or permanent erosion channels, typically only occurs in specific landscapes and climate conditions (e.g. steep hillslopes with sparse vegetation and heavy rainfall, causing water to accumulate to a sufficient level to form a gully). Reported erosion rates often vary around 4–15 t ha^{-1} yr^{-1} (Poesen *et al.*, 2003), but extreme rainfall events have resulted in erosion rates of more than 500 t ha^{-1} yr^{-1} in Spain (Hayas *et al.*, 2017). Overall, gully erosion is a process that depends on a complex combination of natural and anthropogenic factors (topography, land use and management, soil properties, meteorology) operating at various spatial and temporal scales. This makes predictions at the European scale difficult (Vanmaercke *et al.*, 2021). Nonetheless, the most susceptible areas to gully erosion in the EU are in the Mediterranean region, and in particular in southern Spain (Borrelli *et al.*, 2022, 2023). Other regions, such as central Belgium, parts of France and eastern Romania, can also be sensitive to this process (Vanmaercke *et al.*, 2021). Climate change, and in particular longer periods of drought (damaging the protective vegetation cover), in combination with more intense rainfall during extreme events, aggravate the problem (Vanmaercke *et al.*, 2016).

Piping erosion is the removal of soil particles by concentrated subsurface flows, leading to the formation of underground channels called pipes (Ber-

Figure 7. Assessment of different types of erosion processes (water erosion, wind erosion, tillage erosion, soil loss by crop harvesting) occurring in agricultural lands in the EU and United Kingdom.



Source: EUSO, based on Panagos et al. (2019, 2020) and Borrelli et al. (2017, 2023).

natek-Jakiel and Poesen, 2018). The occurrence of this process becomes visible at the surface when the roof of a pipe collapses and thus transforms the pipe into a gully. As such, piping erosion may accelerate gully erosion by stimulating the formation of new gullies and intensifying gully headcut retreating rates. Piping erosion leads to soil losses with significant variability; in affected areas of Europe, they have been estimated to range from 1.3 t ha^{-1} yr^{-1} to 15 t ha^{-1} yr^{-1} in grasslands (Verachtert *et al.*, 2011; Bernatek-Jakiel and Poesen, 2018), and they can even reach 120 t ha^{-1} yr^{-1} in Spanish farmlands (Díaz and Sinoga, 2015). It is estimated that the area threatened by piping erosion in the EU exceeds 260 000 km^2 (Faulkner, 2006).

Geography and co-occurrence of soil erosion in Europe:

Recently, Borrelli *et al.* (2023) proposed a multi-model approach to estimate gross soil displacement by water, wind, tillage and crop harvesting based on a 100 × 100 m grid for arable land in the EU and United Kingdom (around 110 million hectares) (Figure 7). Across the region simulated, these four erosion processes are expected to move 575^{+108}_{-56} Tg (million tonnes) of soil yearly, which translates to an average area-specific soil displacement of $5.2^{+1}_{-0.5}$ t ha^{-1} y^{-1}. This figure exceeds the average soil displacement resulting from sheet and interrill processes, which are usually the only processes considered, by 95 %. Large areas of the region are predicted to have soil displacement rates ranging from moderate (class 3, 2–5 t ha^{-1} yr^{-1}) to severe (class 5, > 10 t ha^{-1} yr^{-1}). The co-occurrence assessments of several processes revealed that 43 million hectares of land were vulnerable to a single driver of erosion (about twice the land area of the United Kingdom), 15.6 million hectares to two drivers and 0.81 million hectares to three or more drivers. The results of this modelling exercise show that unsustainable soil erosion rates (> 2 t ha^{-1} yr^{-1}) occur across over half of the EU's arable land (i.e. 53.7 % or around 55 Mha). With regard to the specific processes, soil displacement due to water erosion predominates both spatially (57 % of the total area) and quantitatively (51 % of total displacement). At an estimated 36 %, tillage erosion is the second-biggest cause of soil displacement, behind crop harvesting at 2.7 % and wind erosion at 10 %. Even though water erosion is geographically and statistically predominant, tillage, wind or crop harvesting in arable landscapes account for around an estimated 40 % of soil displacement in the EU and United Kingdom. That said, it should be noted that these numbers do not include the contribution of landslides, piping and gully erosion, which currently cannot be modelled quantitatively at the European scale.

Türkiye's soils are very sensitive to erosion due to a combination of environmental factors, such as climate, topographical structure, soil properties and land use. The amount of soil lost by erosion in Türkiye is approximately five times the world average (Erpul and Oztas, 2022).A water erosion Map of Türkiye was produced using the dynamic erosion model and monitoring system developed by the General Directorate of Combating Desertification and Erosion of the Turkish Ministry of Agriculture and Forestry. The system indicates that land with severe erosion damage occupies 12.7 % of the country's surface area. In Türkiye, 642 million tons of soil are lost every year as a result of water erosion. The amount of soil displaced by water erosion is 248.6 Mt in agricultural areas, 344.6 Mt in pastures and 26.8 Mt in forests (Erpul *et al.*, 2018).

Even though Switzerland boasts extensive legal provisions to prevent soil erosion (Prasuhn *et al.*, 2013), 40 % of the arable land in the country is affected by erosion, largely due to farming practices ill-suited to the sloping terrain (Prasuhn and Blaser, 2018). Depending on slope steepness and/or agricultural practice used, erosion rates may increase dramatically, up to 400 t ha^{-1} yr^{-1} on slopes between 10° and 18° (Ledermann *et al.*, 2010). In Switzerland, 70 % of the agricultural area utilised is grassland for which soil erosion had been largely underestimated in the past, as most large-scale modelling studies assume nearly zero soil loss on grasslands. The soil erosion rate estimated using the RUSLE, which accounted for these grasslands having largely low or damaged vegetation cover (Meusburger *et al.*, 2010), was 4.6 t ha^{-1} yr^{-1} at the national scale (Schmidt *et al.*, 2019), aligning well with measured erosion rates. Hotspots of soil loss in degraded Alpine grasslands were indicated by rates between 16 t ha^{-1} yr^{-1} and 30 t ha^{-1} yr^{-1} (Alewell *et al.*, 2014).

In contrast to other European geographical regions, there is a lack of official data and erosion monitoring systems for most western Balkan countries. Estimates suggest that approximately 30 % of agricultural land in the region suffers from water-erosion-induced failure, with soil erosion impacting about 45 % of the total land area (Zdruli *et al.*, 2022). Recently, North Macedonia produced a new soil erosion map, using the erosion potential method for the entire country and the RUSLE model for agricultural zones. Results revealed that nearly one third of the country's territory is affected by soil erosion (Gavrilovic *et al.*, 2008), with an average annual soil loss of 4.1 t ha^{-1} yr^{-1} from agricultural land. In Albania, the countrywide average soil loss stands at about 30 t ha^{-1} yr^{-1}. Some 22 % of the area experiences a soil loss rate exceeding

box
2

Use of remote sensing and ^{137}Cs for gully erosion research in Malčanska River Basin, Eastern Serbia.

The area consists of hilly terrain, with elevations ranging from 590 m to 650 m. Factors influencing erosion include topography, soil type, geology, climate and vegetation. Human activities play a crucial role in altering vegetation cover and, consequently, erosion intensity.

The study aimed to assess gully morphology and soil erosion using ^{137}Cs, small-scale erosion variability within gullies and variability between gullies to evaluate control measures' effectiveness. Methods included unmanned aerial vehicle and terrestrial photogrammetry, soil sampling, high purity germanium gamma-ray spectrometry, and the creation of a profile distribution model for soil erosion rate estimation from ^{137}Cs inventories.

The results found that dense canopies hindered unmanned aerial vehicle remote sensing and photogrammetry, but 360° camera terrestrial photogrammetry successfully captured gully morphology, producing detailed terrain models. The use of ^{137}Cs revealed erosion predominantly in the gullies, with low soil deposition in some areas. Estimated average annual soil loss ranged from 0.1 t ha^{-1} yr^{-1} to 34.3 t $ha^{-1}yr^{-1}$. The use of 360° camera photogrammetric modelling proved effective in identifying sampling locations and monitoring gully changes over time, emphasising its importance in erosion research and management.

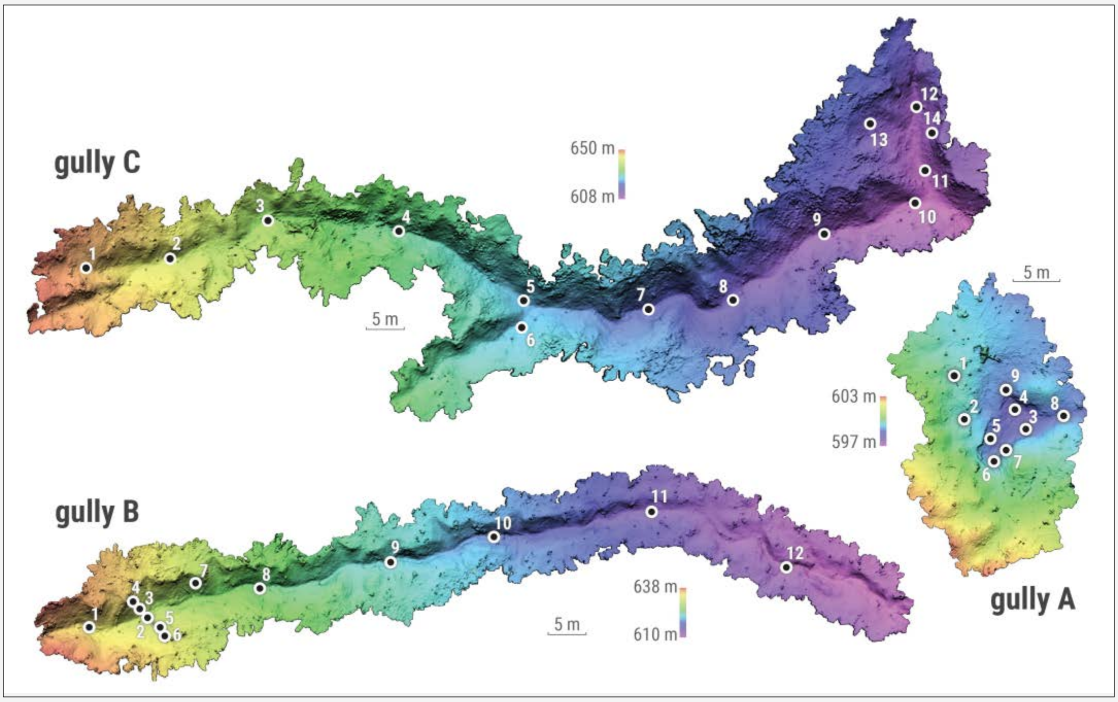


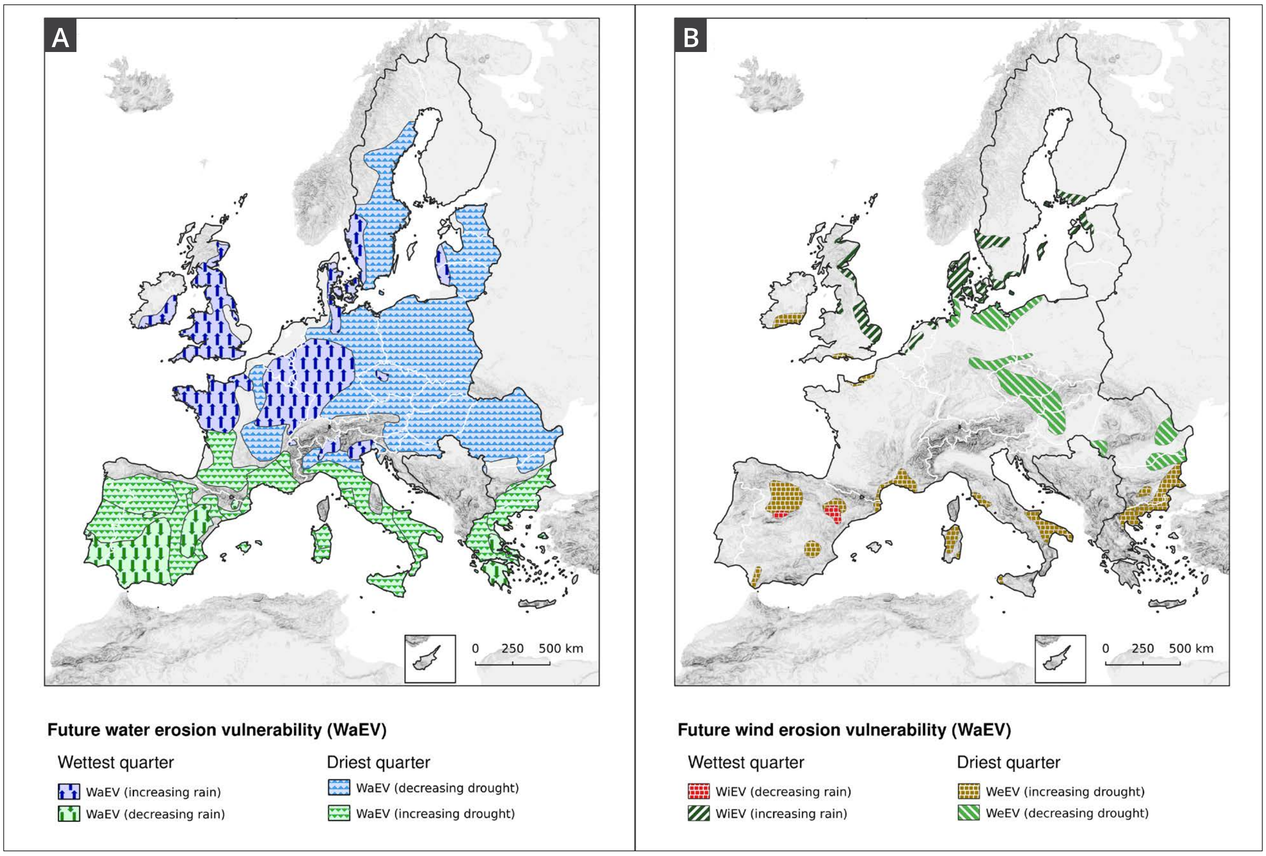
Figure box 2: Digital elevation models of gullies with sampling points. *Source: Đokić et al., (2023)* 100 t ha^{-1} yr^{-1}, accounting for 93 % of soil erosion. Serbia faces erosion issues on 80 % of its agricultural land, with water erosion prevalent in central and hilly/mountainous regions and wind erosion predominant in Vojvodina, affecting approximately 85 % of agricultural land. Water erosion in Montenegro affects about 13 135 km^2, or 95 %, of its total area (Spalevic, 2024). The intensity of erosion varies significantly across the regions of Montenegro, with the coastal area being the most vulnerable. Of the coastal river basins, estimates suggest that 13 %, 25 % and 35 % of areas experience excessive, high and moderate erosion, respectively. In general, a high proportion of this region experiences high and excessive erosion, meaning actual soil losses are in the range of 20 t ha^{-1} yr^{-1} to 23 t ha^{-1} yr^{-1} (Spalevic, 2024).

In Ukraine, expert assessments indicate that 10.5 million hectares of soil are eroded, with sheet and rill erosion impacting 17 % of arable land, gully erosion affecting 3 % and wind erosion affecting 11 %. Intensive cultivation practices, including excessive planting of row crops and insufficient contour farming, alongside poor land management practices such as deforestation, overgrazing and cultivation on steep slopes, contribute to erosion processes. More than 6 million hectares of arable land are systematically affected by wind erosion, and up to 20 million hectares in years with dust storms. Experts estimate that between 300 Mt and 600 Mt of soil are lost annually due to erosion (Baliuk *et al.*, 2021).

Projection of future trends in soil erosion in Europe

Soil erosion is unlikely to remain stable in Europe due to several evolving factors, which will determine its future trends. By 2050, soil erosion rates are projected to increase by 13–22.5 %in the agricultural lands of the EU and the United Kingdom (Panagos *et al.*, 2021). Changes in soil erosion rates are driven by changes in climatic conditions and land use patterns, socioeconomic development, farmers' choices and, importantly, changes to agro-environmental policies. The consideration of all these factors is required to meaningfully predict future soil erosion rates in Europe (Panagos *et al.*, 2021; Borrelli *et al.*, 2023). Compared with current baselines, future model projections identify the Atlantic and the continental climate zones as the locations most vulnerable to water erosion, with

Figure 8. Future trends in water and wind erosion across agricultural landscapes in the EU and United Kingdom.



Source: EUSO, based on Panagos et al., (2021) and Borrelli et al., (2023).

a higher risk of experiencing extreme weather during the wettest quarter. During the driest quarter, vulnerability to water erosion is predicted to increase in an expansive region covering most of central eastern Europe. In contrast, noteworthy decreases in water erosion are predicted in Bulgaria, Greece, Spain, western France, southern Italy and Portugal.

Given that soil erosion involves a mix of concurrent processes, predictions need to account for the uniquely changing spatial and temporal characteristics of each process. For example, concerning wind erosion, Mediterranean regions include the most vulnerable areas due to longer periods of drought during the driest quarter (Borrelli *et al.*, 2023). Identifying and understanding areas that are more susceptible to specific erosion processes can help in the delineation of strata to allow the definition of (quasi-)homogenous regions for targeted mitigation strategies (Figure 8). The predictions suggest that monitoring programmes need to be adopted not only to address water erosion but also to determine strategies to mitigate tillage and wind erosion. For example, areas affected by both wind and water erosion may benefit from monitoring activities that aim to detect dust emissions from fields or landscapes.

Post-wildfire erosion also makes a critical contribution to total soil loss in the EU, which can cause a twelve-fold increase in erosion rates compared with pre-fire conditions (Vieira *et al.*, 2023a). Furthermore, the predicted trends of post-fire soil erosion in the EU indicate a potential increase compared with current rates, driven by projected increases in the total burned area due to prolonged periods of drought (Dupuy *et al.*, 2020) combined with increasing rainfall erosivity during torrential events (Panagos *et al.*, 2022). Globally, post-fire debris-flow activity is expected to increase by 68 % in regions that have previously experienced wildfires in the past and to decrease by less than 2 % by the late 21st century. While some researchers have shown that approximately 85 % of post-fire debris flow occurs within the first 2 years following a fire (McGuire *et al.*, 2024), others conclude that in the Mediterranean regions, where wildfires are most common in Europe, their total impact is shown to be enduring (Vieira *et al.*, 2023a). The latter emphasises the critical temporal aspect of post- fire soil erosion in the EU.

4.4.2 Drivers

The drivers of soil erosion are numerous and vary depending on the erosion process, specific geographical location and land use practices employed. In the first part of this section, we summarise the main characteristics of each erosion process.

The processes of water erosion include splash erosion, sheetwash, rill erosion, piping erosion (or tunnel erosion) and (ephemeral or permanent) gully erosion. Soil erosion by water is driven by hydromechanical forces and is one of the major threats to soils in the EU (Panagos *et al.*, 2015b, 2021). Water erosion is caused in Europe by natural factors such as steep topography, landscape position (i.e. causing areas to experience a high degree of water accumulation), soil properties and climatic conditions (i.e. heavy rainstorms), but primarily by inappropriate land management in areas susceptible to erosion (owing to deforestation, tillage, etc.).

Wind erosion occurs in dry conditions when the soil is exposed to wind (Webb *et al.*, 2006). Wind erosion is the wind-forced (aeolian) movement of soil (Shao, 2008). In recent times, intensive farming has increased the frequency and magnitude of this geomorphic process, with consequences especially for sensitive lands that are important for food production (Dostál *et al.*, 2006). While wind erosion mainly affects soils with low vegetation cover, land management practices such as intensive crop cultivation, increased mechanisation, enlargement of field sizes, removal of hedges, the intensive exploitation of residues / biomass of vegetation and allowing consecutive bare fallow years in cultivated lands exacerbate both the environmental and economic effects of wind erosion (Colazo and Buschiazzo, 2015). SLCH depends to a significant degree on soil disturbance during harvesting in croplands (Arnhold *et al.*, 2014).

Several key factors control the magnitude of SLCH, namely (a) soil properties (e.g. moisture, texture, organic matter and structure), (b) crop characteristics (e.g. type, size and morphology), (c) agronomic practices (e.g. the frequency of root/tuber crops in the crop succession, plant density and crop yield) and (d) harvest techniques (e.g. technology, the effectiveness of cleaning devices and the velocity of the harvester) (Ruysschaert *et al.*, 2004, 2005; Kuhwald *et al.*, 2022).

Tillage erosion occurs in cultivated fields due to tillage operations that result in the downhill displacement of soil. The variation in soil displacement rates due to tillage erosion may be rather large, depending primarily on topographic characteristics, tillage depth and tillage direction, and to a lesser extent on the tillage velocity and implementation characteristics (Van Oost *et al.*, 2006). Tillage erosion displaces soil over small areas, but it may cause the significant movement of soil over multiple years (Van Oost *et al.*, 2009).

Involved in each of the aforementioned erosion processes are specific driving forces, typically deriving from interactions between anthropogenic and natural phenomena. The most prominent factor is scarce or no vegetation cover, which can be caused by one factor or a combination of multiple factors. These factors include the following.

- Poor land management practices. Unsustainable land management practices such as overgrazing, inappropriate tillage methods, monoculture farming and improper irrigation practices can accelerate soil erosion (Evans *et al.*, 2022). These practices can disturb soil structure, decrease vegetation cover and increase soil's vulnerability to erosion. In land management cycles, the removal of vegetation cover during periods when the risk of erosion is high greatly increases the overall vulnerability of soil to water and wind erosion (Boardman and Favis-Mortlock, 2014; Matthews *et al.*, 2023). In addition to increasing susceptibility to other erosion processes, tillage erosion in cultivated fields causes a significant net downhill movement of soil (Lindstrom *et al.*, 1992).

- Deforestation and mining. Deforestation, driven by agricultural expansion, urban development and logging activities, removes the protective vegetation cover crucial for stabilising soil. With this protective layer gone, soil becomes susceptible to erosion by water and wind (Vanwalleghem *et al.*, 2017). In addition, mining and quarrying activities disrupt soil integrity through excavation,

box 3

Estimating sediment removal costs from the reservoirs of the EU.

A key off-site impact of the erosion of soil and rock is the infilling of reservoirs with sediment, limiting their water storage and energy production capacities. The cost of removing an estimated 135 million cubic metres of accumulated sediment due to water erosion only is estimated at roughly EUR 2.3 (± 0.9) billion per year in the EU and United Kingdom, with large regional differences between countries.

When applying a method that considers all types of soil loss processes, a simple extrapolation puts the sediment input at an order of magnitude higher (> 1 billion cubic metres), but lumped extrapolations do not consider that the removal cost (per cubic metre) may be less due to the application of less costly techniques in silted dams across different countries.

With a conservative estimation that accounts for all erosion processes, the removal of sediment from EU dams is predicted to cost at least EUR 5–8 billion per year.

Photo box 3: Sediment build up in Val Formaza, Italy.
Source: *A. Jones*

vegetation removal and waste disposal, accelerating erosion rates in affected areas (Pacetti *et al.*, 2020).

- Land levelling. When the local topography does not allow particular agricultural operations (e.g. tillage, irrigation, harvesting), land is often reshaped by levelling. Such land levelling leads locally to very large soil losses, resulting in highly truncated soil profiles and a drastic lowering of soil quality (Poesen, 2018). Land that is levelled also becomes more prone to other soil erosion processes such as piping and gully erosion, and landslides (Borselli *et al.*, 2006).

- Climate change. Climate change further exacerbates soil erosion by altering precipitation patterns, increasing the frequency and intensity of extreme weather events and disrupting temperature regimes (Fowler *et al.*, 2021). Depending on the spatial and temporal patterns of the change (Panagos *et al.*, 2021; Borrelli *et al.*, 2023), it can intensify erosion processes and jeopardise soil stability (Pruski and Nearing, 2002). In Europe, regional and local studies have projected the impact of climate change on soil erosion (e.g. Klik and Eitzinger, 2010; Mullan *et al.*, 2012; Routschek *et al.*, 2014; Grillakis *et al.*, 2020; Luetzenburg *et al.*, 2020; Eekhout and de Vente, 2022).

- Fire. Anthropogenic or naturally induced wildfires can lead to a significant (approximately twelve-fold) increase in soil erosion in recently burned areas compared with pre-fire conditions. Outcomes are highly variable between geographical regions, for example depending on burn severity (Vieira *et al.*, 2015, 2023). Wildfires also trigger the occurrence of extreme erosion events, debris flows and landslides, all affecting downstream the integrity of water bodies and other essential infrastructures (Moody *et al.*, 2013). In the most recent assessment conducted at the EU scale, additional soil losses of 19.4 million megagrams were estimated for the first post-fire year. Over a 5-year period, that same affected area may cause 44 million megagrams of additional soil losses, since a significant portion (46 %) of the burned area presented no signs of full recovery (Vieira *et al.*, 2023a).

4.4.3 Impacts

Soil erosion in Europe can have significant impacts on both the environment and human activities. These impacts can be divided into on-site (associated with the eroded area at its source) and off-site (associated with the downstream transport and deposition of eroded soil) impacts, and the consequential monetary losses. Some of the main impacts include the following.

- Loss of soil fertility and soil biodiversity. Soil erosion removes the top fertile layer of soil, which contains the nutrients necessary for plant growth. In addition to a reduction in soil fertility, important soil functions are impacted, such as the soil's ability to store carbon, nutrients and water, and provide habitats for organisms (Lal, 1998). For rill and interrill erosion, the thinning of the soil profile is progressive over long periods, while gully and piping erosion, which may affect entire soil profiles (both topsoils and subsoils), can render areas of land uncultivatable (Vanmaercke *et al.*, 2021). Erosion events resulting in sediment inundation in fields can cause crop damage in addition to reducing the land's natural fertility for crop cultivation (Verstraeten and Poesen, 1999; Bielders *et al.*, 2003).

- Food security. Soil erosion can have significant effects on food security by reducing agricultural productivity and undermining soil's capacity to produce enough food to meet the needs of growing populations (Bakker *et al.*, 2004, 2007; García-Ruiz *et al.*, 2017). The loss of P due to soil erosion, in particular, can be considered a serious threat to future food and feed production, as globally between 15 % and 85 % of P losses from agricultural systems can be attributed to soil erosion by water only (Alewell *et al.*, 2020). In a recent study, integrating economical and biophysical models, Sartori *et al.* (2019) reported losses of USD 8 billion annually to the global economy as a result of soil erosion. The accompanying impact on food security is a reduction in global agri-food production by 33.7 million tonnes, with accompanying rises in agri- food world prices of 0.4–3.5 %, depending on the food product category. Under pressure to use more marginal land due to the loss of fertile land through erosion, abstracted water volumes increase by an estimated 48 billion cubic metres. Finally, there is tentative evidence that soil erosion is accelerating the competitive shifts in comparative advantage on world agri-food markets (Sartori *et al.*, 2019).

- Sedimentation. Eroded soil particles are often transported by run-off into water bodies such as rivers, lakes and streams, or deposited in fields or urbanised areas (Verstraeten and Poesen, 1999; Patault *et al.*, 2021). This sedimentation can degrade water quality, disrupt aquatic ecosystems and harm aquatic organisms by smothering habitats and reducing light penetration (Boardman *et al.*, 2003; Owens *et al.*, 2005). In addition to the damage caused by the mineral components of soils, considerable ecological damage can occur because particle-bound nutrients, heavy metals and pesticides are transported into neighbouring aquatic habitats where damage to biotic communities is caused (Rickson, 2014).

- Decline in terrestrial biodiversity. Soil erosion can lead to habitat loss and fragmentation, which can reduce biodiversity. Many plant and animal species depend on stable soil ecosystems for survival. Erosion can disrupt the equilibrium in these ecosystems, leading to declines in biodiversity and ecosystem services (Pimentel *et al.*, 1995; Guerra *et al.*, 2020; Rendon *et al.*, 2020). Moreover, soil erosion and soil biodiversity interact bi-directionally: below-ground organisms affect soil loss through their mixing activities, while intensive erosive events shape the soil-occupying organisms and the functions and services that they provide (Orgiazzi and Panagos, 2018).

- Increased flooding and landslides. Soil erosion can contribute to increased flooding and landslides, especially in areas with steep slopes, heavy rainfall and low vegetation cover. Soil degradation reduces the infiltration capacity of soils, increasing the likelihood of run-off and flooding (de la Paix *et al.*, 2013). Furthermore, eroded soil can clog waterways, increasing the risk of flooding, inhibiting navigability, damaging flood prevention infrastructure (Boardman, 2021) and leading to the negative effects on aquatic biodiversity discussed above. The destabilisation of slopes by water and wind erosion can also result in landslides, which directly endanger human lives and property (Ionita *et al.*, 2015).

- Economic costs. Soil erosion imposes economic costs on agriculture, forestry and infrastructure. The current estimate of agricultural productivity loss in the EU due to the on-site impacts of water erosion is about EUR 1.25 billion per year (Panagos *et al.*, 2018). This includes the impact of severe soil erosion by water on crop productivity. While the on-site effects are mostly paid by the farmer, the off-site effects of soil erosion are often paid by society (Boardman, 2021; Patault *et al.*, 2021). A major off-site impact with significant monetary cost is the removal of sediments from reservoirs, which may cost between EUR 2.5 billion and EUR 8 billion per year (Panagos *et al.*, 2024a).

- Climate change. Soil erosion reduces soil's stability, alters its structure, impedes its biological activities, reduces its water-holding capacity, causes soil nutrient loss and can reduce SOC pools (Kuhn *et al.*, 2009), therefore, impairing all major functions of soil, and not only its productivity. Soil erosion may exacerbate climate change by releasing carbon stored in soil organic matter into the atmosphere from displaced sediment (Jacinthe *et al.*, 2002). However, numerous complex interactions between soil erosion and biogeochemical cycling mean that the net effects of soil erosion on the carbon cycle remain, which is a topic of high interest (Quinton and Fiener, 2024). With regard to the hydrological cycle, eroded soils also have reduced water-holding capacity, which can exacerbate drought conditions and contribute to desertification, further amplifying the impacts of climate change (Lal, 2012).

- Impact on cultural heritage. Soil erosion can impact cultural heritage sites, such as archaeological sites and historic buildings. Erosion can degrade or destroy these sites, leading to the loss of valuable cultural and historical resources (Agapiou *et al.*, 2020; Polykretis *et al.*, 2022).

- Social impacts, such as land abandonment (and possibly migration). The main reason for land abandonment is degradation and the loss of soil fertility, either as a consequence of erosion processes or as a result of soil nutrient depletion (Lasanta *et al.*, 2017). Such trends have been noticed in Spain (central and southern mountainous areas) and other areas of southern Europe (Bakker *et al.*, 2005; Díaz and Sinoga, 2015). From a global perspective, soil erosion causing nutrient depletion and enhancing desertification is a serious threat to subsistence farmers and thus contributes to famine, migration and violent political conflicts/wars.

Overall, soil erosion poses significant challenges to sustainable development and ecosystem resilience in Europe, highlighting the importance of effective soil conservation and land management practices.

4.5 Soil compaction

Soil compaction is a prevalent issue in Europe. It affects soil properties, reduces crop yields, impairs water infiltration, diminishes soil fertility and increases GHG emissions. It poses significant challenges to sustainable land management and agriculture, highlighting the need for preventive measures and conservation practices such cover cropping and reduced tillage. While the compaction of topsoil can be mitigated with conservation practices, subsoil compaction persists and affects various soil functions.

Compaction is defined as the densification of soil due to the application of mechanical stresses that exceed soils' internal strength. These stresses can be applied by natural processes (overbearing weight from upper layers of soil or thick layers of ice) and by human activities (construction of infrastructures, frequent traffic on pathways, high animal stocking densities). Therefore, soil compaction is not a recent phenomenon, and its natural or anthropogenic origin can be identified (Schneider and Don, 2019). Soils with high clay and low organic matter content are more prone to compaction due to their tendency to form hard, dense layers when subjected to high surface pressures. In fact, sandy and clay-rich soils with a bulk density (BD) above 1.80 g cm^{-3} and 1.47 g cm^{-3}, respectively, could constrain root development (USDA, 1987). Soils are more susceptible to compaction in wet conditions (Greenwood and McKenzie, 2001; Hamza and Anderson, 2005). Under such conditions, the risk of compaction increases as soil clay content increases and soil organic matter content decreases. When soil moisture reaches or exceeds field capacity, there is greater potential for soil compaction, particularly in topsoil.

4.5.1 Status and trends

Despite the extensive documentation of adverse impacts of soil compaction on soil properties and functions, determining the extent and severity of compaction in Europe remains challenging (EEA, 2022b). Concern over the extent of land affected by soil compaction is widespread. Birkás *et al.* (2009) reported that approximately 33 million hectares in Europe are affected, while Schjønning *et al.* (2015) estimated that about 25 % of European subsoils (at depths 0.25–0.7 m) exhibit critically high relative normalised densities. According to the European database of soil properties, SPADE8 (Koue *et al.*, 2008), Schjønning *et al.* (2016) estimated that 23 % of Europe's total agricultural area is affected by critically high levels of soil compaction.

The degree of topsoil compaction is difficult to clearly describe with thresholds because conditions are highly unstable and dynamic; such conditions include the negative effects of mechanical seedbed preparation, recovery after the growing season and the use of cover crops. The degree of topsoil deformation can therefore be rather temporary; however, it can also be a warning sign that any continuation of current (harmful) practices is likely to affect the subsoil.

The EU Soil Observatory (EUSO) Soil Degradation Dashboard provides insight into the natural susceptibility of agricultural soils to compaction (Houskova and Montanarella, 2008). It is estimated that a third of European subsoils are very vulnerable to compaction and a fifth moderately so.

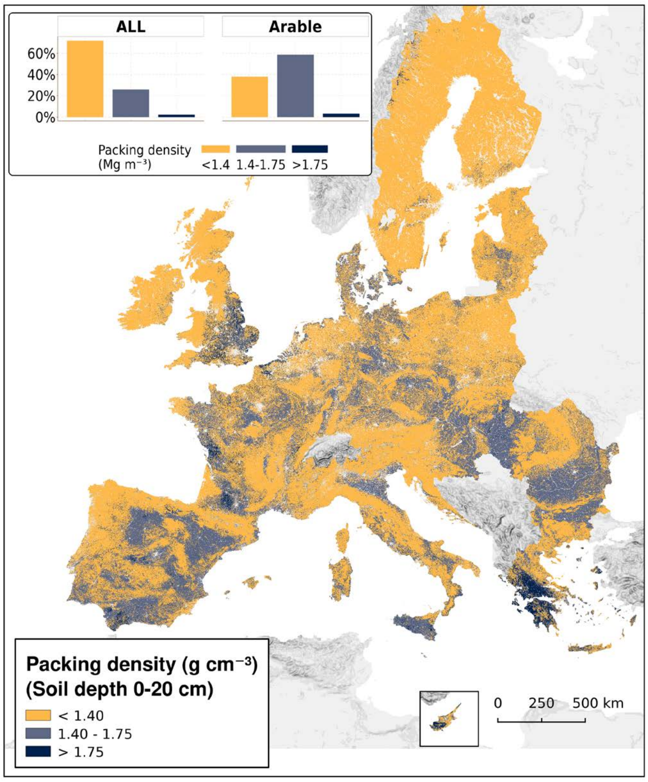
Different tools have been proposed to monitor soil compaction (EEA, 2022b). Parameters that can be easily measured or that are common in many soil surveys include BD, air capacity, soil texture and visual features of compaction, such as platy structure. A BD of less than or equal to 1.1 g cm^{-3} is ideal for plant growth; between 1.3 g cm^{-3} and 1.55 g cm^{-3} is fair; and greater than 1.8 g cm^{-3} is considered extremely bad, as it restricts root growth. However, it should be noted that the optimal and critical limits of soil BD are dependent on soil texture, particle size, management practices and organic matter content.

BD was measured in more than 6 000 soil samples from the LUCAS 2018 campaign. A high resolution map of BD for the whole of Europe was recently published (Panagos *et al.*, 2024b) for different soil depths. The mean soil BD for the depth 0–20 cm is 1.01 g cm^{-3}, with high variability between different land uses. Arable lands have the highest mean BD, at 1.26 g cm^{-3}, followed by permanent crops (BD = 1.23 g cm^{-3}), heterogeneous agricultural areas (BD = 1.14 g cm^{-3}), pastures (BD = 1.08 g cm^{-3}), shrublands (BD = 1.01 g cm^{-3}) and woodlands (BD = 0.84 g cm^{-3}). The main drivers of BD variation are land cover type, and, in the case of agricultural areas, crop type. Trafficking, land use and management practices have such an important impact on BD as the BD of arable lands is almost 1.5 times higher than woodlands. Countries with a large proportion of woodlands (Austria, Finland, Sweden and the Baltic states) have quite high biases in their BD estimates.

It should be noted that areas with naturally high soil BD may not necessarily be compacted. BD is a parameter with high spatial and temporal variability. While BD is compaction sensitive, it is considered a rather unspecific parameter because it describes only changes in volume and does not quantify the potentially negative impacts on pore functions. If BD is used because of its widespread availability in soil monitoring, additional (visual) information about, for example, texture or soil structure is needed to make a better qualitative assessment of compaction.

Packing density (PD) is sometimes used instead of BD as an indicator for natural and human-made soil compaction (Jones *et al.*, 2003; Tobias and Tietje, 2007; Shamal *et al.*, 2016; Panagos *et al.*, 2024b. The use of PD as a proxy for soil compaction facilitates practical monitoring and assessment efforts. Panagos *et al.* (2024b) estimated for the EU and United Kingdom the packing PD using the BD and the clay content of soil (Ballabio *et al.*, 2016). Soils with high PD (> 1.75 g cm^{-3}) are likely compacted and not susceptible to further compaction. Medium-compacted soils have a PD in the range of 1.40 g cm^{-3} to 1.75 g cm^{-3} while the less compacted soils are those with PD < 1.40 g cm^{-3} (Jones *et al.*, 2003; Păltineanu *et al.*, 2015). Based on the currently avaialble European data sets, 71.8% of all soils would appear less compacted,

Figure 9. Use of PD as a proxy for soil compaction to identify hotspots where soils are highly compacted.



Source: EUSO, based on Panagos et al. (2024a).

2.2% compacted and 26% with medium packing density. In the arable lands, medium packing density predominates (58.7%) while 3.2% would be compacted (Figure 9).

The pan-European assessment does not challenge any local or regional assessments made with a higher number of analysed samples. In Switzerland, BD has increased since the 1980s in the majority of agricultural soils. Moreover, the compaction of forest soils is also increasing, and it is estimated that 0.7 % of forest soils are compacted (BAFU, 2017). In England and Wales, almost 4 million hectares of soil are at risk of compaction (UK Environment Agency, 2019). Soil compaction is also of growing concern in northern Europe, mainly due to increasing production costs and economic pressure, which lead to the use of heavier machinery and to more contract machinery operation on smaller farms (Thorsøe *et al.*, 2019; Seehusen *et al.*, 2021). Soil BD is not measured in soil monitoring programmes in Ukraine ,but soil compaction is widespread on arable land of more than 22 million hectares (Baliuk *et al.*, 2021). Additional areas of possible soil compaction due to the manoeuvres of heavy military vehicles are being assessed (Bonchkovskyi *et al.*, 2023).

In the western Balkans, soil compaction is not of great importance in most agricultural lands in the region due to the lower use of agricultural machinery than in developed agricultural countries. However, further investigations should be conducted to determine the real impact. According to experts' assessments, in Türkiye, the human-induced compaction of agricultural land has become a serious and growing problem for soil, due to the increasing weight and use of soil cultivation and harvesting machines. Soil compaction is a new phenomenon among the country's farmers and is yet to be fully assessed. The main obstacle to preventing or reversing soil compaction is failing to recognise it. Natural soil compaction occurs spontaneously when alkaline (sodium) soils are formed in arid regions on the old lake bottom in Central Anatolia.

4.5.2 Drivers

In Europe, several factors contribute to soil compaction. The driving force is the economic conditions for crop, animal and timber production: in order to minimise costs, larger and more efficient machinery is used, or animal density is increased. This increases the mechanical stresses applied to soil (Schjønning *et al.*, 2015).

- Agricultural and forestry activities. Large and heavy machinery, such as tractors and harvesters, and equipment used in forestry operations exert significant pressure on the soil, leading to compaction – especially when operating under wet conditions. Intensive or improper tillage practices can contribute to soil compaction by breaking down soil aggregates and reducing soil porosity.

- Trampling by livestock. Continuous grazing and trampling by livestock can compact the soil, particularly in pastures and grazing areas. This is more likely to occur in areas with high stocking densities or in wet conditions.

- Infrastructure development. Urbanisation and construction activities can result in soil compaction due to the use of heavy construction equipment, increased soil disturbance and the creation of impervious surfaces.

- Continuous mono-cropping. Cropping the same plant in the same field repeatedly causes soil compaction due to the conduct of the same mechanisation activities over time. Identical root development and systems can also accelerate compaction. Diversified cropping systems with complementary root growth strategies improve crops' adaptation to and the remediation of hostile soils (Zhang *et al.*, 2024).

4.5.3 Impacts

Soil compaction in Europe can have several significant impacts on the environment, agriculture and ecosystems. Several studies have shown that soil compaction (a) affects soil properties such as structure, increases BD and reduces soil porosity, water infiltration, water availability for plants and hydraulic conductivity; and (b) reduces crop growth by increasing mechanical impediments to root growth, hampering root architecture and decreasing root propagation (Schjønning *et al.*, 2015; Keller *et al.*, 2021). Some of the main impacts include the following.

- Crop yield reduction. Compacted soil has reduced pore space, limiting the movement of air, water, and nutrients within the soil profile (Zhanget *al.*, 2024). This reduction in soil porosity can hinder root growth and penetration, leading to decreased crop yields and productivity (Pandey *et al.*, 2021). Stunted plant root growth due to the compaction of soil affects crop growth and development, and yield. Soil compaction resulting from heavy machinery traffic causes a significant reduction in crop yield reduction, of as much as 50 % or even more, depending on the magnitude and severity of soil compaction (Shaheb *et al.*, 2021). The effects of compaction can significantly reduce crops yield by 10–15 % (Godwin *et al.*, 2022).

- Impaired water infiltration. Compacted soils have a reduced ability to absorb water, leading to increased surface run-off and erosion. This can contribute to water pollution through the transport of sediment, nutrients and agrochemicals into water bodies, impacting aquatic ecosystems and water quality. Soil compaction can also increase the frequency and severity of floods (Chyba *et al.*, 2017; Alaoui *et al.*, 2018).

- Reduced fertility. Soil compaction restricts the movement of air into the soil, which can lead to decreased microbial activity and nutrient cycling. This can result in soil degradation and reduced soil fertility over time. Besides the changes in soil structure, compaction reduces soil pore space and increases soil strength while decreasing root growth and root elongation rate, which results in reduced water and nutrient uptake by plants (Nawaz *et al.*, 2013; Sadras *et al.*, 2016; Colombi and Keller, 2019). The adverse effects of compaction on soil conditions also reduce plant emergence, establishment and height (Sidhu and Duiker, 2006).

- Increased GHG emissions. Compaction may change the fluxes of GHGs from the soil to the atmosphere through mechanisms associated with effects on soil permeability, aeration and crop development. A range of studies have clearly indicated significant increases in N_2O emission following the compaction of topsoil (Ball, 2013). In addition, compaction increases CO_2 emissions because the cultivation of compacted soils requires significantly more energy than the cultivation of uncompacted soils (van den Akker and Soane, 2005).

- Constraints on land use. Soil compaction can limit the suitability of land for various agricultural and land management practices. It can restrict the use of heavy machinery, limit crop growth and increase the cost of soil restoration and rehabilitation efforts. Graves *et al.* (2015) estimated the compaction costs to be higher than EUR 500 million per year in England and Wales, of which productivity losses account for more than 40 % (Graves *et al.*, 2015). In severe cases, soil compaction has a substantial impact on crop growth, development and yield, and farm income (Shaheb *et al.*, 2021).

- Increase tillage costs. As soil compaction increases, the cost of tillage increases. Periodic deep ripping becomes necessary, especially in regions where crops such as sugar beet are grown (de Cárcer *et al.*, 2019; Shaheb *et al.*, 2021).

Overall, soil compaction poses significant challenges to sustainable land management, agriculture and ecosystem health in Europe, highlighting the importance of implementing measures to prevent and mitigate its impacts. The compaction of topsoil (regularly tilled layers, close to the soil surface) has a significant impact on crop yield. Conservative agricultural practices such as the use of cover crops, non-tillage and organic amendments improve soil structure and therefore drastically reduce soil compaction. However, compaction of the subsoil is persistent, and it has significant effects on a range of soil functions.

4.6 Soil pollution

Soil pollution is a degradation process identified by the presence of substances in soil with levels considered unacceptable from an environmental risk point of view. Soil pollution may affect soil layers, including the root zone and connected compartments. Point-source pollution occurs when substances are released from a single well-defined source but to a relatively restricted extent, while diffuse pollution refers to the presence of substances over large geographical areas from a single source or a range of sources.

4.6.1 Status and trends

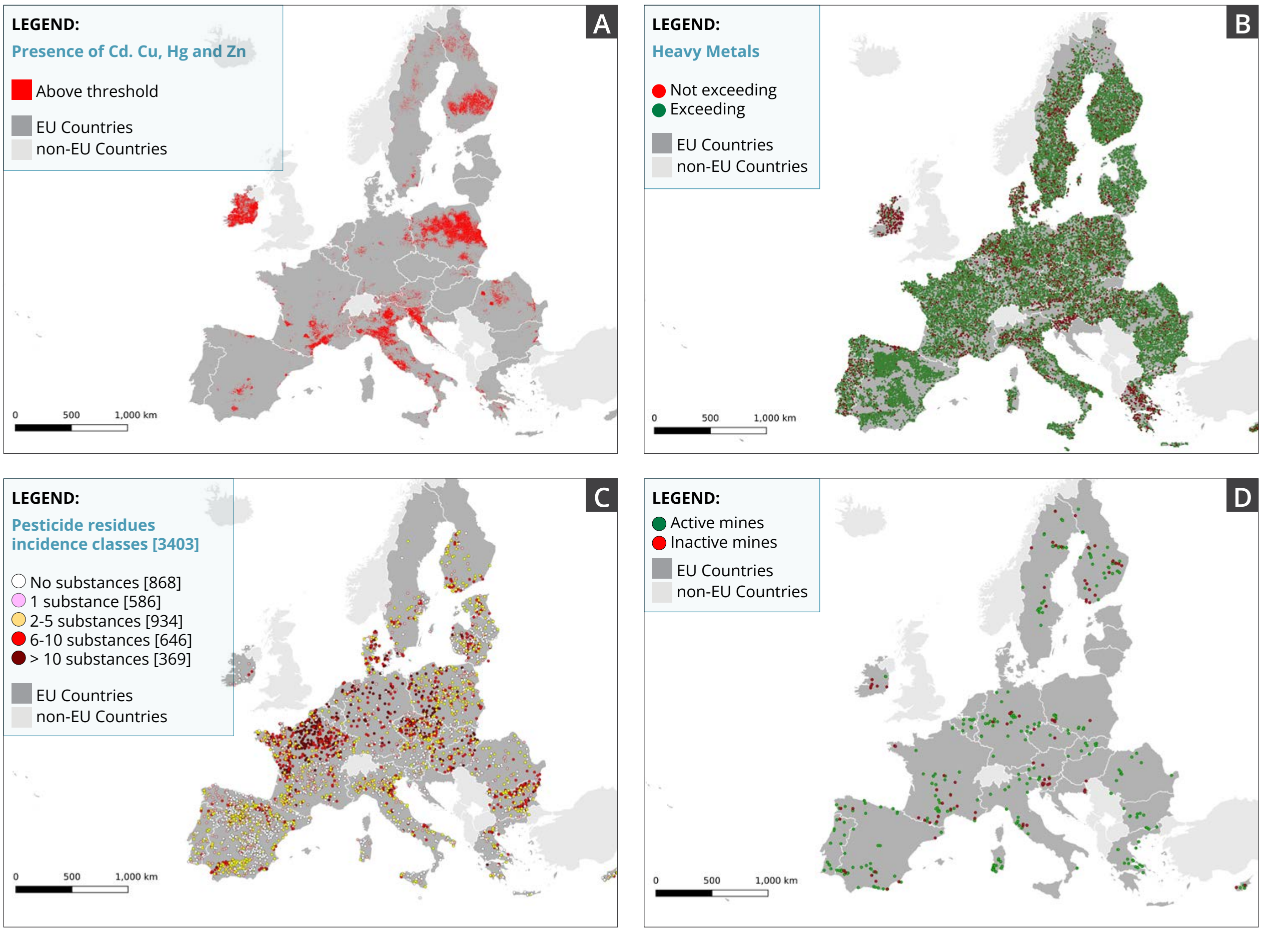
Soil pollution in Europe arises from a variety of sources, including industrial activities, urbanisation, agriculture and military operations. These activities release contaminants such as heavy metals, pesticides and industrial chemicals into the soil, posing significant risks to environmental and human health. Despite efforts to address soil pollution, comprehensive assessments remain limited, making it challenging to fully understand its extent and impact. Indicators such as the presence of heavy metals and pesticides suggest concerning trends. Soil pollution has far-reaching consequences, affecting not only human health but also ecosystem services and agricultural productivity. To address these challenges, concerted efforts are needed to fill knowledge gaps, establish harmonised monitoring practices and implement effective pollution prevention and remediation measures.

Despite the fact that there is a common understanding of the impacts of soil pollution in the EU, comprehensive, large-scale assessments are scarce. Most of the data at the EU scale originate from the various LUCAS rounds, while data from individual Member States are often obtained using different approaches, hampering comparisons. Nonetheless, it is possible to recognise a set of indicators: for metals, from LUCAS 2009 (Figure 10a, Figure 10b); for pesticides, from LUCAS 2018 (Figure 10c); and for mine sites, from the Water and Planetary Health Analytics database (Figure 10d).

The spatial distribution of cadmium in topsoil across the EU and United Kingdom was assessed using the 21 682 soil samples from the LUCAS soil module (with sampling conducted in 2009). Of these samples, 5.5 % had cadmium concentrations above 1 mg kg^{-1}. This threshold is a limit defined by the Finnish Ministry of the Environment and corresponds to the lower limit for cadmium in soils in the sewage sludge directive (Directive 86/278/EEC) (European Commission, 1986). Natural factors such as soil pH, clay content, topography, erosion and leaching significantly affect soil cadmium concentrations (Ballabio *et al.*, 2024). As anthropogenic factors, P inputs to agricultural lands were identified as the most important variable explaining cadmium levels. The application of the EU fertilising products directive should further limit cadmium inputs to soils. High copper concentrations have been identified in EU croplands and linked to anthropogenic activities. This is the case in vineyards and orchards in regions of northern Italy and parts of France, probably related to fungicide treatment and the wet and humid climate (Ballabio *et al.*, 2018). Copper compounds, including copper sulphate, are authorised for use in the EU as bactericides and fungicides, despite being considered substances of particular concern to public health or the environment (EFSA, 2018). Copper-based fungicides are also authorised for use in organic farming (Tamm *et al.*, 2022). In the case of mercury, high concentrations have been found close to mining sites such as Almadén and Asturias (Spain), Mount Amiata (Italy), Idrija (Slovenia) and Rudňany (Slovakia). In a more detailed investigation, 42 % of mercury hotspots were associated with mining activities, while the rest could be related to either coal combustion industries or local diffuse contamination. Overall, mercury hotspots in the EU (top 1 %) have been identified with concentrations of more than 422 µg kg^{-1} (Ballabio *et al.*, 2021). High Zn concentrations were found in 1 % of all samples (> 167 mg kg^{-1}) from Europe. The distance from natural Zn deposits or Zn mines was one of the most important variables in explaining Zn concentrations in Europe. Moreover, the high likelihood of grasslands having Zn concentrations above 167 mg kg^{-1} indicates that collecting data on fertiliser and manure inputs would improve the estimation of topsoil Zn concentrations in Europe (Van Eynde *et al.*, 2023).

An analysis of heavy metal concentrations in EU agricultural soils (based on LUCAS 2009) under the sewage sludge directive found that 19 % of samples exceeded the limit values as laid down in the national legislations for at least one single heavy metal as defined by Yunta *et al.* (2024) (Figure 10b). In the same way, accurate standard methods should be used to determine the actual heavy metal fractions that may be taken

Figure 10. Compilation of soil pollution assessments at the EU level, showing indicators of diffuse pollution: (a) cadmium, copper, mercury and zinc (combined); (b) heavy metal exceedance of sewage sludge limits; (c) pesticide residues and point-source pollution; and (d) active and inactive mine sites.



Sources: EUSO, based on (a) Ballabio et al. (2018, 2021, 2024) and Van Eynde et al. (2023), (b) Yunta et al. (2024), (c) Vieira et al. (2023) and (d) Hudson-Edwards et al. (2023); modified from Vieira et al. (2024).

up by crops or actively affect human health. The distribution of heavy metals in agricultural soils was recently documented by the EEA (De Vries *et al.*, 2022), with exceedances seen across a significant proportion of Europe's agricultural areas. Future pollution monitoring at the EU level will build on the LUCAS soil module, through which heavy metals and other contaminants are now regularly monitored.

Pesticide residues are commonly found in European agricultural soils (74.5 %), whereas most samples (57.1 %) present mixtures of residues across crops and farming systems (Vieira *et al.*, 2023b). In organically managed soils, mostly long-banned substances are found, while conventionally managed soils host mostly a mix of compounds currently in use and recently or long banned. Glyphosate and its main metabolite aminomethylphosphonic acid, and dichlorodiphenyltrichloroethane, are the compounds most frequently found in soils (Geissen *et al.*, 2021; Riedo *et al.*, 2021; Knuth *et al.*, 2024). Comparison with past assessments (Silva *et al.*, 2019) indicates a higher prevalence of pesticides residues, and a higher toxicity risk, in 2018 than in 2015 (Vieira *et al.*, 2023b; Franco *et al.*, 2024).

The global database on mine sites (Hudson-Edwards *et al.*, 2023) allows the identification of active (75 %) and inactive (25 %) mines in EU territory, as well as the major commodities under exploration (18 % copper, 16 % gold, 15 % lead, 12 % zinc). In the Member States, about 2.8 million sites are suspected to be polluted (Payá Pérez and Rodríguez Eugenio, 2018; EEA, 2022b), although only one quarter are included in national registries.

In the western Balkans, soil contamination is a significant issue, resulting from over a century of industrialisation. The extent of contamination in the region is difficult to determine precisely, although some countries, such as Serbia, have made initial estimates (Arias-Navarro *et al.*, 2024). Inadequate waste management remains a significant contributor to soil pollution despite efforts to improve legislation. Agriculture, which occupies 45 % of the land in the region, faces challenges brought by trace elements in fertilisers and pesticide residues. In addition, emerging contaminants, such as microplastics, pharmaceuticals, and per- and polyfluoroalkyl substances, are under-researched but require attention to implement effective soil management strategies (Vidojevic *et al.*, 2022).

The extent of contamination in Türkiye is difficult to determine due to a lack of data. A national project in Türkiye titled 'Determination of plant nutrient and potential toxic element contents of Türkiye's agricultural soils: Creation of a database and mapping' is being conducted by the General

box
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Assessment of the impact of military activities on soil quality in Ukraine

An analysis conducted by the Institute of Soil Protection of Ukraine assessed the impact of military activities on soil quality in regions including Kyiv, Zhytomyr, Sumy and Kharkiv. Soil samples were analysed for heavy metals, oil products and agrochemical parameters. The results showed that the maximum allowable concentrations were exceeded for Pb, Zn, Cu and Mn in the Sumy region due to military activities. In Kharkiv, nickel (Ni) concentrations surpassed the maximum allowable concentration at various sites affected by explosions. In addition, research on soil flooding after the destruction of the Kakhovka Reservoir dam revealed Pb, Cd, Zn and Ni contamination in the Kherson and Zaporizhzhia regions. Experts identified pollutants such as petroleum products, heavy metals and toxic organic chemicals in war zones. They noted soil changes including increased heavy metal content, increased carbon content due to burning and alterations in particle size distribution and density in areas affected by military machinery. Preliminary estimates by experts suggested significant economic losses totalling USD 34.442 billion, for example because of damage to land resources and soils due to pollution and contamination.

The assessment of the impact of military activities on soil quality in Ukraine underscores the urgent need for remediation efforts and proactive measures to mitigate further environmental degradation. The findings highlight widespread contamination by heavy metals and pollutants, posing risks to both agricultural productivity and public health. Addressing these challenges requires coordinated efforts from government agencies, environmental organisations and the international community to restore soil health and safeguard the well-being of affected communities.

Photos box 4: *The impact of war on soil.* Source: *Y. Dmytruk.*

Directorate of Agricultural Research and Policies. The project aims to establish a comprehensive database by collecting soil samples nationwide, creating soil property distribution maps, supported by the geographic information system, at a scale of 1/100 000, and develop software to monitor changes in soil properties over time. This initiative is part of efforts to assess and manage soil quality and identify potentially toxic elements present in soils across Türkiye (CBSBB, 2023).

In Ukraine, soil pollution stems primarily from three sources: residual radionuclides from the Chernobyl nuclear disaster; industrial activities such as metallurgy, the use of chemicals and mining, which release trace elements and radionuclides; and agricultural practices involving pesticides, fertilisers and liquid waste.

Expert assessments suggest that 9–11 % of arable land is affected by soil pollution. The state sanitary inspectorate monitors pollutant levels in urban soils, identifying significant contamination with heavy metals such as Cd, Mn, Pb, Cu and Zn in cities such as Pavlohrad, Mariupol and Pervomaisk. The exceedance of maximum allowable concentrations for Pb and Cd was observed in various regions. Moreover, approximately 5.35 million hectares of Ukrainian territory remain radioactively contaminated, with 1.24 million hectares of agricultural land exhibiting high levels of ^{137}Cs contamination (Ministry of Environmental Protection and Natural Resources of Ukraine, 2021).

4.6.2 Drivers

Soil pollution in Europe is driven by various factors, each contributing to the degradation of soil quality and posing risks to environmental and human health.

- Industrial activity. Due to the long industrial history of EU, industrial activities represent two thirds of point sources of soil pollution, in combination with commercial and waste disposal and treatment activities (Payá Pérez and Rodríguez Eugenio, 2018; EEA, 2022b). The main associated contaminants are mineral oils, trace elements (e.g. arsenic, cadmium, lead, nickel, and zinc), and organic contaminants such as halogenated and non-halogenated solvents, polychlorinated biphenyls and polycyclic aromatic hydrocarbons.
  - Industrial waste products from food production, leather tanneries and the pharmaceutical industry are some of many drivers of heavy metal contamination (Cicchella *et al.*, 2014).
  - Primary sources of polychlorinated biphenyls are silicon rubber (Perron, 2021) and iron-steel manufacturing facilities (Kuzu *et al.*, 2016), recycling facilities (Tang *et al.*, 2010) and scrap metal sites (Odabasi *et al.*, 2016).
  - Besides mining activities, coal burning and cement production (atmospheric deposition) are drivers of thallium pollution (Legrand *et al.*, 2022). Per- and polyfluoroalkyl substances, which can be found in slurry on agricultural land, and in firefighting foam and metal plating facilities, are now threatening soil and groundwater quality (Brunn *et al.*, 2023).
- Urban areas and the transport sector. Severely polluted urbanised areas can have an impact to soils for several kilometres surrounding the source (Miśkowiec *et al.*, 2015; Ordóñez *et al.*, 2015; Miśkowiec, 2022).
  - According to FAO (Abel *et al.*, 2015), 60 % of the inner-city soils of Berlin are classified as Urbic Technosols. These anthropogenic soils are, in many cases, 'multi-contaminated', as they contain multiple (heavy) metals and metalloids but also organic pollutants.
  - Lead, zinc, copper and cadmium contamination were found in samples taken on the surface and in the immediate vicinity of a highway in France. The observed concentrations decreased rapidly with an increase in distance and depth (Pagotto *et al.*, 2001). Other studies identify these sources of pollution as a global problem (Stojic *et al.*, 2017; De Silva et al., 2021).
  - The design and operation of landfills, and inappropriate site selection, may result in the leakage of contaminated leachates into the surrounding water and soil (Ma, Zhou *et al.*, 2022).
- Agriculture. Agricultural soils can be contaminated due to traditional farming activities, such as the application of pesticides, fertilisers, manure

and sewage sludges and the use of plastic mulches, and motivated by increasing demand for crop production (FAO, 2021).

- Ostermann *et al.* (2014) found correlations between concentrations of the antibiotic sulfamethazine and Cu or Zn, suggesting that in regions with a high rate of manure application the assessment of metals currently in soils may help to identify potential hotspots for antibiotic pollution.

- The release of antibiotics and other pharmaceuticals to soils tends to result from the spreading of manure (de la Torre *et al.*, 2012), the discharge of effluent from manufacturing plants, the spreading of sewage sludge or grazing livestock (European Parliament, 2021). The release of these pharmaceuticals results, among other things, in the development of antibiotic resistance genes in soil (Delgado-Baquerizo *et al.*, 2020). Similarly, heavy metals and biocides have been described as factors promoting the development of antimicrobial resistance by selective pressure (Cycoń *et al.*, 2019).

- Plastic mulches, used in agricultural lands to improve water use and reduce the prevalence of weeds, are a source of microplastics, known to affect soil organisms (Lin *et al.*, 2020) and soil's physico-chemical and hydrological properties (Qi *et al.*, 2020). Moreover, plastic debris can adsorb pesticides, affecting their transport and slowing down their degradation (Peña *et al.*, 2023).

- Hazards and military activities. Soil pollution can also be caused by punctual events with unprecedented impacts, triggered by natural hazards but also by exceptional anthropogenic circumstances such as military activities or wars. Examples of those at the EU level are as follows.

  - Radionuclides emitted by atmospheric nuclear weapons tests, which peaked in the 1960s, and the Chernobyl accident in 1986 are found ubiquitously in soils across Europe. Nevertheless, the spatial patterns and the contributions of these two sources remain poorly constrained (Meusburger *et al.*, 2020).

  - Warfare and military activities can lead to the physical disturbance of soils and their enrichment with heavy metals (e.g. copper and lead) from fragments of shells, munitions, etc. (Williams and Rintoul-Hynes, 2022; Dmytruk *et al.*, 2023).

- Fires. Fires are known to drive soil pollution due to the release of toxic compounds during combustion, not only in forests (e.g. polycyclic aromatic hydrocarbons, metals; Ré *et al.*, 2021) but also in urban areas (e.g. lead release from the Notre Dame Cathedral fire; Briard *et al.*, 2023) and industrial waste sites or other brown field sites (Abraham *et al.*, 2017).

4.6.3 Impacts

The impacts of soil pollution in Europe are multifaceted and far-reaching (De Vries *et al.*, 2022), posing significant challenges to environmental sustainability, public health and socioeconomic well-being.

- Animal and human health. Living in areas with a higher concentration of heavy metals and metalloids in soil was associated with all-cause cardiovascular disease mortality, the aetiology of some types of cancer and an increased probability of having a mental disorder (Núñez *et al.*, 2017; Ayuso-Álvarez *et al.*, 2019). It should be highlighted, however, that most of the studies identified refer to the total amount of a given pollutant in soil, and do not consider the bioavailable fraction that has the capacity to be incorporated and accumulate in the body (Hemphill *et al.*, 1991; Zhao *et al.*, 2020).

- Ecosystem service degradation. More than 50 % of people in European countries live in cities (Eurostat, 2023), but all of them depend on soil health status, especially for food supply and a healthy environment. The potential impacts of pollutants in soils ecosystem's services provision could be identified by the following examples:

- Metal and pesticide pollution. Affects soil invertebrates and soil microbial communities, impacting carbon cycling and storage (Azarbad *et al.*, 2015; Faggioli *et al.*, 2019; Soudzilovskaia *et al.*, 2019; Gunstone *et al.*, 2021).

- Microplastics and nanoplastics. Have negative effects on soils' chemical and physical properties. The degradation of these substances often releases additional contaminants, affecting soil organisms and plant growth, and accumulating in the food chain. However, the long-term effects of microplastics on soil are still poorly understood (Shafea *et al.*, 2023).

It should be highlighted that soils with naturally high pollutant (e.g. arsenic, cadmium, lead) levels should not be considered degraded soils or to degrade ecosystem service provision, unless their natural equilibrium is disrupted.

The assessment of soil pollution presents significant challenges due to substantial gaps in knowledge. These gaps stem from historical deficiencies in monitoring practices and a limited understanding of the complex interactions between pollutants and soil ecosystems. Despite the recognised presence of various pollutants and their adverse impacts on soils, comprehensive assessment frameworks remain incomplete. The main knowledge gaps can be divided into four groups.

- Processes. Due to a general lack of knowledge on individual substances, it is often not possible to identify their pathways to soil or interactions with soil properties, which also affect their residence, transport and fate, nor identify their ecotoxicological properties, bioaccumulation and bioavailability, or their exposure and risk to the environment and humans.

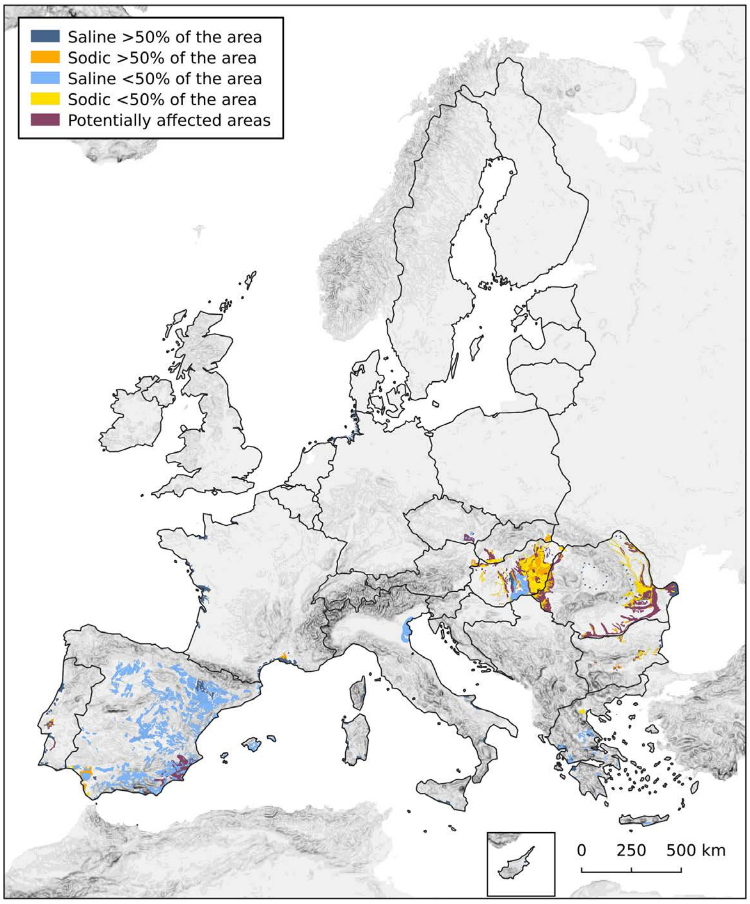
- Monitoring. Our limited capacity to quantify and determine the level and spatial extent of various pollutants in EU soils, for both diffuse and point-source pollution, limits the development of knowledge and regulations. A harmonised inventory and an impact assessment of contaminated sites across Member States are examples of unavailable knowledge products.

- Synergies. Several studies show that soils are often contaminated by several different substances simultaneously, and very little is known regarding the combined effect of mixtures. This is also an issue when defining reference values (thresholds, background levels and values for screening) for soil health at the EU scale, given the natural background pollution, the variability of soils in the EU and other pressures currently in place.

- Emerging pollutants. There is no priority watch list for pollutants in soil that could help in specifically addressing the former points in relation to emerging pollutants.

Addressing these gaps, in a holistic and harmonised way, with policy support, is essential for developing effective strategies to mitigate soil pollution and ensure the sustainability of soil resources for future generations. The consequences of soil pollution extend beyond environmental degradation to include risks to human health, food security and ecosystem integrity. Addressing these challenges requires concerted efforts from policymakers, industries and the public to implement effective pollution prevention and remediation measures, promote sustainable land management practices and foster greater awareness of the importance of preserving soil health for current and future generations. By taking decisive action to mitigate soil pollution, Europe can work towards ensuring a more sustainable and resilient future.

Figure 11. Saline and sodic soils map for the EU-27 showing the area distribution of saline, sodic and potentially salt-affected areas, 2008.



Source: EUSO, based on Tóth et al. (2008).

4.7 Soil salinisation and sodification

Soil salinisation is a major soil degradation process in Europe, diminishing soil fertility. It can stem from natural factors such as geological and climatic conditions or human-induced practices such as improper irrigation methods and poor drainage, with Mediterranean countries being most affected. Rising trends in soil salinisation are evident in Spain, Italy, Cyprus and Portugal due to various factors, including climate change and intensive agriculture. Addressing soil salinisation necessitates integrated management approaches focusing on drainage improvement, sustainable irrigation, crop selection and ecosystem restoration.

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Soil salinisation is the increase in soluble salt concentration in soil. It is considered one of the major causes of soil degradation, decreases soil fertility in Europe. It can happen naturally (geological, climatic, topographic and hydrological origin) or be human induced. Human activities, such as unsustainable irrigation practices and inappropriate management of water reservoirs and canals, can cause secondary salinisation (Daliakopoulos *et al.*, 2016), as can the use of salt-rich irrigation water or poor drainage conditions (FAO and ITPS, 2015). Similarly, sodification is the process by which the exchangeable sodium (Na+) content of soil is increased (Hopmans *et al.*, 2021). This results in the soil having unfavourable physical and chemical properties, which makes it difficult to utilise the soil and reduces its ecosystem service potential.

4.7.1 Status and trends

In Europe, salt-affected soils occur in the Caspian basin, Ukraine, the Carpathian Basin and the Iberian peninsula. Soil salinity affects an estimated 1 million hectares of land in the EU, mainly in the Mediterranean countries (Tóth *et al.*, 2006). Excess levels of salts affect around 4 million hectares of European soils because of secondary salinisation (Van-camp *et al.*, 2004), especially in the coastal areas of southern Europe (Daliakopoulos *et al.*, 2016). These areas include the Ebro valley in

box
5

Coastal vulnerability and groundwater salinisation in Türkiye: Implications and solutions.

Türkiye faces significant coastal impacts due to rising sea levels, with millions of people residing in vulnerable regions along the Mediterranean, Aegean, Marmara, and Black Sea coasts. Coastal cities, though occupying a small percentage of the country's land area, house a substantial portion of its population and contribute significantly to its GDP (Güven, 2007).

The Ministry of Agriculture and Forestry (MoAF) in Türkiye conducted a research project in the Kızılırmak Delta Coastal Region to study groundwater characteristics and the impact of sea water intrusion on water and soil - The Bafra Plain Irrigation Project. The project exemplifies the challenges faced, where groundwater salinity and seawater intrusion have escalated due to excessive irrigation from underground wells. Despite efforts to mitigate salinity issues, groundwater remains saline, affecting agricultural productivity and soil quality.

Urgent action is needed to address coastal vulnerability and groundwater salinization, emphasizing the importance of site-specific studies and integrated coastal management strategies to safeguard Türkiye's coastal regions and agricultural lands.

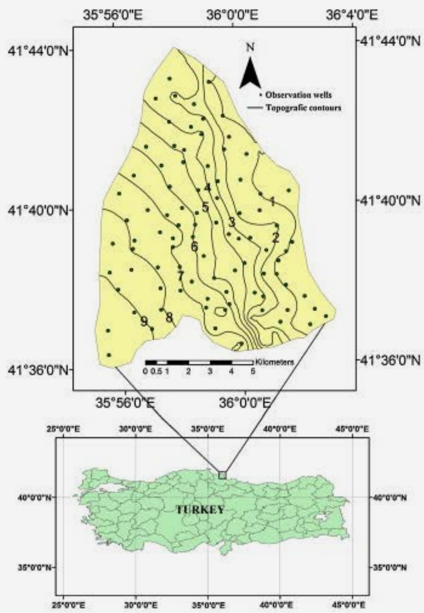


Figure box 5: Location of the study area. Samsun Bafra Kızılırmak Delta.
Source: Arslan et al., (2007) and MoAF (2022).

Spain, Sicily and other parts of Italy (Tarolli *et al.*, 2024), Greece, France, Hungary, Portugal, Romania and Slovakia (Jones*et al.*, 2012). While the precise extent remains uncertain, it is estimated that in Europe Mediterranean regions are most susceptible to soil salinisation (Daliakopoulos *et al.*, 2016; Stolte *et al.*, 2016).

An EU-27 map of saline and sodic soils (Tóth *et al.*, 2008) delineates the spatial distribution of regions classified as saline, sodic and potentially affected by salt areas (Figure 11). The accuracy of input data only allows the designation of salt-affected areas with a limited degree of reliability (e.g. < 50 % or > 50 % of the area); therefore, the results presented in the map should only be used for guiding purposes.

Agriculture-induced salinisation is a significant form of soil degradation in certain areas, with moderate to high salinisation levels affecting approximately 25 % of irrigated cropland in the Mediterranean (Mateo-Sagasta and Burke, 2011; IPBES, 2018). Such salinisation impacts parts of Greece, Spain (south-east areas, the Ebro valley), France (west coast), Italy (Sicily, Campania), Cyprus and Portugal (coastal areas) (Marien *et al.*, 2023). In Spain, for example, 3 % of the 3.5 million hectares of irrigated land has reduced agricultural yield due to soil salinity, and another 15 % faces a similar risk. Similarly, about 9 % of Greece's 1.4 million hectares of irrigated land experiences soil salinisation (Daliakopoulos *et al.*, 2016) due to seawater intrusion (Jones *et al.*, 2003; OECD, 2009). In addition, some soils in Albania, southern France and northern Portugal, and other regions, also hinder agriculture due to their high levels of salinity and sodicity (Daliakopoulos *et al.*, 2016). However, these areas do not always align with those identified in the saline and sodic soil maps of the European Soil Data Centre (ESDAC) database, indicating a limited degree of reliability. These findings should therefore primarily be used for guiding purposes (Tóth *et al.*, 2006).

While no systematic data on soil salinisation trends are available, research indicates that salinisation is increasing in Spain and Italy due to the large extent of irrigated areas with a high evapotranspiration demand (aridity index < 0.2). In addition, there is a high risk of saline intrusion in coastal areas in Portugal owing to groundwater abstraction and rising sea levels (European Commission, 2020), and in Cyprus due to mining activities (Stolte *et al.*, 2016). In addition, the EUSO Soil Degradation Dashboard measures irrigation in climatic areas with more evaporation than precipitation to estimate the soil salinisation risk.

Solonetz soils, characterised by a high clay content and the significant accumulation of sodium ions within them, cover an estimated area of 135 million hectares worldwide (Cherlet *et al.*, 2018) and 0.5 % of Europe (European Commission, 2005), in regions such as Bulgaria, Spain, Hungary and Romania.

These soils are predominantly found in steppe climatic zones and flat terrains with poor drainage (Otlewska *et al.*, 2020). Due to their high clay and sodium content, these soils crack during droughts, when they dry out, and swell during extreme rainfall events, leading to the build-up of inland water, making them vulnerable to climatic extremes. Over time, the extent of saline, sodic and saline-sodic croplands has increased, resulting in accelerated land degradation and desertification and decreased agricultural productivity, and consequently jeopardising environmental and food security (Stavi *et al.*, 2021).

The western Balkans is home to a special soil type: the dark black heavy clay Chromic Vertisol (called, in Serbian, Smonitsa) (Stebutt, 1926; Pavlović *et al.*, 2017). Despite being difficult to cultivate when very dry or wet, this soil is extensively cultivated in Albania, North Macedonia and Serbia, covering nearly 10 % of the entire western Balkans region (Zdruli *et al.*, 2022). Albania reported that salinisation and acidification altogether affect about 15 000 ha, largely owing to natural conditions, except for when salinity build-up due to poor-quality irrigation water (Vidojevic *et al.*, 2022).

Soil salinisation and alkalisation processes are widespread on 4.1 % of Ukraine's arable land (Baliuk *et al.*, 2021). There are 2.8 million hectares of saline soils in Ukraine, 2 million hectares of which are on arable land, and about 0.7 million hectares are irrigated. Salinisation processes are almost widespread on Kastanozems (Haplic Kastanozems, Luvic Kastanozems, Luvic Gleyic Kastanozems) of the Ukrainian steppe. In some areas, Solonetz (Mollic Gleyic, Stagnic and Gleyic) and Solonchaks are present.

Recent studies highlight significant salinity and alkalinity issues across Türkiye, affecting approximately 1.5 million hectares of land, with 1.1 million of hectares experiencing salinisation, 390 000 hectares facing saline-alkaline conditions, and 10 000 hectares afflicted by alkalinity (Okur and Örçen, 2020). Moreover, these issues impact 3.8 % of cultivated agricultural land and 9.0 % with drainage challenges. Türkiye faces significant impacts in coastal regions due to rising sea levels, with millions of people residing in vulnerable regions along the Mediterranean, Aegean, Marmara and Black Sea coasts. Institutional research projects are being conducted to study groundwater characteristics and the impact of sea water intrusion on water and soil (Arslan *et al.*, 2007; MoAF, 2022).

Urgent action is needed to address coastal vulnerability and groundwater salinisation, and integrated coastal management strategies must be implemented to safeguard coastal regions and agricultural lands.

4.7.2 Drivers

The main drivers of soil salinisation in Europe can vary depending on the region, but some common factors include the following.

- Irrigation practices. Improper irrigation practices, such as excessive or poorly managed irrigation with salty water, can lead to the build-up of salts in the soil. In arid regions, where irrigation is necessary for agriculture, such as southern Europe, the accumulation of salt deposits can become a significant issue due to the high salt content of irrigation water. Drivers encountered in agricultural irrigation arise at successive stages, starting from the development of water resources to the use of water at the field level. Additional problems arise from factors such as insufficient knowledge about irrigation among farmers, misguidance and the inadequate use of technology (Obi *et al.*, 2014; Shahid *et al.*, 2018)

- Poor drainage. The most important factor in the occurrence of drainage problems is uncontrolled surface irrigation, which is inefficient. In addition, damage to and poor maintenance of irrigation canals and water intake structures cause unnecessary and uncontrolled water inflow to land. The depth of groundwater in irrigated areas may vary depending on the efficiency of the drainage system. Groundwater rising to the effective root zone causes a decrease in yield in irrigated agricultural areas due to salinity and alkalinity problems, and may even render these areas unsuitable for agriculture. Poorly drained soils are particularly susceptible to salinisation, especially in areas with high water tables or clay-rich soils (Bahçeci *et al.*, 2006; Mukhopadhyay *et al.*, 2021).

- Intensive agriculture. Intensive farming often relies on fertiliser supply to maximise crop yields. Some fertilisers contain soluble salts, such as potassium chloride and ammonium nitrate, which can contribute to soil salinity when applied in uncontrolled amounts (Corwin and Scudiero, 2019; Corwin, 2021; Liu *et al.*, 2023; Tarolli *et al.*, 2024). It is noteworthy that the use of mineral fertilisers in some Mediterranean countries, such as Greece, France, and Italy, contribute to soil salinisation in agricultural lands (Katerji *et al.*, 2000).

- Climate change. Climate change can exacerbate soil salinisation by altering precipitation patterns and increasing temperatures, leading to changes in evaporation rates and water availability (Ajilogba and Walker, 2020) . The harmful impacts of climate change accelerate the development of soil salinity, potentially spreading the problem to unaffected regions (Mukhopadhyay *et al.*, 2021). The rising temperatures and droughts increase evapotranspiration. As a result, water evaporates and the salt remains in the soil, increasing soil salinity. However, salt-affected soils used for agriculture could act as a carbon sink if these negative effects can be offset by a combination of sustainable land management practices (Garcia-Franco *et al.*, 2021).

- Coastal waterlogging. In coastal areas, saltwater intrusion into freshwater sources can result in saline soils. This can occur due to factors such as rising sea levels, the over-extraction of groundwater or changes in coastal hydrology. Drivers of rising sea levels are the thermal expansion of ocean water, the melting of glaciers and the mass loss of polar and circumpolar ice sheets. The rise in seawater intrusion, driven by climate change and human activities, is a major concern in coastal areas of Greece, Spain, Italy, Cyprus and Portugal (Daliakopoulos *et al.*, 2016).

4.7.3 Impacts

Soil salinisation disrupts the natural cycles of various earth processes, including biochemical (Wong *et al.*, 2010; Setia *et al.*, 2013), hydrological (Zhou *et al.*, 2017) and biological (Baumann and Marschner, 2013) cycles. Elevated levels of salinisation can lead to the depletion of valuable soil resources, and essential goods and services, which in turn can have adverse effects on agricultural production and the overall health of the environment (Rengasamy, 2006). Soil salinisation can have significant impacts on both agricultural productivity and ecosystem health. Some of the key impacts include the following.

- Reduced crop yields and food security. High soil salinity levels can inhibit plant growth and reduce crop. Irrigated areas in arid and semi-arid regions have different levels of salinity problems. The reports prepared by FAO and the United Nations Educational, Scientific and Cultural Organization based on the data from the Soil Map of the World state that 954 million hectares of land have been affected by salinity and limited fertility worldwide (Shahid *et al.*, 2018). Potential impacts of the formation of Solonetz soils within the EU include the loss of arable land due to swelling clay, increased sodium content and waterlogging, decreasing agricultural productivity (Hateffard *et al.*, 2022).

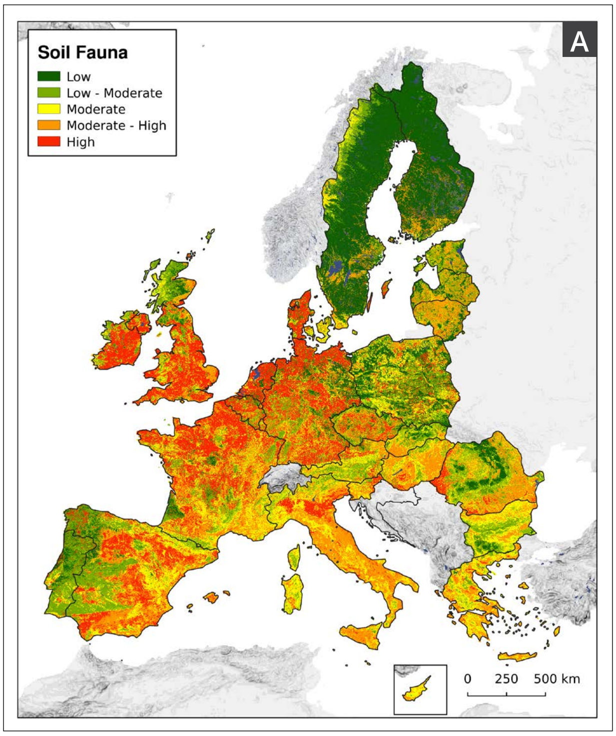
- Economic impacts. Soil salinisation can have economic repercussions for agricultural industries, including reduced crop yields, increased irrigation costs and decreased land values. Farmers may incur additional expenses for soil remediation measures such as leaching, soil amendments and land reclamation, impacting profitability and livelihoods. Research conducted in three countries (Bulgaria, Spain and Hungary) revealed that the annual costs associated with soil salinisation, primarily attributable to agricultural yield losses, fall within the range of EUR 158 million and EUR 321 million (Montanarella, 2007). Another study conducted by Bosello *et al.* (2012), which focused on specific rivers and deltas, estimated that the current economic impact of salinity within the EU, primarily in the agricultural sector, amounts to approximately EUR 600 million.

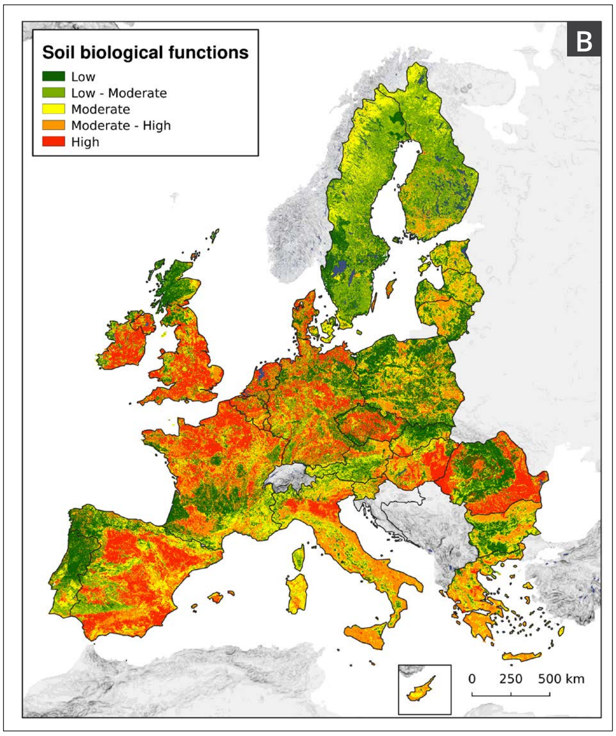
- Environmental degradation. Soil salinisation can lead to the degradation of natural habitats, including wetlands, grasslands and forests, as salt-tolerant species may outcompete native vegetation. The loss of habitat diversity and ecosystem services can further exacerbate the impacts of soil salinisation on overall ecosystem health and resilience (Daliakopoulos *et al.*, 2016).Increasing salinity can alter soil microbial communities and inhibit the growth of native plant species, leading to reduced biodiversity and ecosystem resilience. Changes in soil salinity can also impact soil-dwelling organisms, such as earthworms and beneficial microbes, which play crucial roles in nutrient cycling and soil health (Saviozzi *et al.*, 2011).

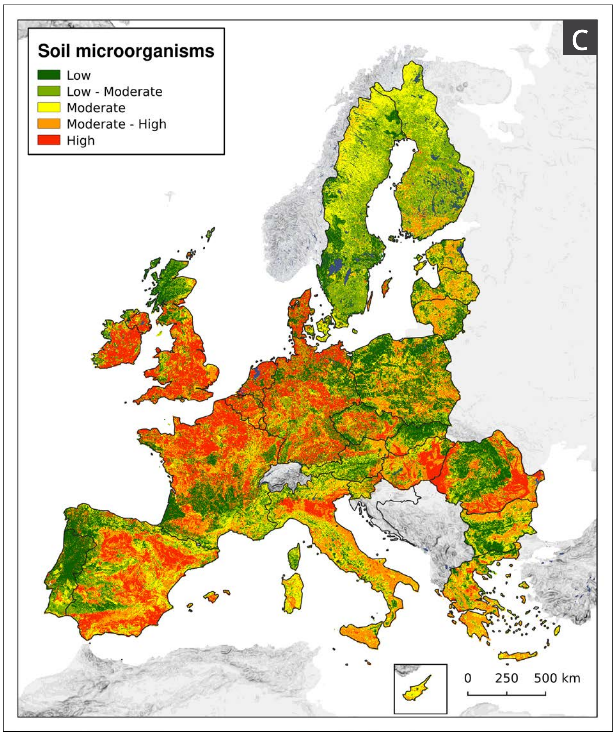
- Desertification. Soil salinisation is a major driver of desertification in the Mediterranean region, primarily due to human activities, including extensive irrigation and the unreasonable use of saline water, causing over-pumping and seawater infiltration (Abu Hammad and Tumeizi, 2012; Domínguez-Beisiegel *et al.*, 2013).

Despite being recognised as a major soil threat in the soil thematic strategy (Panagos and Montanarella, 2018), specific EU legislative policies do not address salinisation yet (Ferreira *et al.*, 2022). Moreover, salinisation and sodification are not subject to specific CAP measures, even if they contribute indirectly to soil degradation (Ronchi *et al.*, 2019). Addressing soil salinisation requires integrated management approaches that focus on improving soil drainage and implementing sustainable irrigation practices. Adaptation strategies in the long run should include selecting salt-tolerant crop varieties and developing new restoration methodologies (Tarolli *et al.*, 2024). By mitigating the impacts of soil salinisation, Europe can safeguard agricultural productivity, protect natural resources and promote environmental sustainability.

Figure 12. Distribution of potential risks to soil biodiversity (i.e., soil microorganisms, soil fauna) and soil biological functions in the EU + United Kingdom.







Source: EUSO based on Orgiazzi et al. (2016).

4.8 Soil biodiversity change

Soil biodiversity – including microorganisms, such asfungi and bacteria, and fauna, such as springtails and earthworms – is vital for the provision of ecosystem service s such as food production, medicine discovery and water regulation. Factors such as pH, land use and climate influence soil biodiversity. Urbanisation, agricultural intensification and pollution pose significant threats. Climate change exacerbates these risks, affecting the distribution and abundance of soil organisms. Addressing biodiversity changes is imperative for maintaining soil health, ecosystem resilience and food security.

Soil organisms span a wide range of body sizes, from microorganisms (e.g., fungi and bacteria) to macro-fauna (e.g., earthworms). Soil biodiversity (number and diversity of species) is an essential component for the delivery of soil ecosystem services, such as food production, pest control, and water and climate regulations (Barrios, 2007; Delgado-Baquerizo *et al.,* 2020).

4.8.1 Status and trends

An assessment of soil biodiversity was included in the LUCAS soil module for the first time in 2018, gathering data from over 880 soil samples collected across all the current Member States and the United Kingdom. The sampling method was repeated in the 2022 survey, and expanded to over 1 500 samples. Data collected in 2018 enabled the generation of the first ever EU-wide assessment of soil biodiversity by means of DNA metabarcoding (Köninger *et al.*, 2023; Labouyrie *et al.*, 2023). This analysis led to the elucidation of consistent trends between prokaryotic and eukaryotic communities: usually, higher biodiversity was hosted in croplands than grasslands and woodlands. Additional analyses have been carried out on the fresh soil samples collected in 2018 to determine the spatial distribution of microbial biomass and basal respiration across the EU (Smith *et al.*, 2021). Basal respiration was incorporated as a biological indicator of soil health in the European Commission's proposal for a soil monitoring and resilience directive (European Commission, 2023).

Previously, to assess the status of life in EU soils, an inventory was made of the risk of 13 potential threats to soil biodiversity in the EU, including habitat fragmentation, land use change, soil pollution and soil sealing (Figure 12) (Orgiazzi *et al.*, 2016). The results of this study were used to populate the EUSO Soil Degradation Dashboard, which shows areas where the risk is estimated to be moderately high or high. Despite the intrinsic limits of this knowledge-based assessment, a remarkable potential risk to soil biodiversity was observed.

Beside the LUCAS soil biodiversity dataset, some Member States have national soil monitoring schemes that include soil biodiversity (e.g. France and the Netherlands). Looking beyond the EU, in Switzerland, 30 long-term monitoring sites in the Swiss Soil Monitoring Network were surveyed over 5 years to assess the long-term stability of bacterial and fungal communities in soil (Gschwend *et al.*, 2021). In the United Kingdom, for 2013–2016, an ecological survey was undertaken at the national scale in Wales to determine environmental status and trends,

Table 1. Drivers of changes in communities of the main groups of soil organisms. The top three driving factors (1 to 3) are shown; see source publications for additional details. C, carbon; temp., temperature.

Soil organism	Driving factors		
	1	2	3
Bacterial chemoheterotrophs	Isothermality	pH	Annual temp. range
Bacterial N-fixers	Carbonate	C:N ratio	Temp. range
Bacterial pathogens	pH	Clay	Isothermality
Ectomycorrhizal fungi	Monthly aridity	P	pH
Arbuscular mycorrhizal fungi	Clay	Extractable K	Temp. seasonality
Fungal saprotrophs	P	Carbonate	Monthly aridity
Fungal plant pathogens	pH	Temp. seasonality	Annual temp. range
Protists	P	C:N ratio	Bulk density
Rotifers	pH	Microbial biomass C	C:N ratio
Tardigrades	Basal respiration	P	Soil water content
Nematodes	C:N ratio	P	Bulk density
Arthropods	C:N ratio	Intensity gradient 2009-2018	Ecosystem type 2015
Annelids	pH	P	Respiration quotient

Sources: Köninger et al. (2023) and Labouyrie et al. (2023).

among which trends in soil biodiversity were included (Emmet *et al.* 2017). The Norwegian agricultural soil monitoring programme will include a soil biodiversity module in 2024. Soil biodiversity data collection is lacking in all the countries of the western Balkans, and data on biodiversity is not included in the soil monitoring programmes in Iceland, Liechtenstein, Türkiye and Ukraine.

4.8.2 Drivers

Soil biodiversity may be driven by both edaphic factors, such as pH and organic carbon, and anthropogenic factors, such as land use intensification, climate change and above-ground vegetation cover (Tsiafouli *et al.*, 2015; Orgiazzi *et al.*, 2016). The first-ever assessment of soil microbial and faunal distribution across Europe (Köninger *et al.*, 2023; Labouyrie *et al.*, 2023) allowed the description of the main factors driving both the taxonomical and the functional diversity of soil organisms. While microbial alpha diversity (i.e. taxonomical diversity in a site) is mainly shaped by soil properties, especially pH (for bacteria, see Table 1) and vegetation cover (for fungi, see Table 1), soil animals are also affected by historical conditions, including climatic conditions and land use. In Table 1, the full list of drivers is presented for the taxonomical and functional groups of soil organisms examined.

- Land use change. Land use changes, including urbanisation, agricultural intensification and deforestation, have profound impacts on soil biodiversity and ecosystems. Urban expansion converts natural habitats into impervious surfaces, reducing soil organism habitats. Population growth, and subsequent urbanisation of green spaces, has increased soil sealing, and decreased soil biodiversity by impeding organic matter inputs and water infiltration (Tibbett *et al.*, 2020). The effects of agriculture may be contrasting depending on whether taxonomical diversity or functional diversity is considered. Intensive practices tend to affect larger-bodied soil organisms negatively and alter soil food webs (Tsiafouli *et al.*, 2015). Deforestation for conversion to agricultural land or for other uses also eliminates habitats supporting diverse soil communities (Nielsen *et al.*, 2015; Wachira *et al.*, 2015).

- Pollution. Chemical pollution, stemming from agrochemicals, industrial pollutants and other sources, may contribute to the loss of soil biodiversity, although the effects reported can vary. Pesticides, for example, can deplete or disrupt non-target invertebrates, such as earthworms, and soil microbial communities, impacting not just taxonomy but also critical functions, such as N fixation and nutrient uptake (Jordaan *et al.*, 2012; Chagnon *et al.*, 2015; Mahmood *et al.*, 2016; Pagano *et al.*, 2017). However, large-scale assessments of the effects of pesticides on the whole soil-occupying community are still missing.

- Microplastics. Soils are likely to serve as a significant sink for microplastics (Hurley and Nizzetto, 2018), especially agricultural soils (Nizzetto *et al.*, 2016). However, the effects of microplastics on soil biota are largely unknown, making them an emerging threat to soil biodiversity that warrants increased attention in research and continued study in the future (Rillig and Bonkowski, 2018; Möhrke *et al.*, 2022; Sajjad *et al.*, 2022). Of particular concern is the potential for earthworms to transport microplastics through the soil profile, potentially exposing other subsoil organisms to this new threat (Rillig *et al.*, 2017).

- Climate change. Climate change can significantly influence the distribution and abundance of soil organisms, with some species proving more sensitive than others to changes.

4.8.3 Impacts

The loss of soil biodiversity may have far-reaching impacts on soil health and ecosystem functioning.

- Reduced soil fertility. The loss of key functional groups of soil organisms can decrease decomposition rates, reduce nutrient cycling and impede soil structure maintenance, resulting in reduced agricultural productivity and increased dependency on fertilisers (Janušauskaite *et al.*, 2013; Paes *et al.*, 2024).

- Disruption of ecosystem services. Soil biodiversity changes may contribute to the disruption of crucial ecosystem services such as carbon sequestration, water filtration and pest regulation, compromising the resilience of ecosystems to environmental stressors (Delgado-Baquerizo *et al.*, 2020; Le Provost *et al.*, 2023).

- Reduced food security. The maintenance of high levels of functional diversity in the soil is closely related to the functional diversity above ground. For instance, it has been shown recently that earthworms contribute to 6.5 % of global grain production and 2.3 % of legume production (Fonte *et al.*, 2023).

- Human health. Changes in soil biodiversity can alter the occurrence and distribution of disease-carrying organisms. This can increase the prevalence of vector-borne diseases, posing risks to human health (Wall *et al.*, 2015). In addition, decreased soil microbial diversity may reduce the soil's ability to break down pollutants, leading to increased levels of contaminants in food and water sources (Tibbett *et al.*, 2020).

Addressing soil biodiversity change is critical for maintaining soil health, ecosystem services and food security in Europe. Historically, soil organisms and their diversity have been underrepresented in the assessment of soil condition compared with chemical and physical characteristics (Orgiazzi *et al.*, 2018). This is due to a primary focus on properties that are well known to affect crop performance (e.g. major nutrients), but also to methodological constraints and the inability to monitor a wide range of organisms. In recent years, the evaluation of soil biodiversity has become increasingly feasible thanks to advancements in molecular biology techniques (e.g. metagenomics and metabarcoding). In this context, the European Commission's LUCAS soil biodiversity dataset will support the production of maps that provide information on the richness and abundance of the main groups of soil organisms (to be released in late 2024). These data will be fundamental to characterising soil biological condition and start developing a monitoring scheme for life in EU soils.

4.9 Soil sealing and land take

In Europe, soil sealing varies by country, with significant proportions observed in Malta, the Netherlands, Türkiye and the United Kingdom. Urbanisation and industrialisation are major drivers, leading to the conversion of agricultural and natural land into built-up areas. Albania, North Macedonia, Serbia, Türkiye and Ukraine have experienced significant soil sealing due to urban expansion and infrastructure development. The impacts of soil sealing are profound, affecting soil and ecosystem services. Soil sealing disrupts natural processes such as water infiltration and gas exchange, leading to increased flood risk, carbon loss and higher temperatures in urban areas. Biodiversity loss is also a concern. Sustainable spatial planning is crucial for mitigating these impacts and ensuring a healthy environment in the face of climate change. Efforts to unseal soils and restore their functions through multistakeholder approaches are under way in some regions, but challenges persist amid ongoing trends towards urbanisation.

4.9.1 Soil sealing

Soil sealing is the permanent covering of an area of land and its soil by impermeable artificial material, such as asphalt and concrete. It was identified as one of the main soil degradation processes in the EU's soil thematic strategy (COM(2006) 231) (European Commission, 2012), in the latest report of the EEA on the status of the European environment (EEA, 2019b) and in the EU's soil strategy for 2030 (European Commission, 2021). Soil sealing is the most serious, irreversible and unsustainable form of soil degradation.

4.9.1.1 Status and trend

Soil sealing is usually expressed as a percentage of a country's or region's (a) total area or (b) sealed area (per capita). Data used for estimating soil sealing at the national or regional level concern (FAO, 2022) include Earth observation box 6

SOIL SEALING MAPS OF FLANDERS

The annual soil sealing maps of Flanders are produced by combining the strengths of different types of data. The maps combine 'known' sealing, from the administrative Large-scale Reference Database, with modelled sealing determined by a machine learning model based on aerial images (of a 25 cm resolution). The database is continuously updated and provides a highly accurate vectorial representation of Flanders' buildings and infrastructure. The aerial images are each year produced by flights organised by Flanders and made publicly available. This has resulted in the availability of annual soil sealing maps at a resolution of 1 m since 2013.

data (satellite and aerial images) (EEA, Hungary, Italy, Spain and Flanders), cadastral data (Austria), building and infrastructure data (Flanders), spatial planning documents (Latvia), Corine Land Cover multitemporal maps (Czechia), and field survey and census data or information from ground-based data collection (e.g. obtained through the LUCAS programme). Cadastral data, however, may be imprecise and lag behind in time (Disperati and Virdis, 2015). The most common method for measuring soil sealing is by classifying high-resolution satellite imagery. A wide range of classification methodologies are used for this purpose (e.g. spectral mixture analysis, including linear spectral mixture analysis; image classification; and vegetation index analysis) (Rodarmel and Shan, 2002; Liu and Yang, 2015). To capture spatial patterns of sealing and determine the effectiveness of policy measures adequately, very-high-resolution data are required (going from 0.25 m to 1 m pixel size (Bhaskaran *et al.*, 2010; Disperati and Virdis, 2015; Codemo *et al.*, 2022). In addition, a high temporal resolution is necessary, with measurements every year or two (Viana *et al.*, 2019). Consider using threshold values for soil sealing, for example for a defined land use pattern (core city, peri-urban area, rural area) (Estoque and Murayama, 2015; Romano *et al.*, 2017). The differences between soil sealing and imperviousness are not always well addressed. Confusingly, soil sealing indicators are being defined based on imperviousness and actual soil sealing data. Imperviousness only considers soils covered by non-permeable materials, while soil sealing also considers soils covered by partly impermeable artificial material (e.g. railways). Although the utilisation of imperviousness as an indicator may not be entirely accurate, it serves as a metric at a regional scale. The EEA's data viewer and the EUSO dashboard provides accounts of imperviousness for 2018. According to the EEA, 2.72 % of European territory (the 38 EEA countries and the United Kingdom) was sealed in 2016, increasing to 2.95 % in 2018. The extent of sealed surface (relative percentage) varies by country, being highest in Türkiye (32.82 %), followed by the Malta (5.95 %), the Netherlands (5.08 %) and the United Kingdom (3.99 %). In Albania, the proportion of surface sealed is lower than in other parts of Europe (0.66 %).

Albania reported a potential loss of about 50 000 ha of agricultural land due to urbanisation for 1990–2020. It is estimated that the annual rate of soil sealing is 4.69 % per year, mostly driven by housing needs, followed by industrial activities and infrastructure development. The greatest impacts of soil sealing are observable around the largest urban areas in North Macedonia. The continuous increase in the population of the Skopje region results in the radical sealing of agricultural land. The mean annual rate of soil sealing for the whole region is 0.14 %. An analysis of contributions of certain land use categories and classes of the soils that have been sealed by urban development in Serbia from 1990 to 2018 shows that mostly pastures and heterogeneous agricultural areas were sealed.

In Ukraine, developed land falls into several categories, including residential and public buildings, industrial buildings, and buildings with transport, communications, energy, defence and other purposes, and totals 2 467 500 ha (4.1 % of the total area of the country). Ukraine is one of the top 30 countries in terms of urbanisation according to UN rankings, and there has been a marked increase in the area of sealing and urbanisation in the country in recent years.

In recent years, the scientific agenda in Türkiye has shifted towards recognising soil sealing as a significant problem, along with massive land take. This has led to actions to protect and maintain existing green areas despite urban and suburban growth (Gül *et al.*, 2006; Doygun, 2009). Case studies underline that the unsealing of soils and restoration of soil functions can be achieved by applying multistakeholder approaches involving local authorities and inhabitants (Gül *et al.*, 2006; Artmann, 2013). Initial results show that open green spaces are more actively managed and planned in Turkish agglomerations: roadside vegetation (Seyidoglu Akdeniz *et al.*, 2019) and urban and peri-urban forests (Çinis *et al.*, 2017) receive more attention than other areas. Lighthouse projects such as the Atatürk Forest Farm in Ankara stand out as models of how to convert alternative urban land use into value (Yilmaz, 2009); they have potential to create Turkish identity (Kaçar, 2011) and can act as climate mitigation tools (Ramyar *et al.*, 2021). However, currently there are no signs of urbanisation decreasing in Türkiye. While intact urban soils and their functions become more and more constrained (Nurlu *et al.*, 2015), it is important to recognise the need to safeguard valuable soil resources and manage urban sprawl effectively (Tanrivermis, 2003; Genc *et al.*, 2021).

4.9.1.2 Drivers

Rapid urbanisation, driven by population growth, necessitates the expansion of urban areas for housing, infrastructure and industry. This expansion, coupled with the development of infrastructure such as roads, highways and airports, leads to the significant sealing of land with impermeable materials. Furthermore, the conversion of agricultural or natural land into urban or suburban areas, alongside the establishment of industrial zones and factories, contributes to soil sealing. In addition, the construction of commercial buildings such as shopping malls and office complexes further exacerbates this phenomenon.

4.9.1.3 Impacts

Sealing, by nature, has a major effect on soil, reducing the supply of many of its services. It is normal practice to remove the upper layer of topsoil, which delivers most soil-related ecosystem services, and to develop strong foundations in the subsoil and/or underlying rock to support buildings or infrastructure, before proceeding with the rest of construction. This process usually results in irreversible land cover and land use change, permanently altering the soil's natural state and its ability to provide essential ecosystem services. It usually cuts off the soil from the atmosphere, preventing the infiltration of rainwater and the exchange of gases between the soil and the air. Soil sealing increases the risk of flooding, reduces water infiltration, reduces soil's ability to absorb and store carbon, increases temperatures in urban areas and reduces biodiversity (Fokaides *et al.*, 2016). Hence, sustainable spatial management is crucial to ensure a healthy living environment and address climate change.

4.9.2 Land take

Land take is a process, often driven by economic development needs, that transforms natural and semi-natural areas (including agricultural and forestry land, gardens and parks) into artificial land, using soil as a platform for construction and infrastructure, as a direct source of raw material or as an archive for historic patrimony at the expense of the capacity to provide other ecosystem services (European Commission, 2023a). On the contrary, 'land recultivation' (or 'reverse land take') means 'the conversion of artificial land into natural or semi-natural land' (European Commission, 2023a) or 'land converted from urban areas into agriculture, forest or other semi-natural areas', while 'net land take is the mathematical difference between land take and land recultivation' (Ivits *et al.*, 2020). Land take should be referred to as 'artificial land cover' and distinguished by the 'settlement area', which is 'The area of land used for housing, industrial and commercial purposes, health care, education, nursing infrastructure, roads and rail networks, recreation (parks and sports grounds), etc. In land use planning, it usually corresponds to all land uses beyond agriculture, semi-natural areas, forestry, and water bodies' (European Commission, 2023a).

box 7

Annual land take maps of Italy.

The annual land take maps of Italy are for example produced by Earth Observation techniques, using both Copernicus Sentinel 1 and 2 data and other VHR satellite images. In addition to land take maps, soil sealing and settlement areas maps are also produced every year. These data are used for the development of several indicators and for the assessment of the impact of land take (e.g. in terms of loss of ecosystem services or landscape fragmentation). Data are available for the period 2006-2022.

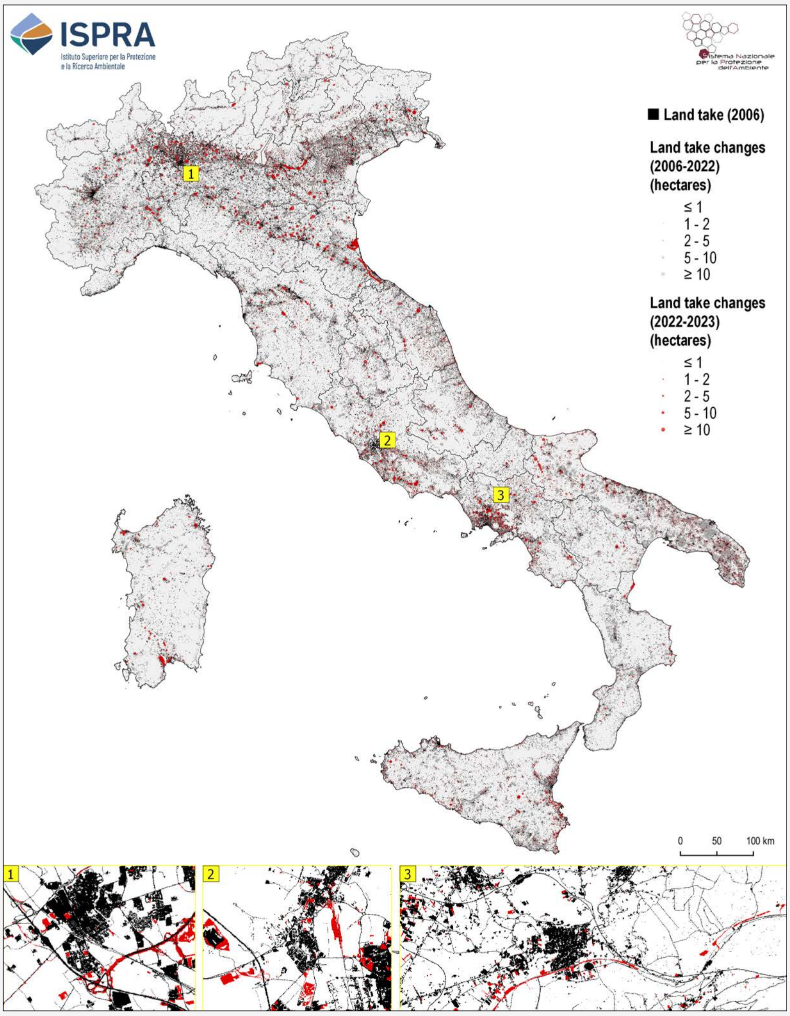


Figure box 7: *Land take changes (2006-2022) for Italy.* Source: *Munafò (2023).*

The concept of land take is often generic but should always exclude land that has been taken to build new urban green areas. So the concepts of urbanisation, which considers all settlement areas, and soil sealing should be considered alongside it.

4.9.2.1 Status and trends

Land take in 2012–2018 increased by 2.6 % in the EU and the United Kingdom, affecting 3 581 km^2 of functional urban areas. Almost 80 % of land take took place in commuting zones. Net land take, calculated by subtracting the area of recultivated land from the area of land taken, in the EU and the United Kingdom amounted to 3 013 km^2, mostly at the expense of croplands and pastures.

4.9.2.2 Drivers and impacts

Major drivers of land take include population growth, the need for transport infrastructure, cultural preferences and economic welfare (Ivits *et al.*, 2020). The process of land take may cause the, often irreversible, loss of the capacity of soils to provide other ecosystem services (food and biomass provision, water and nutrient cycling, biodiversity, and carbon storage). In particular, land take often affects the most fertile agricultural soils, jeopardising food security. Sealed soil also exposes human settlements to higher flood peaks and more intense heat island effects.

4.9.3 Landscape fragmentation

Landscape fragmentation is 'the result of transforming large habitat patches into smaller, more isolated fragments of habitat' (Dupras *et al.*, 2016). This process has a wide range of environmental and social implications, and implications for climate change adaptation and mitigation, and biodiversity. It is most evident in urbanised or heavily developed areas, where fragmentation is the product of the linkage of built-up areas through linear infrastructure such as roads and railways.

4.9.3.1 Status and trend

Based on an EEA analysis, large parts of Europe have become fragmented because of the expansion of urban and transport infrastructure (EEA, 2022c). The agency states that '27 % of land in the EU-27 and United Kingdom is considered highly fragmented where habitats are less than 0.02 km^2 on average'. Moreover, it says, 'As distance from city centres increases, the extent of landscape fragmentation drops rapidly.' The extent of landscape fragmentation varies considerably by country in the EU and United Kingdom, being highest in Malta, followed by the Netherlands, Belgium, Germany and Luxembourg. Luxembourg and Belgium have the largest areas of highly fragmented habitats. In contrast, In Finland, the Baltic states and Sweden, habitats are much less fragmented than in other parts of Europe.

4.9.3.2 Drivers

Landscape fragmentation is the outcome of complex interactions between policies, the geophysical characteristics of the landscape and socioeconomic drivers of development. Land take, urban sprawl and economic activities lead to habitat fragmentation, decreasing the resilience of ecosystems.

4.9.3.3 Impacts

Landscape fragmentation is a threat to ecosystem service supply, landscape quality and the sustainability of human land use. Landscape fragmentation changes the visual aspects of landscapes: roads, railways and built-up areas are the most prominent contributors to the transformation of natural landscapes into fragmented anthropic landscapes. Landscape fragmentation is a major cause of the rapid decline in many wildlife populations. As landscape fragmentation contributes to the destruction of established ecological connections between adjoining areas of the landscape, it also affects entire communities and ecosystems (Biswas *et al.*, 2023).

Uncertainties about the ecological effects of roads are not taken seriously enough in the planning process, which contributes to the 'spiral of landscape fragmentation' (Jaeger, 2000). Another issue is that the lack of accountability for most uncertain effects manifests years after the construction of new transport infrastructure, as the effect on wildlife populations cannot be observed until long after the infrastructure is built.

4.9.4 Land recycling rate

Land recycling is defined as the reuse of land, including the redevelopment of previously developed land (brownfields) for economic purposes; the ecological upgrading of land for the purpose of soft use (e.g. green areas in urban centres); or the renaturalisation of land (bringing it back to nature) by removing existing structures and/or by de-sealing surfaces (EEA, 2016; Ivits *et al.*, 2020). Land recycling includes grey recycling (i.e. the building of urban objects on already-developed land) and green recycling (i.e. the building of green urban areas such as golf courses and parks) (Ivits *et al.*, 2020).

Land recycling can be estimated based on multiple surface-related indicators. However, such indicators are often considered limited by the availability of initial data with a high spatial resolution, and, in some cases, they can overestimate built areas.

The reuse of artificial land may involve the de-sealing of previously sealed areas and the development of anthropogenic soils such as Technosols (Rodríguez-Espinosa *et al.*, 2021). For instance, in 2020, 2.4 % of soil was sealed and only 13 % of urban development occurred on recycled urban land in Europe (Rodríguez-Espinosa *et al.*, 2021). According to Ivits *et al.* (2020), land recycling increased from 1.96 % for the total consumed land during 1990–2000 to 2.6 % for 2006–2012. Although the general trend is an increase in recycled lands during this period, for some countries the trend is inverted. For example, in France, land recycling decreased from 2.04 % (1990–2000) to 0.87 % (2006–2012).

Land recycling rates can be considered an indicator of previously sealed soils becoming functional again. This oversimplification of the soil sealing–de-sealing process, while easy to use and accessible for decision-making, focuses only on land use, excluding the analysis of soil features and characteristics to identify and quantify their specific ecosystem services.

Further investigations should focus on tools and methods that allow the assessment and monitoring of land recycling in terms of functionality over time.

Indicators should not be limited to land use data but must integrate soil properties and processes that provide a wide range of ecosystem services.

4.9.5 Conclusions

In conclusion, the ramifications of soil sealing and land take reverberate across ecological, social and economic spheres, underscoring the need for proactive measures. From compromised soil functionality to heightened urban heat island effects and increased water pollution, the impacts highlight the need for sustainable land management practices. Addressing these challenges requires holistic approaches, incorporating green infrastructure, compact urban design and stringent land use regulations. By prioritising the preservation of natural landscapes, promoting permeable paving techniques and fostering resilient communities, we can mitigate the adverse effects of soil sealing and land take, ensuring a more sustainable and harmonious co-existence between human activities and the environment.

#05

Convergence of evidence of soil degradation in Europe

05 Convergence of evidence for soil degradation in Europe

The interplay of diverse drivers and soil degradation processes creates a complex web impacting soil condition in Europe. Soil acidity, influenced by factors such as mineral fertilisation, can deplete soil carbonates, affecting fertility and nutrient availability. Soil erosion, caused by unsustainable agricultural practices, leads to nutrient loss and diminishes soil functions. Declines in soil carbon also disrupt soil biodiversity and ecosystem services.

Chemical pollution further compounds these pressures. The EUSO (EU Soil Observatory) convergence of evidence map illustrates overlapping soil degradation processes, emphasising the need for integrated approaches to address multiple threats simultaneously. Holistic soil management practices are essential for preserving soil health and ensuring ecosystem sustainability.

Without detailed information on soil properties, characteristics, indicators and their thresholds for the delivery of multiple ecosystem services at a regional scale, policymakers, land managers, and researchers face difficulties in accurately assessing soil degradation, identifying areas of concern, and implementing targeted interventions. This gap in data and knowledge hinders our ability to understand the extent and severity of soil threats, such as compaction or contamination, which can have profound implications for agricultural productivity, ecosystem resilience, and environmental sustainability. Addressing this knowledge gap requires investments in soil monitoring and mapping initiatives, data collection efforts, and research collaborations to generate comprehensive, up-to-date information on soil health parameters across Europe. By enhancing our understanding of soil condition at a regional scale, we can better protect and manage this vital natural resource for current and future generations.

5.1 Monitoring

Soil monitoring is essential for assessing soil health and guiding sustainable land management practices (EEA, 2022b). Monitoring programmes collect data on physical, chemical and biological soil indicators, enabling the identification of trends and the effectiveness of management practices. National soil monitoring programmes vary widely in scope and methodology across Europe. The lack of comprehensive and standardised soil data across the region has led to inconsistencies and challenges in comparing soil conditions among countries.

Addressing this knowledge gap requires investments in soil monitoring and mapping initiatives, data collection efforts, and research collaborations to generate comprehensive, up-to-date information on soil health parameters across Europe. Monitoring programmes play a crucial role in assessing soil condition and guiding sustainable land management practices. These programmes typically involve systematic collection of data on various soil parameters, including physical, chemical and biological indicators. Physical indicators may include soil texture, structure and porosity, which influence water infiltration, aeration and root growth. Chemical indicators such as pH, nutrient levels, and heavy metal concentrations provide insights into soil fertility and contamination risks. Biological indicators, including microbial biomass, enzyme activity and earthworm abundance, offer valuable information on soil biodiversity and ecosystem functioning. By tracking changes in soil properties and associated soil functions over time, these programmes help identify trends, assess the effectiveness of soil management practices, and inform decision-making processes aimed at preserving soil health and promoting sustainable land use practices. In addition, monitoring data serve as a valuable resource for scientific research, policy development, and public awareness initiatives aimed at addressing soil deg-radation and advancing soil conservation efforts at the local, regional and global scales.

5.1.1 National Soil Monitoring programs

Several countries have already invested in the implementation of national soil monitoring systems, whereas some of those have been continuously active for several decades (e.g. in France). However, during their development the primary objectives of such programmes stemmed from their national priorities, resulting thus in a highly variable set of monitoring schemes.

Previous research has already reviewed existing national soil monitoring programmes in Europe for assessing soil quality through the assessment of a minimum set of attributes, e.g. in the environmental assessment of soil for monitoring project for soil threats (Morvan *et al.*, 2008) and the Forest Soil Condition Database, which include physicochemical and hydraulic properties for forest Level II sites across Europe (Fleck *et al.*, 2016). Van Leeuwen *et al.*(2017) compared existing national (regional) and EU-wide soil monitoring networks.

The environmental assessment of soil for monitoring project (2005–2008) stands out as the most comprehensive review of European soil monitoring networks to date (Huber *et al.*, 2008; Arrouays *et al.*, 2009). In addition, a recent review conducted by the European joint programme on agricultural soil management (EJP SOIL) (EJP SOIL, 2021) adds further insights to the landscape. However, results from EJP SOIL should be interpreted with caution, as not all countries have disclosed information regarding their forest soil monitoring systems, suggesting that the landscape of soil monitoring across Europe may be more varied and complex than initially apparent.

In this section, we briefly summarise national soil monitoring programmes to understand the monitoring landscape.

5.1.1.1 Central and western Europe

In 2008, the German Federal Ministry of Food and Agriculture commissioned the Thünen Institute of Climate-Smart Agriculture to conduct the first agricultural soil inventory at the national scale (Poeplau et al., 2020) and collaborates with various networks for soil protection and contaminated sites (UBA, 2015). These efforts involve about 800 measurement points across the country, covering cropland, grassland, forests and other areas. In addition, Germany has a long history of long-term field studies of agriculture, contributing valuable data to soil research. The peatland monitoring programme for climate protection – forest aims to improve the reporting of GHG emissions of forested peatlands in a comparable and representative way. This nationwide basis can then also be used to derive measures for peatland soil protection. The peatland monitoring thus provides the long-term and area-wide emission data of organic soils under forest needed for the IPCC reporting. France operates a comprehensive soil quality monitoring system (réseau de mesures de la qualité des sols), conducting soil sampling, measurements and observations every 15 years at 2 240 sites across the country since 2000. This systematic approach ensures periodic assessment and monitoring of soil conditions. In the Netherlands, national soil monitoring was done for more than 18 chemical, physical and biological indicators in 1998 and 2018, whereas each province monitors soil quality each year. Soil data are stored and available via a digital soil information system. In addition, private research institutes deliver detailed soil property maps derived from agricultural routine laboratories for regional policy support.

5.1.1.2 Northern Europe

Denmark has a long history of soil mapping, with extensive soil databases used at the national and European levels. The nationwide Danish soil databases have been widely used for the planning of rural land at the county and national levels.

Although Finland has an uneven distribution of soil measurement points (they are much denser in the south than in the northern part of the country), it does have several soil databases. In Sweden, systematic soil monitoring is conducted at both the national and regional levels by various departments of the Swedish University of Agricultural Sciences and the National Board of Forestry. These monitoring efforts are commissioned by the Environmental Protection Agency and coordinated with common protocols by county boards on a regional scale. The data collected by the university are publicly available, contributing to transparency and informed decision-making. The Geological Survey of Sweden initially conducted historical surveys and mapping relevant to soil conditions in the mid 20th century. It continues to collect data on soil depths and geochemistry, particularly focusing on the natural occurrence of metals and other substances in forest-covered moraines. Meanwhile, Ireland embarked on the Irish soil information system project between 2008 and 2014, resulting in a new national soil map and associated digital soil information system. Furthermore, Ireland has established the National Soil Database, which includes comprehensive soil geochemistry and microbiolog ical analysis, providing valuable resources for soil research and management initiatives.

Estonia has denser monitoring networks than countries such as Lithuania. In Lithuania, several national survey networks do exist. For example, the Lithuanian Geological Survey under the Ministry of Environment is responsible for soil monitoring in the 71 agricultural land sites in the context of state environmental monitoring. Monitored soil properties within this programme are related to general soil condition (soil acidity, loss of carbon, etc.) and diffuse soil contamination from agriculture and industry.

5.1.1.3 Southern Europe

Soil monitoring networks are much denser in northern and eastern Europe than in southern parts of Europe (Greece, Spain, Italy, Malta, and Portugal). Greece and Spain lack active soil monitoring networks, and their soil survey resources have historically declined. However, the Spanish Ministry of Agriculture, Fisheries and Food will conduct a comprehensive analysis of the carbon content in agricultural soils across the country. This initiative involves the analysis of soils from 16 000 agricultural plots every 2 years, indicating a significant sample size. The purpose of this exercise is to evaluate the outcomes of the recently implemented new CAP, which began this year. In Italy, soil surveying, soil mapping and information system implementation have traditionally been conducted primarily at the regional level, with approximately 20 administrative regions serving as centres for these activities. However, since 1999, there has been a notable increase in soil survey activities, mapping efforts and the development of soil databases across the country. Portugal lacks a national soil monitoring system.

5.1.1.4 Eastern Europe

Countries such as Czechia, Hungary, Poland, Romania and Slovakia have established soil monitoring systems, with varying levels of data accessibility and coordination. In Poland, the permanent monitoring of agricultural soils was initiated in 1995 as part of the State Monitoring of the Environment. The obligation to conduct soil monitoring and observe changes in soil quality is established in the Environmental Protection Law. The soil information and monitoring system in Hungary is designed to continuously monitor changes in soil quality mand environmental status, and its operation is required by law (Act CXXIX of 2007). Since 1992, annual soil sampling has been carried out at 1 236 points throughout the country. The monitoring network comprises three types of monitoring points: the national core network, which covers areas under agricultural cultivation; the forestry monitoring points for monitoring soils under forest ecosystems; and the special monitoring points for characterising areas at risk or already polluted.

The collected data are public and in the public interest, so anyone can request them to supplement scientific, research or statistical data by writing to the National Food Chain Safety Office. In Bulgaria, currently no soil monitoring network exists and the only data are collected by LUCAS. Croatia lacks a national soil monitoring network but has made some attempts to develop one.

5.1.1.5 Non-EU countries

Across non EU-countries, the state of soil monitoring varies significantly. While nations such as Norway have made substantial advances by implementing comprehensive soil monitoring programmes, others such as Türkiye lack a structured monitoring system altogether. In the United Kingdom, the National Soil Inventory plays a crucial role in assessing soil quality and land use trends. Similarly, Switzerland's National Soil Monitoring

Network has been in operation since 1984, providing valuable insights into soil quality changes over time. Ukraine faces a challenge with the absence of proper national soil monitoring despite partial coverage through soil surveys in agricultural land areas. The 'agrochemical certification of land' defined by the specific law is carried out only on agricultural land. At the same time, there are 750 monitoring sites across Ukraine, where some soil health indicators are regularly monitored.

Meanwhile, in the western Balkans, the only new regional source is the LUCAS survey of 2015. There is a pressing need for updated soil data and the establishment of comprehensive monitoring systems to address outdated information and facilitate regional comparisons. These diverse approaches highlight the importance of robust soil monitoring systems for informed decision-making and sustainable land management practices.

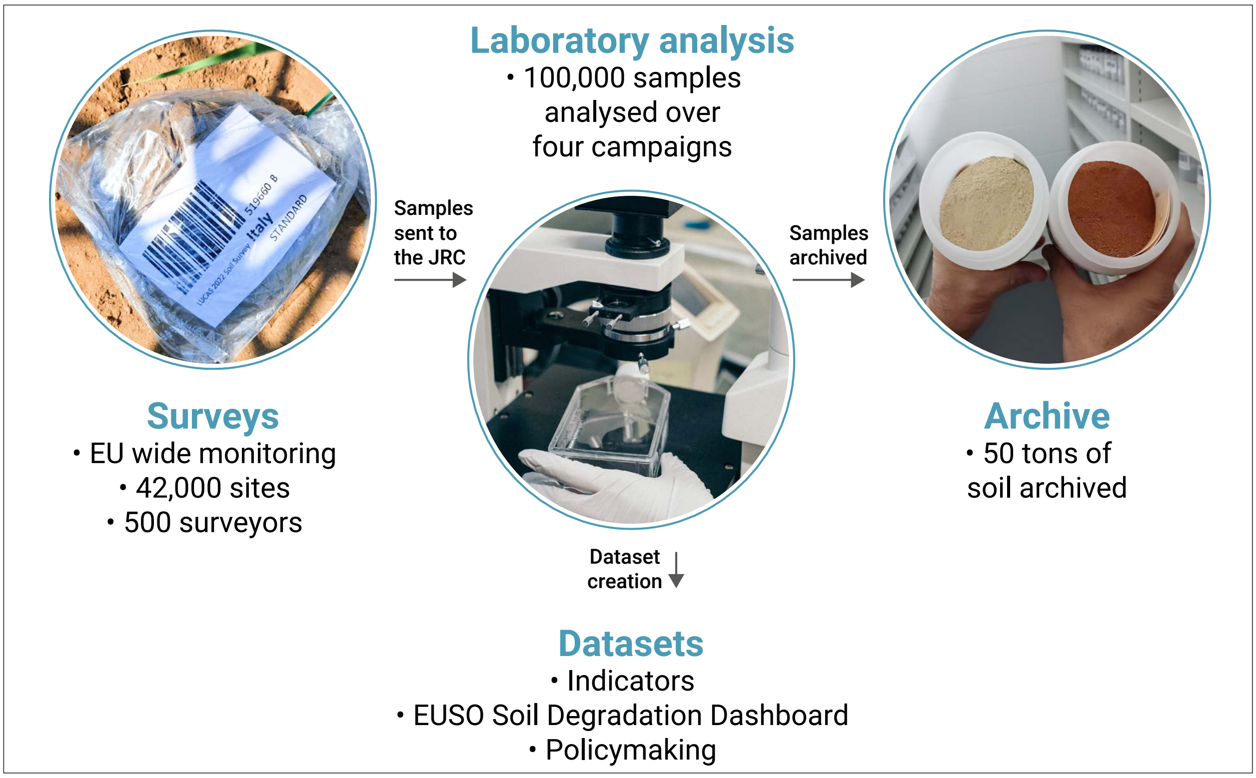
Official frameworks for comprehensive soil monitoring exist in most EU countries, but uniformity in methodology and coverage is far from standard even within national systems. Soil organic carbon and pH are among the most commonly measured parameters, reflecting their importance in assessing soil health and their direct relationship with crop productivity. However, several other soil health indicators exhibit limited coverage, even in areas deemed at risk. Parameters related to soil biodiversity and erosion are particularly under-represented in monitoring efforts. In addition, while some trace elements such as lead are measured extensively across countries, others such as mercury show substantial disparities in monitoring frequency. Indicators related to soil compaction, such as bulk density and packing density, are also lacking in approximately half of the countries. Moreover, there is a lack of uniformity in methodology and coverage, even within national systems. The need for harmonisation of procedures across different soil monitoring schemes is a significant concern. This includes analytical protocols, resampling intervals, and metadata collection and storage. Achieving harmonisation in these areas would facilitate data sharing and the comparison of procedures across different national monitoring systems, as envisaged by the proposed EU soil monitoring and resilience directive.

5.1.2 International co-operative programme on assessment and monitoring of air pollution effects on forests

The international cooperative programme on the assessment and monitoring of air pollution in forests (ICP Forests), established in 1985, initiated a comprehensive monitoring effort known as ICP Forests Levels I and II. The programme aims to enhance understanding of air pollution and its impact on forest ecosystems through intensive and continuous monitoring. ICP Forests Level I consists of an extensive systematic network, with sampling conducted within forested areas based on a 16 km x 16 km grid. Soil resampling for Level I has occurred only once, under the forest focus regulation (Regulation (EC) No 2152/2003) as part of a demonstration project. ICP Forest Level II involves regular, detailed monitoring of forest ecosystems, including crown condition assessments, soil and foliar surveys, increment studies, deposition measurements and meteorological observations over a span of at least 15–20 years.

Across the European Union, Belarus, Moldova, Montenegro, Russia, Serbia and Switzerland, 5 915 plots have been established as part of these networks. The selection of parameters measured specifically focuses on mineral layers. Detailed information regarding the collected data is provided by Arrouays *et al.* (2009).

Figure 13. LUCAS soil survey procedure.



Source: EUSO.

5.1.1.3 Land Use / Cover Area Frame Survey soil module

The LUCAS Soil programme collects soil samples across Member States and neighbouring countries, providing harmonised datasets for soil properties at a continental scale. Unlike other EU-wide soil sampling initiatives, LUCAS is a repeated sampling scheme, enabling trend analysis of soil health indicators across different land covers. LUCAS Soil contributes valuable data for scientific research, policy development and informed decision-making in soil conservation and land management. Moreover, LUCAS Soil offers opportunities for collabora tion with national monitoring systems, serving as a valuable resource for countries lacking their own soil monitoring infrastructure.

The LUCAS soil programme (Figure 13), a component of the LUCAS initiative, is a comprehensive effort to collect and analyse soil samples across the EU. Initiated by the European Statistical Office (Eurostat) in 2006 in collaboration with the Directorate-General for Agriculture and Rural Development and the JRC, LUCAS conducts regular surveys to gather information on land cover and land use. In 2009, the European Commission extended LUCAS to sample and anal yse topsoil properties in 23 Member States. Around 20 000 points were selected for soil sampling, with standardised procedures for collection and analysis carried out in a single laboratory. The same procedure, sampling method and analysis standards were extended in 2012 to Bulgaria and Romania, where samples were collected from about 2 000 locations.

In 2015, the survey was carried out for all the current 27 Member States and the United Kingdom. In addition, the soil module was extended by the JRC enlargement and integration programme

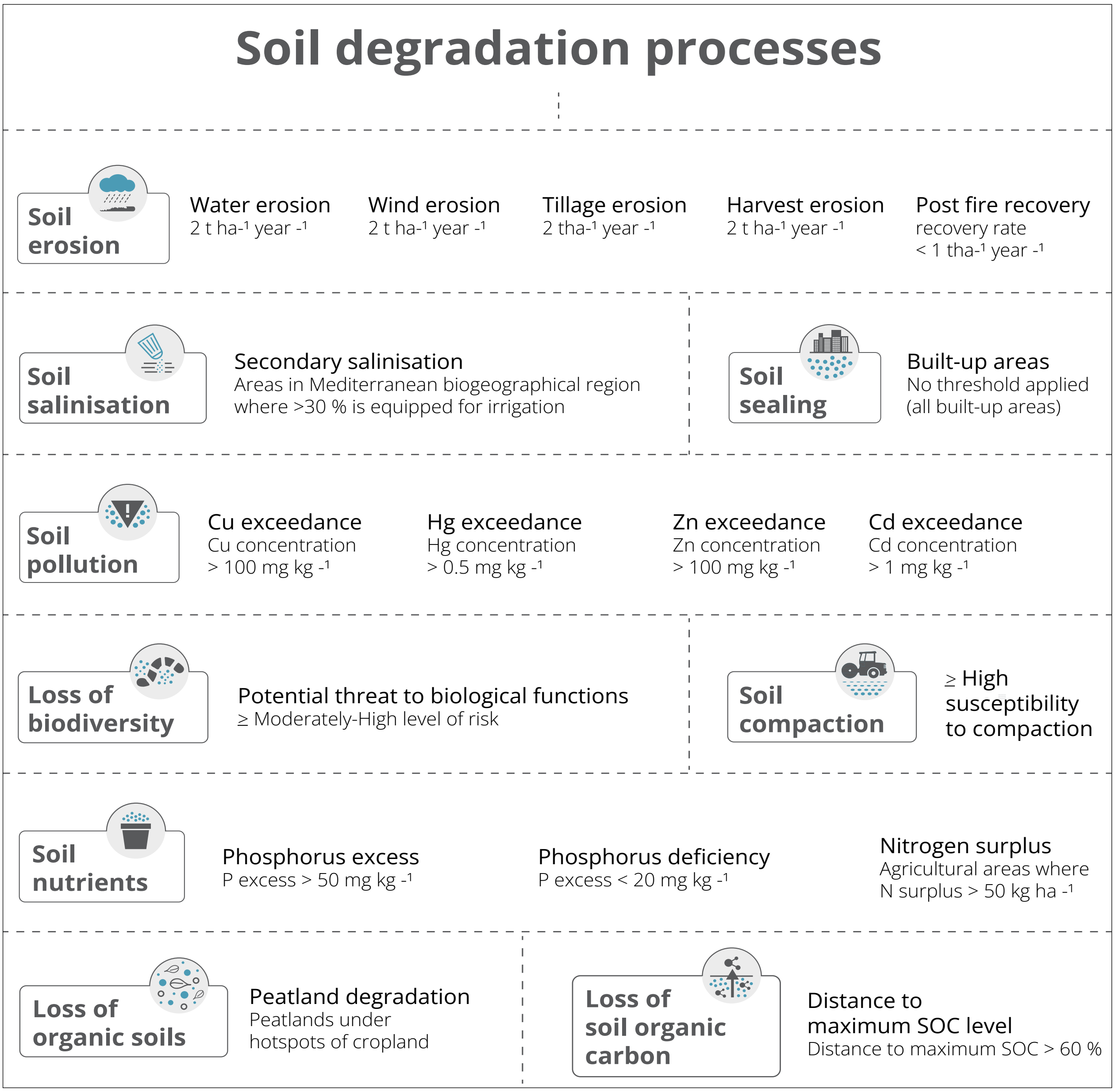
Table 2. LUCAS's integration in Member States and research bodies, including in soil monitoring systems, research programmes (e.g. the European joint programme on agricultural soil management) and data harmonisation efforts across the EU. NB: AI, artificial intelligence; EJP SOIL, European joint programme on agricultural soil management.

Aspect of integration	Description	National/research Involvement
Data use for derived products	LUCAS soil data are used to determine the physical and chemical characteristics of soil, and nutrient fluxes and pollutant levels.	Data contribute to national and European research efforts to model soil attributes and pollution levels.
Geostatistical modelling and datasets	Spatial datasets are developed for soil attributes such as clay, silt, sand, pH, C ratio and key nutrients.	National systems use these datasets to enhance models, with research from the JRC and others improving predictions for stakeholders.
Biogeochemical modelling	LUCAS data are integrated into biogeochemical models to assess carbon sequestration, N2O fluxes and soil erodibility.	The data from the modelling are used by national systems and for EU-wide studies on soil health and carbon sequestration.
Pesticides & antibiotic residues	Samples are analysed from the 2018 survey to detect pesticide and antibiotic residues.	Residues are analysed to enable the national and EU-level validation and calibration of pesticide fate models.
Soil health indicators	Biodiversity indicators are developed through the genetic analysis of soil to assess impacts on land management.	Research collaboration across Member States under the LUCAS soil module and the Directorate-General for Environment's European Monitoring of Biodiversity in Agricultural Landscapes initiative.
AI & machine learning for crop classification	The JRC and national systems use LUCAS data to train AI models to classify Sentinel-1 data and generate information on crop types between surveys.	The JRC collaborates with national research agencies and Colorado State University.
European soil data centre (ESDAC)	LUCAS soil data are accessible through the ESDAC for various national and international research projects.	Data are available to national agencies and stakeholders across Europe for policy development and environmental monitoring.
Soil organic carbon mapping	LUCAS data was used by FAO to produce the Global Soil Organic Carbon Map.	Member States and FAO use LUCAS data for SOC monitoring and climate regulation efforts.
LANDMARK H2020 methodology	The method is applied to predict synergies and trade-offs in key soil functions, such as climate regulation and nutrient cycling.	LUCAS is integrated in national research systems as part of the Horizon 2020 initiative.
Collaboration with Member States	A goal of LUCAS is to form systematic links with Member States to facilitate site access, data collection and supplementary analysis.	Discussions are ongoing between the EEA/Eionet task force for soil monitoring and the Commission Expert Group on the implementation of the EU soil strategy for 2030 to integrate national efforts.
National soil monitoring systems	Member States have national soil mapping surveys with varying degrees of repeated sampling and monitoring.	The task force for soil monitoring was established to harmonise national programmes with LUCAS's soil module to facilitate comprehensive monitoring.
EJP SOIL integration	EJP SOIL aims to harmonise information on soil across Europe, focusing on agricultural soil management and ecosystem services.	LUCAS's soil module will benefit from EJP SOIL's outputs, especially in integrating soil sampling protocols and data from Member States.
Remote sensing and machine learning	Remote sensing is integrated in LUCAS to enhance soil carbon monitoring and predictions.	The JRC collaborates with international and national institutions to apply AI and machine learning tools for soil data integration.

Source: Based on Jones et al. (2022).

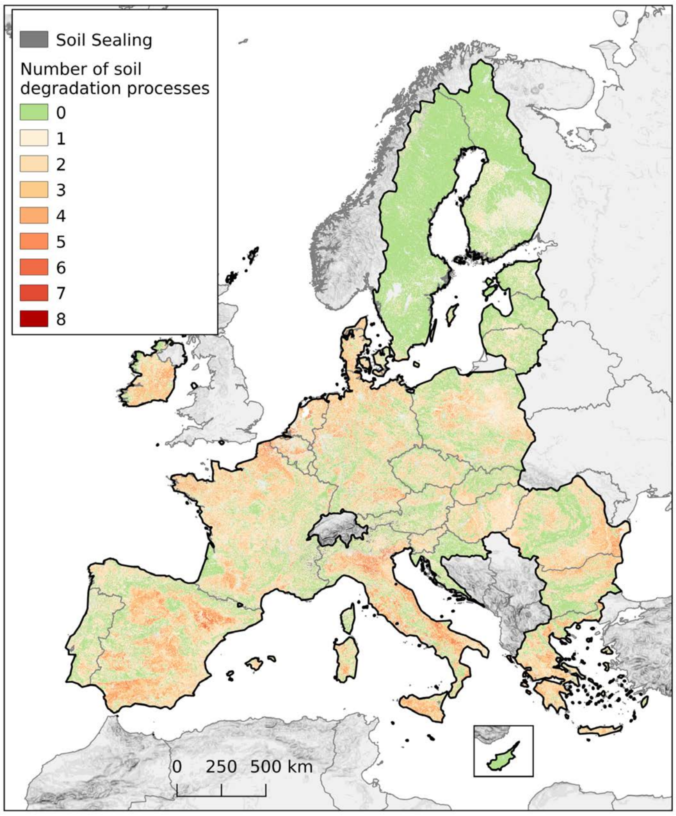
to Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia. Switzerland also participated following standard LUCAS protocols. Overall, 27 069 locations were selected for the soil sampling of LUCAS 2015. Topsoil samples are analysed for various properties, including coarse fragments, particle size distribution, pH, SOC, carbonates, total N, extractable nutrients, cation exchange capacity, trace elements and multispectral properties. The 2018 edition also includes assessments of soil erosion, organic horizon thickness, bulk density and soil biodiversity. In 2022, about 40 000 soil samples were collected for the analysis of chemical, physical and biological properties. The data collected by the LUCAS Soil programme provide the first harmonised and comparable datasets of topsoil properties at the EU level, allowing correlations with land cover and land use types. The programme differs from other EU-wide soil sampling schemes (e.g. geochemical mapping of agricultural and grazing land soil), as it is a repeated sampling scheme that can provide trends in soil condition indicators for all land covers. LUCAS Soil offers the potential for collaboration with national monitoring systems, and provides valuable data for countries lacking a soil monitoring system, as

Figure 14. Soil degradation processes included in the EUSO Soil Degradation Dashboard. NB: Currently, 18 processes are included, grouped in nine themes (soil erosion, soil sealing, soil pollution, loss of soil biodiversity, soil nutrients, loss of organic soils, loss of SOC, soil compaction and soil salinisation). The threshold values indicated are used in the dashboard to estimate whether soils can be considered degraded or not.



Source: EUSO.

Figure 15. Convergence of evidence map of the EUSO Soil Degradation Dashboard. The map shows where current scientific evidence convergences to indicate areas that are likely to be affected by soil degradation. Currently, 18 soil degradation processes are included (see Figure 14).



Source: EUSO.

envisaged by the proposed EU soil monitoring and resilience directive (Jones *et al.*, 2022) (Table 2).

In 2023, the European Soil Data Centre (ESDAC) website saw around 562 000 page visits, twice as aa many as in 2022. It handled 11 675 dataset requests, an 18 % increase from 2022 and a 150 % rise over 5 years. Of the datasets distributed, 62 % were downloaded in EU Member States, with the most requests from Italy, Germany and Spain. Academic users accounted for 57 % of downloads, followed by private companies and research organisations. Soil erosion datasets were particularly popular, especially following the release of the 2018 LUCAS Module (Broothaerts *et al.*, 2024).

5.2 EU Soil Observatory Soil Degradation Dashboard

The EUSO Soil Degradation Dashboard provides a spatial assessment of soil health across the EU, highlighting areas affected by soil degradation processes. By harmonising soil datasets, the dashboard offers insights into the intensity and location of soil degradation. The dashboard will be enriched with new indicators and thresholds, aligning with multiple ecosystem service considerations and expanding to include data from countries beyond the EU. This continuous development reflects the commitment of the European Commission to addressing soil degradation and fostering sustainable land management practices on a broader scale.

The Soil Degradation Dashboard developed by the JRC (2023) has provided a unique spatial assessment of where degraded soils may be located in the EU and which degradation processes are responsible for their condition (assuming single thresholds across the whole of Europe). Harmonised soil datasets from ESDAC (Panagos *et al.*, 2022c), the EEA and other institutions (Figure 14) together with a novel methodology provides for the first time a view of the state of soil across the EU. The novelty lies in the use of the 'convergence of evidence' approach, which spatially combines multiple independent datasets to highlight areas where scientific evidence consistently points to likely soil degradation processes.

The resulting map (Figure 15) indicates areas that are likely to be affected by one or more soil degradation processes. At least a staggering 61 % of EU soils were determined to be in a degraded state using the prescribed assessment method, based on the evidence currently available and current knowledge on thresholds. The loss of SOC (48 % of EU soils), the potential loss of soil biodiversity (37.5 %) and soil erosion by water (32 %) are the most prev alent types of soil degradation.

In reality, this figure is an underestimate of the- actual extent of soil degradation, given the recognised lack of data on many other soil degradation issues, such as soil contamination and subsoil compaction. In addition, the map shows that most of the degraded soils are subject to more than one type of soil degradation process, an important finding for the soil restoration agenda.

The dashboard supports evidence-based decision-making and policy development by offering insights into the drivers of soil degradation. In addition, it serves as a valuable resource for stakeholders, policymakers and researchers to access and analyse soil-related information, fostering a better understanding of soil degradation and supporting efforts to promote sustainable soil management practices. The EUSO soil degradation dashboard will be enriched with new available indicators and scientifically underpinned thresholds related to multiple ecosystem services (see, for example, Landmark) and expanded to include data on countries beyond the EU.

#06

Understanding the interplay between drivers and impacts of soil degradation

06 Understanding the interplay between drivers and impacts of soil degradation

Soil degradation exacerbates climate change by releasing stored carbon, impacting food and biomass productivity, and leading to economic strain through remediation costs and decreased agricultural yields . Human health risks arise from nutrient-deficient crops and increased exposure to contaminants in polluted soil. Cultural and recreational values suffer as landscapes change, affecting community well-being. Water quality is compromised due to sediment transport, while soil biodiversity change affects ecosystem balance.

Building on the foundational knowledge established in preceding chapters, this section unravels the intricate mechanisms driving soil degradation, exploring the diverse array of pressures exerted by anthropogenic and natural forces alike.

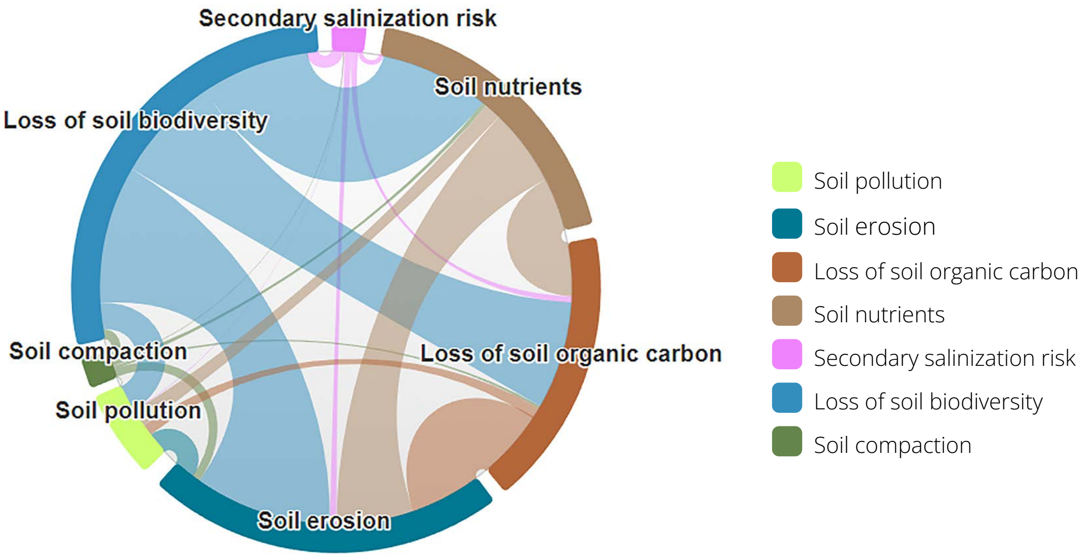
6.1 Interconnections between soil degradation factors: Understanding complexities in European soil health

Previous chapters have elucidated the intricate connections among various soil degradation processes in Europe, portraying them as interlinked and mutually reinforcing processes that collectively contribute to the degradation of soils. For instance, soil acidity, influenced by factors such as mineral fertilisation, can lead to the dissolving and progressive loss of soil carbonates. This process not only releases CO_2 but also reduces the availability of essential nutrients such as calcium and magnesium, ultimately impacting soil fertility.

Moreover, soil erosion, driven by various factors including unsustainable agricultural practices, removes the top fertile layer of soil. This not only results in a loss of nutrients such as P to surface waters but also diminishes the soil's ability to store carbon, nutrients and water. This, in turn, affects important soil functions such as providing habitats for soil organisms and purifying water. Additionally, soil biodiversity is impacted by declines in soil carbon, and the loss of biodiversity in the soil disrupts soil functions and ecosystem services. Chemical pollution from agrochemicals and microplastics further exacerbates these threats, posing risks to soil biodiversity and ecosystem functioning. Adding complexity, these processes overlap, as shown by the EUSO convergence of evidence map. The dependency wheel (Figure 16) shows the extent of the overlapping area (in hectares) between pairs of soil degradation processes shown on the convergence of evidence map. The size of the area linking two soil degradations in the diagram is proportional to the extent of their overlap in the map. This diagram provides insights into the type and magnitude of soil degradation combinations estimated to be occurring in the EU.

These interlinks highlight the complex nature of soil degradation and the need for integrated approaches to address multiple soil threats simultaneously. These interconnected threats highlight the need for holistic and sustainable soil management practices. Addressing one aspect of soil health often requires considering its impact on other aspects. By understanding and mitigating these interconnections, we can work towards preserving soil health and ensuring the long-term sustainability of our ecosystems.

Figure 16. Combination of soil degradation factors by area.



Source: EUSO.

6.2 Assessing the impacts of soil degradation on Ecosystems, Agriculture, and Society in Europe

Soil degradation has a range of significant impacts, affecting agricultural productivity, ecosystem resilience, water quality, biodiversity and human well-being. Table 3 provides an overview of key impacts identified in preceding sections. It is important to note that the table is not exhaustive but rather represents a selection based on report highlights and expert opinion. The confidence scale utilised adheres to IPCC guidelines concerning the correlation between evidence, consensus and confidence levels in scientific findings (Mastrandrea *et al.*, 2010).

Some of the key impacts include:

- Climate change impact. Soils act as a carbon sink, playing a crucial role in mitigating climate change by sequestering CO_2. Soil degradation, especially through activities such as deforestation and improper land use, releases stored carbon back into the atmosphere, contributing to climate change.

- Loss of food and biomass productivity. Soil degradation leads to a decline in its ability to support healthy plant growth. This results in lower agricultural yields, affecting food production and economic sustainability.

- Soil erosion. Caused by factors such as water and wind, this is a major form of soil degradation. It leads to the loss of the topsoil layer, which is rich in nutrients. This negatively impacts agriculture and may result in increased sedimentation in rivers and water bodies. In some regions, soil degradation can progress to desertification, where once-fertile land becomes arid and unproductive. This process is linked to unsustainable land use practices, climate change and deforestation.

- Economic impact. The impacts of soil degradation on agriculture, water resources and other ecosystem services have economic consequences. Decreased agricultural productivity, increased input costs and the need for remediation efforts can strain economies.

- Human health concerns. Soil degradation affects the quality of crops grown in degraded soils, potentially leading to nutrient deficiencies in food. This has implications for human health, as the nutritional content of food may be compromised. Exposure to contaminants in polluted soil can pose risks to human health through direct contact with contaminated soil, ingestion of contaminated dust or water, or consumption of crops grown in polluted areas.

Table 3. Soil degradation processes and their impacts.

SOIL DEGRADATION	NEGATIVE IMPACTS: Climate change	Food and biomass production	Economic impact	Human health	Cultural and recreational value / social impact	Water	Biodiversity
Sealing	High agreement, limited evidence	High agreement, robust evidence	Limited evidence	Limited evidence	High agreement, limited evidence	High agreement, robust evidence	High agreement, robust evidence
Nutrients imbalances	High agreement, robust evidence	High agreement, robust evidence	High agreement, robust evidence	High agreement, limited evidence	Limited evidence	High agreement, robust evidence	High agreement, robust evidence
Compaction	High agreement, robust evidence	High agreement, robust evidence	High agreement, robust evidence	Limited evidence	Limited evidence	High agreement, robust evidence	High agreement, limited evidence
Acidification	Low agreement, robust evidence	High agreement, robust evidence	High agreement, robust evidence	High agreement, limited evidence	Limited evidence	High agreement, limited evidence	High agreement, robust evidence
Pollution	Limited evidence	High agreement, limited evidence	High agreement, robust evidence	High agreement, limited evidence	Limited evidence	High agreement, robust evidence	High agreement, limited evidence
Loss of carbon (mineral)	High agreement, robust evidence	Low agreement, robust evidence	Limited evidence	Limited evidence	Limited evidence	High agreement, robust evidence	High agreement, robust evidence
Loss of carbon (peatlands)	High agreement, robust evidence	Limited evidence	Limited evidence	Limited evidence	High agreement, limited evidence	High agreement, robust evidence	High agreement, robust evidence
Salinisation	Limited evidence	High agreement, robust evidence	High agreement, robust evidence	Limited evidence	High agreement, limited evidence	High agreement, robust evidence	High agreement, robust evidence
Erosion	Low agreement, robust evidence	High agreement, robust evidence	High agreement, robust evidence	High agreement, limited evidence	High agreement, limited evidence	High agreement, robust evidence	High agreement, robust evidence
Change in biodiversity	Low agreement, robust evidence	High agreement, limited evidence	Limited evidence	High agreement, limited evidence	Limited evidence	High agreement, limited evidence	High agreement, robust evidence

CONFIDENCE SCALE (BASED ON EVIDENCE AND AGREEMENT)	
High agreement, robust evidence	Low agreement, robust evidence
High agreement, limited evidence	Limited evidence

Source: Own elaboration.

- Loss of cultural and recreational values. Soil degradation also impacts cultural landscapes and recreational areas. Changes in soil quality and landscape structure may affect the aesthetic and recreational value of certain areas, impacting the well-being of local communities. The expansion of urban areas may result in the loss of green spaces and recreational areas, affecting the quality of life for residents. Access to nature and open spaces is important for physical and mental well-being.
- Water quality issues. Degraded soils contribute to water pollution. The run-off from degraded soils may contain sediments, nutrients and pesticides, negatively affecting water quality. This has implications for aquatic ecosystems and human health. Degraded soils have reduced water retention capacity, leading to increased susceptibility to both flooding and droughts. This can have significant implications for agriculture, water supply and overall ecosystem resilience.
- Biodiversity loss. Healthy soils support living ecosystems, including a wide variety of microorganisms, plants and animals. Soil degradation leads to a loss of below- and above-ground biodiversity, as many organisms depend on specific soil conditions for survival.

Our analysis has identified knowledge gaps in two crucial areas: human health; and the loss of cultural and recreational value, which encompasses social impacts. These gaps represent areas where further research and understanding are needed to fully comprehend the implications of soil health on human well-being and societal dynamics.

#07

The role of citizen science in assessing soil conditions

07 The role of citizen science in assessing soil conditions

Research in soil science plays a critical role in addressing societal challenges, but engaging the public is essential for bridging knowledge gaps and fostering sustainable practices. Citizen science offers a participatory approach to soil research, empowering communities to contribute data and insights. Collaboration between citizens and researchers fosters co-creation of projects, leading to sustainable behaviour change and societal impact. However, challenges such as data dissemination, quality assurance and scalability require attention. Integrating citizen science data into existing platforms such as the European Soil Data Centre can enhance its utility. Addressing these challenges will be crucial for realising the full potential of citizen science in soil monitoring and management.

Research in soil science is crucial for comprehending and enhancing the role of soils in addressing significant societal challenges. To effectively bridge the gap between our current knowledge and societal needs, a collaborative effort involving diverse stakeholders, including the general public, is imperative (Mol & Keesstra, 2012). However, it is estimated that approximately half of the world's population lives in urban environments (MacEwan *et al.*, 2017). This suggests that a significant portion of the global population may also lack engagement or connection with the topic of soils.

Citizen science is a participatory research method that actively engages the public in scientific inquiry to generate new data and knowledge or understanding through their active involvement. Although there is no official definition of its methods and there is debate about what kind of activities and practices are part of it (Haklay *et al.*, 2021), citizen science projects most commonly consist of engaging with communities and seeking their participation in the recording, collection and/or creation of data and their interpretation (Reynolds *et al.*, 2021; Pino *et al.*, 2022). Citizen science projects on soil have gained increasing interest, driven by among others the prominence of soil within policy agendas (Panagos *et al.*, 2022c; Gascuel *et al.*, 2023).

The importance of increasing citizen engagement and awareness about soils is recognized in the following policy frameworks: the 'EU Soil Strategy for 2030' (COM, 2021), the Horizon Europe Mission 'A Soil Deal for Europe' (European Commission, 2021, 2023b) and the 'Global Soil Partnership' (FAO, 2023). Briefly, these frameworks underscore that citizen science can: i) promote equal access to scientific data and information, ii) foster education and learning opportunities contributing to soil literacy, iii) engage citizens with key policy developments on soils and let them participate in the assessment of their impact, iv) raise awareness on the importance of soil health.

Citizen science can also potentially improve our ability to capture information from the field at different, challenging spatial and temporal scales. In 2015, the European Citizen Science Association (ECSA) developed best practice guidelines for good citizen science, summarised as the ten principles of citizen science (ECSA, 2015). These principles provide a benchmark to review existing citizen science projects and support the development of new, high-quality projects (ECSA, 2015; Robinson *et al.*, 2019). The number of such projects is growing rapidly (Pocock *et al.*, 2017), including projects on soils (Ranjard, 2020; Ranjard *et al.*, 2022; Arias-Navarro *et al.*, 2023).

7.1 Current citizen science activities

Soil is still poorly monitored by citizen scientists compared with water and air, mainly due to the complexity of soils, the absence of government regulation aimed at soil protection and a lack of funding for soil monitoring (Paleari, 2017; Head *et al.*, 2020). Nevertheless, citizen science has a clear role to play in monitoring soil health (Head *et al.*, 2020). Mason *et al.*(2024) recently reviewed current and past European citizen science projects on agricultural soils and grouped them into three clusters: (a) national low-budget projects with a crowdsourcing approach, (b) European limited-term projects and (c) regional and national high-budget projects. Over 66 % of projects (n = 24) generated soil biodiversity data. In comparison, 54 % and 42 % generated data on vegetation cover and SOC, respectively. Over 30 % of the projects generated data on soil nutrients and pH, followed by 29 % on soil structure, 20 % on excess nutrients and salts and 17 % on both landscape heterogeneity and soil pollutants. More than half of the projects investigated urban gardens (58 %), 42 % arable land, 33 % fruit and vegetables or grassland, and 21 % arboriculture and vineyards.

A recently started Horizon Europe project called Engaging citizens in soil science: the road to healthier soils (ECHO, 2023–2027) has citizen science as its primary focus. The project aims to engage citizens by enhancing their knowledge and interest in soil health, motivating them to protect and restore soils. It empowers citizens to actively participate in data collection and soil science, generating valuable knowledge for the benefit of all. Through this involvement, citizens gain the capability to directly contribute to decision-making on soil issues, utilising their acquired knowledge. With

Photo 5. Citizen engagement.

Source: C. Kabala (distributed through imaggeo.egu.eu).

the implementation of 28 citizen science initiatives, ECHO aims to collect data from up to 16 500 sites across Europe, consolidating this information into Echorepo, a long-term open-access data repository. This valuable data resource is intended to benefit not only scientists but also the broader public and end users, including farmers, landowners, businesses, educators and institutions responsible for soil management. By doing so, ECHO seeks to optimise the utilisation of project findings and evaluate project outcomes against existing data from other pertinent soil monitoring initiatives. Generating high-quality soil data is key to developing sustainable land management strategies and driving policy actions that protect our essential soil resources. In addition, several European research projects on soils and agriculture, including Benchmarks, Prepsoil, Nati00ns, LOESS, EUdaphobase, SOLO and Increase, are including citizen science aspects in their research agendas.

7.2 Outlook

Mason *et al.* (2024) showed that positive feedback from participants, increased awareness of soil among participating citizen scientists and collaboration were key outcomes of successful citizen science projects. The citizen science community is beginning to explore and adopt 'collaborative' and 'co-created' methods (Hidalgo *et al.*, 2021), where participation goes beyond data collection to the co-design of projects. When citizens and researchers join in interdisciplinary settings, developing and implementing long-term research projects, outcomes are more likely to contribute to sustainable behaviour change (Lobry de Bruyn *et al.*, 2017). Previous research has shown that collaboration with citizens is a key factor in societal trans formation (Turrini *et al.*, 2018) or enhancing societal impact, for example through adequate response in times of environmental stress (Thomas *et al.*, 2016).

Hence, there is a need to further promote co-creation to bring citizens - as individuals and NGO's, for example - together with politicians and scientists throughout the research process (Leino and Puumala, 2021), ultimately leading to policy outcomes and the institutionalisation of citizen science (Criscuolo *et al.*, 2023). To bring this together, the ECSA network offers the opportunity to collaborate in working groups on specific topics, such as agri-food, legal aspects of citizen science or citizen science in schools. In November 2023, a session with over 100 participants was held on the role of citizen science in soil monitoring, at the stakeholder forum hosted by EUSO. The main aim was to highlight relevant methodological aspects and identify associated challenges for citizen science for soil monitoring. One of the key messages was that existing data generated by citizen science can be integrated into ESDAC data. Time limitations often constrain the dissemination of citizen science project outputs, and the maintenance of outputs can be resource intensive.

Other potential pitfalls are complications with the sharing of data under the general data protection regulation framework. Future research should assess the quality control and quality assurance of data generated by citizen science and whether they can be compared directly, due to the type and nature of the data generated in citizen science. Lastly, an open question was how citizen science projects and participation can be scaled up in terms of geographic scope (national, international) and the number of participants. Given that citizen science projects have a different structure and skill requirement from conventional research projects, attention should be paid to how citizen science projects are funded and to involving team members with appropriate skills such as science communication.

#08

Towards sustainable soil governance: Policy pathways for preserving soil health in Europe

08 Towards sustainable soil governance: Policy pathways for preserving soil health in Europe

Research in soil science plays a critical role in addressing societal challenges, but engaging the public is essential for bridging knowledge gaps and fostering sustainable practices. Citizen science offers a participatory approach to soil research, empowering communities to contribute data and insights. Collaboration between citizens and researchers fosters co-creation of projects, leading to sustainable behaviour change and societal impact. However, challenges such as data dissemination, quality assurance and scalability require attention. Integrating citizen science data into existing platforms, such as the ESDAC, can enhance its utility. Addressing these challenges will be crucial for realising the full potential of citizen science in soil monitoring and management.

8.1 From the soil thematic strategy to the Soil Monitoring and Resilience Law: Advancing soil protection policies in the EU

Over the years, soil policy has evolved from the soil thematic strategy of 2006 to the forthcoming legislation on soil monitoring and resilience (Arias-Navarro *et al.*, 2023; Panagos *et al.*, 2024c). The thematic strategy laid the groundwork for addressing soil degradation and promoting sustainable soil management practices at the EU level. Building on this foundation, the EU's soil strategy for 2030 and the proposal for a soil monitoring and resilience directive (Soil Monitoring and Resilience Law) reflect a continued commitment to soil protection and resilience-building measures (Figure 17). This legislation emphasises the importance of monitoring soil health indicators, assessing soil's resilience to environmental stressors and implementing measures to enhance soil health and ecosystem service provision. By advancing soil policy from strategy to action, the EU aims to safeguard soil health, promote sustainable land management practices and ensure the long-term resilience of its ecosystems.

The forthcoming Soil Monitoring and Resilience Law is intricately linked with other key policies aimed at safeguarding soil health and promoting sustainable land management practices within the EU. This legislation intersects with existing environmental, agricultural and biodiversity policies, forming a cohesive framework for soil protection and resilience-building efforts. In particular, it aligns closely with the CAP, which integrates measures to address soil degradation and promote sustainable farming practices. In addition, the Soil Monitoring and Resilience Law complements the water framework directive (Directive 2000/60/EC) by addressing soil-related pressures on water quality and hydrological systems. Moreover, it reinforces the objectives of the biodiversity strategy for 2030 and the regulation on nature restoration, because healthy soils are essential for supporting diverse ecosystems and conserving biodiversity. By linking with these policies, the upcoming legislation on soil monitoring and resilience underscores the EU's commitment to holistic environmental governance, ensuring the long-term sustainability of its soils and ecosystems.

The EU's soil strategy for 2030 sets out a monitoring framework and specific measures to protect and restore soils and to ensure that they are used sustainably. The new Soil Monitoring and Resilience Law will put the EU on a path towards healthy soils by 2050. The proposed law will be the first EU legislation on soils, providing a harmonised definition of soil health, putting in place a comprehensive and coherent monitoring framework and fostering sustainable soil management and the identification and remediation of contaminated sites

8.2 Soil conservation policies beyond the EU

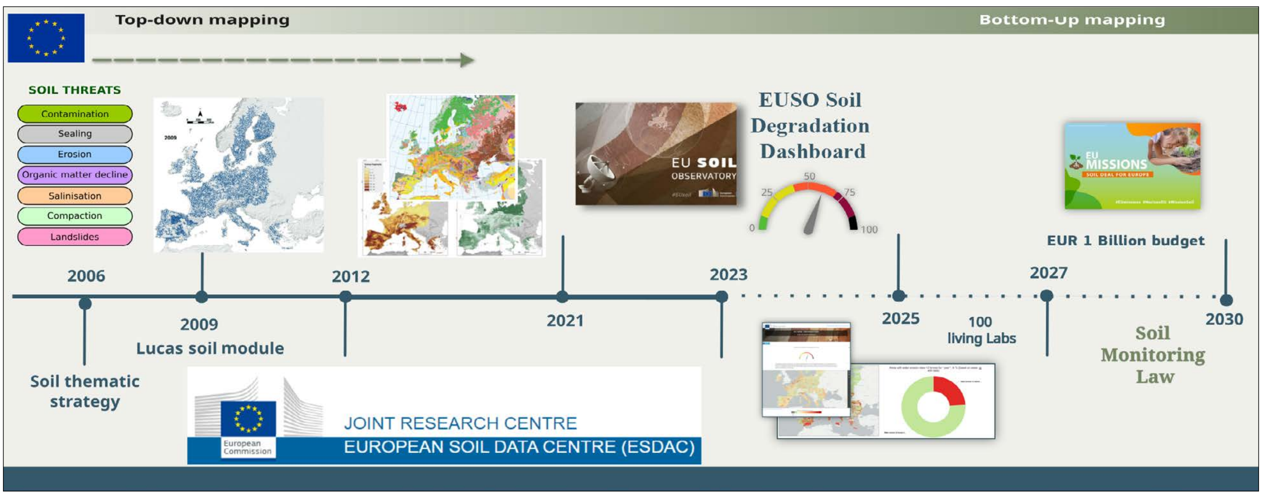
The soil in the western Balkan region is highly vulnerable, requiring careful design and application of effective management practices. There is a need for more evidence to bolster a robust soil protection policy and to effectively target and monitor its implementation. Prioritizing the establishment of a soil protection framework is essential for ensuring healthy soils and aligning with the Green Agenda for the western Balkans.

A soil strategy for England was published in September 2009, setting out the policy on soils at the time and a number of core objectives for policy and research. Current policies focus on protecting soils and the important ecosystem services they provide. Research is focused on addressing evidence gaps to adapt and refine these policies in order to strengthen the protection of soils and their resilience to climate change. The Swiss national soil strategy, adopted in 2020, aims to ensure that future generations benefit from soil services. It addresses unsustainable practices, such as soil consumption and degradation, and aims to achieve zero net soil use by 2050. The strategy focuses on managing soil use, protecting soil from harm, restoring degraded soils, raising awareness of soil's value and promoting international cooperation for sustainable soil management.

Ukrainian legislation focuses on the concept of 'land' rather than 'soil'. There is no clear legislation on soil monitoring, protection and management. The main focus is on soils on agricultural land, which is regulated by agrochemical land certification. The identification of trends in and types of soil degradation and of individual indicators of soil condition (to enable its protection), the implementation of measures for education and awareness in this area, and the identification of soil science priorities as part of the state's development strategy are not systematic processes.

In Türkiye, the Law on Soil Conservation and Land Use came into effect in 2005. The purpose of this law is to protect and improve the soil, to classify agricultural lands, and to determine the minimum area of agricultural land required to provide sufficient income while mitigating the risk of fragmentation. The law sets out the procedures and standards for ensuring that agricultural land is used in a planned manner, in line with the notion of sustainable development and environmental priorities. In addition to this law, the Regulation of Conservation, Use and Planning of Agricultural Areas (2017), the Law on Environment (1983), the Regulation of Controlling of Soil Pollution and Point Source Polluted Areas (2010), and the Law on Grassland (1998) are other important laws and regulations in force covering soil conservation in the country.

Figure 17. Roadmap towards assessing soil health in the EU until 2030 to achieve the Green Deal objectives
NB: Top-down mapping was performed with indicators developed by the ESDAC (between 2012 and 2023). This endeavour resulted in the creation of the EUSO Soil Degradation Dashboard (in 2023). These efforts will contribute to Soil Monitoring and Resilience Law assessments up to 2030.



Source: EUSO, based on Panagos et al. (2024c).

#09

Ensuring soil health and ecosystem resilience amid diverse land use demands in Europe

09 Ensuring soil health and ecosystem resilience amid diverse land use demands in Europe

Knowledge gaps persist in the understanding of social impacts of soil degradation, including its effects on human health and cultural values. In addition, the impacts of warfare on soils remain poorly understood, and further research in this area is required. The soil in the western Balkans is highly vulnerable, necessitating the careful design and implementation of effective management practices.

Reconciling competing demands for land use while safeguarding soil health and ensuring the long-term resilience of European agriculture and ecosystems requires a comprehensive and balanced approach that considers multiple stakeholders and objectives. Several strategies can be employed:

- Integrated land use planning. Develop integrated holistic land use planning strategies considering multiple objectives, including agriculture, biodiversity conservation, urban development, and mitigation of and adaptation to climate change. This approach involves identifying priority areas for different land uses and implementing measures to minimise conflicts and optimise resource allocation.

- Promotion of sustainable agricultural practices. Encourage the adoption of sustainable agricultural practices that prioritise soil health and resilience, such as conservation tillage, crop rotation, the use of cover crops, agroforestry, and the balancing of nutrient inputs. Providing incentives, technical assistance and training programmes can help farmers transition towards more sustainable land management practices.

- Ecosystem-based approaches. Emphasise ecosystem-based approaches to land management that enhance the resilience of agricultural landscapes and ecosystems. This includes restoring and preserving natural habitats, promoting biodiversity-friendly farming practices and incorporating green infrastructure measures to support ecosystem services.

- Soil conservation measures. Implement soil conservation measures, such as erosion control measures, soil conservation buffers and reforestation projects, to prevent soil degradation and loss. Investing in soil restoration techniques, such as soil remediation and the rehabilitation of degraded land, can also help restore soil health and fertility.

- Multistakeholder collaboration. Foster collaboration among stakeholders, including farmers, landowners, environmental organisations, policymakers and local communities, to develop and implement land use plans and policies that balance competing demands and prioritise soil health and resilience.

- Science-based decision-making. Land use decisions should be based on reliable scientific knowledge and monitoring data in order to better comprehend the effects of various land uses on soil health, biodiversity, water quality and other ecosystem services. Conducting comprehensive impact assessments and modelling exercises can help predict the long-term consequences of land use decisions and inform policy development.

- Addressing significant knowledge gaps. Filling gaps in knowledge regarding soil's social values is crucial for developing more holistic and sustainable land use policies. The values relate to the influence of soil on physical and mental health, education, diversity and cultural identity. By understanding these social values, policymakers can better incorporate them into land use management decisions, ensuring that the full range of ecosystem services provided by soils is considered.
- Soil literacy. Improve the understanding of citizens and stakeholders of how healthy soils impact their lives. Collaborate with teachers and soil scientists to develop soil-related educational products.
- Policy integration and coordination. Integrate soil protection objectives into broader policy frameworks, such as agricultural, environmental, climate change, biodiversity and spatial planning policies. Enhance coordination among different policy sectors to ensure coherence and synergy in addressing competing demands for land use while safeguarding soil health and ecosystem resilience.

By adopting a multifaceted approach that combines sustainable land management practices, ecosystem-based approaches, stakeholder collaboration, the inclusion of soil sciences in teaching programmes and science-based decision-making, it is possible to reconcile competing demands for land use while safeguarding soil health and ensuring the long-term resilience of European agriculture and ecosystems.

Conclusions

The interplay among various drivers and degradation processes underscores the intricate nature of soil health. Both natural phenomena and human activities contribute to soil degradation, emphasising the need for integrated approaches to address these challenges comprehensively. Citizen science is a valuable avenue for raising awareness of the importance of soil health and increasing public engagement in soil monitoring, although efforts are required to enhance participation, particularly in urban areas. Policy initiatives within the EU demonstrate a commitment to holistic soil governance; yet challenges persist globally, with varying approaches to soil conservation having differing levels of success and involving different obstacles.

Moving forward, it will be imperative to prioritise data enhancement, policy strengthening and stakeholder engagement in sustainable soil governance. Future efforts should focus on facilitating long-term monitoring, embracing technological innovation and fostering international collaboration to ensure the resilience and sustainability of our soils. By combining scientific knowledge, citizen engagement and robust policy frameworks, we can collectively preserve soil health, safeguarding this invaluable resource for the benefit of present and future generations and securing the health and well-being of our planet.

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List of abbreviations and definitions

Abbreviation	Definition
AMPA	Aminomethylphosphonic acid
BD	Bulk density
C	Carbon
CAP	Common Agricultural Policy
CH_4	Methane
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
DDT	Dichlorodiphenyltrichloroethane
DEMIS	Dynamic Erosion Model and Monitoring System
EC	European Commission
ECHO	Engaging Citizens in soil science: the road to Healthier sOils
ECSA	European Citizen Science Association
EJP SOIL	European Joint Programme on Agricultural Soil Management
ES	Ecosystem Service
ESDAC	European Soil Data Centre
EEA	European Environment Agency
EU	European Union
EUROSTAT	European Statistical Office
EUSO	EU Soil Observatory
FAO	Food and Agricultural Organisation
FUA	Functional Urban Area
GAEC	Good Agricultural and Environmental Condition

Abbreviation	Definition
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GHG	Greenhouse gases
Gt	Gigatonnes
ICP Forest	International Co-operative Programme on the Assessment and Monitoring of Air Pollution in Forests
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
K	Potassium
Kg	Kilogram
LDN	Land degradation neutrality
LRD	Large-scale Reference Database
LUCAS	Land Use/Cover Area frame Survey
LULUCF	Land Use, Land Use Change, and Forestry
MAC	Maximum allowable concentrations
Mt	Million tonnes
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Nitrogen oxides
NRR	Regulation on Nature Restoration
P	Phosphorus

Abbreviation	Definition
PAHs	Biphenyls polycyclic aromatic hydrocarbons
PCBs	Polychlorinated
PD	Packing Density
RMQS	Réseau de Mesures de la Qualité des Sols
RUSLE	Revised Universal Soil Loss Equation
RWEQ	Revised Wind Erosion Equation
SDGs	Sustainable Development Goals
SGU	Geological Survey of Sweden
SIC	Soil Inorganic Carbon
SLCH	Soil Loss due to Crop Harvesting
SLU	Swedish University of Agricultural Sciences

Abbreviation	Definition
SMA	Spectral Mixture Analysis
SML	Soil Monitoring and Resilience Directive (Soil Monitoring Law)
SOC	Soil organic carbon
SOx	Sulphur oxides
UK	United Kingdom
UNEP	United Nations Environment Programme
WAPHA	Water and Planetary Health Analytics
WEFE	Water, Energy, Food Security, and Ecosystems
WFD	Water Framework Directive
WRB	World Reference Base for Soil Resources

Glossary

Term	Definition	Reference
Soil	The top layer of the Earth's crust situated between the bedrock and the land surface, which is composed of mineral particles, organic matter, water, air and living organisms;	SML
Ecosystem	A dynamic complex of plant, animal, and microorganism communities and their non-living environment interacting as a functional unit;	SML
Ecosystem services	Contributions of ecosystems to the economic, social, cultural and other benefits that people derive from those ecosystems;	SML
Soil health	The physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services;	SML
Sustainable soil management	Soil management practices that maintain or enhance the ecosystem services provided by the soil without impairing the functions enabling those services, or being detrimental to other properties of the environment;	SML
Soil management practices	Practices that impact the physical, chemical or biological qualities of a soil;	SML

Term	Definition	Reference
Managed soils	Soils where soil management practices are carried out;	SML
Soil health assessment	The evaluation of the health of the soil based on the measurement or estimation of soil descriptors;	SML
Contaminated site	A delineated area of one or several plots with confirmed presence of soil contamination caused by point-source anthropogenic activities;	SML
Soil descriptor	A parameter describing a physical, chemical, or biological characteristic of soil health;	SML
Land	The surface of the Earth that is not covered by water;	SML
Land cover	The physical and biological cover of the earth's surface;	SML
Natural land	An area where human activity has not substantially modified an area's primary ecological functions and species composition;	SML
Semi-natural land	An area where ecological assemblages have been substantially modified in their composition, balance or function by human activities, but maintain potentially high value in terms of biodiversity and the ecosystem services it provides;	SML
Artificial land	Land used as a platform for constructions and infrastructure or as a direct source of raw material or as archive for historic patrimony at the expense of the capacity of soils to provide other ecosystem services;	SML
Land take	The conversion of natural and semi-natural land into artificial land;	SML
Transfer function	A mathematical rule that allows to convert the value of a measurement, performed using a methodology different from a reference methodology, into the value that would be obtained by performing the soil measurement using the reference methodology;	SML
Soil contamination	The presence of a chemical or substance in the soil in a concentration that may be harmful to human health or the environment;	SML
Contaminant	A substance liable to cause soil contamination;	SML
Regeneration	An intentional activity aimed at reversing soil from degraded to healthy condition;	SML
Risk	The possibility of harmful effects to human health or the environment;	SML
Soil remediation	A regeneration action that reduces, isolates or immobilises contaminant concentrations in the soil;	SML
Soil erosion	The wearing away of the land surface by water, wind, ice, gravity or other natural or anthropogenic agents that abrade, detach and remove soil particles or rock material from one point on the earth's surface, for deposition elsewhere, including gravitational creep and so-called tillage erosion;	ESDAC

Term	Definition	Reference
Acidification	Process whereby soil becomes acid (pH < 7) because acid parent material is present or in regions with high rainfall, where soil leaching occurs. Acidification can be accelerated by human activities (use of fertilisers, deposition of industrial and vehicular pollutants);	ESDAC
Carbon cycle	Sequence of transformations whereby carbon dioxide is converted to organic forms by photosynthesis or chemosynthesis, recycled through the biosphere (with partial incorporation into sediments), and ultimately returned to its original state through respiration or combustion;	ESDAC
Organic soil	A soil in which the sum of the thicknesses of layers comprising organic soil materials is generally greater than the sum of the thicknesses of mineral layers;	ESDAC
Peat	Organic soil material with more than 50% of organic matter derived from plant residues with not fully destroyed structure. Peat forms in a wet soil environment or below the water table where mineralisation of organic matter comes close to zero; a peat horizon or layer is normally more than 30 cm thick;	ESDAC
Peatland	A generic term for any wetland where partially decayed plant matter accumulates; mire, moor and muskeg are terms used for peatlands in Europe;	ESDAC
Saline soil	A non-sodic soil (see sodic soil) containing sufficient soluble salt to adversely affect the growth of most crop plants. The lower limit of electrical conductivity in the saturation extract of such soils is conventionally set at 4 dS m^{-1}(at 25°C), though sensitive plants are affected at about half this salinity and highly tolerant ones at about twice this salinity;	ESDAC
Saline-sodic soil	Salt-affected soils with a high exchangeable sodium percentage (ESP) greater than 15%, pH usually more than 8.5; in general, these soils are not suitable for agriculture;	ESDAC
Salt-affected soil	Soil that has been adversely affected by the presence of soluble salts, with or without high amounts of exchangeable sodium. See also saline soil, saline-sodic soil, and sodic soil;	ESDAC
Sodic soil	Soil with excess of sodium, pH is higher than 7, usually in the range 8 - 10, exchangeable sodium percentage, ESP > 15 and very poor soil structure. These soils need special management and are not used for agriculture; non-sodic soils are without excess of sodium;	ESDAC
Soil degradation	Negative process often accelerated by human activities (improper soil use and cultivation practices, building areas) that leads to deterioration of soil properties and functions or destruction of soil as a whole, e.g. compaction, erosion, salinisation;	ESDAC
Soil fertility	A measure of the ability of soil to provide plants with sufficient amount of nutrients and water, and a suitable medium for root development to assure proper plant growth and maturity;	ESDAC
Soil monitoring	Repeated observation and measurement of selected soil properties and functions, mainly for studying changes in soil conditions;	ESDAC

Term	Definition	Reference
Soil microorganisms	Represented by protozoa, viruses, bacteria, fungi and algae. The most prevalent are bacteria and fungi, and depending on conditions (water and nutrients content, temperature, etc.) they can be in an active or non-active state. According to nutrient (and oxygen) demand, micro-organisms are divided to autotropic and heterotrophic, (aerobic and anaerobic) groups. Micro-organisms are a good indicator of soil status and quality;	ESDAC
Threshold	Critical value at which lost soil functions have significant negative effects on the ecosystem services provided by soils. Thresholds are used to estimate whether soils can be considered in good condition or degraded;	EUSO
Excess of soil nutrients	Presence of nutrients in the soil that could potentially cause adverse effects on the soil, plant, animal and human health, and water quality;	FAO
Deficiencies of soil nutrients	Too low availability of soil nutrients that results in reduced plant health, crop productivity and the nutritional quality of food for human and animal consumption;	FAO
Nutrients imbalance	Incorrect land use and management (underuse, misuse and overuse of nutrients) may result in an excess of nutrient causing soil contamination and contributing to water quality deterioration and greenhouse gas emissions, or a lack of nutrients resulting in low soil fertility;	FAO
Soil biodiversity	The variety of life below ground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes;	FAO
Habitat provision	Refers to the capacity of soil to create and sustain suitable habitats for a wide range of organisms, including microorganisms, plants, and animals. It encompasses the physical, chemical, and biological characteristics of the soil environment that enable the establishment and maintenance of diverse communities;	BENCHMARKS
Soil threat	A process that could degrade (some of) the functions of soils and the services that soils provide. Examples of soil threats are: acidification, compaction, contamination (pollution), decline in soil organic matter, decline in soil biodiversity, desertification, erosion, flooding and water logging, landslides, salinisation;	BENCHMARKS
Soil condition	Refers to the state of the soil, which includes its physical, chemical, and biological characteristics and the processes and interactions that connect them; and which in turn determine the capacity of the soil to support ecosystem services;	BENCHMARKS
Cultural	All the non-material, and normally non-rival and non-consumptive, outputs of ecosystems (biotic and abiotic) that affect physical and mental states of people. Examples: aesthetic experience, symbolic or religious/sacred meaning, existence value, enter-tainment, education/knowledge;	(Haines-Young & Potschin, 2018)

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