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SOIL HEALTH AND BUSINESS MODELS: A REVIEW AND ANALYSIS CARRIED OUT IN THE NOVASOIL PROJECT

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ABSTRACT. Soil health is critical for sustainable agriculture, healthy ecosystems, and environmental resilience. Soil degradation caused by unsustainable practices must be addressed through innovative economic and environmental solutions. This review explores how innovative environmental monitoring technologies, such as remote sensing, drones, and soil sensors, and innovative business models that influence soil management contribute significantly to the improvement of soil health. This study first highlights the key indicators of soil health, including soil organic carbon, nutrient levels, erosion rates and their potential use in ecosystem service markets, such as carbon credits, to incentivise improved soil management. Additionally, this study considers the legal and policy frameworks necessary to support these business models, with a particular focus on the European Union's Soil Monitoring Law and its implications for the agricultural and environmental sectors. Together, these innovative components offer a comprehensive analysis of the challenges and opportunities for transforming soil health management into a profitable and sustainable enterprise,

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contributing to global goals, such as climate mitigation and biodiversity preservation.

Keywords: ecosystem services; soil monitoring law; soil indicators; sustainability.

INTRODUCTION

Soils and our society are facing formidable challenges as the global population is projected to reach 9.1 billion by 2050 (Godfray *et al.*, 2010). Indeed, 95% of our food is directly or indirectly produced from these soils (FAO, 2015), which also play a crucial role in the production of raw materials for biofuels and fibers (Bagnall *et al.*, 2021). Consequently, agricultural land will need to produce more food, feed, and fiber in the next 50 years than it has in the previous 5000 years combined (Stott and Moebius-Clune, 2017).

Moreover, the Food Mission Board (MB) and the European Commission's Joint Research Centre (JRC) have found that 60-70% of EU soils are unhealthy, with an uncertain percentage of this unhealthiness attributed to poorly quantified pollution issues (Montanarella *et al.*, 2021; Veerman *et al.*, 2020).

Furthermore, excessive fertilizer applications have led to nitrogen values exceeding critical thresholds in 65-75% of agricultural soils, impacting air and water quality and necessitating substantial reductions in livestock farming in high-density regions (de Vries *et al.*, 2021; EUROSTAT, 2020; SOER, 2020).

Additionally, soil organic matter, measured as soil organic carbon (SOC), has been depleted through microbial activity and aggressive agricultural practices such as ploughing, which damage the soil structure and disturb functions related to SOC sequestration and storage. LUCAS soil data indicate that cultivated and permanent crops have the lowest SOC concentrations among all major land cover classes, with levels in permanent grasslands being 2.4 times higher (Hiederer and Castillo, 2018). Moreover, approximately 60% of agricultural areas have experienced a decline in average carbon stock due to land use changes.

According to Panagos *et al.* (2015), Borrelli *et al.* (2017) and Panagos et al. (2020) and non-permanent crops and bare soils exhibit the highest rates of soil erosion. For instance, mean soil erosion by water in EU agricultural lands is estimated at 2.46 t ha^{-1} yr^{-1}, leading to an annual total soil loss of 970 Mt. In contrast, the average annual soil loss predicted by GIS-RWEQ in EU arable land is 0.53 Mg ha^{-1} yr^{-1}. This degradation impacts approximately 23% of cropland and 30% of non-agricultural areas.

Furthermore, the JRC reports that soil compaction is a significant issue, affecting 33% of European soils, with 20% affected moderately (Borrelli *et al.*, 2017; Panagos *et al.*, 2015; Panagos *et al.*, 2020)

In terms of soil pollution, accurately determining the total affected area remains a formidable challenge. There are multitude pahtways through which soil can become polluted – from industrial spills to pesticides runoff -, complicate efforts to quantify impacts precisely. Although many studies have reported the negative impact of pollution on soil health but estimate the full extent of affected areas is difficult. For example, it is recorded 21% of European agricultural soils contain levels of that exceed limits from drinking water. Additionally, 2.93 million square kilometres, representing 5% of European land, are critically acidified, while 2.65 million square kilometres suffer from severe nitrogen deposition, leading to problems like eutrophication (Jutterström et al., 2021). Other challenges, such as pollution from plastics, sewage sludge, and trace elements, further threaten both human and biodiversity health.

While the role of soil in food production was always well recognised, the conservation and enhancement of soil to provide ecosystem services (ES) has only recently gained recognition. The term "ecosystem service", is defined as the array of goods and services that human societies derived from the planet's ecosystems.

According to CICES (Common Classification of Ecosystem Services), there are several types of ecosystem services: (a) provisioning services; (b) regulating and maintenance services; and (c) cultural services. Soils in natural ecosystems are part of a dynamic system, self-regulated by known soil functions, which oversee and support the provision of these ecosystem services (Adhikari and Hartemink, 2016; CEC, 2006; Hannam and Boer, 2004). Considerable knowledge exists about soil formation and distribution, yet understanding of soil functions and their provision of ecosystem services remains limited. Soils play a crucial role in most studies related to ecosystem services and are central to policymaking, particularly in rural development across various regions (Daily *et al.*, 1997; Hewitt *et al.*, 2015).

The capacity of soils to provide ecosystem services is determined by their properties and the interactions these properties have with soil use and management practices. Factors such as water and wind erosion, loss of soil organic carbon, and biodiversity depletion contribute to soil degradation. This degradation poses a significant global challenge to food security and ecosystem sustainability (Adhikari and Hartemink, 2016).

Soil health is a multifaceted concept influenced by various perspectives. It has been traditionally assessed through physical, biological, and chemical factors as described in wide literature. While historical focus has often been on agricultural lands and food production, soil health is now recognised for its critical roles in water regulation and quality, human health, climate change adaptation, biodiversity maintenance, and more (Lehmann *et al.*, 2020).

Assessing and defining soil health today requires the modernisation of traditional methodologies. Soil functions are influenced by globally driven variables that exhibit regional variability in their responses.

Key factors to consider include rising global temperatures, elevated carbon dioxide levels, altered precipitation patterns, and the increased frequency of extreme events such as droughts and floods. European soils are subject to considerable threats and degradation processes (*Table 1*), as highlighted by the European Environment Agency (EEA, 2024) and several authors including Bünemann *et al.* (2018), Guo (2021), Lehmann *et al.* (2020) and Stolte *et al.* (2016), among others, through various soil health indicators (*Figure 1*).

Table 1 – Main categories of threats to European soils (adaptation from Stolte *et al.,* 2016) including their primary impacts and supporting references

Threat category	Description of impact	Key references
1. Urbanisation, soil sealing, pollution, and industrialisation	**Urbanisation**: Urban expansion increases soil imperviousness, reducing water infiltration and enhancing surface runoff, thereby increasing the risk of flooding	EEA, 2020
	Soil Sealing: Sealing adversely affects the soil's ability to perform hydrological and life-support functions	Stolte *et al.,* 2016; EEA, 2024
	Pollution: Industrial activities emit contaminants that accumulate in the soil, affecting its fertility and the health of ecosystems	Panagos *et al.*, 2013; EEA, 2024; Payá Pérez and Rodríguez, 2018
	Industrialisation: Contributes to the accumulation of heavy metals in agricultural and urban soils	Payá Pérez and Rodríguez Eugenio, 2018
	Microclimate Alteration: Urban areas exhibit higher temperatures, known as the urban heat island effect, which can alter local microclimates, impacting local flora and fauna and exacerbating the heat stress on vegetated areas.	Stolte *et al.,* 2016
	Air and Soil Pollution: Emissions from industrial processes and urban transport systems deposit pollutants like heavy metals, PAHs, and particulates in the soil, adversely affecting soil quality and health, as well as human health through bioaccumulation.	Payá Pérez and Rodríguez Eugenio, 2018
2. Agricultural expansion with unsustainable practices	**Deforestation and Land Conversion**: Agricultural expansion often involves deforestation and conversion of natural habitats into farmland, leading to soil erosion and biodiversity loss	EEA, 2024
	Unsustainable Farming Practices: Practices such as monoculture and excessive use of chemical fertilisers and pesticides can degrade soil quality, reducing its fertility and structure	Tilman *et al.*, 2002
	Degradation of Soil Structure: Intensive agricultural practices often result in soil compaction, loss of soil structure, and reduced water permeability, leading to increased runoff and erosion. This degradation diminishes soil's natural ability to filter water, recycle organic wastes, and support a balanced ecosystem.	Stolte *et al.,* 2016
	Nutrient Leaching: Overuse of fertilizers, particularly nitrogen and phosphorus, can lead to nutrient leaching where excess nutrients are washed into waterways, causing eutrophication which can lead to dead zones in aquatic environments.	Stolte *et al.,* 2016

	Pesticide Contamination: Heavy reliance on pesticides can lead to contamination of soil and water bodies. Persistent pesticides can accumulate in the food chain, leading to toxic effects on wildlife and humans.	Stolte *et al.,* 2016; EEA, 2024
	Reduced Genetic Diversity: Monocropping and the use of genetically modified organisms (GMOs) can reduce the genetic diversity of plants, making crops more vulnerable to diseases and pests. This can also impact the associated biodiversity, including soil microbes essential for nutrient cycling.	Bolin and Lau, 2022
	Soil Organic Matter Depletion: Unsustainable agricultural practices often involve frequent tillage and insufficient organic matter return to the soil, leading to a decline in soil organic matter. This loss affects soil fertility, structure, and its ability to retain water and nutrients.	Stolte *et al.,* 2016; EEA, 2024
3. Short-term land businesses increasing soil degradation	**Profit-driven Investments**: Investments focused on short-term profitability, such as certain forms of intensive agriculture and real estate development, can compromise soil sustainability	Lal, 2009
	Resource Overexploitation: These practices can lead to overexploitation of soil resources, diminishing their capacity for natural recovery	EEA, 2024
	Loss of Topsoil: Quick turnover of land use, particularly in construction and certain types of agriculture, often leads to significant loss of topsoil,	EEA, 2024
	Disruption of Soil Biota: Intensive land use disrupts the soil microbial community, which is vital for nutrient cycling, organic matter decomposition, and overall soil fertility.	Lehmann *et al.,* 2020
	Chemical Pollution: Short-term land businesses may involve the use of various chemicals, such as herbicides, pesticides, and industrial waste, which can pollute the soil and lead to long-term fertility issues.	Payá Pérez and Rodríguez Eugenio, 2018
	Reduced Water Retention: As soil structure deteriorates from frequent use and poor management, its ability to retain water diminishes, affecting plant growth and increasing susceptibility to drought.	EEA, 2024
	Increased Greenhouse Gas Emissions: Disruption of soil carbon storage through frequent tillage and deforestation linked to short-term land business practices contributes to increased CO2 and other greenhouse gas emissions.	IPCC,2023

4. Intensive forestry activities Particularly affecting woodland species and forest habitats	**Soil Compaction**: Intensive forestry can lead to soil compaction and a decrease in species diversity due to the use of heavy machinery and management techniques that do not respect forest biodiversity	Stolte *et al.,* 2016; EEA, 2024
	Nutrient and Water Cycle Alterations: These activities can alter soil nutrient and water cycles, affecting the overall health of the forest ecosystem	FAO, 2015
	Reduction of Biodiversity: Intensive forestry practices often lead to the replacement of diverse forest ecosystems with monocultures, which significantly reduces biodiversity and the resilience of forests to pests and diseases.	Lehmann *et al.*, 2020; EEA, 2024
	Alteration of Habitat Structures: The removal of undergrowth and the selective logging of mature trees can alter the structural complexity of forests, which is crucial for many species' survival and biodiversity.	EEA, 2024
	Soil Erosion: The removal of vegetation cover during logging operations increases soil erosion rates, which can lead to the degradation of soil quality and reduce its capacity to support future forest growth.	Panagos *et al.*, 2015
	Impact on Carbon Sequestration: Intensive forestry activities can reduce the carbon sequestration capabilities of forests by affecting soil organic carbon and the biomass stored in trees.	EEA, 2024
	Precipitation and Temperature Changes: Changes in precipitation patterns and extreme temperatures affect the soil's ability to store water and carbon, which can alter crop productivity and ecosystem resilience	IPCC, 2023
5. Drastic climate changes cause weather extremes	**Droughts and Floods**: Drought and floods can increase soil erosion and decrease its organic quality	Panagos *et al.*, 2015
	Increased Soil Temperature: Rising global temperatures can lead to increased soil temperatures, which may alter microbial activity and nutrient cycling, reducing soil fertility.	IPCC, 2023
	Altered Precipitation Patterns: Shifts in precipitation can lead to periods of intense drought or heavy rainfall, each stressing soil structures and leading to nutrient loss and erosion.	IPCC, 2023
	Enhanced Soil Respiration: Higher temperatures accelerate soil respiration, releasing stored carbon into the atmosphere and contributing to further climate change.	Yan *et al.*, 2025
	Increased Evaporation Rates: Increased temperatures can also lead to higher evaporation	IPCC, 2023

	rates, reducing soil moisture and affecting plant water availability and crop yields.	
	Shifts in Plant Growing Seasons: Climate change can cause shifts in the timing of plant phenological events, affecting interactions between plants and their pollinators, pests, and diseases.	Yuan *et al.*, 2024
	Intensification of Weather Extremes: More frequent and intense weather events such as hurricanes and floods can devastate ecosystems, lead to massive soil erosion, and disrupt land use.	IPCC, 2023; Yuan *et al.*, 2024
	Inefficient Water Management: Inefficient water management, including poorly designed irrigation systems, can lead to soil salinization and alkalization, reducing its viability for agriculture	EEA, 2024
6. Improper water management, reuse, and irrigation	**Inappropriate Reuse of Wastewater**: Inadequate reuse of wastewater in agriculture can introduce contaminants into the soil	Scott *et al.*, 2010
	Salinization: Poor irrigation practices can lead to salt accumulation in the soil, which impedes plant growth and can ultimately render fertile lands barren.	Stolte *et al.,* 2016
	Waterlogging: Excessive irrigation without proper drainage can cause waterlogging, which suffocates plant roots and disrupts nutrient uptake, leading to reduced agricultural yields.	EEA, 2024
	Reused Water Pollution: The reuse of untreated or poorly treated wastewater can introduce heavy metals, pathogens, and other contaminants into the soil, posing risks to human health and the environment.	EEA, 2024
	Nutrient Imbalance: Over-irrigation can lead to leaching of essential nutrients such as nitrogen and phosphorus from the soil, which diminishes its fertility and increases the need for chemical fertilizers.	EEA, 2024
	Reduction in Groundwater Recharge: Inefficient water use in agriculture can significantly reduce the natural recharge of groundwater, leading to depletion of aquifers and reduced water availability for other uses.	EEA, 2024
	Erosion and Sedimentation: Improper irrigation methods can increase surface runoff, which not only causes soil erosion but also leads to sedimentation in rivers and water bodies, affecting aquatic habitats.	Panagos *et al.*, 2015
	Extraction of Resources: Excessive extraction of resources such as peat, minerals, and biomass can degrade the soil structure and reduce biodiversity	EEA, 2024

7. Overexploitation and uncompensated consumption of natural resources	**Nutrient Depletion**: These practices can deplete soil nutrients and reduce its capacity to support plant and animal life	Payá Pérez and Rodríguez Eugenio, 2018
	Loss of Soil Fertility: Excessive extraction of natural resources like minerals and biomass can lead to significant loss of soil nutrients, disrupting the natural fertility cycles of the soil.	Yuan *et al.*, 2024; EEA, 2024
	Biodiversity Loss: Overexploitation of natural habitats for resources such as timber, minerals, and land for agriculture leads to habitat destruction and loss of biodiversity, which is crucial for ecosystem resilience and functionality.	Lehmann *et al.* 2020; EEA, 2024
	Soil Compaction and Disruption: Heavy machinery used in resource extraction operations compacts the soil, which reduces its porosity and ability to retain water and nutrients, impacting plant growth and soil microorganisms.	EEA, 2024
	Pollution from Mining Activities: Mining operations often lead to severe soil and water pollution due to the release of toxic chemicals and heavy metals, which can have long-term detrimental effects on wildlife and human health.	Payá Pérez and Rodríguez Eugenio, 2018

This table summarises the key anthropogenic and environmental pressures affecting soil health across Europe. Each threat category is described through specific mechanisms of degradation and is supported by relevant scientific and institutional references. Similar impacts may arise from distinct threat categories, reflecting the interconnected nature of soil degradation processes.

Furthermore, the concept of healthy soils must be considered through useful measures known as soil health indicators, which are sensitive to changes and represent the different properties of the soil. According to latest findings, soil health can be understood as the sensitivity of soil attributes to changes and how these changes impact the soil's functioning and its ability to provide ecosystem services (Bunemann *et al.* 2018; Lehmann *et al.*, 2020; Vogel *et al.*, 2021). These parameters, also referred to as "soil attributes," are quantifiable, but the interpretation of these indicators remains challenging due to the absence of well-established conceptual or mechanistic links between the indicators and the corresponding soil functions. Unlike basic parameters, indicators carry significance within a well-developed interpretative framework that provides insight beyond the raw measurement.

For these indicators to be operationable, reliable analytical methods must be available, and the results must be interpretable by the end users, location-specific and time-dependent (Lichtenberg, 2024). Furthermore, indicators must be consistent, reproducible, and adaptable. Ultimately, indicators bridge the gap between soil functions and services by providing a measure of how well the soil can perform these functions or deliver ecosystem services. In this context, soil health can be viewed as the state of the soil relative to critical thresholds, beyond which functionality may be compromised.

The emergence of soil health indicators dates to the mid-20th century, coinciding with increased attention on soil management practices and their implications for agricultural productivity and environmental sustainability (Lehmann *et al.*, 2020). Early research focused primarily on physical and chemical indicators, such as soil texture, nutrient content, and erosion rates, to address soil degradation caused by intensive farming (Doran and Parkin, 1994). As the understanding of soil ecosystems evolved, researchers began incorporating biological indicators, recognizing that soil biodiversity plays a critical role in maintaining soil functions and ecosystem services (Karlen *et al.*, 1997). By the early 2000s, integrated approaches were developed, incorporating a broader set of parameters to assess soil health holistically, thus supporting sustainable land management strategies. This shift reflected growing concerns about environmental degradation, climate change, and the need for resilient agricultural systems (Schjønning *et al.*, 2004).

Soil health is commonly evaluated through a set of indicators that reflect its physical, biological, and chemical properties (*Figure 1*). Physical indicators provide essential information on the structural condition of the soil, including texture, structure, bulk density, and macroporosity, as well as its capacity for water drainage and storage. Characteristics such as soil type and stoniness are also considered, as they influence the soil's ability to support plant growth and regulate hydrological processes. Biological indicators capture the activity and diversity of soil organisms and the organic matter that sustains them. These include vegetation cover, soil organic carbon content, enzymatic activity, and microbial respiration. The presence of soil fauna, particularly earthworms and collembolans, is also widely used as a proxy for biological functioning and soil ecosystem health. Chemical indicators focus on nutrient dynamics and potential constraints to plant and microbial activity. Key variables include pH, nutrient content and availability, cation exchange capacity, as well as the presence of trace elements.

Understanding the pressure factors that threaten European soils, along with the most commonly used soil health indicators, provides a foundation for better management of business models that rely on soil as their primary resource or derive benefits from it, such as agriculture, agroforestry, or silviculture. By identifying and monitoring these pressure factors, stakeholders can make more informed decisions aimed at mitigating damage and enhancing soil health. Agriculture remains the most prominent and well-established sector for advancing soil health through new business models. It operates in a highly developed market with comprehensive policies already in place, making it fertile ground for further innovation. The diversity of market opportunities within agriculture is vast, encompassing a range of practices aimed at improving soil quality, enhancing productivity, and promoting sustainability. The established sector of organic farming shows that consumers are willing to pay for enhanced ecosystem benefits associated with agricultural products. Given new challenges posed by climatic change, farmers must adapt soil management towards greater resilience (Zeilinger *et al.,* 2024). However, the private benefits of investing in soil health might not be guaranteed for farmers or can be realised only in the long run (Miner *et al.,* 2020). In this case, novel business models can help farmers to be remunerated for soil health investments, by monetising co-benefits valuable to society such as carbon sequestration. New or re-discovered agricultural practices play a vital role in this respect. For example, agroforestry represents an emerging technology with the potential to enhance agricultural production. Unlike conventional agriculture, agroforestry integrates trees or shrubs into agricultural landscapes, aiming to capitalise on production synergies between crops and woody plants (Scordia *et al.*, 2023), and resulting in a diversification in agricultural production as well as more diverse ecosystem services. This approach offers significant potential for improving soil health through enhanced carbon sequestration, erosion control, and biodiversity conservation (Blanco-Canqui, 2024). Although relatively underexplored in terms of business models, urban, semi-urban, and green spaces offer further substantial potential for improving soil health and providing ecosystem services (Elmqvist *et al.*, 2015). These areas are often overlooked in the context of soil health, yet proper management can yield significant environmental and social benefits (Elmqvist *et al.*, 2015; Pereira *et al.*, 2023). Literature suggests that these spaces can enhance cultural ecosystem services, such as recreation and aesthetic value, while simultaneously contributing to soil health through improved land management practices. Developing targeted business models for these zones could unlock new avenues for integrating soil health initiatives into urban planning and green infrastructure development (Ding *et al.*, 2023; Elmqvist *et al.*, 2015; Pereira *et al.*, 2023). In this paper, we aim to critically review the soil health indicators used to define and characterize soils in Europe, main monitoring methods and business models related with the investment in soil. The focus of the review is on analytical measurements, monitoring methods and potentially business models which invest in soil. The following sections present a compilation of the most suggested soil health indicators, followed by a discussion of emerging indicators that could offer additional insights into soil health. We also address the potential limitations and challenges associated with aggregating diverse indicators into a single, operational framework.

The present manuscript comprises eight sections that together introduce and analyse the principal dimensions of soil-health research and praxis, as follows. Section 3 delineates the key variables and indicators currently used to quantify soil status across European agro ecosystems, clarifying the scientific rationale for each metric. Section 4 surveys the technological repertoire that is reshaping data acquisition, decision support, and business innovation in soil management. Section 5 maps the broader policy landscape that frames these technological and managerial choices, while Section 6 scrutinises the forthcoming EU Soil Monitoring Law and related legal instruments in greater detail. Section 7 turns to the economic dimension, examining the market mechanisms and business models capable of converting investments in soil health into viable revenue streams. Finally, Section 8 synthesises the cross-cutting implications of the review, identifies the persisting policy gaps, and outlines the ways in which the NOVASOIL project intends to bridge them.

Monitoring soil health: key variables

Effective monitoring of soil health is essential for understanding and mitigating the various threats that impact soil ecosystems. According to the recent report from the EEA, a comprehensive approach to soil monitoring relies on tracking key variables through a set of well-established and widely recognized indicators. These indicators are designed to be both scientifically robust and easily interpretable, providing stakeholders with critical insights into soil conditions (*Figure 1*). Soil health monitoring typically involves the assessment of physical, chemical, and biological parameters that collectively offer a detailed picture of the soil's overall functionality and capacity to provide essential ecosystem services. These parameters allow for the evaluation of key threats such as erosion, compaction, contamination, and loss of organic matter, among others. By systematically tracking these variables, it becomes possible to address degradation issues, guide sustainable land management practices, and support policy development aimed at preserving soil resources. The following table (*Table 2*) outlines the main threats to soil health and the corresponding indicators used to monitor them. These indicators serve as essential tools for assessing the resilience and sustainability of soils across different land uses and geographical regions.

Soil organic carbon

Soil organic carbon (SOC) can be expressed in two main ways: as the SOC content, which represents the concentration of total fine fraction organic carbon (C/kg or %), and as SOC stock (expressed in C/ha), which indicates the pool of organic carbon within a specific soil layer. The quantification of SOC stock depends on additional variables, such as bulk density, coarse mineral fragment content, and layer thickness. Assessing soil health by defining a monitoring threshold for SOC remains a complex task. Considerable debate exists regarding whether a universal optimal or critical minimum level of soil organic matter (SOM) or SOC can be established due to the wide variability in soil characteristics globally (Goulding *et al.*, 2013). SOC levels influence multiple soil properties, further complicating threshold determination. Deluz *et al.* (2020) proposed a double-diagonal sampling method with 20 sampling points as a suitable approach for in situ SOC monitoring in small- to medium-sized farms. Gholizadeh *et al.* (2018) showed the best SOC and Sentinel-2 spectral band correlation (Random Forest modelling) from B4 and B5, followed by B11 and B12. Among all spectral indices, BI, BI2, GNDVI, and SATVI (*Table 3*) had the strongest correlations with SOC. Spectral models can be improved through the implementation of predictors, such as vegetation, topography, climate, and geology, which have a high correlation with SOC. This dataset can be combined using machine learning to predict and monitor SOC with an acceptable spatial resolution for better management and decision making in soil health.

Table 2 – Overview of the main threats and their indicators (updated by EEA in Jan 2023)

Land use	Indicator	Thresholds	Comment
Soil organic carbon loss			
Cropland	Falling below optimal SOC level	Light soils: <1.2% SOC Medium soils: 1.2-1.9% SOC Heavy soils: >1.9% SOC	SOC: clay ratio (Johannes *et al.*, 2017): optimum SOC content as 10% of the clay content/vulnerability limit
Nutrient loss			
Forest land	N limitation based on exceedance of C: N ratio	C: N ratio 20-25	Forest floor organic layer
		Leakage from forests: 1m	
Forest land	P limitation based on exceedance of N:P ratio	N:P ratio >25 (deciduous forests)	Extractable P concentration < optimum (value range refers to Mehlich 3-ICP; also available P-Bray PI and Olsen P)
Acidification			
Agriculture	Exceedance of critical pH levels	pH<4.5 -4.7 (critical)	Risk of Al toxicity
		pH<5-5.5 (avoid)	Limited availability of Ca, Mg and P
All land uses	Exceedance of screening values for critical risk from heavy metals and organic pollutants	Cd, Cu, Pb, Zn, As, Hg, Ni, Cr	Country-specific values vary broadly and are not necessarily comparable
		Organic pollutants	Stratification by land use and soil texture
Soil erosion			
Agriculture	Exceedance of actual rate of soil loss by water erosion	2t/ha/year for shallow soils (<70 cm depth)	Soil formation rate: 0.3-1.4t/ha/year
		4/ha/year for deeper soils (>70 cm)	Preliminary thresholds, derivation of site-adapted tolerable soil loss rates recommended
			The current indicator description in this report includes only soil erosion by water, whereas the threshold addresses all other erosion types
Soil biodiversity loss			
Loss of soil biodiversity (sub-indicators)	To be developed: excedance of safe minimum standards of ecosystem conservation. Excedance of operating ranges (OR) for specific soil animals and microorganisms		Requires sub-indicators by species and/or functional group
Soil compaction			
Harmful subsoil compaction (sub-indicators)	Priority (sub)-indicators: Satured hydraulic conductivity (Ks)<10cm/day Air capacity (AC) <5%, Bulk density (g/cm3) Sandy soil: 1.4–1.6; Loamy soil: 1.2–1.5; Clay soil: 1.1–1.4 (optimal bulk density depends on soil texture)		Exceedance of 'action' values (Zink *et al.* 2011) Secondary sub-indicators with available thresholds: bulk density, internal soil strength, air permeability and oxygen diffusion.

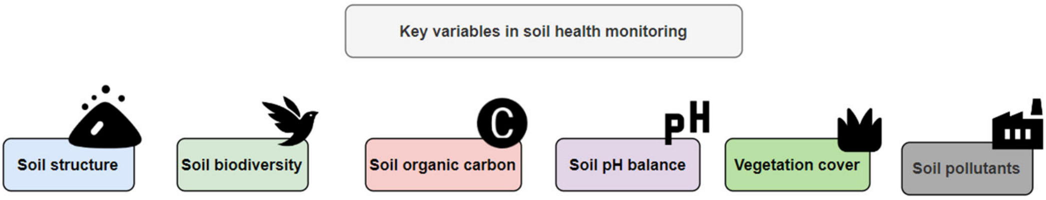

Figure 1 – Main variables to monitor soil health (EEA,2024)

SOC is strongly correlated with other soil properties, particularly the clay content. The SOC/clay ratio is a valid indicator for monitoring soil structural stability, at least in soils dominated by a 2:1 layer of clay minerals (Johannes *et al.*, 2017; Fell *et al.*, 2018; Prout *et al.*, 2020; Schjønning *et al.*, 2012). The ratio should be translated into a different threshold for other soils with differences in clay mineralogy. According to the Soil Monitoring Report by the European Environment Agency, defining ideal SOC stocks is challenging, as it may vary depending on the site and the specific functions of the soil. Dedicated monitoring programs are required for organic soils and to determine the depth of accumulated organic matter. Although existing programs for monitoring SOC in mineral soils are valuable, they should strive to improve their spatial resolution at the European Union (EU) level. This should involve not only assessing bulk density, texture, and fine fraction carbon (<20 μm, Mineral Associated Organic Matter; MAOM but also incorporating data on yield differences and historical/current land use information.

Vegetation cover

Vegetation cover plays a fundamental role in both preventing soil degradation and maintaining soil health. Processes, such as erosion and structural degradation, often begin in areas where the soil surface is left bare and lacks vegetative protection. A decline in perennial vegetation cover is widely recognised as an early indicator of desertification. Numerous studies have demonstrated that vegetation cover contributes significantly to safeguarding the soil against raindrop impact, enhancing the SOM content, improving aggregate stability, increasing water retention and hydraulic conductivity, and reducing and delaying surface runoff.

Vegetation cover can be assessed using various methods, either through direct field measurements − estimating the percentage of ground covered by vegetation − or via remote-sensing technologies. Given its seasonal variability, vegetation is typically evaluated just before the onset of the wet season, when the risk of soil erosion is highest. Raid Almalki *et al.* (2022) recommends the use of different vegetation indices that have been developed to predict changes in vegetation for different purposes. Each monitoring area requires the vegetation indices that suit it best; thus, the strengths and weaknesses of the different indices proposed should be measured (*Table 3*).

Soil structure

The main threats related to soil structure are soil compaction and soil sealing (Hamza and Anderson, 2005). In addition to erosion and soil removal in agricultural soils, soil compaction is one of the worst soil threats, causing a reduction in agricultural productivity (Chamen *et al.*, 2015). Several factors are responsible for soil compaction, including poor soil management practices (high mechanical and tillage systems), which destabilise the physicochemical balance of the soil.

The bulk density has high spatial and temporal variability because it is related to texture, aggregation, SOC content, and water drainage. It is the most commonly used indicator for monitoring the soil structure (Huber *et al.*, 2008). The air capacity (%) and soil texture are other factors for the correct assessment of soil compaction. Considering the European Environment Agency's report, there are many more variables to consider (*Table 4*). *Table 4* shows the parameters according to complexity as well as the measurement methods.

Table 3 – Overview of different indexes and references related to monitoring changes in vegetation cover

Sensor	Index	Reference
Multispectral Vegetation Index	Normalized Differences Vegetation Index (NDVI)	Bannari *et al.*, 1995; Albalawi and Kumar, 2013
	Enhanced Vegetation Index (EVI)	Bannari *et al.*, 1995; Albalawi and Kumar, 2013
	Soil Adjusted Vegetation Index (SAVI)	Bannari *et al.*, 1995; Somvanshi and Kumari, 2020
	Atmospherically Resistant Vegetation Index (ARVI)	Bannari *et al.*, 1995
	Ratio Vegetation Index (RVI)	Allbed and Kumar, 2013
	Green Normalized Diference Vegetation Index (GNDVI)	Allbed and Kumar, 2013
	Chlorophyll Index Green (CI green)	Sishodia *et al.*, 2020
	Difference Vegetation Index (DVI)	Sishodia *et al.*, 2020
	Chlorophyll Vegetation Index (CVI)	Sishodia *et al.*, 2020
Hyperspectral Vegetation Index	Optimized Soil Adjusted Vegetation Index (OSAVI)	Sishodia *et al.*, 2020
	Transformed Vegetation Index (TVI)	Allbed and Kumar, 2013
	Modified Transformed Vegetation Index (MTVI)	Allbed and Kumar, 2013
	Normalized Differences Vegetation Index (NDVI)	Morier *et al.*, 2015
	Enhanced Vegetation Index (EVI)	Liu and Huete, 1995
	Soil Adjusted Vegetation Index (SAVI)	Huete, 1988
	Atmospherically Resistant Vegetation Index (ARVI)	Bannari *et al.*, 1995
	Transformed Difference Vegetation Index (TDVI)	Morier *et al.*, 2015
	Weigthed Difference Vegetation Index (WDVI)	Bannari *et al.*, 1995
	Optimized Soil Adjusted Vegetation Index (OSAVI)	Morier *et al.*, 2015

Source: Raid Almalki *et al.*, 2022

Table 4 – Soil indicators and properties for soil compaction

Soil environment	Indicator	Soil property
Air regime	Air storage	Air capacity
		Bulk density
	Air flow	Pore continuity
		Oxygen diffusion
		Air permeability
Water regime	Water storage	Available water capacity
		Bulk density
	Water seepage	Hydraulic conductivity (saturated/unsaturated)
		Pore continuity
		Flux directions: isotropy/anisotropy
Thermal regime	Heat storage / Heat flux	Heat capacity and conductivity
		Thermal diffusivity
		Pore continuity
		Water content
Habitat for living organisms	Microbial composition	Diversity and community structure
	Abundance of functional species groups	Oxic/anoxic taxa and distribution (e.g. methanogens; sulphate-reducing bacteria or ectomycorrhizal fungi)
Physical soil regime: soil strength	Deformation status	Bulk density
		Proctor density (a)
		Average mean diameter of aggregates
	Stress strain (b)	Stress propagation
		Precompression stress
		Crushing strength
		Shear strength
		Ratio of precompression stress to actually applied
		Changes in air, water, thermal flow processes and biological regimes due to stress strain and shear stress-induced distortion
Root functions	Rootability	Root length and root surface density
	Nutrient availability	Penetration resistance

Source: EEA Soil monitoring in Europe 2022

Soil pollutants

Soil pollution is a serious concern rising from a variety of sources. The two main types of soil pollution are point source pollution and diffuse pollution. Point source pollution is caused by a single identifiable source, such as an industrial spill, while diffuse pollution comes from multiple sources, such as agricultural land management practices and atmospheric deposition (Rodríguez-Eugenio *et al.*, 2018). Detecting the impact of pollutants due to diffusion is a complex process that requires careful monitoring over time (*Table 5*). In most cases, the assessment of trends related to soil pollution is based on modelling techniques.

Heavy metals, such as lead, cadmium, and mercury, are some of the most common and damaging contaminants. These metals accumulate in soil over time, leading to toxic levels that can harm plants, animals, and humans. They can also leach into groundwater, posing a threat to drinking water.

Another major group of soil contaminants includes pesticides and herbicides, which are widely used in agriculture and landscaping. The residuals from these chemicals can persist in the soil for years, affecting soil fertility and potentially contaminating water sources. Some pesticides have been linked to cancer and other serious health problems, making their presence in soil a significant public health concern. Industrial pollutants, such as petroleum products, solvents, and chemicals, can also contaminate soil. These substances are often released into the environment through spills, leaks, and improper disposal and can have serious long-term effects on soil quality and fertility. In addition, radionuclides, which are radioactive materials that occur naturally or as a result of human activities, cause serious health problems, including cancer and genetic damage, and can persist in the soil for thousands of years.

To manage and remediate polluted sites, several sub-indicators can be used, including soil polluting activity, the number of contaminated sites, progress in site management, expenditures on remediation, groundwater incidents, and dominant pollutants. Proper monitoring and management of these indicators can prevent further soil pollution and ensure that polluted sites are remediated in a timely and effective manner (EEA, 2022).

Soil biodiversity

Increasing soil biodiversity has a positive impact on almost all soil functions (Delgado-Baquerizo *et al.*, 2017).

Table 5 – Overview of the common pollutant groups and their monitoring and indicator methods

Pollutant group	Typical contaminants	Common monitoring method	Sub-indicators for site management
Heavy metals and metalloids	Lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr)	Soil-core sampling followed by ICP-MS or AAS for total and bio-available metal content.	Total load (mg kg^{-1}) vs. regulatory threshold.
Pesticides and herbicides	Organochlorines (e.g. DDT), organo-phosphates (e.g. parathion), triazines (atrazine), glyphosate	Solvent extraction followed by GC-MS or LC-MS/MS for parent compounds and metabolites.	Mass loading to groundwater (kg yr^{-1}).
Industrial organics	Petroleum hydrocarbons (TPH), PAHs, BTEX, chlorinated solvents (TCE, PCE)	GC-MS for PAHs and BTEX.	Concentration classes (e.g. <100, 100–1 000, >1 000 mg kg^{-1} TPH).
Diffuse nutrient excess	Nitrate (NO_3^--N), phosphate (PO_4^{3-}-P), ammonium (NH_4^+-N)	Colorimetric or ion-chromatography analysis of 2 mm sieved samples.	N-surplus (kg ha^{-1} yr^{-1})
Radionuclides	Cs-137, Sr-90, U-238 series, Am-241	Gamma-spectrometry of dried samples	Activity concentration (Bq kg^{-1}) above background.

Despite the many positive impacts of healthy soil biodiversity, there is a lack of knowledge about the status of soil biodiversity and how to quantify it correctly (Wall *et al.*, 2015). A variety of biodiversity quantification methods exist, but most of them are not based on species due to the great diversity and lack of knowledge about the relationships among the taxa found in the soil.

The French Soil Quality Monitoring Network Initiative enabled the sampling of 1700 points and characterised the microbial communities, bacterial biodiversity, and microbial biomass under different soil types and land uses (*Table 6*). The Land Use and Land Cover Surveys (LUCAS) in 2018 coordinated by the European Commission's Joint Research Centre included a soil biodiversity component in which DNA metabarcoding was performed for bacteria, archaea, fungi, and other eukaryotes. The aim of this was to characterise communities of soil organisms and identify species by associating them with soil properties, climatic conditions, and land cover.

According to Aksoy *et al.* (2017), variables, such as pH, soil textural class, SOM, and land use/land cover, are the "changeable" parameters with the highest importance for estimating the soil biodiversity potential. This potential can be mapped indirectly through these variables. Thresholds for these variables can be used to spatially delineate "risk" areas for certain soil faunal groups, such as earthworms and collembolans (*Table 7*).

It is crucial to assess and monitor soil biodiversity to determine the impacts of contamination at an early stage and to guide conservation efforts. Historically, edaphic diversity has been evaluated with classical morphological and taxonomic approaches; biotic indices based on nematode or earthworm communities have long served as bioindicators distinguishing healthy from contaminated soils. Nevertheless, conventional techniques suffer from marked limitations. A large proportion of microbial species are unculturable under standard laboratory conditions (it is estimated that >99% of soil bacteria do not grow on routine media). Taxonomic identification is slow and demands specialised expertise, and sampling may be biased, as very small or deep-dwelling fauna often remain undetected. In the past two decades, DNA-based molecular tools have revolutionised soil biodiversity research, enabling entire communities to be characterised more rapidly, sensitively, and comprehensively (Francioli *et al.*, 2021).

Environmental DNA (eDNA) metabarcoding has emerged as a particularly powerful technique. Total DNA is extracted from a soil sample, and one or several universal genetic markers (e.g., the 16S rRNA gene for bacteria, the ITS region for fungi, the COI gene for invertebrates) are subjected to high-throughput sequencing. Platforms, such as Illumina, can generate thousands to millions of reads that are subsequently assigned to known taxa via reference databases. This strategy uncovers immense hidden diversity, routinely revealing many more species or lineages than morphological methods and capturing microorganisms and microfauna that are difficult to observe directly (Llanos *et al.*, 2025). Recent studies have demonstrated that soil eDNA metabarcoding not only detects significantly more invertebrate taxa than traditional manual sampling but also provides finer taxonomic resolution. Likewise, for microorganisms, sequencing has uncovered entire groups that were previously unknown in certain soils (Llanos *et al.*, 2025).

Quantitative real-time PCR (qPCR) constitutes another widely used molecular method, oriented more toward quantification than species detection. qPCR can estimate absolute abundances of organisms or target genes in soil − for instance, enumerating 16S rRNA gene copies as a proxy for total bacterial biomass or quantifying functional genes involved in nitrification, hydrocarbon degradation, or antibiotic resistance to evaluate the functional consequences of contamination.

This approach has proven valuable for tracking declines in nitrifying populations in metal-impacted soils or increases in antibiotic resistance genes in soils amended with pharmaceutically contaminated manure (Wydro, 2022). Traditional bioindicators also remain valuable. Earthworms provide a classic example, as their absence signals adverse conditions (contamination, severe acidification, and extreme drought), whereas a plentiful earthworm community denotes healthy soil (Fründ *et al.*, 2010; Lehmann *et al.*, 2020). Within the microfauna, particular nematode taxa are used to calculate nematode-based soil quality indices that integrate the trophic structure and environmental stress (Lehmann *et al.*, 2020).

Soil pH balance

Soil acidity has long been recognised as a major constraint to crop and forest productivity, emerging when the acid-neutralising capacity (ANC) of the exchange complex is depleted and the activities of hydrogen (H^+) and aluminium (Al^{3+}) ions increase (Guo et al., 2010). The dominant anthropogenic drivers are (i) atmospheric deposition of sulphur and nitrogen (N) compounds and (ii) the widespread use of ammonium-based fertilisers, whose nitrification releases equimolar amounts of H^+ .

Table 6 – List of parameters of high importance for estimating the soil biodiversity potential (EEA Soil monitoring in Europe 2022)

Indicator	Francioli *et al.* (2021)	Creamer *et al.* (2019)	Huberet *et al.* (2008)	Breure (2004)
Diversity of earthworms		×	×	×
Diversity of collembolans			×	
Microbial biomass	×	×	×	×
Diversity of nematodes		×		×
Soil texture		×		
Bulk density		×		
Groundwater table depth		×		
pH		×		
C:N ratio		×		
N:P ratio		×		
Soil organic matter		×		
Organic carbon content		×		
eDNA	×			

Acidification is accelerated on coarse-textured, low-buffering soils derived from siliceous parent materials, whereas clay-rich or carbonate-bearing substrates can resist the pH decline for decades (EEA, 2022). Below a pH threshold of 5.2, the availability of base cations (Ca^{2+} , Mg^{2+} , and K^+) falls sharply, while toxic Al^{3+} and Mn^{2+} increase, inhibiting root elongation, nodulation, and microbial enzyme activity; in forests, these processes manifest as foliar nutrient imbalances, reduced tree vitality, and a loss of understorey species diversity (Johnson *et al.*, 1982). Recent continent-wide monitoring has confirmed that despite declining sulphur deposition, 85% of European forest plots showed a further pH decline between 1995 and 2018, underscoring the cumulative nature of acidification (Michel *et al.*, 2023).

Soil alkalinisation − a rise in pH above 7.8 driven by the accumulation of carbonates, bicarbonates, or exchangeable sodium (Na^+) − is less often highlighted but is equally detrimental (Rengasamy, 2010). Calcareous loess and limestone landscapes are naturally alkaline, but secondary alkalinity is expanding in arid and semi-arid regions where irrigation water with high residual alkalinity or poor drainage causes carbonate precipitation and selective leaching of acidic cations (Qadir and Oster, 2004). High pH precipitates phosphorus as calcium phosphates and converts micronutrients, such as iron, manganese, zinc, and copper, into sparingly soluble forms, producing characteristic chlorosis and yield losses in sensitive crops (Brady and Weil, 2016). Sodic (alkaline) soils, defined by an exchangeable sodium percentage >15%, suffer additional structural collapse because Na^+ disperses clay particles, leading to poor infiltration, surface crusting, and heightened erosion risk (Sumner and Naidu, 1998).

Therefore, monitoring the pH spectrum requires complementary indicators. In acid-prone systems, pH (1:2.5 soil:H_2O) and base saturation remain the most practical metrics, while exchangeable Al^{3+} provides an early warning of toxicity. In alkaline or sodic soils, pH alone can be misleading; electrical conductivity, the sodium adsorption ratio, and dissolved carbonate alkalinity furnish a more complete diagnosis (Rengel, 2011). Management similarly diverges. Liming, balanced N fertiliser regimes, and cover crops counteract acidification, whereas alkalinisation is mitigated through the application of elemental sulphur or acidifying amendments, which improve drainage and the use of salt-tolerant cultivars (Brady and Weil, 2016; Qadir and Oster, 2004).

Taken together, the soil pH balance encapsulates two opposing but interconnected processes that shape nutrient availability, biological activity, and structural stability. Because both extreme acidity and extreme alkalinity constrain the delivery of ecosystem services, maintaining pH within crop- and site-specific optimum ranges (typically 5.5–7.5 for temperate arable systems) should remain a cornerstone of soil health assessments and the adaptive management frameworks envisioned under the forthcoming policies.

Technologies

The term ‘technology’ pertains to the vast array of tools and systems utilised to execute a business. The collection of available technologies dictates the potential for production, costs, and profitability of business models and the possibilities for soil monitoring and management practices. This also includes the implementation of information technology that is suitable for minimising input usage, managing transactions, and monitoring outcomes and the environment (Rajkhowa and Baumüller, 2024). The availability and application of these technologies significantly influence the production capacity, cost structures, and profitability of business models, including those related to soil health management.

Additionally, advancements in information technology are crucial for optimising input use, managing transactions, and effectively monitoring environmental outcomes (*Figure 3*).

From a decision-support perspective, mobile and cloud-based platforms are already translating complex datasets into practical recommendations. The FAO-backed SoilInfo App supplies location-specific pedological data, and the LandPKS suite couples smartphone photography with big data algorithms to benchmark land potential across contrasting agroecological zones (Herrick *et al.*, 2022). Building on these precedents, the EU project iSQAPER finalised the Soil Quality Assessment Tool (SQAPP), an interactive dashboard that ranks management options according to user-defined sustainability goals (Cerda-Bullón *et al.*, 2023).

Monitoring and evaluation have benefited equally from technological convergence. Internet of Things (IoT) arrays measure moisture, redox potential, and nutrient fluxes at sub-hourly resolution. Proximal sensing devices, such as portable VNIR spectrometers, deliver rapid estimates of SOC, and satellite constellations (Sentinel-2, Landsat-9, and EnMAP) provide cloud-free, fortnightly coverage over Europe. The forthcoming Soil Health Data Cube, developed within AI4SoilHealth, will merge more than three decades of Landsat imagery with ground observations to generate harmonised indicators for all EU member states (AI4SoilHealth Consortium, 2024).

Finally, the same digital infrastructure feeds directly into emerging business models. Transaction-certified data streams support result-based payments, carbon credit issuance, and parametric insurance products, narrowing the gap between soil stewardship and financial returns (Chandrasekaran and van den Bosch, 2023). As these examples demonstrate, technological innovation is no longer an ancillary component but rather a central driver of soil health investments, policy compliance, and market uptake.

Soil health is a critical factor in agricultural productivity and environmental sustainability (Gurmu, 2019). Soil health impacts not only crop yield but also ecosystem services that support the broader natural environment (Ferrarini *et al.*, 2018). Soil degradation can result from various factors, including chemical contamination, overuse, and erosion. As such, monitoring soil health is vital in maintaining sustainable agricultural practices and mitigating environmental damage.

Precision farming technologies have emerged as useful tools in monitoring soils. These technologies are designed to assess the status of agricultural soils and to provide recommendations for sustainable land use. By using these technologies, farmers can track the effectiveness of their practices in improving soil health and take corrective measures if necessary. One example of a precision agriculture technology is GPS mapping and remote sensing to assess soil quality and recommend appropriate fertilisation and irrigation practices (Abdellatif *et al.*, 2021; Lehmann *et al.*, 2020). This technology provides land managers with real-time data on soil health, which they can use to make informed decisions on land use and crop management (Abdellatif *et al.*, 2021).

In addition to farm-level optimisation, remote sensing technologies, such as satellite imaging, can be used to monitor soil health over a large area (*Table 7*). Thus, a comprehensive view of soil health can be achieved in specific regions, and potential issues that may require further investigation can be identified. The current state-of-the-art technologies related to Earth observation techniques allow predictions very close to reality. One of the objectives to be achieved is the measurement of soil data and soil conditions without the need for on-site sampling.

Satellite- and aircraft-based remote sensing already underpins many inspection and compliance workflows because it reduces the number of time-consuming on-farm visits. When fused with ancillary datasets, multispectral imagery sharpens the identification of management practices that require closer scrutiny. A pertinent illustration is the use of light detection and ranging (LiDAR), which is an active sensor that emits laser pulses to retrieve vegetation height across entire landscapes, allowing agencies to delineate eligible grassland under the pro-rata method for permanent pasture. Coupled with crop identification algorithms, LiDAR can also accelerate greening inspections, supplying the evidence needed for crop diversification checks before the statutory deadlines. The approach, however, is not without constraints; persistent cloud cover over remote regions and rugged topography can degrade image reliability and delay data acquisition. Where satellite coverage is insufficient, drones step in to provide missing granularity. These lightweight platforms can be deployed on demand to collect centimetre-resolution imagery, bypassing both cloud interference and physical inaccessibility on the ground. Legal frameworks differ among member states, as flight authorisations, operator registration, and land-owner consent may be required, but the operational gains are considerable. Targeted drone sorties document suspected erosion scars, nutrient-deficient patches, or waterlogging within hours, feeding high-resolution optical, thermal, or multispectral data into the same analytic pipeline used for satellite scenes. Equipped with compact sensors, unmanned aerial vehicles (UAVs) capture spectral signatures that proxy soil moisture, chlorophyll content, or canopy temperature, thereby extending the remote-sensing continuum from space to field scale and closing the information gap left by broad-area systems (*Table 8*).

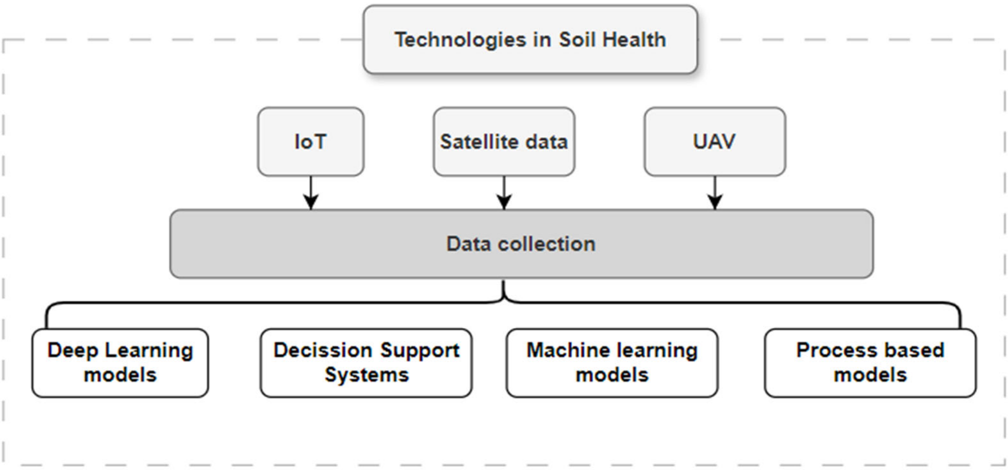

Figure 3 – Most commonly used types of technologies in soil health assessment

Table 7 – Summary of existing technologies/models by the typeof targeted soil data (derived from Fan *et al.*, 2022)

Soil data targeted	Methods	Input	Output
Soil moisture estimation	SVM, ANN	Spaceborne remote sensing data	Estimated soil moisture
	SVM, ANN	Air temperature, relative humidity, average solar radiation	
	DBN, MLP	Evapotranspiration, leaf area index, meteorological information, land surface temperature	
Drougth prediction	SVR, drougtht index	Area index, intensity index, ridge position index, western ridge point index, nothern boundary position index	Standarized precipitation evapotrans-piration index
	DT, RF	Automatic synoptic observation system data, drought indicator, remote sensing data	Drought accuracy
Water depth	LSTM	Irrigation volume, rainfall volume, evaporation volume, temperature	Water table depth
Soil organic carbon	MARS, ANN, SVM, PLSR, RF	Spectral measurements, total carbon, total nitrogen, pH	Soil organic carbon
Soil mapping workflow	k-NN, SVM, RF	Soil texture, horizon, depth, mottle, soil moisture, landform	Soil mapping covariates
Soil erosion and remediation	DT	geological formation, soil type, annual precipitation, elevation, inclination, vegetation	Soil erosion prediction
	RF	topographic wetness index, stream power index, transport capacity index, slope, curvature, relief elevation, land use	Erosion process class
Soil contaminants	RF, ERF, SVM, MLP	high-resolution aerial imaging of arsenic contaminated agricultural field	Soil risk level
	MPL, ANN, M5P, LR	moisture, organic carbon, total carbon, total nitrogen, total phosphorus, available phosphorus, loss on ignition	PAH bioavailability

Table 8 – Common soil and plant properties measured using drones and UAV technologies

Soil properties	Plant properties
Soil moisture content	Vegetation indices (e.g. NDVI, EVI, SAVI)
Soil temperature	Photosynthetic activity
Soil organic matter content	Canopy cover
Soil texture	Biomass and productivity
Soil pH	Plant height
Soil compaction	Water stress
Soil salinity	Leaf nitrogen content
Soil nutrient content (e.g. N, P, K)	Leaf area index (LAI)

This information can be used to create detailed maps of soil properties and crop health, which can help farmers and land managers identify areas that require targeted interventions or monitor changes over time. Overall, while there are legal limitations to the use of drones in land monitoring, their potential to provide accurate and detailed information makes them a valuable tool for sustainable land management.

UAVs are used as an environmental remote sensing application to reduce the data gaps between in situ data collection and satellite resolution. Photogrammetric image processing enables the creation of digital terrain models (DTMs) and ortho-image mosaics with very high resolution on a sub-decimetre level. It can be used to quantify gully and badland erosion in 2D and 3D as well as for landscape development over very large areas (D'Oleire-Oltmanns *et al.*, 2012). UAVs are considered a very good tool for the management, digitisation, and analysis of high-precision agricultural systems but are still too expensive, and image processing requires that conventional users have the skills and time (Barbosa-Junior *et al.*, 2022). Collected data can be exploited for almost continuous (in space and time) monitoring of the exploitation resources, enabling better decision making with higher precision, optimising crop yield, and making predictions about the future to prevent the spread of pests and diseases.

Policy environment

The EU Soil Strategy for 2030 sets an unambiguous political horizon; by 2050 every soil in the Union should be demonstrably healthy (European Commission, 2021a). A dedicated Soil Monitoring Law, expected in 2025, will translate that vision into binding standards and a common indicator set. The law is designed to dovetail with the forthcoming Nature Restoration Regulation, which already requires that at least 20% of EU land and sea be under active restoration by 2030 and 2050, respectively (European Commission, 2022). Together with the Zero-Pollution Action Plan for Air, Water and Soil (European Commission, 2021b), these initiatives elevate soil protection from a largely voluntary agenda to a core legal obligation of the European Green Deal.

Within this high-level architecture, the Common Agricultural Policy (CAP) 2023–2027 is the chief delivery mechanism on the ground. Regulation (EU) 2021/2115 requires every member state to draw up a CAP Strategic Plan that converts 10 Union-wide objectives into measurable results (European Union, 2021). Payments are channelled through conditionality, eco-schemes, and agri–environment–climate measures that link support to concrete gains, such as sustained ground cover, higher SOC stocks, and lower pesticide risk scores (Batáry et al., 2015; Birge and Herzon, 2019).

Soil outcomes nevertheless depend on a broader policy mix. The LULUCF Regulation counts carbon-rich soils in national greenhouse gas inventories (European Union, 2018), and the National Emission Ceilings Directive limits atmospheric inputs of acidifying compounds (European Union, 2016). The Water Framework Directive internalises the cost of nutrient and pesticide run-off (European Union, 2000), and the Eighth Environment Action Programme provides the overarching “live well, within planetary boundaries” compass for 2030 (European Union, 2022). As emphasised by the Organization of Economic Co-operation and Development (OECD), the effectiveness of any single instrument depends on how coherently it interacts with others within such a mix (OECD, 2016).

From 2022 to 2025, NOVASOIL has responded to three main issues: 1) its field-tested data streams on carbon gains, erosion control, and biodiversity proxies can inform the indicator set that the Soil Monitoring Law will require; 2) its prototype business models align directly with CAP eco-schemes and the financing architecture of the Nature Restoration Regulation, bridging public incentives and private investment; and 3) by bundling soil-based climate mitigation, nutrient retention, and biodiversity gains, NOVASOIL advances several Sustainable Development Goals (SDGs) − most visibly SDG 2 on food security, SDG 6 on clean water, SDG 13 on climate action, and SDG 15 on life on land − demonstrating that soil stewardship is an indispensable lever for the 2030 Agenda.

In summary, the EU soil policy is moving from fragmented, largely voluntary measures to an integrated, legally enforceable framework in which CAP finance, horizontal environmental directives, and the forthcoming Soil Monitoring Law operate as mutually reinforcing pillars. NOVASOIL occupies the intersection of these strands, offering real-world test beds that can show how coherent policies turn high-level ambitions into measurable improvements on a field scale, while also pinpointing the institutional gaps that still hinder the emergence of sustainable soil-centred business models (Rahman *et al.*, 2017).

Legal conditions

The aim of the NOVASOIL project is to contribute to the strengthening of soil health legislation and to implement sustainable business models that invest in improving soil health. Legal guarantees are essential for developing this kind of business. Currently, European environmental legislation covers some but not all, environmental aspects. The degrees of legal protection for air or water differ from those for soil resources. Without strict laws to protect soil, all efforts to achieve the objectives of the European Green Deal (climate neutrality, biodiversity restoration, zero pollution, or sustainable food systems) will be in vain.

The EU is moving from a patchwork of voluntary guidelines to a cohesive body of hard law that treats soil as a strategic asset. The political cornerstone is the EU Soil Strategy for 2030, which commits every member state to place all soils on a demonstrably healthy trajectory by 2050 (European Commission, 2021a). To make that vision enforceable, the Commission announced a dedicated Soil Monitoring Law to be tabled in 2025. The draft concept, published in 2023, positions the new regulation as the soil-specific counterpart to the Nature Restoration Regulation, which already mandates the active recovery of at least 20% of Union land and sea by 2030 (European Commission, 2022). Once adopted, the two acts will form an integrated legal umbrella under the European Green Deal and its Zero-Pollution Action Plan (European Commission, 2021b).

A pivotal design feature of the forthcoming law is the principle of integration, in which soil protection must be mainstreamed across agriculture, climate, water, and spatial-planning legislation. In practice, this means that conditionality and eco-schemes under the Common Agricultural Policy 2023–2027 (Regulation (EU) 2021/2115) link direct payments to soil-friendly practices, such as permanent ground cover, minimum tillage, and nutrient loss reduction, while climate files, such as the LULUCF Regulation (Regulation (EU) 2018/841), count carbon-rich soils towards national greenhouse gas inventories, and the Water Framework Directive (Directive 2000/60/EC) constrains diffuse pollution from fertilisers and pesticides. Therefore, the effectiveness of any single instrument hinges on how coherently it interacts with the others, a logic captured in OECD guidance on “policy mixes” for sustainable soil management (OECD, 2016).

Equally important is subsidiarity. Soil threats vary with climate, geology, and farming systems. Many remedial measures are thus best designed locally, but problems with single-market or transboundary externalities require Union-level rules. The Soil Monitoring Law proposes to resolve this tension by defining a common baseline (e.g., mandatory thresholds for SOC loss or erosion) while leaving member states free to choose the instruments − payments, regulation, or advisory services − that achieve those targets most cost-effectively.

Credibility depends on harmonised monitoring and reporting. The law is expected to integrate the LUCAS soil survey, now covering > 45,000 georeferenced sites, into the legal text and to recognise remote-sensing outputs from Copernicus alongside in situ sensor networks. A shared indicator set (including SOC stocks, erosion risk, nutrient surpluses, and selected biodiversity proxies) will feed both compliance checks and adaptive management. Such a system provides the evidence base that innovative business models, such as those piloted by NOVASOIL, need to monetise verified improvements in soil functions.

Finally, an institutional gap analysis shows that many member states still lack agencies or financing windows able to blend public and private capital for soil restoration; addressing these gaps is essential if market-oriented schemes are to scale (Rahman *et al.*, 2017). The Soil Monitoring Law can catalyse change by requiring national implementation plans that identify missing competences, financing bottlenecks, and capacity-building needs.

Market situation

The market related to soil health and the goods that can be obtained from it are very varied. This wide range of possibilities in the market makes it difficult to define a clear-cut situation. The literature has emphasised the role of payment for ecosystem services (PES) schemes as a win–win opportunity for both the supplier and buyers of the service. PES schemes succeed with a robust and credible business case and an accurate estimate of costs, including transactions. We can identify different spatial scales. International, such as the mechanism for Reducing Emissions from Deforestation and Forest Degradation (REDD+), developed by different countries paying to avoid this degradation and reduce emissions, to the local or national level, as watershed protections or incentives to land managers. One of the most widely used PES schemes is related to climate change mitigation through carbon credits. The market is quite developed around carbon credits and some other PES schemes (Bond *et al.*, 2013).

Good market access is one of the most powerful mechanisms for generating and investing in business models that are enthusiastic about improving soil health, especially in developing regions. For example, areas of relatively high agricultural potential but remote from major markets, face numerous challenges in marketing their outputs. If there is a good market situation and market access, transaction costs will be low, and profits in the business model will be transformed into substantial incomes.

For PES schemes, the process that determines how to access the market and set prices involves different considerations. As explained in the PES feasibility guide (Fripp, 2014), the producers of the service who accept the price adjusted by international markets, such as in the carbon market, or an international body or entity, such as for a debt-for-nature swap, should be clarified. The price is negotiated depending on the buyer’s willingness to pay for the service and the supplier’s willingness to accept the price. Defining the spatial level of the business model, which rules and how accessible it is, are fundamental steps to establish and implement PES schemes (Schomers and Matzdorf, 2013). For example, if a user decides to sell carbon credits because the area in which they are interested is the most viable and efficient business model, they will need advice on how to access the international carbon market. Regarding the ecosystem service of carbon sequestration and climate mitigation, according to NGFS TSVCM McKinsey and Company, the global annual demand for carbon credits could amount to between 1.5 and 2 Gt of carbon dioxide by 2030 and up to 13 gTCO2 by 2050. The latter would imply an increase in market size between $5 billion and $30 billion. However, several factors could make it difficult to mobilise the potential supply and bring it to the market. Furthermore, buyers, and sellers face the problem that high-quality carbon credit is scarce due to time-varying carbon verification and quantification methodologies (Blaufelder *et al.*, 2021).

An example of an integrated production business model is the “Flora

Aromatica Santa Luce" project (Scaramuzzi *et al.*, 2020). This project involves 16 actors, 11 farmers, 2 research institutes, 1 farmer organisation and the commercial firm Flora. The goal was to "create a new symbolic capital of the rural area at the borders between the provinces of Pisa and Livorno and valorize it as a new touristic destination" (Scaramuzzi *et al.*, 2020), similar to agrotourism but recognising the importance of direct selling. This model is based on the agrotourism market and supply chains around the lavender crop. This project is a good example of how to enrich rural territorial capital in its social, environmental, human, and symbolic components, promoting the construction of a sustainable territorial model capable of self-feeding with a specific tourism demand and economic development (Scaramuzzi *et al.*, 2020).

In recent years, stakeholders in the agricultural sector have realised the importance of healthy soils and the importance of maintaining a stable crop yield without degrading the soil, reducing costs and increasing ecosystem services. This is not only for croplands but also for forests, pastures, orchards, etc. Many areas of the world, including Europe, are under threat from different degradation factors, such as soil loss, soil sealing, nutrient loss, and droughts. However, another way to invest in soil health is to implement management techniques that prevent soil degradation and, in turn, promote and increase the provision of ecosystem services. In the literature, many case studies have implemented certain soil management practices to leave soils to a better state. Soil degradation in sub-Saharan Africa is largely a result of prolonged crop cultivation without adequate return of organic matter or plant nutrients to replenish the soil. To improve these areas, the application of N fertilisers and cattle manure boost maize yields and soil health, thus receiving more income for smallholders (Kihara *et al.*, 2016). Another case is olive farmers, who are implementing cover cropping practices to improve biodiversity and reduce erosion, providing an example of integrated production (Bruggeman *et al.*, 2008; WBCSD, 2018). The market situation of these cases is the same; only the costs and benefits obtained from the investment in soil health change. It is an adaptation of the business model to the current climate change and soil pressure situation.

A problem we encounter is that many ecosystem services are not sold on the market and no price reflects the service's economic value. This is a great opportunity to dive into the existing knowledge and create and implement business models that, in addition to the commonly quantifiable ecosystem services, can evaluate and give economic value to those ecosystem services (ESs) through valuation techniques. There is extensive literature assessing the economic value of ecosystem services that are not on the market.

Market economic tools

Incentives represent a multifaceted and complex concept that varies according to different contexts and interpretations. Generally, they are viewed as rewards or penalties designed to influence behaviour. In some contexts, incentives are understood as external rewards or reinforcements capable of influencing behaviour without necessarily altering intrinsic motivation or beliefs (Deci *et al.*, 1999). Alternatively, incentives may broadly include both rewards and penalties that guide individuals towards specific behaviours (Deci *et al.*, 1999). Moreover, incentives are strongly influenced by social norms and values, determining what is considered acceptable or desirable behaviour in a given context (Bryan, 2013). Consequently, they serve as essential tools in the economic, social, and environmental domains, encouraging desirable actions.

In economic terms, incentives often seek alignment between individual objectives and collective goals. For instance, they may encourage sustainable economic behaviour, enhance resource allocation efficiency, and influence market decisions (Mckinsey and Company, 2021; Pagiola, 2008). Social incentives are commonly tied to societal norms, promoting behaviours, such as charitable actions or ethical practices that society deems favourable (Bryan, 2013; GEF, 2014). Environmental incentives specifically promote practices beneficial to ecosystem health, biodiversity conservation, and ecosystem services, which are commonly employed through policy instruments, such as PES (Bryan, 2013; Blundo-Canto et al., 2018; Pagiola, 2008; Chever, Gonçalves, Lepeule -AND International, 2022; Schomers and Matzdorf, 2013).

PES schemes provide a prominent example of environmental incentives, ranging from narrow definitions involving direct transactions between service providers and beneficiaries to broader approaches where beneficiaries indirectly compensate providers of ecosystem services (Bryan, 2013; Blundo-Canto et al. 2018; Chever, Gonçalves, Lepeule -AND International, 2022). These schemes often exist concurrently, interacting to influence multiple land-use practices simultaneously, thus affecting multiple ecosystem services and creating both intended and unintended outcomes. This interplay of incentives can result in complex dynamics in which actions designed for one ecosystem service unintentionally influence others, generating trade-offs or co-benefits (Piñeiro et al., 2020). Consequently, relationships among incentives, management practices, and ecosystem service outcomes can become multifaceted, with incentives frequently operating in overlapping or complementary ways.

Considering that these interactions can lead to more efficient policy design and better management of agricultural and environmental systems, avoiding unintended negative consequences and promoting desirable outcomes (Bryan, 2013; Huberman, 2008; GEF, 2014; Snilstveit *et al.*, 2019).

Bryan (2013) highlighted that financial incentives can produce both synergies (i.e., positive outcomes) and tensions (i.e., negative trade-offs) in driving changes in land use and management. These changes, in turn, influence multiple ecosystem services, generating a complex array of co-benefits and trade-offs. The relationships between incentives, land use, and ecosystem services are spatially and temporally variable, often exhibiting non-linear and multidimensional interactions, including many-to-one, one-to-many, and many-to-many configurations. The lower tier of the conceptual framework illustrates potential dynamic feedback whereby variations in ecosystem service supply may affect incentive pricing mechanisms. Garrett and Neves (2016) further distinguished between short- and long-term incentive mechanisms and provide concrete examples of their implementation (*Table 9*). In addition to market dynamics, it is important to define the economic instruments and regulatory frameworks through which such business models may be operationalised and scaled.

Table 9 – Incentives or market economic tools to promote business models

Category	**Tool (Incentives tipology)**	**Description**	**Reference**
1. Direct public payments	Subsidies	Financial incentives from the government to promote sustainable agricultural practices.	SPDA, 2024
	Prohibition of use	Legal restrictions to protect natural resources and promote soil conservation.	SPDA, 2024
	Property use rights	Regulations that define how land can be used to encourage sustainable practices.	SPDA, 2024
	Mandatory farm set-asides	Policies requiring certain agricultural areas to remain uncultivated for soil conservation.	SPDA, 2024
	Offsets	Mechanisms allowing companies to compensate for environmental impact through conservation projects.	SPDA, 2024
	Green bonds	Financial instruments funding projects with environmental benefits.	SPDA, 2024; García *et al.*, 2023
	Direct payment for ecosystem services (PES)	Financial compensation for landowners implementing conservation practices.	IDB, 2022
	Rewards for ecosystem services	Incentives given to individuals or organizations contributing to environmental protection.	IDB, 2022; Le *et al.,* 2023
2. Direct private payments	Offsets	Private companies invest in conservation projects to mitigate environmental impact.	IDB, 2022
	Corporate social responsibility (CSR)	Voluntary initiatives by companies to improve environmental and social well-being.	IDB, 2022
	Direct payment for ecosystem services (PES)	Companies pay landowners for conservation actions that provide ecosystem services.	IDB, 2022; Le *et al.*, 2023
	Rewards for ecosystem services	Private incentives to encourage environmental sustainability.	IDB, 2022; Le *et al.*, 2023
3. Tax incentives	Conservation easements	Legal agreements that limit land use to preserve environmental values.	SPDA, 2024, Brown *et al.*, 2023

	Taxes and charges	Fiscal policies discouraging harmful practices and promoting conservation.	SPDA, 2024; Farooq *et al*., 2023
4. Cap-and-trade markets	Permits and Quotas	Regulatory limits on environmental degradation with tradable allowances.	SPDA, 2024
5. Voluntary markets	Conservation easements	Voluntary agreements to protect natural resources.	VCMI, 2023; Spilker and Nugent, 2022
	Voluntary farm set-asides	Farmers voluntarily keep portions of their land uncultivated for conservation.	VCMI, 2023
	Green bonds	Financial products funding voluntary environmental projects.	VCMI, 2023; García *et al*., 2023
	Conservation concessions	Agreements granting conservation rights over a specified area in exchange for economic benefits.	VCMI, 2023
	Rewards and direct payments for pes	Voluntary financial incentives for environmental conservation.	VCMI, 2023; Le *et al*., 2023
6. Certification programs	Marketing labels (certified products)	Certification programs ensuring sustainable production (e.g., organic, Fair Trade).	ECLAC, 2020
	Marketing labels (non-certified)	Labels suggesting ecological benefits without formal certification.	ECLAC, 2020
	Green bonds	Environmental financial instruments promoting certified sustainable projects.	ECLAC, 2020; García *et al*., 2023

DISCUSSION

Soil health assessment perspectives

Soil health is based largely on the choice and interpretation of effective indicators that capture soils' intricate physical, chemical, and biological characteristics, including SOC, pH, bulk density, NPK content, and biological activity (Lehmann *et al*., 2020; Vogel *et al*., 2021). They are crucial because they capture both the resources contained in the soil and its ability to provide ecosystem services. Among them, SOC is the strongest and most frequently used indicator because it is directly correlated with soil structure, fertility, water holding capacity, and carbon sequestration (Fell *et al*., 2018; Goulding *et al*., 2013; Johannes *et al*., 2017). The SOC/clay ratio has also been used increasingly as a good indicator of soil stability, particularly for temperate agricultural soils (Prout *et al*., 2020; Schjønning *et al*., 2012). With advances in remote sensing, it is now possible to monitor SOC, SOM, and other soil properties with spectral indices, such as GNDVI, BI, and SATVI (Gholizadeh *et al*., 2018; Li *et al*., 2022), and this makes them very useful for larger spatial areas. However, it is still difficult to enhance the relation between spectral information and soil properties and to incorporate machine learning techniques to enhance these estimations and make them more reliable (Li *et al*., 2022)

Soil pH and nutrient levels (C:N and N:P ratios) remain critical for evaluating chemical fertility and potential toxicities or deficiencies. Biological indicators, although historically underrepresented, are gaining relevance due to their close link to soil function (Lehmann *et al.*, 2020). For instance, microbial biomass, enzymatic activity, and macrofauna diversity (earthworms and collembola) are being integrated into monitoring schemes, such as the LUCAS soil survey (European Commission, 2018) and national soil quality programs (Creamer *et al.*, 2019; Huber *et al.*, 2008).

Despite this progress, one of the persistent challenges is establishing clear thresholds and functional interpretations of these indicators. As highlighted by Bunemann *et al.* (2018), many indicators provide raw data but lack a consistent conceptual framework linking measurements to soil functions and ecosystem service delivery. This gap hampers their integration into decision-making processes, particularly for land managers and policymakers.

Future soil health monitoring efforts should place greater emphasis on expanding the use of biological indicators to better capture soil biodiversity and its critical functional roles in nutrient cycling, structural stability, and resilience (Delgado-Baquerizo *et al.*, 2017; Wall *et al.*, 2015). A key challenge remains the development of functional thresholds that are context specific − accounting for variables, such as soil type, climate, and land use − to translate measurements into meaningful insights that can guide management decisions (Lehmann *et al.*, 2020).

Additionally, the integration of machine learning and big data approaches represents a promising pathway for handling the increasing complexity of soil health assessments. Initiatives, such as the Soil Health Data Cube, exemplify the potential to synthesise large datasets from remote sensing, in situ sensors, and laboratory analyses, thereby enabling more comprehensive and scalable soil monitoring systems.

Furthermore, improving the dynamic monitoring of indicators that are particularly sensitive to climate change impacts will be essential to capturing the evolving pressures on soil systems (Vogel *et al.*, 2021). These advancements will help refine our understanding of soil responses in future climate scenarios and support more targeted interventions.

In conclusion, although physical and chemical indicators of soil health have been well established and widely applied, the next frontier lies in mainstreaming biological indicators and moving towards the creation of integrated, multifunctional soil health indices. Such an approach would not only facilitate a more holistic evaluation of soils but also enhance the capacity to monitor their contribution to climate mitigation, biodiversity conservation, and food security. A critical task for future research and policy is to balance the need for comprehensive soil health assessments with the practicality of their application in the field, ensuring that indicators remain scientifically robust, yet accessible and interpretable by farmers, land planners, and policymakers alike.

Policy and legislation perspectives

The growing awareness of soil health as a central pillar of environmental sustainability, food safety, and climatic resilience has increasingly been translated into policy and law, notably in the EU. Soil has been grossly underprioritised in environmental law compared to air and water, with corresponding enormous gaps in conserving it. This is now being addressed as soil multifunctionality and the role of providing basic ecosystem services, such as climatic regulation by sequestering carbon and managing water and other resources. The EU's Soil Strategy for 2030 is clear and ambitious: all soils should be in good condition by 2050.

This strategy is a paradigm shift, viewing soils not merely as a productive medium for agriculture but as a key resource for mitigating climate change, conserving biodiversity, and regulating water. At the heart of this vision is the future EU Soil Monitoring Law, which aims to provide binding commitments, establish quantifiable objectives, and provide mechanisms for periodic monitoring and reporting. This legal initiative aims to address the patchwork nature of existing soil governance and to locate soil health objectives in larger policy frameworks, such as the Common Agricultural Policy (CAP), Biodiversity Strategy, and Green Deal.

The general principle behind these policies is soil protection across sectors because agriculture, forestry, urban development, and energy production all exert pressures on soil systems. Ensuring consistency between these sectors is necessary to avoid conflicting objectives and to create synergies that benefit soil health.

Subsidiarity is also necessary because it allows decision making to take place on the best possible level—local, regional, national, or EU—so that there is collective action in case challenges that are transnational. Additional specific decision making will also consider local conditions that will enhance precision in soil health status determination by considering site conditions and establishing site-specific thresholds accordingly.

The important impact of the CAP on soil health policies in the areas under consideration, particularly soil conservation, is explicitly stated in Article 6 of Regulation 2021/2115 and reiterated again in Article 47, letter (a), as part of sectoral intervention priorities. Nevertheless, there remain uncertainties regarding the overall effectiveness of these provisions.

One of the continuing criticisms is that there is too excessive a reliance on voluntary mechanisms, such as agri-environmental schemes and eco-schemes. As these initiatives are non-mandatory, they are prone to lack widespread uptake (Abadi *et al.*, 2020; Barreiro-Hurle *et al.*, 2023). Farmers are incentivised to take part to a large degree by financial factors and how they weigh costs against possible gains through more sustainable practices. This is indicative of the need for more precisely tuned policies to promote the widespread uptake of soil-friendly practices (Raggi *et al.*, 2015). In this regard, the newly adopted Nature Restoration Law, with a clear target to increase the SOC content in cropland mineral soils, is a clear case of a focused and directed policy intervention.

References are made to the fact that soil health is generally addressed indirectly through general policies on biodiversity, climate change, and water management. This indirect approach tends to generate fragmented and weaker actions than a focused soil health policy.

While integrating soil health into other policy areas is a clear policy direction, it results in the diffusion of responsibilities and weakened action across multiple Directorates-GeneralDGs and stakeholders. This is indicative of the weakness of the reliance on non-binding objectives, and there is a requirement for focused policies and programs that make soil health a top priority (Winkler *et al.*, 2025). This is confirmed by the lack of clear soil health objectives in addition to general objectives of the CAP.

CONCLUSIONS

Despite these advances, there are still significant challenges to operationalising soil health policies. One is to translate scientific indicators into legal standards that can take management action when soil health is below acceptable thresholds (Montanarella *et al.*, 2016). This is compounded by the diversity of soil types, land uses, and socioeconomic contexts in Europe.

Technologies, such as the LUCAS soil survey, have been effective in providing harmonised information on the soil status, but future policies must invest in building these monitoring systems to add new data and new technologies, such as remote sensing, to increase the spatial resolution and capability for real-time evaluation.

Legal systems also need to evolve to support emerging business models that invest in soil health and move to sustainable land management, such as carbon farming, PES, and green bonds.

Credibility and scalability demand clear definitions, certification schemes, and robust verification mechanisms.

Policies also need to be equitable to safeguard small and medium landholders to make compliance costs not a barrier but a means of inclusive participation in sustainable land management. In this context, the future EU Soil Monitoring Law has the potential to be a landmark in environmental law that puts soil at the heart of Europe's biodiversity and climate agendas. Its success will depend on effective implementation, continued dialogue between scientists, policymakers, and land managers and sustained investment in developing capacity and innovation.

This review has demonstrated that a coherent appraisal of soil health hinges on a limited set of biophysical indicators whose monitoring is being revolutionised by emerging in situ and remote-sensing technologies (Section 4).

However, our analysis also reveals three persistent policy gaps. First, pan-European comparability is hampered by the absence of harmonised metrics and sampling protocols. Second, economic incentives remain poorly aligned with the restoration of soil-based ecosystem services, constraining private investment. Third, policy instruments still struggle to integrate multi-scale data streams into actionable regulation. The NOVASOIL project is designed to bridge these gaps by piloting a harmonised "soil health dashboard" that standardises indicator reporting, tests result-based remuneration schemes to reward farmers for verified improvements, and deploys a federated data platform that fuses ground and Earth observation inputs for policy compliance checks.

Overall, these innovations can accelerate progress towards the forthcoming EU Soil MonitoringLaw and offer a blueprint for other regions.

Future research should refine cost-effective verification protocols and explore public–private coalitions that scale soil–health finance across diverse agroecosystems.

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