CODEX PLANETARIUS

Soil Organic Matter as a Global Metric for Soil Heath: Integrating Soil Biology and Agro-Ecosystem Management

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About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of Codex Planetarius is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

This proof-of-concept research and analysis is funded by the Gordon and Betty Moore Foundation and led by World Wildlife Fund in collaboration with a number of global organizations and experts. For more information, visit www.codexplanetarius.org

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Abstract

Soil is fundamental to sustaining life on Earth, supporting agricultural productivity, water and climate regulation and habitat for biodiversity. Increasing pressures from agricultural intensification, climate change, and land-use changes pose existential threats to our soils as well as impairing their quality or health. Both these terms are subject to considerable criticism. Consequently, accurate measurement and monitoring are essential actions to support more informed research guidelines and policies towards sustainable land management.

Soil microorganisms play a crucial role in maintaining soil health by driving organic matter decomposition and nutrient cycling, soil structure formation, synthesis of bioactive compounds and promotion of plant growth. However, measuring microbial diversity and activity remains challenging because of the complexity of soil ecosystems, spatial and temporal variability, and technical limitations. While techniques like amplicon metagenomics and enzyme activity assessments provide valuable insights, their cost and operational procedures hinder large-scale application.

Soil microbial activity is coupled with soil organic matter (SOM) content, which supplies the habitat, nutrients, and energy required for microbial growth. SOM and its transformations are shaped by and essential to microbial life. Predominantly related to soil microbial activity, SOM is easier to assess and can act as an indirect yet robust proxy for soil biological health and ecosystem function. Additionally, SOM also reflects important chemical and physical dimensions of soil health, serving as an operational and integrative indicator of soil quality. Advances in analytical methods, such as spectroscopic techniques and remote sensing, now allow for accurate and cost-effective quantification and monitoring of SOM. Observations made globally and over time provide a comprehensive understanding of patterns across different regions, reflecting environmental changes, different land uses and cropping systems. Access to such data helps identify emerging issues, track progress, and implement solutions that are both relevant and scalable, ensuring that policies are adaptive and impactful.

We cannot afford to wait for the perfect set of indicators of soil health to address environmental and agronomic challenges. Delaying political action risks deepening the crisis and missing crucial opportunities for change. When it comes to selecting a soil health indicator, SOM is certainly the most comprehensive and one of the easiest to measure. Adopting SOM as a global metric for soil health is a practical and scientifically grounded approach. Its ability to capture key soil functions, combined with advancements in measurement technology, makes SOM a pivotal tool for safeguarding soil quality, enhancing ecosystem resilience, and ensuring long-term food security.

1. The Importance of Soil Health or Quality

By the end of 19th century, public health problems were often associated with soil and its characteristics because of diseases such as anthrax and tetanus. In 1893, Miers and Crosskey felt the need to explain why soil should not be held responsible for common illnesses. Today, the concern is much more focussed on the threat that humans pose to the soil, on which life on this planet largely depends. In fact, the term 'soil health' has been developed as a means of focusing attention on the fragile skin of our planet in a way that can evoke support for its protection. Importantly, a key aspect of the use of 'soil health' is the emphasis on soil as a living system driven by its biological components (Doran & Zeis, 2000).

The terms 'soil health' and 'soil quality' are currently used by practitioners of land management and many scientists as alternative expressions. However, this is not consensual (see Box 1, page #2). Moebius-Clune et al., (2016) argue that soil quality includes both inherent and dynamic quality. Inherent soil quality refers to the aspects of soil natural composition and type, resulting from its formation process and which cannot be influenced by human management.

Dynamic soil quality refers to soil properties that change as a result of soil use and management over human time scale, and it is this aspect they equate to soil health. Lal (2016) concludes that soil quality is related to soil functions and soil health treats soil as a living entity, influencing plant health, and is the basis of ecosystem health. Soil quality assessments need to include baseline or reference values to enable identification of management effects (Bünemann et al., 2018) and also consider the specific use or function expected of that soil, as different crops or uses require different soil characteristics such as pH, nutrient status or physical conditions (Powlson, 2021). Soil plays a crucial role contributing to numerous functions that sustain life on Earth (FAO and ITPS, 2015), including provisioning of food and fiber production, water and climate regulation, nutrients cycling and habitat for biodiversity. Evangelista et al., (2024) maintain soil faces a global existential challenge and its security is essential for human and planetary functioning.

Although agricultural intensification has enabled the feeding of a growing global population, it has greatly increased pressure on soils and accelerated their degradation, thus endangering long-term agricultural productivity (see Box 2).

Monoculture cropping, together with intensive use of heavy machinery and agrochemicals, have caused losses of biodiversity, chemical contamination, soil erosion, salinization, compaction and organic matter decline (FAO and ITPS, 2015), progressively undermining the ability of soils to provide ecosystem services. Soil degradation also results from industrial pollution, deforestation and land-use changes and climate change impacts such as extreme weather events. Controlling and reversing soil degradation to increase soil health is thus pivotal when addressing global challenges, including food security, water scarcity, and resilience to climate change. To evaluate the progress of this mission, soil metrics that provide data-driven insights are central to quantify and interpret the changes that have been occurring in the soil, establish acceptable limits, and develop tools to support more informed and effective land use management, research guidelines and policies.

Box 1. Definitions of Soil Quality and Soil Health

We have considered some definitions of soil health. There seems to be general support for the view that Soil Quality and Soil Health are different (see Karlen et al.,1997; Lal, 2016), although they have frequently been used interchangeably. Doran & Zeiss (2000) used the two terms synonymously, although they attempted to separate their definitions, identifying soil quality as “a soils’ fitness for a specific use” and soil health as “the capacity of soil to function as a vital living system to sustain biological productivity, promote environmental quality, and maintain plant and animal health”.

In the extensively quoted paper by Karlen et al. (1997) the given definition of soil quality in its simplest form is “the capacity (of soil) to function". This is further clarified by stating that it “reflects the living and dynamic nature of soil”. Soil quality is further viewed as requiring “sustained biological productivity, environmental quality, and plant and animal health” to establish an equilibrium. The authors state that “The concept attempts to balance multiple soil uses (e.g., for agricultural production, remediation of wastes, urban development, forest, range, or recreation) with goals for environmental quality” (Karlen et al., 1997). It is difficult to deduce a significant difference in meaning between this definition of Soil Quality with the working definition of Soil Health (“the continued capacity of soils to support ecosystem services”) used in the EU document entitled ‘A proposal for soil health indicators at EU-level’ (Broothaerts, et al., 2024). The critique of soil health provided by Bavaye (2021) should be at the forefront of consideration.

Box 2. Land Degradation

The United Nations Convention to Combat Desertification (UNCCD 1994) defines land degradation as the "reduction or loss of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices." Under this definition, the extent of land degradation for reporting on SDG Indicator 15.3.1 is calculated using its three sub-indicators: land productivity, land cover, and soil organic carbon. They estimated that between 2015 and 2019, the world lost at least 100 million hectares of healthy and productive land annually. Trends since 2015 in developing regions of the Global South show that land is degrading considerably faster than the global average, with increases of 6 to 8 %. Approximately 33% of all soils are moderately to highly degraded due to factors such as erosion, loss of organic matter, and salinization (Smith et al., 2024). During an international conference held in Agadir, Morocco, in July 2024, it was reported by UNESCO that 75% of the world's land is degraded, with projections indicating this could rise to 90% by 2050. Globally, soil degradation costs approximately $400 billion annually in lost agricultural production (Lal, 2020).

2. The Role of Soil Microorganisms in Sustaining Soil Quality

The definition of soil has evolved over time as scientific understanding and technological advancements have taken place. Early definitions were often simple and focused on soil as a medium for plant growth, but now the emphasis is on a broader range of factors recognized, including its physical, chemical, biological, and ecological properties (Adhikari & Hartemink, 2016). Soil formation and properties depend on time together with climate conditions (temperature and precipitations), the living organisms (microbes, plants, animals and human activity), relief and parent material (Jenny,1941). On a global scale, the mean rate of soil formation is 700 kg ha-1yr-1 (Wakatsuki & Rasyidin, 1992), representing about 1cm each 100 years (Stockmann et al., 2014). Although quite slow in its formation, soil is the dynamic interface between the lithosphere (rock), atmosphere (air), hydrosphere (water), and biosphere (living beings) with active interactions taking place between them (Moebius-Clune et al., 2016).

The vast majority of the land used for agricultural production is comprised of naturally occurring unconsolidated mineral and organic matter (‘mineral soils’), but a small part is derived from ‘organic soils. The latter formed in a water-saturated environment as the natural accumulation of plant material, which has been subject to microbiological activity under particular local geological, chemical, topographic, and microclimate conditions. Mineral soils are defined as containing layers with up to 17% (w/w) organic carbon (OC). Organic soils have more than 17% OC and a minimum depth that depends on the extent that the organic material has decomposed from its original form (Agriculture Canada Expert Committee on Soil Survey, 1987).

The mineral soils environment is created by the aggregates of primary particles and the pores of different sizes between them. The pore system, where water and air circulate and plant roots and other living organisms exist, is very heterogeneous at the microscale. It is also extremely dynamic depending on the prevailing seasonal conditions of temperature and water availability. This wide range of habitats and environmental conditions provided by soil supports a great diversity of life forms, creating niches for numerous microorganisms, plants, and animals that are able to co-exist. This is one of the reasons why we find great biodiversity in healthy soil (Young & Ritz, 2000), making it one of the most biodiverse ecosystems on Earth. Anthony et al. (2023) estimate that the soil encloses ~59% of the species on the planet, with microorganisms dominating this biodiversity, having hundreds of thousands of taxa per gram of soil (Maron et al., 2018). It should also be noted that the above ground plant diversity has a major influence on the biodiversity in soil (Wagg et al., 2014; Zang et al., 2021). Soils with high microbial diversity are more resilient to environmental changes and have greater functional redundancy (van Elsas et al., 2006).

Biological diversity is fundamental to assuring the services that ecosystems provide, the functions performed, and therefore their quality (Brussaard, 1997; Bardgett & van der Putten, 2014). Agricultural practices have a profound effect on soil biodiversity, and the perception of this reality has been one of the drivers to change management practices and prevent biodiversity loss or community imbalances in agroecosystems (Brussaard et al., 2007; Scherer et al., 2023; Sun et al., 2019; Zhou et al., 2020; El Mujtar et al., 2019; Górska et al., 2024). Addressing biodiversity changes is imperative for maintaining soil health, ecosystem resilience and food security (Smith et al., 2024).

Archaea, bacteria and fungi form the most taxonomically and functionally diverse component of soil organisms and play fundamental roles in maintaining soil health, fertility, and overall ecosystem stability, and therefore provide better conditions for agricultural activity and food production. Their contributions and influence are felt in a wide range of functions:

i) Soil structural formation and stability (Tisdall & Oades, 1982; Rillig & Mummey, 2006),

ii) Nutrient availability and plant resilience against biotic and abiotic stresses result from microbial activity. All the different types of interactions occur, not only among archaea, bacteria and fungi (Cao et al., 2024) but also with other inhabitants of soil environment, particularly plants. Mutualistic relationships, such as those between plants and arbuscular mycorrhizal fungi, improve nutrient uptake and grant protection against biotic and abiotic stresses (Smith and Read, 2008; Brito et al., 2019). Also, biological nitrogen fixation is a key function of diazotrophic bacteria such as Rhizobium, Frankia, and free-living bacteria like Azospirillum (Postgate, 1982; Goss et al., 2023). Plant growth promoting bacteria, living either in plants rhizosphere or as endophytes, can also confer many benefits to plant development (Glick, 2012; Goss et al., 2023). Recent studies also suggest that microbial consortia and biofilms enhance resilience against environmental stressors, including drought and heavy metal contamination (Compant et al., 2019).

iii) Soil microorganisms can also synthesize various bioactive compounds, including antibiotics, phytohormones, and low molecular weight iron chelators (siderophores) to obtain iron from the soil (Glick, 1995; Gamalero et al., 2023). Streptomycetes, for example, produce over two-thirds of clinically used antibiotics (Berdy, 2005). More recently, microbial secondary metabolites have gained attention as potential biocontrol agents and biostimulants in sustainable agriculture (Lugtenberg & Kamilova, 2009).

iv) Microorganisms play a crucial role in degrading xenobiotic compounds, including pesticides, hydrocarbons, and industrial pollutants (Alexander, 1999). Bioremediation strategies leverage microbial metabolism to detoxify contaminated soils (Megharaj et al., 2011) and advances in synthetic biology are enhancing microbial capabilities for targeted pollutant degradation (Singh et al., 2020).

v) Soil microbes mediate carbon cycling by decomposing organic matter and stabilizing soil organic carbon (Schmidt et al., 2011; Gougoulias et al., 2014; Lal, 2020). Mycorrhizal fungi and saprotrophic microbes contribute to long-term carbon storage, mitigating climate change effects (Frey et al., 2013). Microbial-driven carbon stabilization mechanisms vary by ecosystem type and management practices (Cotrufo et al., 2019).

2.1 A Global Metric for Soil Health Based on Soil Microbial Diversity and Functional Parameters - Why Not?

Considering the processes where soil microbes are involved and their importance for soil health and also the fact that they are sensitive to agronomic management practices and different land use types, (Pankhurst et al., 1997; Brito et al., 2012; Brito et al., 2021; Goss et al., 2023; Rutigliano et al., 2023) a metric for soil health based on parameters reflecting soil microbial diversity or activity is needed (Sprunger, 2015) and their accurate assessment central for soil studies. However, quantifying soil biological attributes remains a complex task due to their great variability over time and space and several biological, chemical, and technical challenges (Geisen et al., 2019). These challenges stem from the intricate nature of soil ecosystems and the limitations of current methodologies.

2.1.1 Techniques for Assessing Soil Microbial Diversity

Among the various methodologies employed to assess microbial diversity in soil ecosystems, amplicon metagenomics and fatty acid profiling are among the most widely utilized.

Amplicon metagenomics studies enable the analysis of specific regions of the genetic material within microbial populations in a specific environment. The 16S rRNA gene is widely used to assess bacterial diversity because it contains both conserved and variable regions, enabling accurate taxonomic identification. For fungi, the Internal Transcribed Spacer (ITS) region serves a similar role. Together 16S rRNA and ITS are essential molecular markers for evaluating microbial biodiversity in environmental samples in general, and in soil. A key technology enabling amplicon metagenomics is Next-Generation Sequencing (NGS), a high-throughput sequencing method that allows rapid and increasingly cost-effective sequencing of DNA. The efficiency of NGS has significantly improved over the years, with advancements in sequencing platforms, bioinformatics tools and data analysis techniques (Katara et al., 2024). It allows for the identification of a vast range of microorganisms, including those that are difficult or impossible to study using culture-based techniques. Amplicon metagenomics has proven to be a powerful tool for addressing these challenges and revealing the dynamic characteristics of microbial communities in soil (Garg et al. 2024; Jagadesh et al. 2024).

Shotgun Metagenomic Sequencing (SGS) is a specific application of NGS where all the genetic material in an environmental sample is randomly fragmented and sequenced. This allows not only the identification of organisms but also to infer about their potential functions. In soil microbiome studies using SGS, different available algorithms (Langille et al., 2013; Meyer et al. 2008) help to predict the functional potential of microbial communities by analysing their gene content (Kifle et al., 2024). These tools can infer key soil functions such as organic matter decomposition or resistance to pollutants. However, predictions depend on reference genomes, which are limited for many soil microorganisms, and the accuracy is reduced in complex and diverse soil communities.

Despite their usefulness, these approaches are constrained as they include DNA from microbes in distinct physiological states and comprise dead or not-active cells (Jansson & Hofmocke, 2018; Garg et al. 2024). Thus, soil metagenomic analysis is a valid approach regarding biodiversity studies but for community functional potential it can only have an extrapolative value.

Scientists continue to struggle with linking the microbiome to ecosystems functioning (Sprunger and Martin, 2023; Kang et al., 2024), and therefore other techniques are required to identify the actual functions performed by living and active cells in specific environmental conditions (Jansson & Hofmocke, 2018; Fierer et al., 2021). Metatranscriptomics, which uncovers the dynamic expression of functional genes in soil environment, is not an extensive solution for now. Sample heterogeneity, low RNA yields and the presence of RNA inhibitory compounds, makes extraction and accurate representation of active gene expression technically challenging and inconsistent (Peng et al., 2023).

Fatty Acid Methyl Ester (FAME) analysis is a biochemical technique used to profile microbial communities by analysing their fatty acid signatures, providing insights into the structure, abundance, and physiological state of microbial populations within the soil environment. It can be conducted via phospholipid fatty acid (PLFA) or ester-linked fatty acid methyl ester (EL-FAME) methods. When compared with metagenomic studies, FAME analysis is faster and cost-effective, technically less demanding and useful for detecting active microbial communities, on the other hand it has a limited resolution, and the fatty acid profiles can change with environmental conditions making interpretation challenging. Additionally, its ability to assess microbial functions or genetic potential is very limited (Frostegård et al., 2011).

2.1.2 Indicators for Evaluating Soil Microbial Activity

Several techniques and indicators to study soil microbiome distinguishing between merely present genetic potential and the actual occurring biological processes have been developed. Indicators that reflect the biological activity in the soil can serve as strong proxies for ecological functions (Sprunger & Martin, 2023).

Some metrics rely on parameters that provide a broad representation of microbial activity without specifying the individual microbial groups contributing to this process. Examples include soil basal respiration and dehydrogenases activity, both of which are dependent on metabolically active cells and serve as indicators of microbial activity at a given time. Soil basal respiration quantifies the CO_2 released by heterotrophic soil microorganisms after one week incubation at specific conditions. Among the enzymes in the soil environment dehydrogenases (intracellular oxidoreductase enzymes) are commonly used as an overall indicator of soil microbial activity (Wolińska & Stępneiwska, 2012). These techniques require prompt sample processing, as they are both dependent on living cells; because cell degradation begins upon sample collection, microbial activity measurements may decrease over time, potentially affecting the accuracy of the results.

Soil microorganisms produce extracellular enzymes that play an important role in organic matter decomposition and nutrient cycling and are directly connected to the biochemical transformation of key elements (P, N, C and S) for plant growth. Their activity responds to soil management changes long before other soil quality indicator changes are detectable and hence, they are used as soil biological activity indicators (Burns 1978; Curtright and Tiemann, 2021; Li et al., 2024; Zhu et al., 2024). Phosphatases, urease, β-glucosidase and arylsulfatase are among the more commonly analysed. The evaluation of an individual enzyme activity does not reflect soil quality status since single enzyme activities cannot represent the rate of all metabolic processes and therefore several enzyme activities should be assessed in order to have a comprehensive perception of microbial activity and contribution to soil quality (Adetunji et al., 2017). Depending on the protocols followed for measuring soil enzymatic activity, although in the same order of magnitude, results can be significantly different (Deng et al., 2013). The need to standardize protocols, together with the easiness to use microplates and simultaneously process several samples, are in the base of International Organization for Standardization - ISO 20130 (2018, reviewed in 2024), developed for the measurement of enzyme activity patterns in soil samples using colorimetric substrates in micro-well plates. Enzyme activities of soil vary seasonally and depend on soil chemical, physical and biological characteristics (Wolińska & Stępneiwska, 2012; Adetunji et al., 2017; Zhu et al., 2024).

More dated methods to evaluate soil microorganisms based on biomass measurements, elemental or eco-physiological ratios (Joergensen and Emmerling, 2006), the quantification of culturable bacteria and fungi, either in specific or general culture media (Lawlor et al., 2000), also the bacteria:fungi ratio (Malik et al., 2016) or the use of Biolog™ system to assess metabolic diversity (Conceição et al., 2024) are still used. However, these methods are time consuming, not very informative over large temporal or spatial scales, subject to their own biases and authors are not consensual on the best way for interpreting or analysing the data obtained.
The above methods are far from being an exhaustive list and only represent the frequently used techniques to addressed soil microbial functionality.

2.1.3 Limitations of soil microbial analyses

Differences in soil texture, structure, moisture content, and nutrient availability can significantly influence microbial distribution and activity (Nannipieri et al., 2003). The complex soil matrix can interfere with DNA extraction, enzyme activity assays, and microbial respiration measurements and affect microbial accessibility and measurement accuracy (Ranjard et al., 2001). Furthermore, microbial communities vary spatially and temporally, making it difficult to obtain representative samples (Torsvik & Øvreås, 2002). Considering the diverse factors that can influence the assessment of soil microbial variables, obtaining consistent measurements over time remains challenging (Fierer & Jackson, 2006; Wolińska & Stępneiwska, 2012; Paul, 2014; Adetunji et al., 2017; Bandyopadhyay & Maiti, 2021; Fierer et al., 2021). Different methodologies for assessing microbial biomass, enzyme activities, and genetic markers yield variable results, making cross-study comparisons tricky and standardization of protocols difficult (Lombard et al., 2011). Fierer et al., (2021) contend that some microbial metrics of soil health are currently poorly validated and lack interpretability and are difficult to measure, although they acknowledge the potential for improvement. To overcome current limitations and improve the accuracy of soil microbial assessments, researchers often must employ a combination of methods to comprehensively assess soil microbial communities. Yet, it is important to emphasize that with some degree of control over conditions and influencing factors, inclusively in field experiments, comparisons based on soil microbial studies can not only be valid but have been crucial in advancing our understanding of soil microbial life and its impact on the agroecosystem.

Soil microbial analysis techniques require specialized equipment and expertise and can still be costly and time-consuming. Infrastructure can also be a limitation as many regions lack access to the laboratories and expertise needed for complex analyses, limiting their routine application in large-scale soil health monitoring. Addressing these limitations involves developing simplified, cost-effective, and robust tools that can be scaled globally. In this context, a balance must be struck between the level of detail in the information and the feasibility of obtaining data from multiple locations on a global scale and over time. Determining the appropriate threshold for this balance requires careful consideration. The pursuit of precise data on microbial life as key components of soil health may significantly delay our awareness of the current global situation and indefinitely postpone critical policy decisions.

Box 3. Soil Organic Matter (SOM)

Soil organic matter (SOM) is the carbon-rich (45-60 %C) material initially derived from the breakdown of the above- and below-ground parts of plants, such as leaves, stems, roots and their secretions, that have covered the land. It also includes any recently added animal material. In the soil, plant and any animal parts form the food stock of a multiplicity of soil organisms, which themselves contribute to SOM.

Archaea, bacteria and fungi, either free-living in the soil or present in the gut and faeces of soil fauna or herbivores, are mainly responsible for biochemical degradation of plant and animal residues. They form the most taxonomically and functionally diverse component of soil organisms. Freshly incorporated plant materials are formed mainly of molecules, which are too large to be transported into microorganisms. Hence, their initial breakdown depends on extracellular depolymerization processes, both hydrolytic and oxidative, by enzymes released by microbial cells.

Once compounds smaller than ~600 Da are formed in the process, they can be absorbed into the microbial cells and undergo further degradation. At various stages in the degradation, material can undergo adsorption or precipitation onto mineral articles, where it may be protected from further microbial breakdown. Within the microbes, the oxidative degradation may continue until all the elements are mineralized, forming CO2, NH4+, HPO4−, SO42− and H2O. Breakdown products can also be diverted into anabolic cycles and the formation of new organic microbial molecules, which may be cellular compounds required by the microorganism concerned or contribute to the metabolites being secreted into the soil. Consequently, SOM is made up of an incredibly wide range of compounds.

3. Soil Organic Matter - A Key Element of Soil Quality

Soil organic matter (SOM) is any material produced originally by living organisms that is returned to the soil and goes through the decomposition process **(see Box 3)**.

Owing to the diverse and essential functions it performs within agroecosystems, SOM is considered to be a central component of healthy soils (Allison, 1973; Lal 1998; Rusco et al., 2001; Manlay et al., 2007; Magdoff & Van Es, 2021; Lal, 2021; Wulanningtyas et al., 2021; Helfenstein et al., 2024; Chen et al., 2025).

3.1 Soil Organic Matter Composition and Relevance

Early ideas of the composition of SOM focussed on the concept of how readily compounds could be degraded, with recalcitrance being important for longer residence time. More recently, the interaction with minerals and protection within soil aggregates has been considered as the key mechanisms stabilizing SOM. The evidence suggests that plant-derived compounds containing lignin, together with other biomacromolecules are present in coarse particles and light fractions (<1.6 g cm-3). In contrast, material of microbial origin is associated with clay-sized fractions of dense, mineral-associated organic matter (>2 g cm-3). Partly decomposed plant material is present in silt-sized light fractions occluded within aggregates (Kögel-Knabner & Rumpel, 2018). SOM can be conceptualised as being particulate (POM), mineral associated (MAOM) or dissolved (DOM).

The formation of large-molecular-size and persistent 'humic substances' is questioned in field soils by Lehmann and Kleber (2015). They argue that they are an artifact of the analytical preparation and maintain that SOM is a continuum of progressively decomposing organic compounds. This perspective sparked considerable discussion and debate within the scientific community. Some researchers have questioned the mechanisms controlling soil carbon storage, aiming to reconcile conflicting views on organic carbon dynamics in soil (Derrien et al., 2023). Additionally, several studies have highlighted the significant role of microbial activity in SOM formation, suggesting that chemically diverse microbial-derived compounds contribute substantially to stable SOM (Kallenbach et al., 2016). This microbial pathway emphasizes the dynamic nature of SOM and contrasts with the notion of chemically unique, stable humic substances (McGuire, 2019).

The amount of variation in organic compounds that are carbon and nitrogen based in soils is much greater than that of the mineralogy of the soil parent material. SOM combines the organic compounds and polymers present together with the microbial biomass that transforms it. Converting soil organic matter (SOM) data to soil organic carbon (SOC) data often assumes the applicability of the van Bemmelen factor of 0.58 as a universal conversion factor, but this is questionable (Schumacher, 2002; Pribyl, 2010).

The foremost remaining elements of SOM are oxygen (O), hydrogen (H), sulphur (S), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). According to the Tipping et al., (2016) model, a nutrient-poor SOM has a N:C ratio of 0.039 and the P:C and S:C ratios are 0.0011 and 0.0054, respectively. However, in a nutrient rich SOM the ratios are 0.12 for N:C and 0.016 for P:C and S:C, so that P is especially improved in nutrient rich SOM.

Soil microorganisms are the primary contributors to the global carbon balance that serve as key driving forces behind formation and decomposition of organic matter (Wu et al., 2024) and carbon turnover is achieved in plant-soil-microorganism system. The activity of archaea, bacteria, fungi and other micro-eukaryotes is critical in the process of transforming dead organic material into forms that can be reused by other organisms, mainly plants. They break down complex organic compounds into simpler molecules, facilitating nutrient mineralization and mobilization, interfering in four biogeochemical cycles critical for the maintenance of life intersect in SOM: the C, N, P and S cycles. The P cycle is essential to the energetics of living organisms and commonly limits productivity in many natural ecosystems. Nitrogen is a key element of macromolecules like proteins, DNA and chlorophyll driving plant growth. As a structural component of protein disulphide bonds, amino acids, vitamins and cofactors, S is also a major element for plant development. The C and N cycles are of current focus because of their contribution to greenhouse gas emission. Soil microorganisms perform as biochemical catalysts, regulating the cycle of these essential nutrients, by using SOM as source of carbon compounds and energy for their metabolism (heterotrophs).

The ability of soil microorganism to mineralize SOM is closely related to its supply and quality. Residues with a larger cellulose content, such as residues with C:N ratios of 20 or more can take longer to degrade and can also lead to N immobilization by soil bacteria (van der Sloot et al., 2022). Immobilized N cannot be effectively released in short-term by re-mineralization to satisfy plants N nutritional demands (Chen et al., 2014).

Soil organic matter serves as a critical component of soil functioning, influencing physical, chemical, and biological properties, with their relative significance varying depending on soil type, climate, and land use (Janzen et al., 1997; Craswell and Lefroy, 2001). SOM functions as a crucial nutrient reservoir, storing essential elements and acts as a buffer against changes in soil pH. As SOM mineralizes through microbial activity, there is a gradual release of these nutrients in forms accessible to plants and other microbes. SOM improves soil structure by enhancing aggregation, increasing porosity, and promoting stable soil particles and porosity. These changes improve water retention, drainage, and aeration while reducing erosion and compaction (Six et al., 2002; Hartmann & Six, 2023). By providing energy and nutrients, SOM supports the growth and activity of soil microorganisms, sustaining the crucial roles they perform in soil ecosystem (Lehmann & Kleber, 2015).

Because it stores carbon in stable forms, SOM plays a significant role in mitigating climate change by reduce atmospheric CO_2 levels and simultaneously drives benefits to agronomic yield and soil quality. Globally, the C pool in the soil is three times that in the atmosphere whereas the global potential of SOC sequestration is estimated at 0.6 to 1.2 Gt C year−1, (Lal, 2004; Schmidt et al., 2011; Lal, et al., 2007; Lal. et al., 2008).

The roles of SOM have all round importance and are particularly relevant in agroecosystems (Reeves, 1997) due to its direct and indirect effects on numerous factors that influence plant growth. Nutrients slow-release mechanism can reduce the reliance on synthetic fertilizers. In soils with less than ~2% SOM, potential N reductions associated with increasing SOM amount to 7% and 5% of global N fertilizer inputs across maize and wheat fields, respectively (Oldfield et al., 2019).

3.2 Soil Organic Matter Dynamics in the Agroecosystems

The mineralization of SOM is limited by environmental conditions, specifically temperature and the availability of water and oxygen (Amelung et al., 1997), together with the clay content of the soil (Li et al., 2022). Soil microorganisms are poikilothermic and most on them are mesophiles, meaning they do not control their own temperature and grow best in moderate temperature, with an optimum growth range from 20 to 45 °C. Deprived of water, microbial metabolic processes slow down or cease entirely, leading to dormancy or death. Available oxygen allows aerobic respiration which yields more energy (APT per mol of glucose) and allows faster microbial growth when compared to anoxic conditions (anaerobic respiration or fermentative processes). Clay soils hold more water, creating a moist environment that supports microbial activity. However, in very wet conditions (e.g., waterlogged clay soils), decomposition can slow down due to reduced oxygen availability. Clay can also slow down the decomposition of SOM by protecting it in micro-pores and through chemical bonding, while sandy soils promote faster decomposition due to better aeration and less protection. Clay particles also have a high cation exchange capacity, allowing them to retain and supply nutrients to microbes and plants.

For soils with a similar content of clay, Jenkinson (1988) reported that it took eight years to achieve the same level of breakdown in ryegrass in England compared to two years in Nigeria. This clearly illustrates how temperature and water availability influence SOC mineralization rates in different climatic zones. Despite the poor quality of its soils (primarily Oxisols and Ultisols with low cation exchange capacity) the Amazonian forest in Brazil is renowned for its remarkable vitality and lush vegetation. The region's warm, humid climate promotes rapid decomposition of organic matter and a high rate of nutrient release, which are promptly absorbed by plants, supporting the vigorous development of the forest canopy. Most nutrients are stored in the living biomass rather than in the soil. Due to the high mineralization rates under these climatic conditions, deforestation and subsequent conversion to pasture or cropland led to a swift decline in SOM and the released nutrients are often leached away by rainfall before they can be taken up by plants (Davidson et al., 2004; Fujisaki et al., 2017; Merino et al., 2023). This drastic reduction in SOM has several negative consequences, including the degradation of soil structure, increased erosion, reduced soil biodiversity, and in a short period, areas once rich in SOM become less productive. Wetter climates also result in a greater amount of more labile and not-stabilized SOC (Galluzzi et al., 2024).

Ni et al. (2024) studied the effects of global warming on soil temperature in winter. They concluded that the significant decline observed in crop biomass C (straw and grain), was primary attributable to the loss off SOM and micronutrients induced by warmer soil. The authors drew attention to the critical need to incorporate winter warming into agriculture productivity models to prevent the overestimation of total food production by 4 to 19% under future warming scenarios. This study emphasizes the significant impact of climate and its changes on SOM and how these effects can impact food production.

Apart from fixed factors, such as climate conditions and soil clay content, there are management aspects that greatly affect SOM. Land use choices, including cropping and soil management practices, are key drivers of changes in SOM (Table 1). The evolution of SOM reflects the effects of land use, management practices, and environmental changes and monitoring SOM trends helps inform policies aimed at soil conservation, land management, and climate change mitigation, ensuring that agricultural and environmental practices are aligned with long-term ecological and economic goals.

3.3 Metrics for Soil Organic Matter

In any soil analysis, the initial and fundamental challenge lies in the sampling process considering its spatial and temporal variability. It can be very difficult to obtain a soil sample that fully represents the system complexity, due to the inherent heterogeneity of the biotic component. Consequently, the analytical approach calls

Table 1. Soil and crop management strategies that have the potential to enhance SOM and maximize its benefits.

Strategies / Technique	How SOM is increased	References
Crop rotation and diversification	Rotating different crops helps maintain soil fertility and organic matter. Including legumes improves soil nitrogen content together with supporting microbial activity.	Garcia et al., 2013 Goss et al., 2017
Cover cropping	Planting cover crops (e.g., clover, oats) during fallow periods protects soil from erosion and adds organic residues. It also enhances root biomass and microbial diversity.	Ding et al., 2006 Fohrafellner, et al. 2024
Residue management	Leaving crop residues (e.g., stems, leaves) on the field rather than removing or burning them, increases organic inputs.	Barber, 1979 Magdoff and Weil. 2004
Reduced tillage or No-till practices	Minimizing soil disturbance preserves organic matter and soil structure by reducing oxidation of organic carbon and improving carbon sequestration.	Tanveer et al. 2017 Goss et al., 2017
Perennial cropping systems	Growing perennial crops (e.g., grasses) reduces soil disturbance. Deep root systems contribute to more organic material over time.	Ledo et al. 2020. Sprunger et al., 2020
Soil amendments (e.g., compost, manure, organic mulches)	Applying organic amendments (e.g., compost, manure), directly increases SOM.	Tubeileh and Goss, 2022 Insam et al., 2023
Integrated pest management	Reducing chemical inputs protects beneficial soil organisms that contribute to SOM cycling.	Goss et al.,2017
Agroforestry and intercropping	Combining trees with crops adds organic material through leaf litter and root biomass. Intercropping increases plant diversity and organic inputs.	Beedy et al., 2010
Green manuring	Growing and incorporating specific crops (e.g., legumes) into the soil boosts organic matter and nutrients required by following cash crops.	Cherr et al., 2006 Goss et al., 2013
Relay cropping	Planting a second crop before harvesting the first maintains continuous soil cover and organic input.	Tanveer et al., 2017
Livestock-Grazing management (in Mixed Systems)	Integrating livestock in cropping systems encourages adoption of perennial crops, allows manure deposition, increasing organic matter. Controlled grazing prevents soil degradation.	Piñeiro et al., 2010 Johansson et al., 2024

for a compromise between the ideal scope of sampling and the practical limitations imposed by human capabilities and processing constraints - a balance that is often difficult to manage to reach robust decisions based on analytical results (Fierer et al., 2021).

SOM and SOC can be quantified using different methods, ranging in complexity, depending on the level of precision required and the specific fractions being analysed (Lehmann and Kleber, 2015; Nayak et al., 2019; Loria et al., 2024).

The permanganate oxidizable carbon (POXC) analysis seems to represent the biologically available pool of C (Wade et al., 2021). However, that is not exactly the case as POXC behaves differently from other labile C fractions and reflects a more processed pool of C. It appears to serve as early indicator of soil C sequestration and is a rapid, and inexpensive analysis that consistently detects differences across a range of ecosystems and management intensities. Sprunger & Martin (2023) believe more work is needed to fully understand its functional operational role in the context of soil C dynamics, although it is certainly a very attractive soil health indicator, closely associated to biological activity.

The commonly used quantitative SOM measurement techniques can be broadly classified into two categories, dry combustion methods and wet oxidation methods. Dry combustion methods include an elemental analyser or loss on ignition (LOI) and wet oxidation is based on Walkley–Black (WB) method. Infrared spectroscopy can also be used to quantify functional groups in SOM, providing information about composition and structure of SOM. Several parameters such as humification index, humification degree, humification ratio, carbon pool index, lability, and carbon management index serve as indicators of SOM stability, humification levels, and carbon cycling. Observing shifts in these indicators can reveal insights into the behaviour of SOM and how it responds to management strategies and environmental conditions (Nayak et al., 2019; Murindangabo et al., 2023).

When assessing SOM, quantitative measurements are more frequently used, as they are especially informative in agronomic contexts. The traditionally used methods are sample destructive and SOM can be overestimated when it comes to soils with high level of carbonates or rich in iron or manganese. These methods, although not difficult to perform, can be labor-intensive (sieving the soil samples 2 mm, use several reagent solutions) and need specific equipment (muffle furnace or a CHNS analyser and high-purity oxygen and helium or argon gases) and are not very cost-effective. Additionally, these methods are not consistent, and results may vary depending on calibration sets, the technique or location (Konare et al., 2010; Roper et al., 2019; Hernández et al., 2023; Ratefinjanahary et al., 2025). Using “the standard” dry combustion method and the same soil samples, Brinton et al. (2025) found that SOC levels varied as much between laboratories as they did between the different management systems under study, highlighting the analytical variability both within and between laboratories. The authors conclude that to ensure accurate measurements over time it is important to use the same lab and testing methods and to the extent possible the same standard operational procedures. They acknowledge that establishing a more unified framework for validating soil carbon gains across heterogeneous landscapes will make long-term monitoring more practical, reliable, and efficient, while also enabling more standardized quantification.

Considering these limitations, new approaches mostly based on spectroscopic techniques have been developed and are comprehensively reviewed by Nayak et al., (2019) and Loria et al., (2024). Spectroscopic methods can be applied in laboratory but also in the field and at regional or even global levels. Compared to traditional methods, significant costs (83%) and time (85%) reductions were registered, while maintaining a comparable accuracy, especially in fine-texture soil (Doetterl et al., 2013). These methods include Laser Induced Breakdown Spectroscopy (LIBS), Inelastic Neutron Scattering (INS), Visible and near-infrared (VNIR) and mid-infrared (MIR) (Gehl & Rice, 2007). They opened new possibilities, enabling in situ measurements using portable instruments with great potential for very accurate SOC estimation. Modern handheld devices are equipped with robust data processing capabilities and connectivity features enabling real time analysis. These instruments need to be calibrated using standard laboratory techniques and operational procedures, to ensure reliability across various environmental conditions. The challenge to improve the accuracy for SOC prediction using these portable devices relies on improving the processing techniques and data interpretation, but mostly in ameliorating calibration models, particularly for mitigating inaccuracies related to soil moisture variation.

Remote sensing (RS) techniques, such as satellite images, airborne LiDAR (light detection and ranging), satellite-based EnMAP sensors, and drone-based sensing either with multi or hyperspectral cameras, make it possible to evaluate SOC over large areas and reveal spatial patterns and variations in its distribution. By analysing the spectral signatures, remote sensing algorithms based on measurements taken in the field and the correspondent spectral information, can infer SOC content. Nevertheless, these methods offer indirect measurements and might overlook small-scale details.
In addition, GIS (Geographical Integrated Systems) can play an important role in broad scale evaluation of SOC as it allows the combination of different data layers (satellite imagery, soil characteristics, topographic information, land classification, meteorological data) to drive estimates of SOC content. According to Chen et al., (2025) research on RS-based SOM monitoring has entered a rapid growth phase since 2018. In the models construction high frequency covariates such as soil pH, precipitation, temperatures and topography significantly improved the prediction accuracy. Considerable evolutions have occurred on data processing methods and by the gradual replacement of traditional statistical models by non-linear machine learning and deep learning methods, which are particularly good at handling complex high-dimensional data. Regional spectral libraries together with global ones and the migration learning technique, improved the model generalization ability in low data regions. Additionally, integrated models can be very useful in deriving spatial and temporal dynamics of SOM.

Different types of models have been developed to determine either the trend in any changes of SOM or the prediction of future SOM values (Bruun et al., 2010). A model-based study was able to estimate SOM in the Netherlands to 2050, in a 3D space between 0 and 2 m depth at 25 m resolution (Helfenstein et al., 2024). Fang et al., (2005) suggested a general model, which explicitly incorporates soil microbe as decomposers of SOM. However, the key role of microorganisms in mediating C and nutrient fluxes in soil and its eco-evolutionary dynamics, are currently largely absent in microbial-explicit models aiming to predict SOM dynamics on a global scale (Schwartz et al., 2025) and it is a current matter of study.

4. Soil Organic Matter as a Global Indicator of Biological Potential and Soil Health

Given the scope and complexity of the roles performed, SOM can be assumed as a comprehensive, integrative metric that reflects the physical, chemical, and biological dimensions of soil health, making it essential for global soil quality assessments (Chen et al., 2025).

Physical and chemical soil properties have long been studied, and their metric is quite well established, providing important information about soil health particularly in the long-term (Rutigliano et al., 2023). The analysis of soil biological properties, particularly the microbiota, is far more complex. It is influenced by many unpredictable factors, the laboratory techniques used for its study are not easy to perform and are often quite expensive, making it difficult the of use soil health biological indicators in large-scale comparative terms. Yet, the soil microbiome is a key component in maintaining healthy, productive soils that can sustainably support food production. It promptly echoes changes in the cropping systems and provides important information regarding soil quality.

Soil microbial activity is coupled to its organic matter content, which supplies the habitat, nutrients, and energy required for microbial growth, particularly in its more readily degradable forms. Combined with environmental factors like temperature and water availability, just to mention the most conditioning ones, SOM and its transformations are shaped by and essential to microbial life, highlighting their interconnected relationship. The dynamic interplay between SOM, soil fertility, plant growth and microbial activity operates through feedback mechanisms that can be either beneficial or detrimental to soil health. In a positive feedback loop, elevated SOM levels enhance plant growth and stimulate microbial communities (van der Putten et al., 2013). These microbes decompose organic residues, further enriching the soil with organic matter, thereby perpetuating a cycle of increasing fertility and productivity (Wagg et al., 2014). Conversely, a reduction in SOM can initiate a negative feedback loop. Diminished organic matter leads to poorer soil structure and fertility, hindering plant growth and adversely affecting microbial populations (de Vries et al., 2013). This degradation results in decreased organic inputs, further depleting SOM levels and exacerbating soil quality decline (Lal, 2018). Understanding these feedback loops is crucial for developing sustainable land management practices that maintain or enhance SOM, thereby supporting robust plant and microbial life (Lehmann & Kleber, 2015).

The intricate relationship between SOM and soil microbiology underscores its potential for soil health indicator as a proxy of its biological component. High SOM levels typically correlate with diverse and active microbial communities (Maron et al., 2018; Bastidas et al., 2021), which drive key ecosystem functions. Bastida et al., (2021) showed that soil C content is associated to the microbial diversity-biomass relationship and ratio in soils across global biomes and that the reduction in soil C content associated with land use intensification and climate change could cause dramatic shifts in the microbial diversity-biomass ratio. Microorganisms can show differences in the efficiency with which they use carbon (carbon-use efficiency - CUE) for cell growth and division. In soils with limited SOM availability, those with greater CUE may be able to form a greater proportion of the community than those that are less efficient, whereas when SOM supply is large, the latter may out-compete the more efficient (Roller & Schmidt, 2015).

Soil organic matter does not provide as much detailed information about soil microbial community structure and function as the methods specifically designed for this purpose (see section 2). However, SOM is considerably easier to assess. It is not sensible to establish a direct and universally applicable correlation between SOM and microbial diversity or functional potential. This relationship seats on complex and multifactorial influences and comprehensive models to fully integrate them are overlooking. Obtaining standardized and comparable data on the microbiological features of a soil and accurately assessing their contribution to soil health and fertility can be a challenging task, and SOM can provide a more accessible indirect indicator of soil microbiological potential.

Likewise, SOM is a key driver for many other aspects of soil health, influencing nutrient cycling, water retention, and carbon sequestration, playing a critical role in crop production. Maintaining and increasing SOM is directly or indirectly connected to food security and climate change mitigation. Policies that promote SOM conservation and restoration can improve agricultural resilience, reduce greenhouse gas emissions, and ensure long-term soil productivity, making it a critical focus for global environmental and agricultural agendas. The possibility of monitoring SOM as soil health indicator over extended periods provides a temporal perspective on the changes in cropping systems (see Table 1) at a particular site or region, enabling the assessment of their impacts on soil health.

For an indicator to be globally effective, it must meet certain criteria. It should be robust and applicable to a wide range of soil types and land uses. The indicator should also be easy to understand and simple to implement by non-specialists, requiring minimal infrastructure, resources, and cost, making it feasible for use in regions with limited resources. Furthermore, standardization is crucial to ensure consistent results over time and across different locations. Roper et al. (2019) support that to avoid discrepancies and confusions, assessments should limit comparisons to methodologies with similar measurement protocols. Some parallels can be drawn with how drinking water quality standard tests have long been established by the World Health Organization and are worldwide used (World Health Organization, 2018).

Use of SOM as a critical index of the state of a soil for delivering ecosystem services has been applied overwhelmingly to mineral soils. In general, clay soils have greater SOM content than sandy soils but it has been popularly considered that if the content declines below 2% (w/w) a soil cannot adequately fulfil its ecosystem services. However, the evidence for this is not established. One reason for the lack of evidence may be the need of some farmers to continue cropping such impoverished soil and obtaining production by adding sources of nitrogen (Loveland & Webb, 2003). For mineral soils, the European Soil Monitoring Law (EU 2023) proposes SOC:clay ratio (> 1/13) as a criterium for heathy soil condition, although specific soil types and climatic conditions should be considered.

Thanks to analytical and technological progresses, metrics of SOM have greatly evolved in recent years. While there is still room for improvement, SOM is likely the most comprehensive and simply measurable soil parameter, providing valuable insights into soil conditions at any given time. It also can meet most of the key requirements for global indicators.

5. Mapping SOM Variations Across Space and Time: The Imperative of Global-Scale Analysis

Global-scale and overtime observations provide a comprehensive understanding of patterns across different regions, enabling policymakers to make informed decisions that address global challenges. Access to such data helps identify emerging issues, track progress, and implement solutions that are both relevant and scalable, ensuring that policies are adaptive and impactful on a worldwide scale.

5.1 Significance of Assessing Soil Organic Matter Dynamics Across Broad Spatial and Temporal Scales

Monitoring spatial variation of SOM on a global scale is critical for understanding and managing soil health across regions with diverse levels of development and varying environmental conditions and land uses (Li et al., 2025). Detailed assessments of SOM across the world provide essential insights and enable targeted strategies that cater to both advanced agricultural systems and regions with more plain or familiar farming systems facing soil degradation. In developed areas, robust SOM metrics can refine precision agriculture and environmental policies, while in less developed regions, they offer a foundation for sustainable land restoration and improved food security. Overall, integrating global SOM indicators fosters informed decision-making, bridges regional disparities, and supports resilient, adaptive land management practices worldwide

Monitoring SOM over time is also essential for understanding changes in land use and their effects on soil quality and environmental impacts. For example, the conversion of natural ecosystems to agricultural lands typically leads to a reduction in SOM due to increased soil disturbance and organic matter mineralization. Conversely, the implementation of conservation practices, such as reduced tillage or reforestation, can enhance SOM levels. These trends can only be accurately captured through systematic and continuous observation.

Furthermore, long-term SOM monitoring contributes to climate change research by providing data on carbon fluxes between soils and the atmosphere. Changes in SOM content directly affect soil carbon storage, influencing greenhouse gas emissions. This information is crucial for developing effective climate mitigation strategies and sustainable land-use policies. Therefore, maintaining long-term SOM monitoring programs is vital for preserving soil health, understanding ecological processes, and addressing global environmental challenges.

Environmental issues are becoming increasingly important and as datafication continues to accelerate, private corporations are gaining increasing influence and power over the associated collection of data. Wickberg et al. (2024) believe this is a cause of alarm, as the global environmental commons are a public interest of concern to all people. Political frameworks also play a pivotal role in addressing global ecological issues. While international agreements set ambitious targets, national implementation often falls short due to political and economic constraints as significant disparities can be noticed between global and national policies. In addition, political interests often hinder the effectiveness of ecological governance frameworks (Akhundov et al., 2025).

5.2 The Example of 'Land Use/Cover Area Frame Statistical Survey Soil' (Lucas Soil)

The 'Land Use/Cover Area frame statistical Survey Soil' (LUCAS Soil) is an extensive and regular topsoil survey conducted by the Joint Research Centre (JRC) of the European Commission, that is carried out across the European Union to derive policy-relevant statistics on the effect of land management on soil characteristics. It is the first attempt to build a consistent spatial database across the European Union, based on standard sampling and analytical procedures with JRC ensuring consistency and quality control across all participating laboratories (Tóth et al., 2013). Currently Lucas Soil is the largest harmonized open-access dataset of topsoil properties available for the European Union at the global scale. Physical and chemical parameters, including organic carbon content, were analysed. Resulting from the increasingly recognized importance of soil organisms in the provision of several soil-related ecosystem services, more recently it was decided to insert the assessment of soil biota in the surveys. The identification of key genes for functional assessment of biodiversity and the presence of antibiotics resistance genes constituted an exploratory analysis in 1000 points (Orgiazzi et al., 2018), increased to 1500 points in 2022 (Jones et al., 2025). The LUCAS soil surveys have been conducted in multiple campaigns, and approximately 67,000 soil samples have already been collected across Europe, in different biomes - cropland, grassland, woodland, wetlands, shrubland and bare land. Several aspects have improved over time, such as laboratory standardization, a better understanding of the statistically representative number of sampling points needed in different regions, the introduction of new parameters, and improved cost management.
To adopt a more cost-effective approach, JRC is increasingly looking at possibilities offered by remote sensing to integrate and complement the point measurements of LUCAS, like for example the estimation of soil C through remote sensing-based techniques. The availability of multiple soil datasets, linked to land usage and primary productivity indicators, are showing high potential in soil C predictions. It is however noted that a combination of remote sensing and in situ or point data will still be necessary to derive high resolution and accurate SOC maps, with known uncertainties. Earth observation systems encompass some problems regarding soil properties, namely the reliance on proxies of reflected energy, the limited penetration depth and visibility of bare soil, which fortunately is becoming scarce. In this respect, it should be noted that LUCAS Soil data are viewed as key in situ reference data by the European Space Agency`s World Soils current call for proposals to develop a global Earth Observation-Soil Monitoring System (Jones et al., 2021). ■

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