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Soil biology, health and ecosystem services: an overview

C. Vazquez, T. Mulder, L. Chavez Rodriguez, F. David, D. P. Di Lonardo, A. Garsia, R. E. Creamer, Wageningen University and Research, The Netherlands; E.K. Bünemann, Research Institute of Organic Agriculture (FiBL), Switzerland; H. Soinne, Natural Resources Institute Finland (Luke), Finland; P. Cheval, Université de Lorraine, INRAE, LSE, F-54000 Nancy, France; A. Basile, Institute for Mediterranean Agricultural and Forestry Systems, National Research Council of Italy, Italy; A. Bacq-labreuil, Greenback SAS (commercial name: Genesis Soil Health), France; J. Nordén, Norwegian Institute for Nature Research (NINA), Norway; L. Cunha, University of Coimbra, Portugal; C. Imbert, Leibniz-Centre for Agricultural Landscape Research (ZALF), Germany; C. Boix-Fayos, Soil and Water Conservation Research Group, CEBAS-CSIC, Spain

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1 Introduction

Soil health refers to the ability of soil, at a specified point in time, to function as a dynamic living system within natural or managed ecosystems. A healthy soil sustains plant, fungal, and animal productivity and health, maintains or enhances water and air quality, and delivers essential ecosystem services over the long term, without increasing trade-offs between ecosystem services (Van den Elsen, et al., 2022). The term is often used interchangeably with soil quality (Bünemann et al., 2018). Soils support a range of ecosystem services and they

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provide benefits to human societies (Calvaruso et al., 2021) through the delivery of soil functions. Soil functions commonly considered in soil health assessments from an agricultural context are primary productivity and biomass production, climate regulation, water regulation and purification, nutrient cycling and habitat provision for biodiversity (Haygarth & Ritz, 2009; Schulte et al., 2014, Pereira, 2018). Additional functions, such as pest and disease management (Creamer et al., 2022) and pollutant degradation (Vogel et al., 2018) have also been proposed in the literature. Monitoring of soil health aims to assess the resilience of soil to provide continued support in the provision of ecosystem services.

Despite increasing awareness and research, monitoring soil health remains a major challenge due to several factors:

1. Scale mismatch: the spatial scale of the assessment is often not in line with the selected indicators. Indicator selection should consider the purpose of the monitoring programme, who it is for and with which goals in mind monitoring is done (Schreefel et al., 2024).
2. Resource constraints: soil health monitoring is often driven by resources (cost and logistics) and depends primarily on what monitoring systems are common, or already in place or can be expanded upon (Matson et al., 2024).
3. Benchmarking: due to the heterogeneity of soil and the interactions with climate, landscape and land use there is no clear definition of what constitutes healthy soil, as threshold values to benchmark soil health will vary in different pedo-climatic zones and land use systems.
4. Conceptual ambiguity: soil health is a concept that amalgamates several interacting soil functions. This leaves the concept of soil health open to inappropriate use, and indicators are often selected without transparency or pertinence to the functions being assessed.

Since soil health cannot be measured directly, it is typically assessed through two complementary approaches:

1. Threshold-based indicator approach: here, soil health is evaluated by defining thresholds for a range of soil parameters. This approach is often applied in larger-scale assessments (regional, national and continental), where a harmonized minimum dataset is applied to categorize soil as healthy or degraded (Matson et al., 2024).
2. Process-based clustering approach: this approach defines the processes and underlying properties that are relevant to a range of functions. This considers the interaction of soil processes with local conditions and management practices, assessing how they collectively contribute to the delivery of one or more functions.

A well-defined and scientifically rigorous selection of appropriate indicators is critical to ensuring that the selected indicators are both relevant to the processes and overarching functions they are chosen to represent and applicable to the specific land use, management practices and climatic conditions of the ecosystems being evaluated (EEA, 2023).

2 Selecting indicators to assess soil health

Soil functions themselves are challenging to measure directly, as they consist of bundles of soil processes (Bünemann et al., 2018) which continuously interact. Therefore, selected indicators should reflect the processes that are occurring to support the provision of a given function. The first step is the identification of relevant indicators which can directly measure the process. Soil processes can be described as a series of actions or steps that take place that result in a particular outcome (adapted from PROCESS | English meaning - Cambridge Dictionary). Process-based indicator measurements are usually defined as rates which describe the speed at which the process is taking place. As such, process measurements are often conducted either in the laboratory or the field and can be logistically challenging to include in a monitoring programme. In the absence of direct indicator methods for a given process, it is feasible to measure the presence or abundance of (most common) biological drivers and defining (physical or chemical) conditions in which the process will occur. Creamer et al. (2022) presented the main biologically led processes that supported four soil functions (nutrient cycling, water regulation and filtration, carbon regulation and pest and disease management) in a temperate agricultural context through a series of knowledge graphs referred to as cognitive models. The cognitive models identified which processes were relevant for each soil function and how these processes could be bundled together into 'sub-functions' which describe how the co-occurring processes support a specific underlying mechanism of the function. Biological actors were then identified and considered as the main drivers of each process. This facilitated for the first time a transparent methodological approach to describing the role of soil biota in the provision of soil functions, where the soil biological parameters were ranked for their pertinence to supporting the processes underpinning the four soil functions (Zwetsloot et al., 2022). However, the papers of Creamer et al. (2022) and Zwetsloot et al. (2022) did not identify how the biologically mediated soil processes co-occurred with or were mediated by physical and chemical conditions in the soil.

This chapter will present an update on this work by integrating the chemical and physical components of soil health with that of the biologically mediated processes and further define how environmental conditions may contribute. To achieve this, four soil function cognitive models have been developed: (1) carbon and climate regulation, (2) nutrient cycling, (3) water regulation and filtration and (4) habitat provision for biodiversity. These cognitive models define the chemical, physical and biologically mediated processes that occur in soils to support sustainable agricultural production in temperate climate conditions across Europe. These cognitive models provide a first insight into the processes and parameters which support the delivery of each function. Parameters are defined as the chemical, physical or biological properties or climatic or landscape conditions that define a process system or set the conditions of its operation. In many cases, the processes can be measured directly, making them reliable indicators of the functions. However, process-based measurements are often challenging outside of controlled scientific conditions. To address this, the models also incorporate parameters that support these processes. The parameters – soil properties which interact to drive soil processes, either directly, for example, many biological actors are responsible for bioturbation occurring in the soil, or indirectly which can be parameters which define the presence or absence of the biological actors, for example, pH or moisture. These cognitive models facilitate and provide a transparent method for indicator selection of the four functions and overall soil health assessment through a multi-functional approach. Indicators for soil health assessment can then be defined for the processes that are relevant, in a given pedo-climatic context and that are useful in framing the purpose of the monitoring focus. This chapter will provide the detailed scientific underpinning of the processes involved in the delivery of each of the soil functions but will not deliver a set of indicators, as this is dependent on context and purpose.

3 The process of indicator selection

Indicator selection was achieved through a structured interactive approach, where scientists from across Europe engaged in online and in-person workshops. Over 25 soil experts, specializing in different aspects of soil health, collaborated to identify and rank processes relevant to the four specific soil functions. The indicator selection was completed through an iterative process, starting with brainstorming workshops, which provided the first foundation for each of the function cognitive models, integrating biological, chemical and physical soil expertise with landscape and modelling experts. The workshops were followed by comprehensive scientific literature reviews to validate and confirm the role of the identified processes and parameters and uncover any missing elements. After the initial development of the cognitive models, groups were asked to rank the processes and parameters according to their importance for the delivery of a certain function. The ranking system ranged from 1 (very important) to 3 (less important or relevant). This ranking was instrumental in refining the initially highly complex and detailed cognitive models. Processes

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having minimal relevance were eventually removed, allowing the models to be simplified without losing critical information. Finally, experts were asked to determine if a parameter had a direct or an indirect effect on the rate of a given process. For example, earthworms have a direct effect on bioturbation (Cunha et al., 2016; Vion-Guibert et al., 2024), whereas their effect on erodibility is indirect, mediated through their impact on aggregation processes (Wen, 2022). However, a direct correspondence does not always equate to a larger effect; indirect effects can also play significant roles depending on the pedo-climatic context and the interplay of multiple factors, such as soil management (Jouquet et al., 2012a; Wen et al., 2022). These indirect or contextual effects have a strong influence on the selection of an appropriate indicator. This systematic and iterative approach ensured that the selected indicators are not only process-specific but also aligned with the broader soil health framework. By tailoring the selection to the unique characteristics of each process, the resulting indicators provide robust tools for monitoring and assessment across diverse systems.

Figure 1 describes the basis of the cognitive model concept. For each soil function cognitive model, the function is first defined. Next, key processes which contribute to the provision of that function are defined. Processes may occur in one or several soil function models. The processes are bundled for the sake of visualization in the model into ‘sub-functions’ which account for a set of processes that are focused on a specific aspect of a function. Sub-functions are generally not measurable, as they are a visualization of a series of processes. At the process level, it is possible to measure the individual processes, but this often requires specialized or control conditions in which a process is measured over time. Therefore, soil (biological, chemical and/or physical) and environmental parameters are utilized to define the main drivers and conditions under which the process occurs or the rate at which it occurs.

This approach does not imply that all properties involved in all processes need to be monitored continuously. Rather, we propose to follow an approach similar to the logical sieve approach proposed by Ritz et al. (2009) and later adapted to indicator selection for soil biological indicators by Zwetsloot et al. (2022). This method provides a systematic framework for indicator selection by progressively narrowing down a broad list of processes and parameters via specific selection criteria, to define the final set of indicators. The sieve operates through several steps: (1) Pertinence to the soil function: indicators are first evaluated for their relevance to the soil function under consideration. This ensures that each selected indicator provides meaningful information into the processes and sub-functions that underpin the function; (2) Applicability to context: indicators and methods are assessed for the suitability within a specific context of a specific monitoring program (taking into account issues such as land use type and spatial scale of assessment and environmental conditions).

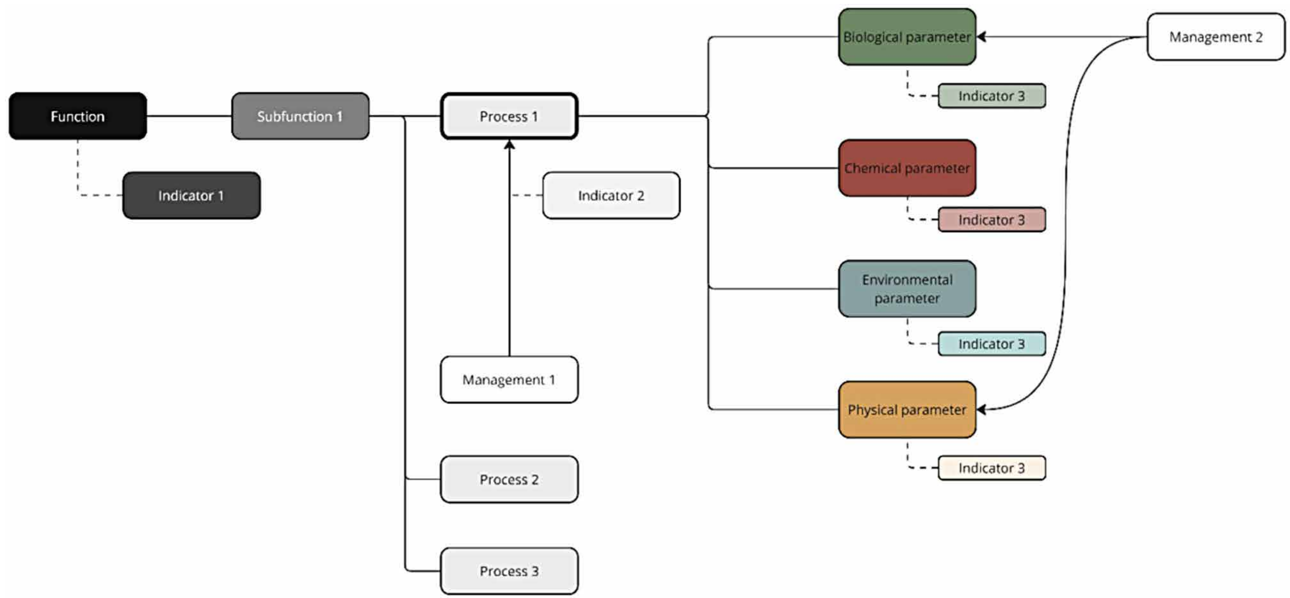

Figure 1 Diagram representing the hierarchical relationship between soil functions, sub-functions, processes, parameters and their associated indicators. At each level of the diagram, indicators could be identified. Indicators used for monitoring purposes should, where possible, be selected at higher levels of the hierarchy. However, indicators at the function or process level are not always available, and indicators at lower levels of the diagram will be needed. In such cases, indicators that represent all parameter types should be selected. Management can affect process rates directly or affect soil functioning through their effect on soil and environmental parameters.

This step ensures that selected indicators better align with the unique characteristics (and constraints) of the monitoring context; and (3) Technical criteria: indicators are further selected based on technical considerations such as the ease of interpretability, throughput, accuracy, cost, and practicality of implementing the associated measurement techniques (Zwetsloot et al., 2022). However, in the context of soil health assessment, the final set of indicators should comprehensively represent all relevant soil functions, ensuring that relevance, applicability and logistical issues have been considered.

In the following sections, each of the soil functions are described in the form of a cognitive model, providing a comprehensive overview of the processes relevant to each of the four functions. As several processes occur across multiple cognitive models, the parameters which define the functions are described in the subsequent section.

4 Carbon and climate regulation

The soil contribution to carbon and climate regulation, i.e. the balance between the uptake of CO_2 and CH_4 by the vegetation and microbes, which is maintained as biomass and carbon compounds in the soil, and the release of greenhouse gas emissions from the soil, encompasses soil processes that contribute to the carbon retention in the soil and regulate the release of major greenhouse gases (BIOSIS, 2023). Within this function, we identified 17 processes underpinning the carbon and climate regulation soil function, which were bundled into four sub-functions: decomposition, organic matter transfer, organic matter stabilization and biochemical transformations (Fig. 2). These sub-functions collectively capture the complex interplay of processes that influence soil carbon dynamics and greenhouse gas emissions. The direct and indirect parameters that support the provision of these processes are described in Table 1.

4.1 Sub-function: decomposition

The breakdown of organic matter (i.e. decomposition) in soil is realized through six processes that result in the production of carbon dioxide (CO_2) and/or methane (CH_4) (Creamer et al., 2022). These processes include: (1) litter photodegradation, (2) fragmentation, (3) faunal respiration, (4) microbial respiration, (5) extracellular depolymerization, and (6) methanogenesis.

Decomposition through these six processes is a careful balance of utilization of existing carbon sources in the soil in combination with new organic matter inputs into the soil. This dual process can result in the release of carbon stored in the soil while simultaneously serving as the basis for the sequestration of new carbon into the soil. Plant material inputs make their way into the soil, where they are fragmented by earthworms, isopods and other macrofauna

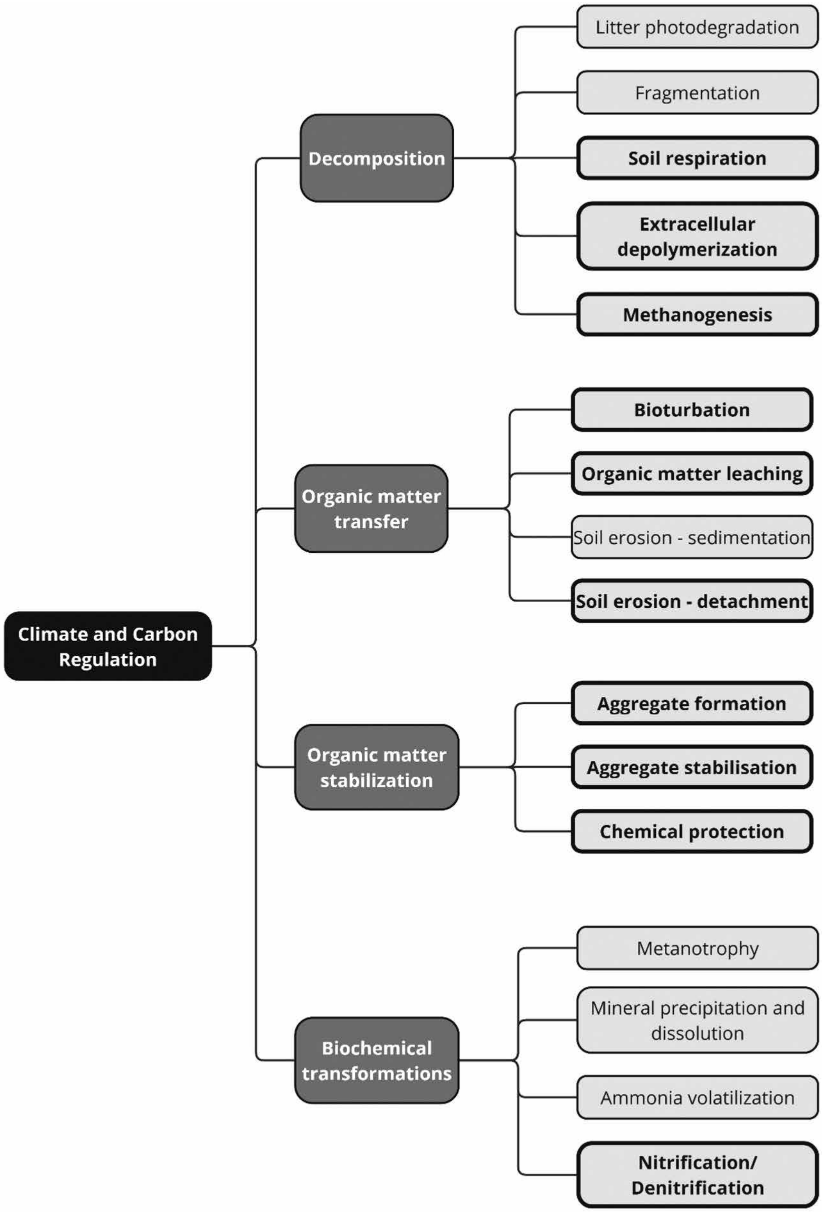

Figure 2 Processes (light grey) and sub-functions (grey) underpinning climate and carbon regulation. Boxes with a thicker outline and bold lettering represent processes deemed as most relevant by the experts.

Table 1 Soil parameters that directly or indirectly mediate the processes that occur in the carbon and climate regulation function. Some parameters or parts of them are expressed with abbreviations or acronyms. Abbreviations and acronyms for chemical parameters: SOM for soil organic matter content, SOM quality for soil organic matter quality, CEC for cation-exchange capacity, oxygen for oxygen concentration, NH_3 for ammonia content, $CaCO_3$ for calcium carbonate, Ca:Mg ratio for calcium to magnesium ratio. Soil functions in which these processes are also present are also present as abbreviations: NC for nutrient cycling and HP for habitat provision for biodiversity

	Soil parameters that underpin each process				
Process	Biological	Physical	Chemical	Environmental	Present in other functions*
Litter photodegradation		Soil moisture	Plant residue quality	Temperature Plant residue layer Solar irradiation	NC
Fragmentation	Acari (Oribatids), Isopods, Collembola, Earthworms, Enchytraeids, Termites, Ants, Millipedes	Soil temperature, Soil moisture,	Soil pH Oxygen Plant residue quality	Temperature Precipitation Plant residue layer	NC; HP
Soil respiration	Archaea, Algae, Bacteria, Fungi, Roots, All soil fauna	Soil temperature, Soil moisture, Soil porosity	Soil pH SOM Nutrient availability Oxygen	Temperature Precipitation	
Extracellular depolymerization	Bacteria, Fungi, Roots	Soil temperature, Soil moisture, Soil porosity	Soil pH, Nutrient availability, SOM, SOM quality		NC; HP

(*Continued*)

Table 1 (*Continued*)

Process	Soil parameters that underpin each process				Present in other functions*
	Biological	Physical	Chemical	Environmental	
Methanogenesis	Archaea (methanogenic)	Soil temperature, Soil porosity	Soil pH, Plant residue quality, Oxygen		
Bioturbation	Earthworms, Enchytraeids, Termites, Ants	Soil texture, Bulk density, Soil temperature, Soil moisture, Soil depth	Soil pH, Nutrient availability, SOM	Temperature, Precipitation, Plant residue layer	HP
Organic matter leaching	Bacteria, Fungi, Roots, Earthworms, Enchytraeids, Termites, Ants	Soil texture, Soil moisture, Preferential flow path, Percolation, Infiltration, Aggregate stability	Soil pH, SOM, Oxygen	Temperature, Precipitation, Wind speed	
Soil erosion – detachment and runoff	Bacteria, Fungi, Roots, Earthworms, Enchytraeids, Termites, Ants	Soil texture, Soil moisture, Aggregate stability, Impeding layer, Surface stoniness, Surface morphology	$CaCO_3$, SOM	Precipitation, Vegetation density, Vegetation cover, Slope, Position in landscape	NC
Soil erosion – sedimentation		Morphology		Flux velocity, Precipitation, Vegetation density, Vegetation cover, Slope, Position in landscape	NC

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Aggregate formation	Earthworms, Enchytraeids, Termites, Ants, Bacteria, Fungi, Roots	Soil temperature, Soil moisture, Soil porosity	Soil pH, CEC, SOM quality, Clay mineralogy	Temperature, Precipitation	HP
Aggregate stabilization	Bacteria, Fungi, Roots, Earthworms, Enchytraeids	Soil texture, Soil temperature, Soil porosity	Soil pH, CEC, Clay mineralogy, Ca:Mg	Freeze-thaw cycles, Dry-rewetting cycles	
Chemical protection	Bacteria, Fungi, Roots	Soil texture	CEC, SOM, SOM quality, Clay mineralogy		
Methanotrophy	Archaea (methanotrophic), Bacteria (methanotrophic)	Soil texture, Soil moisture	Soil pH, Oxygen		
Mineral precipitation and dissolution	Roots	Soil moisture	Soil pH, Oxygen, Clay mineralogy	Freeze-thaw cycles, Bedrock type	
Ammonia volatilization		Soil moisture, Soil temperature, Soil porosity	Soil pH	Temperature, Wind speed	NC
Denitrification	Archaea (denitrifying), Bacteria (denitrifying), Fungi (denitrifying)	Soil moisture, Soil temperature, Soil porosity	Soil pH, Nitrate availability concentration, SOM, Oxygen	Wind speed, Precipitation	

*Where NC is nutrient cycling and HP is habitat provision for biodiversity.

feeding on plant material. Through this process, plant material enters the soil food web and begins transformations into smaller molecules. Root exudates and microbial extracellular enzymes also contribute to the breakdown of larger organic molecules into smaller ones, which then enter the food web. During these processes, both soil fauna and microbes release CO_2 through respiration. When soil conditions are anoxic, decomposition can still take place but it is dominated by methanogenic microorganisms, which release CH_4. Organic matter can remain unprotected, as particulate or dissolved organic matter that is more susceptible to processes of organic matter transfer or can stabilize through physical or chemical protection by associating with mineral surfaces or becoming part of soil aggregates (Cotrufo & Lavallee, 2022).

4.2 Sub-function: organic matter transfer

This sub-function focuses on processes that make resources available, unavailable or that displace them from the site of interest. These processes include bioturbation, organic matter leaching, and soil erosion, including both the accumulation of soil (sedimentation) as well as its loss (detachment).

The overall effect of organic matter leaching on carbon and climate regulation function is difficult to ascertain. Leaching to lower layers of the soil profile could lead to higher levels of protection of organic matter since microbial activity and respiration decrease with depth (Min, 2021) and it would make aggregates less likely to be disturbed by practices such as tillage. However, if dissolved organic matter (DOC) can be leached into groundwater via throughflow to a nearby ditch or stream, this will result in a loss of carbon from the system. A similar problem arises when trying to pinpoint the effect of soil erosion on the carbon and climate regulation function. The impact of soil erosion on the amount and pools of mobilized organic carbon is complex and dependent on the spatial scale. The effect of rain splash and wind on unprotected soil affects detachment and breakdown of aggregates, causing emissions of CO_2. The soil particles can be transported and deposited nearby or further away through the air or stream network. At patch and hillslope scale, selective erosion processes (e.g. sheet runoff) are dominant, mobilizing sediments enriched in organic carbon (Martínez-Mena et al., 2012). At coarser spatial scales (hillslopes, ravines and rivers), non-selective erosion processes (e.g. rill and gully erosion, riverbed and bank erosion) take place, mobilizing sediments from deeper soil layers with lower content of organic carbon (Nadeu et al., 2011; Boix-Fayos et al., 2015). Thus, soil erosion can lead to a loss of both nutrients (see sub-function: nutrient supply) and soil organic carbon at the site and enrichment where the sediment is deposited. At depositional sites the burial of sediments reduces emissions by mineralization, and new soil formation in the upper layers leads to organic carbon enrichment (Martínez-Mena et al., 2019).

In addition, the source of sediments (superficial or deeper soil layers) and the way that organic carbon is transported during the process of erosion (dissolved or protected within stable microaggregates) determine their stabilization in depositional areas (Boix-Fayos et al., 2015, 2017). The stabilization of organic carbon in depositional areas can compensate for organic carbon (OC) losses from eroded sources within catchments (Martínez-Mena et al., 2019).

The erosion potential is strongly determined by the terrain topography and soil physical properties such as aggregate stability, surface roughness and stoniness, soil structure and the presence of a soil crust and seal. Typically, with poor aggregate stability, the presence of stones or a crust can contribute to a higher erosion potential. Transport and sedimentation are also dependent on the topography, especially the terrain roughness and topographic position in the landscape, as they drive the flux velocity and the convergency of fluxes. Furthermore, vegetation cover and vegetation density affect the erosion potential. Vegetation with well-developed root systems typically reduce the erosion potential and positively contribute to the capacity of the soil to retain nutrients in the system. The presence of vegetation is also important for providing soil organic matter to the soil and thereby sustaining soil organisms (bacteria, fungi, earthworms, enchytraeids, termites and ants). Soil organisms can both reduce soil loss, by improving porosity, and increase it, by diminishing soil stability due to mixing activities (Orgiazzi & Panagos, 2018).

4.3 Sub-function: organic matter stabilization

Once organic matter enters the soil, it must be physically or chemically protected to ensure the build-up of organic matter and consequently carbon stocks, which links to the climate regulation component of the function. Processes such as aggregate formation, stabilization and chemical protection are relevant to organic matter protection and stabilization. Aggregate formation and stabilization depend strongly on biological actors that bind soil particles together, such as roots, bacteria or earthworms (Creamer et al., 2022). Environmental variables can also directly affect aggregate formation and stabilization, for example, freeze-thaw cycles have been known to disrupt macroaggregates (Six et al., 2004). Dry-rewetting cycles can also lead to peaks and troughs in decomposition rates. Evidence suggests that soils that undergo dry-rewetting cycles in the long term show higher cumulative soil respiration rates when compared to soils kept under a constant moisture regime (Zhang et al., 2020).

Chemical protection of organic matter leads to the formation of mineral-associated organic matter, which depends strongly on the mineralogy of the soil at hand and the properties of the organic matter (Degens, 1995). The scientific community has recently identified the importance of necromass accumulation to carbon sequestration overall (Liang et al., 2019; Wang et al., 2021; Cotrufo & Lavallee, 2022). Rather than including necromass accumulation as a process relevant to organic matter stabilization, we have included bacterial biomass, which relates to bacterial necromass accumulation in the processes of aggregate formation, stabilization as well as chemical protection.

4.4 Sub-function: biochemical transformations

Biochemical transformations include changes in inorganic molecules that lead to the production of N_2O (denitrification), CO_2 (mineral precipitation and dissolution), NH_3 (ammonia volatilization) as well as the consumption of CH_4 (methanotrophy). In the soil, nitrogen goes through several transformations. Nitrous oxide production is primarily the result of denitrification, which mainly takes place in the presence of NO^{-}_{3} in the soil, which occurs through the process of nitrification. While we include only nitrification in the current function, an assessment of both may be needed to account for the main pathway for N_2O and NOx emissions. The HIP model (hole-in-pipe model) predicts that the production of NOx gases is dependent on the availability of nitrogen in the soil, while the ratio between N_2O and NO production is a function of soil moisture (Davidson, 2000). Other factors, such as soil pH, and soil temperature can also explain N_2O emissions in agricultural systems, particularly when observing emissions during a growing season. Depending on factors like soil diffusivity, temperature and pH, ammonia can also volatilize.

The release of carbon into the atmosphere can be controlled through wider environmental factors. For example, while methanogenesis (see decomposition) is the process by which methanogenic microorganisms acquire energy from the breakdown of organic matter, methanotrophy is the process by which methanotrophic microorganisms oxidize methane. This process happens as soil dries out, or as methane is diffused to higher layers of drier soil. Parent material (geology) of soil can strongly define some processes, such as mineral dissolution, where the release of chemical species from a solid to the surrounding aqueous solution occurs (Noiriel & Daval, 2017). An example of this is the dissolution of carbonates from calcareous parent materials, such as calcite, due to rainwater containing $CaCO_3$ dissolving carbonates from the parent material over time.

5 Nutrient cycling

Nutrient cycling is defined as the capacity of a soil to take up and recycle nutrients from different inputs (e.g. plant residues and manure) and to support the uptake of nutrients from soil minerals and organic matter, water and air by plants and the soil community (BIOSIS, 2023). To understand this function comprehensively, we identified 18 processes allocated to three main sub-functions that determine the delivery of nutrient cycling in soils: nutrient supply, organic matter transformation and nutrient acquisition (Fig. 3). The direct and indirect parameters that support the provision of these processes are described in Table 2.

5.1 Sub-function: nutrient supply

Nutrient supply is determined by processes such as adsorption/desorption, ammonia volatilization, atmospheric deposition, microbial immobilization, nitrification, denitrification, nutrient leaching, precipitation/dissolution, and soil erosion and runoff (specifically soil detachment processes). Plants and soil microorganisms take up dissolved nutrients from the soil solution, primarily in the form of nitrate (NO^{-}_{3}) or ammonium (NH_4). For most nutrients, dynamic equilibria exist between the soil solution and various solid forms. In the absence of soil organisms and growing plants, these equilibria are governed by physico-chemical processes such as adsorption/desorption on surfaces as well as precipitation/dissolution. For example, the abiotic retention of phosphate on particles in the soil can be viewed as a continuum of precipitation and adsorption processes (Bünemann, 2015), while phosphate sorption is governed mainly by the concentration, types and surfaces of iron and aluminium oxides (Borggaard et al., 2005). In living soil, these chemical equilibria are additionally affected by biological uptake from the soil solution, transformation into other chemical forms and release upon death and decay. Nitrification and denitrification, as described previously, are transformation processes that are specific to N.

Unutilized nutrients in the soil are at risk of leaching into deeper soil layers, particularly for soils with a sandier texture, through by-pass flow or where groundwater levels are high. When these nutrients are transferred below the rootable soil depth, they can be adsorbed onto mineral surfaces or lost entirely from the soil system, potentially contributing to groundwater contamination in regions with intensive agricultural practices (Lehmann, 2002). Nutrient losses through leaching can be influenced by preferential water flow paths, which may form due to successions of wetting and drying cycles in clayey soils. These pathways can also emerge from structural modifications in the soil, such as biopores created by faunal activity (e.g. earthworms, ants, termites) and plant roots (Zhang et al., 2018). While these structures typically enhance soil aeration and water infiltration, they may, under certain conditions, facilitate deeper nutrient transport beyond the root zone. Vegetation type and density, with its effect on rooting depth and density, can limit nutrient leaching through assimilation (Creamer et al., 2022).

Nutrient mobility in the soil is nutrient-specific and often dependent on their chemical form (speciation). For instance, nitrate (NO_3) is highly mobile and prone to leaching, while phosphate is generally immobile in most soils because

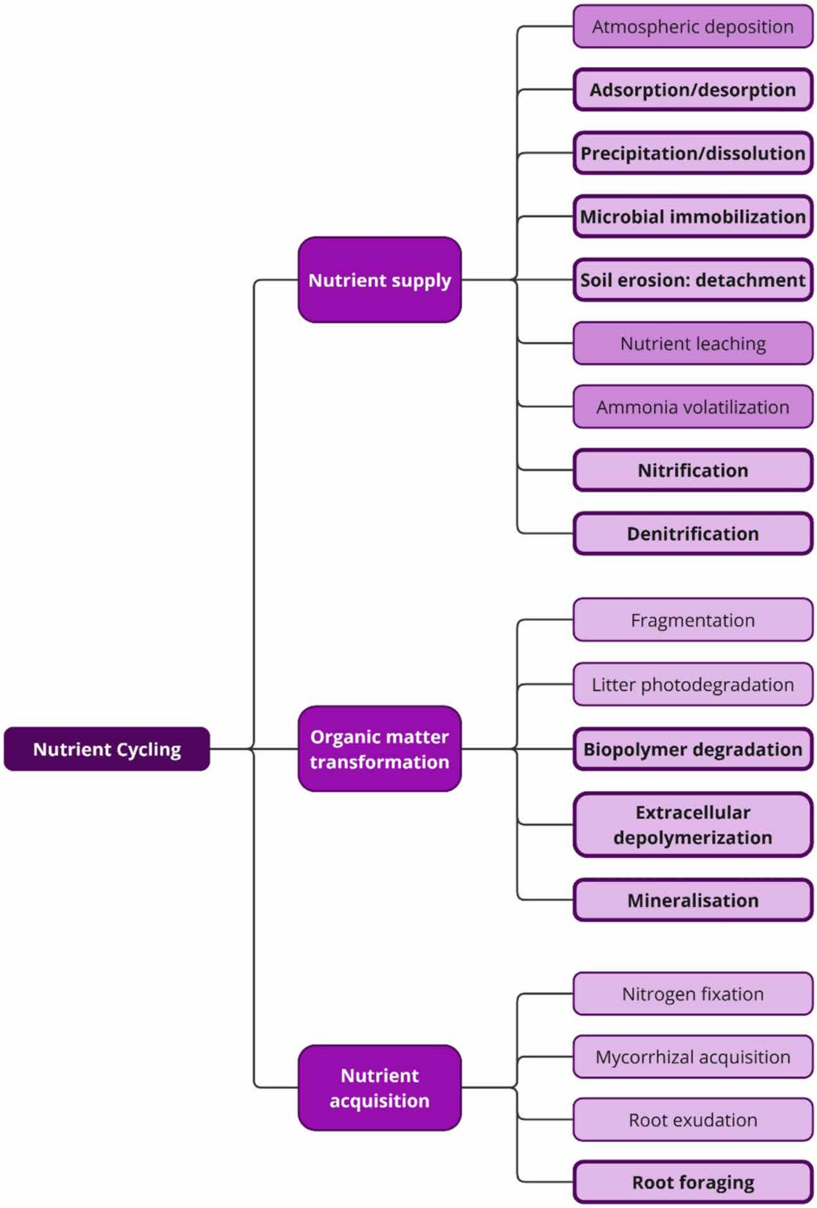

Figure 3 Processes (light purple) and sub-functions (purple) underpinning nutrient cycling. Boxes with a thicker outline and bold lettering represent processes deemed as most relevant by the experts.

Table 2 Soil parameters that directly or indirectly mediate the processes that occur in the nutrient cycling function. Some parameters or parts of them are expressed with abbreviations or acronyms. Abbreviations and acronyms for biological parameters: N-fixing for nitrogen-fixing. Abbreviations and acronyms for chemical parameters: SOM for soil organic matter content, SOM quality for soil organic matter quality, CEC for cation-exchange capacity, $CaCO_3$ for calcium carbonate, MAOM for mineral associated organic matter, oxygen for oxygen concentration, FF for fungivores and BF for bacterivores

	Soil parameters that underpin each process				
Process	Biological*	Physical	Chemical	Environmental	Present in other functions**
Atmospheric deposition				Precipitation Deposit concentration in the air	
Absorption/ desorption	Bacteria Fungi Roots Earthworms	Soil texture Soil moisture Soil temperature Specific surface area Soil porosity	Soil pH CEC Clay mineralogy SOM MAOM	Temperature Precipitation Freeze-thaw cycles	WR
Precipitation/ dissolution	Bacteria Fungi Roots	Soil moisture Soil temperature Soil porosity	Soil pH Chemical saturation Oxygen SOM Clay mineralogy	Temperature Vegetation cover	WR; HP
Microbial immobilization	Bacteria Fungi Nematode (B) Nematode (F) Collembola (B) Collembola (F) Protozoa (B) Protozoa (F) Acari (F)	Soil temperature Soil moisture Soil porosity	Soil pH SOM SOM quality		
Soil erosion – detachment and runoff	Bacteria Fungi Roots Earthworms Enchytraeids Termites Ants	Soil texture Soil moisture Aggregate stability Impeding layer Surface stoniness Morphology	$CaCO_3$ SOM	Precipitation Vegetation density Vegetation cover Slope Position in landscape	CR

(*Continued*)

Table 2 (*Continued*)

	Soil parameters that underpin each process				
Process	Biological*	Physical	Chemical	Environmental	Present in other functions**
Soil erosion – sedimentation				Morphology Flux velocity Precipitation Vegetation density Vegetation cover Slope Position in landscape	CR
Nutrient leachin	Bacteria Fungi Roots Earthworms Enchytraeids Termites Ants	Soil texture Soil moisture Preferential flow path Percolation Infiltration Aggregate stability	Soil pH Sorption/ Desorption Nutrient availability Clay mineralogy	Dry-rewetting cycles Freeze-thaw cycles Vegetation density	
Ammonia volatilization		Soil moisture Soil temperature Soil porosity	Soil pH	Temperature Wind speed	CR
Nitrification	Archaea (nitrifying) Bacteria (nitrifying) Fungi (nitrifying)	Soil moisture Soil temperature Soil porosity	Soil pH Ammonia SOM Oxygen	Temperature Vegetation cover	
Fragmentation	Acari (Oribatids) Isopods Collembola Earthworms Enchytraeids Termites Ants Millipedes	Soil temperature Soil moisture	Soil pH Oxygen Plant residue quality	Temperature Precipitation Plant residue layer depth	CR; HP
Litter photodegradation		Soil moisture	Plant residue quality	Temperature Plant residue layer Solar irradiation	CR

Biopolymer degradation	Acari Collembola Earthworms Nematodes Protozoa Termites Ants Millipedes	Soil texture Soil temperature Soil moisture Soil porosity	Soil pH Nutrient availability SOM Oxygen	Temperature Precipitation	HP
Extracellular depolymerization	Bacteria Fungi Roots	Soil temperature Soil moisture Soil porosity	Soil pH Nutrient availability SOM SOM quality		CR; HP
Mineralization	Bacteria Fungi	Soil texture Soil temperature Soil moisture	Soil pH Nutrient availability SOM SOM quality Oxygen CaCO3	Temperature Precipitation	HP
Nitrogen fixation	Bacteria (N-fixing) Archaea (N-fixing) Legumes	Soil temperature Soil moisture	Soil pH Nutrient availability		
Mycorrhizal acquisition	Plants (mycorrhizal) Fungi (mycorrhizal)	Soil moisture	Soil pH Nutrient availability		
Root exudation	Roots	Soil moisture	Soil pH Nutrient availability Oxygen		HP
Root foraging	Roots	Soil moisture Surface stoniness Effective root depth	Soil pH Nutrient availability Micronutrient availability		

*Where F are fungivores, B are bacterivores.
**Where CR is carbon regulation, WR is water regulation and provision and HP is habitat provision for biodiversity.

of its tendency to precipitate or adsorb onto mineral surfaces (Lehmann, 2002). Another pathway for nitrogen loss is ammonia volatilization, a process that was already discussed under the carbon and climate regulation function model.

Atmospheric deposition is of varying importance, depending on the nutrient. For N, the critical loads theory attributes high nitrogen deposition to the livestock density and type of animals within a local region (Bobbink et al., 2015; Chang et al., 2021). High nitrogen emissions associated with pig and poultry facilities in the local vicinity can significantly increase the rate of nitrogen atmospheric deposition. For sulphur (S), atmospheric deposition has decreased substantially over time, and in the last 2 decades, S deficiency in certain crops has been increasingly observed (Zhao et al., 2003a).

Soil erosion can lead to the transfer of nutrients across the landscape, similar to the erosion processes described in the organic matter transfer sub-function. It is worth highlighting that depositing nutrient-rich sediments may play a dual role. On one hand, it can negatively impact sensitive ecosystems through nutrient enrichment, which may lead to soil or surface water eutrophication. On the other hand, it can benefit agricultural systems that depend on external nutrient inputs to maintain productivity (Nathan et al., 2022).

5.2 Sub-function: organic matter transformation

Through transformations of organic matter, nutrients become available to plants as well as to soil organisms. Processes such as litter photodegradation (Almagro et al., 2015), fragmentation, biopolymer degradation, extracellular depolymerization and mineralization are particularly important in the cycling of nutrients through the soil profile. These processes closely relate to the decomposition sub-function described previously, since as soil organic matter is broken down, nutrients become available to soil organisms as well as to plants after mineralization by biological actors. The parameters that regulate decomposition also play an important part in the release of nutrients.

5.3 Sub-function: nutrient acquisition

Nutrients which are mobile in the soil can reach plant roots via mass flow, while for poorly mobile nutrients, diffusion can replenish depleted nutrients at the root surface (Hinsinger et al., 2011). In addition, the root system often increases to support nutrient acquisition when concentrations are low and/or plant uptake is high. Such root foraging strategies differ between plant species, resulting in below-ground niche complementarity of (e.g.) shallow- vs. deep-rooting species (Zhang, 2014).

Besides growth, many plant species use specific rhizosphere processes such as the exudation of protons or organic ligands to make nutrients more available (Hinsinger et al., 2011). Symbiosis with mycorrhizal fungi can be a possibility to expand the depleted soil volume, partly by growing into smaller soil pores than roots or root hairs. Ectomycorrhizal fungi may also produce exudates that contribute to the mobilization of recalcitrant nutrients such as phosphorus. Biological fixation of nitrogen from the atmosphere mostly occurs in legumes through symbiosis with rhizobia (Buckley, 2007). In addition, free-living diazotrophs have been shown to be present in many soils, even though their contribution to the nitrogen cycle is likely limited compared to that of symbiotic nitrogen fixation.

6 Water regulation and filtration

The water regulation and filtration function includes two main sub-functions: water storage and filtering capacity. We identified 16 main processes that underpin the sub-functions of water storage and filtering capacity (Fig. 4). The direct and indirect parameters that support the provision of these processes are described in Table 3.

6.1 Sub-function: water storage

Water storage is the capacity of the soil to store water as it integrates multiple interrelated processes, influencing one another to determine the overall water storage capacity of the soil. This interconnected nature of processes in the soil-plant-atmosphere continuum justifies their integration under the broader water storage sub-function (Hillel, 2003).

Water enters the soil through infiltration, influenced by rainfall, soil properties, vegetation, land use and temporary barriers like hydrophobic layers or compacted crusts (Coppola et al., 2011). Water that cannot infiltrate may result in runoff or ponding on low-lying ground. Runoff occurs under two conditions: (i) saturation excess runoff (Dunnian process) – when the soil becomes fully saturated, excess water flows over the surface, and (ii) infiltration excess runoff (Hortonian process) – when rainfall exceeds the soil's infiltration capacity, runoff forms even if the soil is not saturated (Blöschl & Sivapalan, 1995). Infiltration and runoff are interconnected – higher runoff reduces infiltration and vice versa (Wang et al., 2016). The rates of infiltration and runoff depend on precipitation intensity, soil properties and landscape features, especially the upper soil horizon and slope. Soil texture plays a crucial role: fine-textured soils have low hydraulic conductivity, slowing water movement and increasing runoff when rainfall exceeds infiltration capacity (Beven and Germann, 2013). In contrast, coarse-textured soils support higher infiltration, reducing runoff under similar conditions. Rock fragments on the surface also influence infiltration, runoff and erosion processes (Cerdà, 2001).

Water returns to the atmosphere through evapotranspiration, which includes evaporation from the soil surface and transpiration through plant

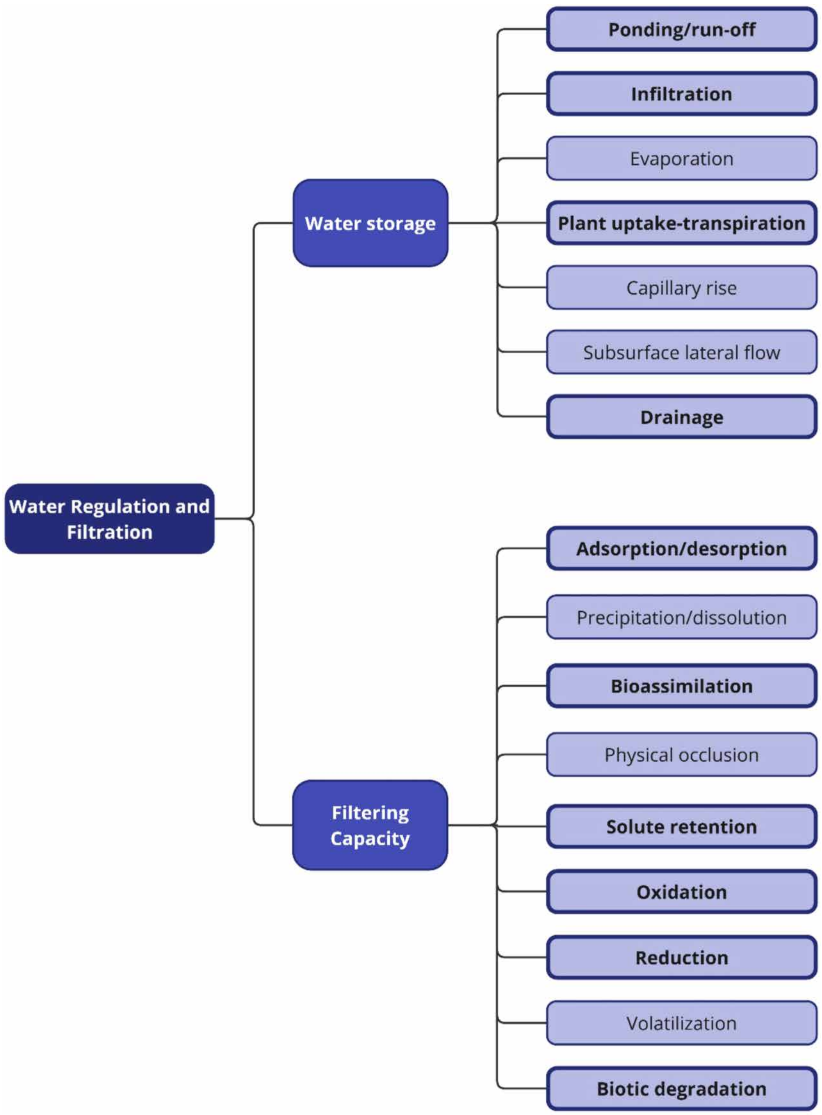

Figure 4 Processes (light blue) and sub-functions (blue) underpinning water regulation and filtration. Boxes with a thicker outline and bold lettering represent processes deemed as most relevant by the experts.

uptake. In crops, over 99% of absorbed water is lost via transpiration, with only a small amount retained in plant tissues (Hillel, 2003). Evapotranspiration is influenced by atmospheric factors (temperature, solar radiation, humidity and wind) and plant traits (root depth, architecture and uptake efficiency) (Feddes

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Table 3 Soil parameters that directly or indirectly mediate the processes that occur in the water regulation and filtration function. Some parameters or parts of them are expressed with abbreviations or acronyms. Abbreviations and acronyms for chemical parameters: SOM for soil organic matter content, SOM quality for soil organic matter quality, CEC for cation-exchange capacity, MAOM for mineral-associated organic matter, oxygen for oxygen concentration

	Soil parameters that underpin each process				
Process	Biological	Physical	Chemical	Environmental	Present in other functions*
Infiltration	Fungi Roots Earthworms Enchytraeids Termites Ants	Soil texture Aggregate stability Saturation Soil porosity Impeding layer Surface stoniness Presence of cracks		Temperature Precipitation Vegetation cover Slope Position in landscape	
Evaporation		Soil texture Soil porosity Aggregate Stability Unsaturated hydraulic conductivity Water retention curve Impeding layer Surface stoniness	SOM	Temperature Precipitation Wind speed Vegetation cover Vegetation density Albedo Plant residue layer Relative humidity Latent heat of evaporation	
Plant uptake and transpiration	Roots Plants Mycorrhizal fungi		Soil salinity	Temperature Precipitation Wind speed Vegetation cover Vegetation density Albedo Plant residue layer Relative humidity Latent heat of evaporation Position in landscape Length of growing season	

(*Continued*)

Table 3 (*Continued*)

	Soil parameters that underpin each process				
Process	Biological	Physical	Chemical	Environmental	Present in other functions*
Capillary rise	Bacteria Fungi Roots Earthworms Nematodes Protozoa	Soil texture Soil porosity Saturation Water retention curve Water table depth Clay mineralogy	Water salinity	Temperature Precipitation Position in landscape	
Subsurface lateral flow	Earthworms Roots	Soil porosity Saturation Impeding layer Hydraulic discontinuity		Temperature Precipitation Position in landscape	
Drainage	Roots Earthworms	Soil texture Saturation Soil porosity Soil depth Water table depth Impeding layer Presence of cracks		Temperature Precipitation	
Adsorption/ desorption	Bacteria Fungi Roots Earthworms	Soil texture Soil moisture Soil temperature Specific surface area Soil porosity	Soil pH CEC Clay mineralogy SOM MAOM	Temperature Precipitation Freeze-thaw cycles	
Precipitation/ dissolution	Roots Bacteria Fungi	Soil moisture Soil temperature Soil porosity	Soil pH Chemical saturation SOM Oxygen Clay mineralogy	Temperature Vegetation cover	NC; HP

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Bio-assimilation	Bacteria Fungi Roots Earthworms Nematodes Protozoa	Soil temperature Soil moisture	Soil pH SOM	Vegetation
Physical occlusion	Bacteria Fungi Roots Earthworms Protozoa	Soil texture Soil temperature Soil moisture Soil porosity	Soil pH CEC SOM quality Clay mineralogy	Dry-rewetting cycles Freeze-thaw cycles
Solute retention	Bacteria Fungi Roots Earthworms	Soil texture Soil porosity	SOM	
Oxidation	Impeding layer		Soil pH SOM Oxygen	
Reduction	Bacteria (denitrifying) Archaea (denitrifying)	Soil moisture Soil porosity Air permeability	Soil pH SOM Oxygen	
Volatilization	Soil **t**emperature Soil Moisture Soil porosity		Soil pH	Wind speed
Biotic degradation	Bacteria Fungi Collembola Earthworms Protozoa Nematodes Acari	Soil temperature Soil moisture	Soil pH SOM Oxygen Nutrient availability	

*Where NC is nutrient cycling and HP is habitat provision for biodiversity.

et al., 1976). Deeper soils support root growth, providing a larger water reservoir that sustains transpiration during dry periods.

Soil parameters, however, have a complex and sometimes contradictory effect on water availability. For example, fine-textured soils have a higher water-holding capacity, meaning they can store more water. However, their low permeability and high density can impede deep root growth, limiting the plant's ability to access moisture at greater depths. In contrast, coarse-textured soils drain quickly and hold less water but allow for deeper root penetration (Dodd & Lauenroth, 1997).

Water can also move upward from wetter regions (e.g. groundwater) towards drier soil zones due to capillary action. This process is particularly relevant in areas with a shallow groundwater table and is strongly impacted by the capillary porosity and clay content of the soil (Li et al., 2014).

Drainage (or deep percolation) is the downward movement of water out of the soil profile, contributing to groundwater recharge. Soil texture and depth play key roles: sandy soils, with large pores and high conductivity, promote rapid drainage, while clay-rich or compacted soils slow water movement (Keese et al., 2005). Shallow soils over bedrock can also enhance recharge by directing water downward more quickly.

Finally, subsurface lateral flow moves water sideways through the soil towards streams or rivers. This process depends on landscape morphology and soil hydraulic properties. It is most significant when a less permeable layer (e.g. clay-rich or compacted soil) impedes vertical movement, redirecting water laterally along soil horizons (Li et al., 2014).

6.2 Sub-function: filtering capacity

The soil's filtering capacity refers to the capacity of the soil to extract, degrade, transform or contain harmful compounds (BIOSIS, 2023), including the mechanism of their physical transport into the soil.

Each pollutant exhibits a different potential for these processes, and the mechanisms leading to their degradation can be different depending on the pollutant at hand. It is outside of the scope of this chapter to provide the parameters needed to model the degradation of each individual pollutant. Instead, our focus is on describing soils with a high potential for containing, degrading, occluding and transporting pollutants.

Containment refers to soil's capacity to retain elements or compounds within the soil matrix or through biological assimilation, thereby limiting their movement and export. Key containment processes include sorption onto solid surfaces, precipitation, physical occlusion and biological uptake. A soil's ability to retain molecules through chemical reactions depends on the characteristics of sorbent materials and solid surfaces, which can vary with factors such as redox potential and pH (Naidu, 1998; Sarkar, 2021; Sposito, 1999).

Physical occlusion sequesters elements by making them inaccessible to soil biota and prevents leaching due to reduced water and gas movement, often a result of discontinuous pore structure and aggregation (Chi et al., 2022; Sexstone, 1985). Bio-assimilation relates to the ability of the soil biota to extract elements and molecules from the soil. Fungi and bacteria are particularly relevant to bio-assimilation, as they are the primary consumers of organic pollutants (Saadi, 2012) and micro-plastics (Fojt et al., 2020), and it is through the consumption of these microbes that the pollutants become assimilated at higher levels of the soil food-web (Armitage, 2007). Soil invertebrates can also play an important role in bio-accumulation, both directly through absorption of chemicals through the skin, particularly in the case of soft-bodied soil organisms such as earthworms and molluscs, and indirectly through feeding on contaminated materials (Heikens, 2001; Chao et al., 2023).

Transformation processes include oxidation, reduction and volatilization. Whether a pollutant becomes more or less impactful to the environment through oxidation and reduction processes depends on the nature of the pollutant itself. Therefore, we consider soil with the highest potential for pollutant transformation to be one where both processes can occur over time, allowing various pollutants to undergo different types of transformations. However, we acknowledge that when a specific pollutant is present in the soil, remediation efforts or management practices may be designed to favour either oxidation or reduction processes, depending on which pathway is most effective for pollutant transformation or removal. Ultimately, the most desirable outcome is the complete degradation of pollutants into non-harmful chemical forms. Transformation processes can sometimes contribute to this degradation. While soil organisms, particularly microorganisms, play a key role in the breakdown of organic pollutants, factors such as freeze-thaw cycles have been shown to influence degradation rates indirectly by affecting the microbial community (Ji et al., 2022).

The filtering capacity of soil is also influenced by the processes that govern the fate of pollutants – or, more generally, solutes – as they move through the soil towards groundwater. Among the many mechanisms involved, we focus here on the main ones (Jury & Horton, 2004; Kutílek & Nielsen, 1994): convection (or advection) is the movement of a solute dissolved in soil water, which occurs in direct proportion to the average water flow and solute concentration; diffusion occurs when solute particles move from high-concentration areas to low-concentration areas, following the concentration gradient; mechanical dispersion arises due to variations in water flow within individual pores and among pores of different sizes. Diffusion and mechanical dispersion contribute to solute spreading by smoothing sharp concentration fronts along the main flow direction. Due to their similarities, they are often represented by a combined hydrodynamic dispersion coefficient, determined through miscible displacement experiments in lab and field settings. Given the complexity of these processes, linking measurable soil properties to solute behaviour is challenging. Dispersivity (μ) is a key parameter influencing solute transport. Vanderborght and Vereecken (2007) found that dispersivity increases with transport distance and scale but is unaffected by soil texture, with higher values under saturated conditions. Koestel et al. (2012) identified process scale, water flow level and saturation as critical factors, while Coppola et al. (2011) observed that local heterogeneities, such as stones, also play a role. Godoy et al. (2019) found that while most soil properties showed weak correlations with transport parameters, the adsorption isotherm slope strongly correlated with cation exchange capacity and was significantly influenced by meso- and micro-porosity.

Finally, pollutants can preferentially move through macropores – large structural pores like root channels, earthworm burrows and fissures. Jarvis (2020) found that these biologically and chemically active microsites influence water flow and solute transport, though adsorption and retardation are minimal due to their limited surface area. The macropore network is shaped by soil biota, soil properties, site conditions and land management. High-intensity rainfall can enhance non-equilibrium flow, accelerating solute transport and impacting water quality, especially for low-mobility solutes like pesticides, which pose risks even at low leaching rates.

7 Habitat provision for biodiversity

Habitat provision for biodiversity refers to the capacity of soil to create and sustain suitable habitats for a wide range of organisms, including microorganisms, plants and animals. It encompasses the physical, chemical and biological characteristics of the soil that enable the establishment and maintenance of diverse communities. We present a set of processes and parameters that would, in theory, lead to higher levels of biodiversity (species richness and abundance), both in terms of taxonomic diversity and functional diversity. The habitat provision for biodiversity function assumes that habitats need to be available for colonization and that increased habitat complexity will increase the opportunities for soil organisms to establish and thrive. Habitat provision is influenced by a variety of interconnected processes, grouped into three main sub-functions: spatial availability and complexity, habitat suitability and stability and biotic interactions (Fig. 5). The direct and indirect parameters that support the provision of these processes are described in Table 4.

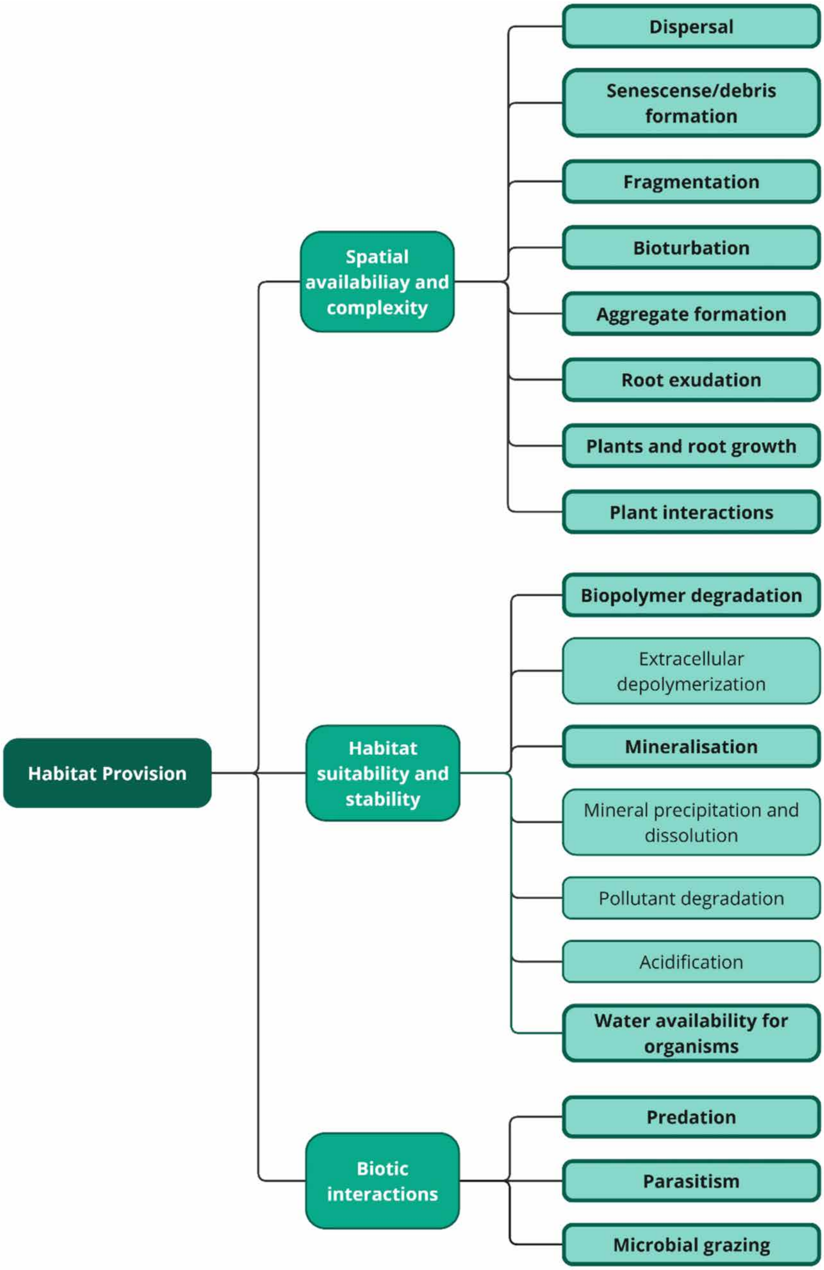

Figure 5 Processes (light green) and sub-functions (green) underpinning habitat provision for biodiversity function. Boxes with a thicker outline and bold lettering represent processes deemed as most relevant by the experts.

Table 4 Soil parameters that directly or indirectly mediate the processes that occur in the habitat provision function. Some parameters or parts of them are expressed with abbreviations or acronyms. Abbreviations and acronyms for biological parameters: N-fixing for nitrogen-fixing. Abbreviations and acronyms for chemical parameters: SOM for soil organic matter content, CEC for cation-exchange capacity, $CaCO_3$ for calcium carbonate, oxygen for oxygen concentration

	Soil parameters that underpin each process				
Process	Biological*	Physical	Chemical	Environmental	Present in other functions**
Dispersal	Earthworms Enchytraeids Termites Ants Nematodes Acari Collembola	Soil texture Bulk density Soil temperature Soil moisture Soil depth	Soil pH Nutrient availability SOM	Temperature Precipitation Wind speed	
Senescence/ debris formation	Plants			Precipitation Wind speed Vegetation cover Vegetation composition	
Fragmentation	Acari (Oribatids) Isopods Collembola Earthworms Enchytraeids Termites Ants Millipedes	Soil temperature Soil moisture	Soil pH Oxygen Plant residue quality	Temperature Precipitation Plant residue layer depth	CR; NC
Bioturbation	Earthworms Enchytraeids Termites Ants	Soil texture Bulk density Soil temperature Soil moisture Soil depth	Soil pH Nutrient availability SOM	Temperature Precipitation Plant residue layer depth	CR

Aggregate formation	Earthworms Enchytraeids Termites Ants Bacteria Fungi Roots	Soil temperature Soil moisture Soil porosity	Soil pH CEC SOM quality Clay mineralogy	Temperature Precipitation	CR
Root exudation	Roots	Soil moisture	Soil pH Nutrient availability Oxygen		NC
Plant and root growth	Roots	Soil moisture Effective root depth Surface stoniness	Soil pH Nutrient availability Micronutrient availability		
Plant interactions	Roots Bacteria (N-fixing) Archaea (N-fixing)	Soil texture Water holding capacity Soil porosity Soil depth	Soil pH Nutrient availability SOM	Temperature Precipitation Topography	
Biopolymer degradation	Acari Collembola Earthworms Nematodes Protozoa Termites Ants Millipedes	Soil texture Soil temperature Soil moisture Soil porosity	Soil pH Nutrient availability SOM Oxygen	Temperature Precipitation	NC
Extracellular depolymerization	Bacteria Fungi Roots	Soil temperature Soil moisture Soil porosity	Soil pH Nutrient availability SOM SOM quality		CR; NC

(*Continued*)

Table 4 (*Continued*)

	Soil parameters that underpin each process				
Process	Biological*	Physical	Chemical	Environmental	Present in other functions**
Mineralization	Bacteria Fungi	Soil texture Soil temperature Soil moisture	Soil pH Nutrient availability SOM SOM quality Oxygen CaCO3	Temperature Precipitation	NC
Precipitation/ dissolution	Bacteria Fungi Roots	Soil temperature Soil moisture Soil porosity	Soil pH Chemical saturation SOM Oxygen Clay mineralogy	Temperature Vegetation cover	NC; WR
Pollutant degradation	Bacteria Fungi Roots Earthworms	Soil temperature Soil moisture Soil porosity	Soil pH CEC SOM Presence of pollutants Presence of surfactants Oxygen Soil enzyme activity		
Acidification	Roots		SOM CEC	Precipitation Vegetation composition Deposit concentration in air Bedrock type	
Water availability		Soil porosity Soil moisture			

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Predation	Acari (O)
	Acari (Pr)
	Collembola (O)
	Collembola (Pr)
	Nematodes (O)
	Nematodes (Pr)
	Spiders
	Insects (Pr)
	Ants (Pr)
Parasitism	Bacteria (Pa)
	Fungi (Pa)
	Insects (Pd)
	Nematodes (Pa)
	Protozoa (Pa)
	Viruses
Microbial grazing	Acari (F)
	Collembola (B)
	Collembola (F)
	Collembola (O)
	Enchytraeids
	Nematodes (B)
	Nematodes (F)
	Nematodes (O)
	Protozoa (B)
	Protozoa (F)
	Protozoa (O)

*Where O are omnivores, Pr are predatory, Pa are parasitic, Pd are parasitoid, F are fungivores, B are bacterivores.
**Where CR is carbon regulation, NC is nutrient cycling and WR is water regulation and provision.

7.1 Sub-function: habitat availability and complexity

This sub-function incorporates the processes that relate to the physical availability of habitats to soil organisms, as well as the complexity of the soil environment. It includes factors that enable organisms to disperse to new habitats and processes that enhance the complexity of the soil habitat. Examples include the variety of soil inputs, for instance, root exudation from a diverse set of plants, or soil organic matter with different properties.

While the habitat provision potential may be high, it is crucial for organisms to physically reach the micro- or macro-sites for these to function as effective habitats. This is also true across scales, from the micro scale (e.g. pore spaces) to the landscape scale. Barriers (whether physical, chemical or anthropogenically derived) at different spatial scales can effectively decrease the habitat provision potential of soil by impeding the dispersal of organisms. Dispersal rates for soil organisms can vary greatly depending on the mode of dispersal, as well as the size of the propagules or dispersal units (*sensu* Kleyer et al., 2008). Smaller dispersal units can be transported long distances by wind or water (Hirst, 1965; Ptatscheck, 2018), but successful (re-)colonization of a habitat patch can still take a long time (e.g. years) (Klein, 2020). Some organisms will also adopt hitchhiking strategies, either on the intestinal tract of other soil organisms or by anchoring themselves to other organisms (Wardle, 2006). However, habitat fragmentation or spatiotemporal discontinuity of the habitat can negatively impact soil biodiversity by limiting the availability of and movement to the habitat, with consequent impacts on the composition and dynamics of local communities as well as biotic interactions (Nordén et al., 2014).

Soil organisms, such as earthworms, ants, enchytraeids and collembola are of great importance to habitat formation through roles such as bioturbation, and the formation of pores and aggregates (Wardle, 2006; Feeney et al., 2006). Microbial activity and plant roots also contribute significantly to these processes by stabilizing aggregates and enriching the soil matrix with exudates and organic matter (Paul, 2016). Through these processes, the physical structure of the soil matrix becomes more complex leading to higher habitat heterogeneity (Coleman et al., 2024). In fact, plants exert a profound influence on the spatial complexity of the soil environment through their root exudates, which alter the composition of microbial communities in their immediate surroundings (Bais et al., 2006; Zhao, et al., 2023b). Different plant species have distinct microbial communities associated with their root system and, therefore, an increase in plant diversity is expected to lead to increasing habitat heterogeneity for associated species (Lamb et al., 2011). Aboveground, different plant species are known to produce litter with varying chemical and physical properties, which can affect detritivore and decomposer communities in the soil. This results in changing patterns of decomposition, fragmentation and organic matter formation, further contributing to habitat heterogeneity.

7.2 Sub-function: habitat suitability and stability

Habitat suitability and stability encompasses the processes that ensure that the soil is a favourable environment for organisms, and remains so over time. These processes are linked to nutrient and water supply, maintenance of soil structure and the mitigation of habitat degradation through mechanisms like acidification control and pollutant degradation. Nutrient cycling is a cornerstone of soil health, driven by the interactions between soil microorganisms, fauna and organic matter inputs. The decomposition of soil organic matter (SOM) is a multi-step process involving fragmentation and depolymerization. Fragmentation involves breaking down plant residues (e.g. leaves and other dead plant material) into smaller, edible pieces for soil fauna and microorganisms (Brown et al., 2018; Frouz, 2018). This process is primarily led by soil fauna such as earthworms, millipedes, isopods, springtails, mites and nematodes. Depolymerization is the further breakdown of complex organic matter into simpler, plant-available elements and is primarily carried out by bacteria and fungi (Kögel-Knabner 2002; Xu et al., 2018; Salvachúa et al., 2016). This leads to the release of plant-available nutrients such as nitrogen and phosphorus (Frouz, 2018; Kögel-Knabner, 2002). The continuous input of SOM, such as crop residues, animal manure and leaf litter, replenishes nutrient pools and maintains microbial activity; in addition, plants release organic compounds as exudates into the rhizosphere, further contributing to microbial nutrient cycling. This creates a feedback loop as plant diversity fosters microbial diversity, which in turn improves nutrient availability for plants (Ehrmann & Ritz, 2014). Additionally, nutrient cycling is linked to biotic and abiotic mineral weathering. Biotic agents, such as bacteria, fungi, lichens and roots, secrete organic acids and enzymes that dissolve primary minerals, releasing essential nutrients into the soil solution. Abiotic factors, such as weathering and erosion, also play a role. These geochemical processes alter the soil's chemical composition over time, influencing parameters like pH, redox potential, and cation exchange capacity (April & Newton, 1992). The release of nutrients depends on intrinsic soil characteristics, such as texture, the presence of coarse fragments, soil depth, mineral composition, and the underlying bedrock (Zhu et al., 2014).

The soil’s ability to allow water to infiltrate and to be retained is critical for maintaining habitat stability and ecosystem functions. Soil structure, particularly aggregation and pore formation, plays a central role in water infiltration and retention. Aggregation as the clustering of soil particles into aggregates, stabilizes soil structure and improves the capacity to retain water. Pore formation, involving the creation of spaces within the soil, facilitates the movement of air, water and organisms. Together, these processes enhance the physical structure of soil. Soil texture, SOM content and bioturbation (mixing of soil elements by organisms) significantly influence aggregation and pore formation. Earthworms, for example, create macropores that improve water infiltration and reduce surface runoff during heavy rainfall (Bottinelli et al., 2010, 2015; Bacq-Labreuil et al., 2018; 2019). Similarly, ants, termites, plant roots and fungi contribute to soil porosity and stability by forming and stabilizing soil aggregates (Cammeraat and Risch 2008; Jouquet et al., 2011; Helliwell et al., 2017; Feeney et al., 2006; Martin et al., 2012). Root architecture, mucilage secretion and vegetation density also play critical roles, directly modulating soil structure and hydrological dynamics (Bacq-Labreuil et al., 2019). From a physical perspective, soil porosity, pore size distribution, and pore connectivity are key parameters that determine water retention and gas exchange in soil. These characteristics influence the soil's ability to store water and buffer against drought or flooding (Zhang et al., 2021), thereby ensuring habitat suitability. Keystone species and biological engineers, such as earthworms, arbuscular mycorrhizal fungi (AMF), and plant roots, play critical roles in maintaining soil health and functionality. Via their movements and activity through the soil layers, they play a key role in litter decomposition (Brown et al., 2000), and pore formation (Bottinelli et al., 2015), improving nutrient availability (Fischer et al., 2014) and water infiltration (Capowiez et al., 2015; Jouquet et al., 2012b). Fungal hyphae grow through fissures and pores and form aggregates at a micro scale important for aggregate stability (Tisdall & Oades, 1982; Dorioz et al., 1993). Arbuscular mycorrhizal fungi are symbiotic fungi that facilitate nutrient cycling and enhance plant root access to essential nutrients, such as phosphorus (Miller & Fitzsimons, 2011). Roots also modify soil structure by forming aggregates, increasing porosity, and secreting mucilage and exudates. These processes stabilize soil structure, enhance water retention and improve soil nutrient dynamics (Whalley et al., 2005; Helliwell et al., 2017; Chenu & Cosentino, 2011; Tisdall & Oades, 1982; Read et al., 2003).

7.3 Sub-function: biotic interactions

Biotic interactions encompass the complex relationships among soil organisms and between soil organisms and plants. This sub-function emphasizes the importance of interactions like predation, microbial grazing and parasitism in supporting soil biodiversity and functionality. The primary indicators for the sub-functions here are centred on the diversity and abundance of predators, microbial grazers and parasites, as these metrics provide critical insights into the balance, functionality and resilience of soil ecosystems by reflecting the variety and activity levels of organisms involved in these processes.

Predation dynamics, involving organisms like nematodes, mites, ants, spiders and larger soil fauna (macrofauna), play a pivotal role in regulating soil ecosystems. Predators control populations of prey species, preventing imbalances that could disrupt soil processes (Meyer et al., 2019; Bernardin et al., 2024). By preventing the overpopulation of any single species, predation contributes to a balanced soil community structure, which enhances functional redundancy and strengthens the resilience of the ecosystem (Feit et al., 2019). In addition to regulating prey populations, predators contribute to soil nutrient cycling. Predators indirectly support nutrient turnover and availability for plants through excretion, egestion and translocation of nutrients (Schmitz et al., 2010). For instance, predatory ants and beetles can redistribute organic matter and nutrients across soil profiles, enhancing soil fertility. Predators also play a crucial role in pest control by managing soil-dwelling pest populations, such as root-feeding nematodes and insect larvae. This natural regulation indirectly supports plant health and productivity by reducing the need for chemical pest control and by promoting sustainable land management (Moore et al., 1988; Beretta et al., 2022). The role of predation in pest control highlights its contribution to ecosystem services, such as crop yield enhancement and biodiversity conservation. Microbial grazers, such as protozoa and nematodes, regulate soil microbial populations, contributing to the balance between different microbial groups, and enhancing nutrient cycling. These grazers release nutrients stored in microbial biomass, particularly nitrogen and phosphorus, making them available for plant uptake (Griffiths, 1994; Bonkowski, 2004; Jiang et al., 2017; Camuy-Vélez et al., 2024). The process of microbial grazing is essential for sustaining microbial diversity and maintaining soil fertility. Microbial grazing also influences the size and turnover rate of organic carbon pools, affecting the carbon dynamics in the soil, and its role as a carbon sink (Jiang et al., 2018). While grazing promotes nutrient mineralization, it can also alter the microbial community structure, influencing decomposition processes and overall soil functionality.

Parasitism in soil ecosystems involves interactions where one organism derives nutrients from a host, often regulating host populations. Parasites, such as parasitic nematodes and fungi, can prevent outbreaks of dominant species, maintaining community structure and fostering biodiversity (Bueno-Pallero et al., 2018). Moreover, parasitic nematodes and fungi also directly suppress soil-borne pathogens, indirectly benefiting plant health and reducing the need for chemical interventions (Klingen & Haukeland, 2006). These interactions make parasitism a critical component of soil health, with significant implications for sustainable agriculture.

Other processes like facilitation and competition are equally important for supporting biodiversity. Facilitation occurs when one species creates conditions favourable for another, such as nitrogen-fixing bacteria improving soil fertility for neighbouring plants (van der Heijden et al., 2008). Conversely, competition shapes community composition by determining access to limited resources like nutrients, water and space. While these processes are vital for understanding soil biodiversity, their effects are highly species-specific, making them difficult to generalize in a soil health assessment. As a result, their inclusion is beyond the scope of this framework.

8 Defining soil health through soil functions

Soil health is best assessed through its capacity to sustain multiple essential functions rather than relying on a rigid set of pre-selected indicators. However, the most commonly applied approach in soil health monitoring is a minimum dataset approach, which often prioritizes feasibility over functional relevance. Indicators are typically selected based on:

1. Availability of existing data: whether an existing scheme measured the indicator previously (legacy data);
2. Expertise of the scientists and practitioners: selection is influenced by the knowledge and familiarity of those conducting the assessments;
3. Ease of application – indicators must be measurable across varying spatial scales and monitoring schemes; and
4. Cost considerations – to ensure the cost of the monitoring scheme is kept to a minimum.

While practical, this approach does not always account for the functional significance of selected indicators. It often overlooks whether the indicators effectively represent soil processes, functions and their interactions across different land uses, landscape complexity or climatic conditions.

Monitoring frameworks should select indicators that directly reflect the soil functions considered rather than convenience or availability. This ensures a more accurate and holistic assessment of soil health. Effective soil health monitoring should include a balanced and integrative set of indicators representing the soil's capacity to sustain multiple soil functions (and deliver ecosystem services).

Given the complexity of the soil systems, monitoring should include at least one or more relevant process(es) per sub-function within each soil function. This structured approach ensures that the monitoring system captures the multifaceted nature of soil health, providing a more comprehensive basis for sustainable land management practices.

While the soil function models present a generalized approach, the selection of processes and parameters must be context-specific (Fig. 6). Relevant indicators should be chosen based on:

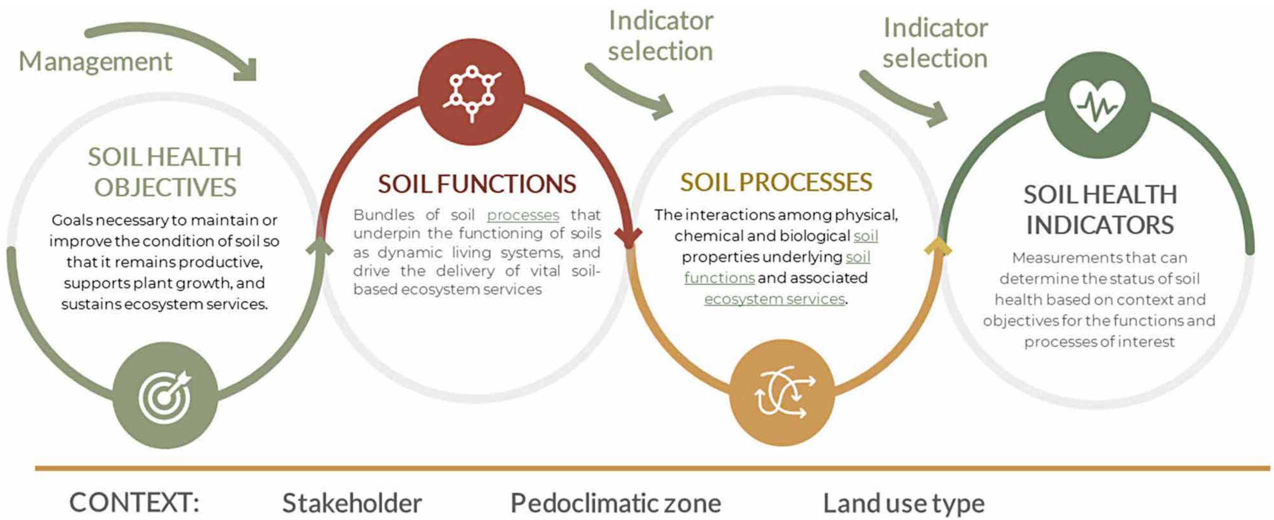

Figure 6 Framework showcasing the relationship between soil health, soil functions, soil processes and soil health objectives.

1. Stakeholder needs: who is the monitoring designed for (e.g. farmers, policymakers)?
2. Pedo-climatic conditions: how do the soil type, climate and environmental constraints affect soil function?
3. Land use: what is the dominant land use (e.g. agriculture, forestry and urban systems), and how does it affect soil health dynamics?

By tailoring indicator selection to these factors, monitoring frameworks can provide more meaningful insights into soil health dynamics and support targeted management strategies.

This research has sought to further clarify the role of soil functions in soil health assessment, by providing a transparent framework from which to select indicators. The soil function cognitive models presented here offer a systematic approach to identifying the most relevant parameters and processes for monitoring the four core functions: carbon and climate regulation, nutrient cycling, water regulation and filtration and habitat provision for biodiversity.

The next steps involve developing an automated system for indicator selection, tailored to context, purpose, and scale of assessment. This would enable more efficient and objective-driven soil health monitoring across different stakeholder levels:

(a) Local scale: at the field level, land managers define the key soil health challenges in their given context and objectives for each function. These objectives guide management decisions to optimize soil health under specific site-specific conditions (local context). The soil processes should align with the objectives enabling the direct assessment of soil functionality. The processes themselves may be measured directly, or a combination of direct and indirect parameters (context-based proxies) can be used to approximate key processes. The measured parameters become indicators, collectively providing a comprehensive picture of soil health at the field scale. This fine-scale assessment allows for a detailed understanding of how soil functions respond to different management practices, supporting adaptive and sustainable land use management strategies.

(b) Regional scale – value chains and agricultural cooperatives: At the value-chain level, soil health monitoring is guided by regional production challenges rather than individual land management decisions. At this level, key soil health challenges are linked to specific crops or livestock systems. Indicators are selected to track the impact of farming practices on soil functions within the region, which enables better alignment of agricultural sustainability strategies across multiple stakeholders, ensuring long-term productivity and resilience.

(c) Broader scales – national and continental monitoring programs: large-scale monitoring efforts focus on assessing the overall soil health trends across diverse landscapes and climatic regions. Standardized indicators must be selected at this scale to ensure comparability across regions. These broad-scale assessments (e.g. European climatic regions) identify the main trends, highlight regions at risk, and inform policy interventions and value-chain support programs. While such assessment provides macro-level insights, they cannot fully capture localized soil health variations, reinforcing the need for nested monitoring approaches that connect local, regional and national assessments.

Structuring soil health monitoring frameworks across multiple scales ensures that assessment remains scientifically robust, stakeholder-relevant and applicable.

9 Conclusion

This chapter has introduced a multi-functional approach to soil health, illustrating the interconnections between key processes and their associated parameters across different soil functions. By integrating this multi-functional perspective, soil health assessment moves beyond isolated measurements towards a more holistic, system-based framework that better reflects soil dynamics and functionality.

The cognitive models presented provide a structured breakdown of function-specific processes, offering deeper insights into the primary drivers and contextual parameters that shape soil health. Recognizing that soil functions are governed by interconnected processes, ensuring that any monitoring efforts capture the complexity of soil systems, rather than relying on individual property measurements in isolation. While some processes are more critical than others, most interact in ways that require a comprehensive, integrated assessment methodology.

By defining appropriate indicators that reflect the underlying mechanisms of soil functions, this work contributes to the development of robust, adaptable and scientifically grounded soil health monitoring frameworks. By identifying the key drivers of soil processes and linking them to relevant, measurable parameters, this work lays the groundwork for a comprehensive and scalable soil health assessment, one that can be tailored to different contexts, land uses and management objectives while ensuring scientific rigour and practical applicability.

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11 References

Almagro, M., Maestre, F. T., Martínez-López, J., Valencia, E., & Rey, A. (2015). Climate change may reduce litter decomposition while enhancing the contribution of photodegradation in dry perennial Mediterranean grasslands. *Soil Biology and Biochemistry*, *90*, 214–223. https://doi.org/10.1016/j.soilbio.2015.08.006

April, R., & Newton, R. (1992). Mineralogy and mineral weathering. In D. W. Johnson & S. E. Lindberg (Eds.), *Atmospheric deposition and forest nutrient cycling: A synthesis of the integrated forest study* (pp. 378–425). Springer. https://doi.org/10.1007/978-1-4612-2806-6_10

Armitage, J. M., & Gobas, F. A. P. C. (2007). A terrestrial food-chain bioaccumulation model for POPs. *Environmental Science & Technology*, *41*(11), 4019–4025. https://doi.org/10.1021/es0700597

Bacq-Labreuil, A., Crawford, J., Mooney, S. J., Neal, A. L., Akkari, E., McAuliffe, C., Zhang, X., Redmile-Gordon, M., & Ritz, K. (2018). Effects of cropping systems upon the three-dimensional architecture of soil systems are modulated by texture. *Geoderma*, *332*, 73–83. https://doi.org/10.1016/j.geoderma.2018.07.002

Bacq-Labreuil, A., Crawford, J., Mooney, S. J., Neal, A. L., & Ritz, K. (2019). Cover crop species have contrasting influence upon soil structural genesis and microbial community phenotype. *Scientific Reports*, *9*(1), 7473. https://doi.org/10.1038/s41598-019-43937-6

Bais, H. P., Weir, T. L., Perry, L. G., Gilroy, S., & Vivanco, J. M. (2006). The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology*, *57*, 233–266. https://doi.org/10.1146/annurev.arplant.57.032905.105159

Bernardin, J. R., Gray, S. M., & Bittleston, L. S. (2024). Arthropod prey type drives decomposition rates and microbial community processes. *Applied and Environmental Microbiology*, *90*(7), e00394-24. https://doi.org/10.1128/aem.00394-241734

Beretta, G. M., Deere, J. A., Messelink, G. J., Muñoz-Cárdenas, K., & Janssen, A. (2022). Review: Predatory soil mites as biocontrol agents of above- and below-ground plant pests. *Experimental and Applied Acarology*, *87*(2), 143–162. https://doi.org/10.1007/s10493-022-00723-w

Beven, K. and Germann, P. (2013). Macropores and water flow in soils revisited. *Water Resources Research* 49: 3071–3092.

BIOSIS. (2023). BIOSIS. Retrieved July 10, 2023, from https://biosisplatform.eu/services/soil-biota-and-functions

Blöschl, G., & Sivapalan, M. (1995). Scale issues in hydrological modelling: A review. *Hydrological Processes*, *9*(3–4), 251–290.

Bobbink, R., Tomassen, H., Weijters, M., van den Berg, L., Strengbom, J., Braun, S., & Hettelingh, J. P. (2015). Effects and empirical critical loads of nitrogen for Europe.

Critical Loads and Dynamic Risk Assessments: Nitrogen, Acidity and Metals in Terrestrial and Aquatic Ecosystems, 85–127.

Boix-Fayos, C., Martínez-Mena, M., Cutillas, P. P., de Vente, J., Barberá, G. G., Mosch, W., & Navas, A. (2017). Carbon redistribution by erosion processes in an intensively disturbed catchment. *Catena*, *149*, 799–809. https://doi.org/10.1016/j.catena.2016.08.003

Boix-Fayos, C., Nadeu, E., Quiñonero, J. M., Martínez-Mena, M., Almagro, M., & De Vente, J. (2015). Sediment flow paths and associated organic carbon dynamics across a Mediterranean catchment. *Hydrology and Earth System Sciences*, *19*(3), 1209–1223. https://doi.org/10.5194/hess-19-1209-2015

Bonkowski, M. (2004). Protozoa and plant growth: The microbial loop in soil revisited. *New Phytologist*, *162*(3), 617–631. https://doi.org/10.1111/j.1469-8137.2004.01066.x

Borggaard, O. K., Raben-Lange, B., Gimsing, A. L., & Strobel, B. W. (2005). Influence of humic substances on phosphate adsorption by aluminium and iron oxides. *Geoderma*, *127*(3), 270–279. https://doi.org/10.1016/j.geoderma.2004.12.011

Bottinelli, N., Henry-des-Tureaux, T., Hallaire, V., Mathieu, J., Benard, Y., Duc Tran, T., & Jouquet, P. (2010). Earthworms accelerate soil porosity turnover under watering conditions. *Geoderma*, *156*(1), 43–47. https://doi.org/10.1016/j.geoderma.2010.01.006

Bottinelli, N., Jouquet, P., Capowiez, Y., Podwojewski, P., Grimaldi, M., & Peng, X. (2015). Why is the influence of soil macrofauna on soil structure only considered by soil ecologists? *Soil and Tillage Research*, *146*, 118–124. https://doi.org/10.1016/j.still.2014.01.007

Brown, G., Da Silva, E., Thomazini, M., Niva, C., Decaëns, T., Cunha, L., Nadolny, H., Demetrio, W., Santos, A., Ferreira, T., Maia, L., Conrado, A., Segalla, R., Casadei-Ferreira, A., Pasini, A., Bartz, M., Sautter, K., James, S., Baretta, D., & Lavelle, P. (2018). *The role of soil fauna in soil health and delivery of ecosystem services* (pp. 197–241). Burleigh Dodds Science Publishing. https://doi.org/10.19103/AS.2017.0033.11

Brown, G. G., Barois, I., & Lavelle, P. (2000). Regulation of soil organic matter dynamics and microbial activityin the drilosphere and the role of interactionswith other edaphic functional domains, Paper presented at the 16th World Congress of Soil Science, 20–26 August 1998, Montpellier, France. *European Journal of Soil Biology*, *36*(3), 177–198. https://doi.org/10.1016/S1164-5563(00)01062-1

Buckley, D. H., Huangyutitham, V., Hsu, S.-F., & Nelson Tyrrell, A. (2007). Stable isotope probing with 15N2 reveals novel noncultivated diazotrophs in soil. *Applied and Environmental Microbiology*, *73*(10), 3196–3204. https://doi.org/10.1128/AEM.02610-06

Bueno-Pallero, F. Á., Blanco-Pérez, R., Dionísio, L., & Campos-Herrera, R. (2018). Simultaneous exposure of nematophagous fungi, entomopathogenic nematodes and entomopathogenic fungi can modulate belowground insect pest control. *Journal of Invertebrate Pathology*, *154*, 85–94. https://doi.org/10.1016/j.jip.2018.04.004

Bünemann, E. K. (2015). Assessment of gross and net mineralization rates of soil organic phosphorus – A review. *Soil Biology and Biochemistry*, *89*, 82–98. https://doi.org/10.1016/j.soilbio.2015.06.026

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W.,

& Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Calvaruso, C., Blanchart, A., Bertin, S., Grand, C., Pierart, A., & Eglin, T. (2021). Quels paramètres du sol mesurer pour évaluer les fonctions et les services écosystémiques associés. *Étude et Gestion des Sols*, *28*, 3–29.

Cammeraat, E. L. H., & Risch, A. C. (2008). The impact of ants on mineral soil properties and processes at different spatial scales. *Journal of Applied Entomology*, *132*(4), 285–294. https://doi.org/10.1111/j.1439-0418.2008.01281.x

Camuy-Vélez, L. A., Banerjee, S., & Sedivec, K. (2024). Grazing intensity alters network complexity and predator–prey relationships in the soil microbiome. *Applied and Environmental Microbiology*, *90*(10), e00425-00424. https://doi.org/10.1128/aem.00425-24

Capowiez, Y., Bottinelli, N., Sammartino, S., Michel, E., & Jouquet, P. (2015). Morphological and functional characterisation of the burrow systems of six earthworm species (Lumbricidae). *Biology and Fertility of Soils*, *51*(7), 869–877. https://doi.org/10.1007/s00374-015-1036-x

Cerdà, A. (2001). Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. *European Journal of Soil Science*, *52*(1), 59–68.

Chang, J., Havlík, P., Leclère, D., de Vries, W., Valin, H., Deppermann, A., Hasegawa, T., & Obersteiner, M. (2021). Reconciling regional nitrogen boundaries with global food security. *Nature Food*, *2*(9), 700–711. https://doi.org/10.1038/s43016-021-00366-x

Chao, J., Feng, S., Hao, Y., Lin, J., & Zhang, B. (2023). Pollution characteristics and risk assessment of organophosphate esters in aquaculture farms and natural water bodies adjacent to the Huanghe River delta. *Journal of Oceanology and Limnology*, *41*(1), 251–266. https://doi.org/10.1007/s00343-021-1233-4

Chenu, C., & Cosentino, D. (2011). Microbial regulation of soil structure dynamics. In K. Ritz & I. Young (Eds.), *The architecture and biology and soils: life in inner space* (pp. 37–70). CAB International. https://doi.org/10.1079/9781845935320.0037

Chi, J., Fan, Y., Wang, L., Putnis, C. V., & Zhang, W. (2022). Retention of soil organic matter by occlusion within soil minerals. *Reviews in Environmental Science and Bio/Technology*, *21*(3), 727–746. https://doi.org/10.1007/s11157-022-09628-x

Coleman, D. C., Geisen, S., & Wall, D. H. (2024). Chapter 5 - Soil fauna: Occurrence, biodiversity, and roles in ecosystem function. In E. A. Paul & S. D. Frey (Eds.), *Soil microbiology, ecology and biochemistry* (5th ed., pp. 131–159). Elsevier. https://doi.org/10.1016/B978-0-12-822941-5.00005-3

Coppola, A., Basile, A., Wang, X., Comegna, V., Tedeschi, A., Mele, G., & Comegna, A. (2011). Hydrological behaviour of microbiotic crusts on sand dunes: Example from NW China comparing infiltration in crusted and crust-removed soil. *Soil and Tillage Research*, *117*, 34–43.

Cotrufo, M. F., & Lavallee, J. M. (2022). Chapter one: Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. In D. L. Sparks (Ed.), *Advances in agronomy* (Vol. 172, pp. 1–66). Academic Press. https://doi.org/10.1016/bs.agron.2021.11.002

Creamer, R. E., Barel, J. M., Bongiorno, G., & Zwetsloot, M. J. (2022). The life of soils: Integrating the who and how of multifunctionality. *Soil Biology and Biochemistry*, *166*, 108561. https://doi.org/10.1016/j.soilbio.2022.108561

Cunha, L., Brown, G. G., Stanton, D. W. G., Da Silva, E., Hansel, F. A., Jorge, G., McKey, D., Vidal-Torrado, P., Macedo, R. S., Velasquez, E., James, S. W., Lavelle, P., Kille, P.,

& The Terra Preta de Indio, N. (2016). Soil animals and pedogenesis: The role of earthworms in anthropogenic soils. *Soil Science*, *181*(3/4), 110–125. https://doi.org/10.1097/SS.0000000000000144

Davidson, E. A., Keller, M., Erickson, H. E., Verchot, L. V., & Veldkamp, E. (2000). Testing a conceptual model of soil emissions of nitrous and nitric oxides: Using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils. *BioScience*, *50*(8), 667–680. https://doi.org/10.1641/0006-3568(2000)050[0667:TACMOS]2.0.CO;2

Degens, B. P., & Sparling, G. P. (1995). Repeated wet-dry cycles do not accelerate the mineralization of organic C involved in the macro-aggregation of a sandy loam soil. *Plant and Soil*, *175*(2), 197–203. https://doi.org/10.1007/BF00011355

Dodd, M. B., & Lauenroth, W. K. (1997). The influence of soil texture on the soil water dynamics and vegetation structure of a shortgrass steppe ecosystem. *Plant Ecology*, *133*, 13–28.

Dorioz, J. M., Robert, M., & Chenu, C. (1993). The role of roots, fungi and bacteria on clay particle organization. An experimental approach. *Geoderma*, *56*(1), 179–194. https://doi.org/10.1016/0016-7061(93)90109-X

EEA. (2023). Soil monitoring in Europe – Indicators and thresholds for soil health assessments (EEA Report No 08/2022). https://www.eea.europa.eu/en/analysis/publications/soil-monitoring-in-europe

Ehrmann, J., & Ritz, K. (2014). Plant: soil interactions in temperate multi-cropping production systems. *Plant and Soil*, *376*(1), 1–29. https://doi.org/10.1007/s11104-013-1921-8

Feddes, R. A., Kowalik, P., Kolinska-Malinka, K., & Zaradny, H. (1976). Simulation of field water uptake by plants using a soil water dependent root extraction function. *Journal of Hydrology*, *31*(1–2), 13–26.

Feeney, D. S., Crawford, J. W., Daniell, T., Hallett, P. D., Nunan, N., Ritz, K., Rivers, M., & Young, I. M. (2006). Three-dimensional microorganization of the soil–root–microbe system. *Microbial Ecology*, *52*(1), 151–158. https://doi.org/10.1007/s00248-006-9062-8

Feit, B., Blüthgen, N., Traugott, M., & Jonsson, M. (2019). Resilience of ecosystem processes: A new approach shows that functional redundancy of biological control services is reduced by landscape simplification. *Ecology Letters*, *22*(10), 1568–1577. https://doi.org/10.1111/ele.13347

Fischer, C., Roscher, C., Jensen, B., Eisenhauer, N., Baade, J., Attinger, S., Scheu, S., Weisser, W. W., Schumacher, J., & Hildebrandt, A. (2014). How do earthworms, soil texture and plant composition affect infiltration along an experimental plant diversity gradient in grassland? *PLoS One*, *9*(2), e98987. https://doi.org/10.1371/journal.pone.0098987

Fojt, J., David, J., Přikryl, R., Řezáčová, V., & Kučerík, J. (2020). A critical review of the overlooked challenge of determining micro-bioplastics in soil. *Science of The Total Environment*, *745*, 140975. https://doi.org/10.1016/j.scitotenv.2020.140975

Frouz, J. (2018). Effects of soil macro- and mesofauna on litter decomposition and soil organic matter stabilization. *Geoderma*, *332*, 161–172. https://doi.org/10.1016/j.geoderma.2017.08.039

Godoy, V. A., Zuquette, L. V., & Gómez-Hernández, J. J. (2019). Spatial variability of hydraulic conductivity and solute transport parameters and their spatial correlations to soil properties. *Geoderma*, *339*, 59–69.

Griffiths, B. S. (1994). Microbial-feeding nematodes and protozoa in soil: Their effectson microbial activity and nitrogen mineralization in decomposition hotspots and the rhizosphere. *Plant and Soil*, *164*(1), 25–33. https://doi.org/10.1007/BF00010107

Haygarth, P. M., & Ritz, K. (2009). The future of soils and land use in the UK: Soil systems for the provision of land-based ecosystem services. *Land Use Policy*, *26*, S187–S197. https://doi.org/10.1016/j.landusepol.2009.09.016

Heikens, A., Peijnenburg, W., & Hendriks, A. (2001). Bioaccumulation of heavy metals in terrestrial invertebrates. *Environmental Pollution*, *113*(3), 385–393. https://doi.org/10.1016/S0269-7491(00)00179-2

Helliwell, J. R., Sturrock, C. J., Mairhofer, S., Craigon, J., Ashton, R. W., Miller, A. J., Whalley, W. R., & Mooney, S. J. (2017). The emergent rhizosphere: Imaging the development of the porous architecture at the root-soil interface. *Scientific Reports*, *7*(1), 14875. https://doi.org/10.1038/s41598-017-14904-w

Hillel, D. (2003). *Introduction to environmental soil physics*. Elsevier. https://doi.org/10.1016/B978-0-12-348655-4.X5000-X

Hinsinger, P., Brauman, A., Devau, N., Gérard, F., Jourdan, C., Laclau, J.-P., Le Cadre, E., Jaillard, B., & Plassard, C. (2011). Acquisition of phosphorus and other poorly mobile nutrients by roots. Where do plant nutrition models fail? *Plant and Soil*, *348*(1), 29–61. https://doi.org/10.1007/s11104-011-0903-y

Hirst, J. M. (1965). Dispersal of Soil Microorganisms. In F. B. Kenneth & C. S. William (Eds.), *Ecology of soil-borne plant pathogens* (pp. 69–81). University of California Press. https://doi.org/10.1525/9780520407992-014

Jarvis, N. J. (2020). A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. *European Journal of Soil Science*, *71*(3), 279–302.

Ji, X., Liu, M., Yang, J., & Feng, F. (2022) Meta-analysis of the impact of freeze–thaw cycles on soil microbial diversity and C and N dynamics. *Soil Biology and Biochemistry*, *168*, 108608.

Jiang, Y., Liu, M., Zhang, J., Chen, Y., Chen, X., Chen, L., Li, H., Zhang, X. X., & Sun, B. (2017). Nematode grazing promotes bacterial community dynamics in soil at the aggregate level. *ISME Journal*, *11*(12), 2705–2717. https://doi.org/10.1038/ismej.2017.120

Jiang, Y., Qian, H., Wang, X., Chen, L., Liu, M., Li, H., & Sun, B. (2018). Nematodes and microbial community affect the sizes and turnover rates of organic carbon pools in soil aggregates. *Soil Biology and Biochemistry*, *119*, 22–31. https://doi.org/10.1016/j.soilbio.2018.01.001

Jouquet, P., Huchet, G., Bottinelli, N., Thu, T. D., & Duc, T. T. (2012a). Does the influence of earthworms on water infiltration, nitrogen leaching and soil respiration depend on the initial soil bulk density? A mesocosm experiment with the endogeic species Metaphire posthuma. *Biology and Fertility of Soils*, *48*(5), 561–567. https://doi.org/10.1007/s00374-011-0652-3

Jouquet, P., Janeau, J.-L., Pisano, A., Sy, H. T., Orange, D., Minh, L. T. N., & Valentin, C. (2012b). Influence of earthworms and termites on runoff and erosion in a tropical steep slope fallow in Vietnam: A rainfall simulation experiment. *Applied Soil Ecology*, *61*, 161–168. https://doi.org/10.1016/j.apsoil.2012.04.004

Jouquet, P., Traoré, S., Choosai, C., Hartmann, C., & Bignell, D. (2011). Influence of termites on ecosystem functioning. Ecosystem services provided by termites. *European Journal of Soil Biology*, *47*(4), 215–222. https://doi.org/10.1016/j.ejsobi.2011.05.005

Jury, W. A., & Horton, R. (2004). *Soil physics*. John Wiley & Sons.

Keese, K. E., Scanlon, B. R., & Reedy, R. C. (2005). Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. *Water Resources Research*, *41*(6). http://dx.doi.org/10.1029/2004WR003841.

Klein, A., Eisenhauer, N., & Schaefer, I. (2020). Invasive lumbricid earthworms in North America—different life histories but common dispersal? *Journal of Biogeography*, *47*(3), 674–685. https://doi.org/10.1111/jbi.13744

Kleyer, M., Bekker, R. M., Knevel, I. C., Bakker, J. P., Thompson, K., Sonnenschein, M., Poschlod, P., Van Groenendael, J. M., Klimeš, L., Klimešová, J., Klotz, S., Rusch, G. M., Hermy, M., Adriaens, D., Boedeltje, G., Bossuyt, B., Dannemann, A., Endels, P., Götzenberger, L.,…Peco, B. (2008). The LEDA Traitbase: A database of life-history traits of the Northwest European flora. *Journal of Ecology*, *96*(6), 1266–1274. https://doi.org/10.1111/j.1365-2745.2008.01430.x

Klingen, I., & Haukeland, S. (2006). The soil as a reservoir for natural enemies of pest insects and mites with emphasis on fungi and nematodes. In J. Eilenberg & H. M. T. Hokkanen (Eds.), *An ecological and societal approach to biological control* (pp. 145–211). Springer. https://doi.org/10.1007/978-1-4020-4401-4_9

Koestel, J. K., Moeys, J., & Jarvis, N. J. (2012). Meta-analysis of the effects of soil properties, site factors and experimental conditions on solute transport. *Hydrology and Earth System Sciences*, *16*(6), 1647–1665.

Kögel-Knabner, I. (2002). The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. *Soil Biology and Biochemistry*, *34*(2), 139–162. https://doi.org/10.1016/S0038-0717(01)00158-4

Kutílek, M., & Nielsen, D. R. (1994). *Soil hydrology: Texbook for students of soil science, agriculture, forestry, geoecology, hydrology, geomorphology and other related disciplines* (p. 370). Catena Verlag.

Lamb, E. G., Kennedy, N., & Siciliano, S. D. (2011). Effects of plant species richness and evenness on soil microbial community diversity and function. *Plant and Soil*, *338*(1), 483–495. https://doi.org/10.1007/s11104-010-0560-6

Lehmann, J., & Schroth, G. (2002). Nutrient leaching. In G. Schroth & F. L. Sinclair (Eds.), *Trees, crops and soil fertility: Concepts and research methods* (pp. 151–166). CABI Publishing. https://doi.org/10.1079/9780851995939.0151

Li, X., Chang, S. X., & Salifu, K. F. (2014). Soil texture and layering effects on water and salt dynamics in the presence of a water table: A review. *Environmental Reviews*, *22*(1), 41–50.

Liang, C., Amelung, W., Lehmann, J., & Kästner, M. (2019). Quantitative assessment of microbial necromass contribution to soil organic matter. *Global Change Biology*, *25*(11), 3578–3590. https://doi.org/10.1111/gcb.14781

Martin, S. L., Mooney, S. J., Dickinson, M. J., & West, H. M. (2012). Soil structural responses to alterations in soil microbiota induced by the dilution method and mycorrhizal fungal inoculation. *Pedobiologia*, *55*(5), 271–281. https://doi.org/10.1016/j.pedobi.2012.06.001

Martínez-Mena, M., Almagro, M., García-Franco, N., de Vente, J., García, E., & Boix-Fayos, C. (2019). Fluvial sedimentary deposits as carbon sinks: Organic carbon pools and stabilization mechanisms across a Mediterranean catchment. *Biogeosciences*, *16*(5), 1035–1051. https://doi.org/10.5194/bg-16-1035-2019

Martínez-Mena, M., López, J., Almagro, M., Albaladejo, J., Castillo, V., Ortiz, R., & Boix-Fayos, C. (2012). Organic carbon enrichment in sediments: Effects of rainfall characteristics under different land uses in a Mediterranean area. *Catena*, *94*, 36–42. https://doi.org/10.1016/j.catena.2011.02.005

Matson, A., Fantappiè, M., Campbell, G. A., Miranda-Vélez, J. F., Faber, J. H., Gomes, L. C., Hessel, R., Lana, M., Mocali, S., Smith, P., Robinson, D. A., Bispo, A., van Egmond, F., Keesstra, S., Saby, N. P. A., Smreczak, B., Froger, C., Suleymanov, A., & Chenu, C. (2024). Four approaches to setting soil health targets and thresholds in agricultural soils. *Journal of Environmental Management*, *371*, 123141. https://doi.org/10.1016/j.jenvman.2024.123141

Meyer, S. T., Heuss, L., Feldhaar, H., Weisser, W. W., & Gossner, M. M. (2019). Land-use components, abundance of predatory arthropods, and vegetation height affect predation rates in grasslands. *Agriculture, Ecosystems & Environment*, *270–271*, 84–92. https://doi.org/10.1016/j.agee.2018.10.015

Miller, R., & Fitzsimons, M. (2011). Fungal Growth in Soils. In *The architecture and biology of soils: Life in inner space* (pp. 149–163). CABI. https://doi.org/10.1079/9781845935320.0149

Min, K., Slessarev, E., Kan, M., McFarlane, K., Oerter, E., Pett-Ridge, J., Nuccio, E., & Berhe, A.A. (2021). Active microbial biomass decreases, but microbial growth potential remains similar across soil depth profiles under deeply-vs. shallow-rooted plants. *Soil Biology and Biochemistry*, *162*, 108401.

Moore, J. C., Walter, D. E., & Hunt, H. W. (1988). Arthropod regulation of micro- and mesobiota in below-ground detrital food webs. *Annual Review of Entomology*, *33*, 419–435. https://doi.org/10.1146/annurev.en.33.010188.002223

Nadeu, E., de Vente, J., Martínez-Mena, M., & Boix-Fayos, C. (2011). Exploring particle size distribution and organic carbon pools mobilized by different erosion processes at the catchment scale. *Journal of Soils and Sediments*, *11*, 667–678. https://doi.org/10.1007/s11368-011-0348-1

Naidu, R., Sumner, M. E., & Harter, R. (1998). Sorption of heavy metals in strongly weathered soils: An overview. *Environmental Geochemistry and Health*, *20*, 5–9.

Nathan, O. O., Monicah, M.-M., Jayne, M. N., Isaya, S., George, N., & Daniel, M. N. (2022). Nutrient and organic carbon losses by erosion, and their economic and environmental implications in the drylands of Kenya. *Environmental Challenges*, *7*, 100519. https://doi.org/10.1016/j.envc.2022.100519

Noiriel, C., & Daval, D. (2017). Pore-scale geochemical reactivity associated with CO(2) storage: New frontiers at the fluid-solid interface. *Accounts of Chemical Research*, *50*(4), 759–768. https://doi.org/10.1021/acs.accounts.7b00019

Nordén, B., Dahlberg, A., Brandrud, T. E., Fritz, Ö., Ejrnaes, R., & Ovaskainen, O. (2014). Effects of ecological continuity on species richness and composition in forests and woodlands: A review. *Écoscience*, *21*(1), 34–45. https://doi.org/10.2980/21-1-3667

Orgiazzi, A., & Panagos, P. (2018). Soil biodiversity and soil erosion: It is time to get married: Adding an earthworm factor to soil erosion modelling. *Global Ecology and Biogeography*, *27*(10), 1155–1167. https://doi.org/10.1111/geb.12782

Paul, E. A. (2016). The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry*, *98*, 109–126. https://doi.org/10.1016/j.soilbio.2016.04.001

Pereira, P., Bogunovic, I., Muñoz-Rojas, M., & Brevik, E. C. (2018). Soil ecosystem services, sustainability, valuation and management. *Current Opinion in Environmental Science & Health*, *5*, 7–13. https://doi.org/10.1016/j.coesh.2017.12.003

Ptatscheck, C., Gansfort, B., & Traunspurger, W. (2018). The extent of wind-mediated dispersal of small metazoans, focusing nematodes. *Scientific Reports*, *8*(1), 6814. https://doi.org/10.1038/s41598-018-24747-8

Read, D. B., Bengough, A. G., Gregory, P. J., Crawford, J. W., Robinson, D., Scrimgeour, C. M., Young, I. M., Zhang, K., & Zhang, X. (2003). Plant roots release phospholipid surfactants that modify the physical and chemical properties of soil. *New Phytologist*, *157*(2), 315–326. https://doi.org/10.1046/j.1469-8137.2003.00665.x

Ritz, K., Black, H. I. J., Campbell, C. D., Harris, J. A., & Wood, C. (2009). Selecting biological indicators for monitoring soils: A framework for balancing scientific and technical opinion to assist policy development. *Ecological Indicators*, *9*(6), 1212–1221. https://doi.org/10.1016/j.ecolind.2009.02.009

Saadi, Z., Rasmont, A., Cesar, G., Bewa, H., & Benguigui, L. (2012). Fungal degradation of Poly(l-lactide) in soil and in compost. *Journal of Polymers and the Environment*, *20*(2), 273–282. https://doi.org/10.1007/s10924-011-0399-9

Salvachúa, D., Katahira, R., Cleveland, N. S., Khanna, P., Resch, M. G., Black, B. A., Purvine, S. O., Zink, E. M., Prieto, A., Martínez, M. J., Martínez, A. T., Simmons, B. A., Gladden, J. M., & Beckham, G. T. (2016). Lignin depolymerization by fungal secretomes and a microbial sink. *Green Chemistry*, *18*(22), 6046–6062. https://doi.org/10.1039/C6GC01531J

Sarkar, B., Mukhopadhyay, R., Ramanayaka, S., Bolan, N., & Ok, Y. S. (2021). The role of soils in the disposition, sequestration and decontamination of environmental contaminants. *Philosophical Transactions of the Royal Society B*, *376*(1834), 20200177. https://doi.org/10.1098/rstb.2020.0177

Schmitz, O. J., Hawlena, D., & Trussell, G. C. (2010). Predator control of ecosystem nutrient dynamics. *Ecology Letters*, *13*(10), 1199–1209. https://doi.org/10.1111/j.1461-0248.2010.01511.x

Schreefel, L., Creamer, R. E., van Zanten, H. H. E., de Olde, E. M., Koppelmäki, K., Debernardini, M., de Boer, I. J. M., & Schulte, R. P. O. (2024). How to monitor the 'success' of agricultural sustainability: A perspective. *Global Food Security*, *43*, 100810. https://doi.org/10.1016/j.gfs.2024.100810

Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., & O'hUallachain, D. (2014). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy*, *38*, 45–58. https://doi.org/10.1016/j.envsci.2013.10.002

Sexstone, A. J., Revsbech, N. P., Parkin, T. B., & Tiedje, J. M. (1985). Direct measurement of oxygen profiles and denitrification rates in soil aggregates. *Soil Science Society of America Journal*, *49*(3), 645–651. https://doi.org/10.2136/sssaj1985.03615995004900030024x

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008

Sposito, G., Skipper, N. T., Sutton, R., Park, S.-h., Soper, A. K., & Greathouse, J. A. (1999). Surface geochemistry of the clay minerals. *Proceedings of the National Academy of Sciences*, *96*(7), 3358–3364. https://doi.org/10.1073/pnas.96.7.3358

Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, *33*(2), 141–163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

Van den Elsen, E., Anton-Sobejano, R., Cousin, I., Fuchs, L., de Haan, J., Teuling, K., Klimkowicz-Pawlas, A., Niedźwiecki, J., Pindral, S., Montagne, D., Scammacca, O., & Weninger, T. (2024). *A framework to assess soil threats, soil functions and soil-based ecosystem services*. Zenodo. https://doi.org/10.5281/zenodo.14056696

Vanderborght, J., & Vereecken, H. (2007). Review of dispersivities for transport modeling in soils. *Vadose Zone Journal*, *6*(1), 29–52.

Van Der Heijden, M. G. A., Bardgett, R. D., & Van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology Letters*, *11*(3), 296–310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

Vion-Guibert, L., Capowiez, Y., Alavoine, G., Besaury, L., Delfosse, O., Hedde, M., Marsden, C., & Lashermes, G. (2024). The effects of earthworm species on organic matter transformations and soil microbial communities are only partially related to their bioturbation activity. *Soil Biology and Biochemistry*, *199*, 109606. https://doi.org/10.1016/j.soilbio.2024.109606

Vogel, H. J., Bartke, S., Daedlow, K., Helming, K., Kögel-Knabner, I., Lang, B., Rabot, E., Russell, D., Stößel, B., Weller, U., Wiesmeier, M., & Wollschläger, U. (2018). A systemic approach for modeling soil functions. *Soil*, *4*(1), 83–92. https://doi.org/10.5194/soil-4-83-2018

Wang, B., An, S., Liang, C., Liu, Y., & Kuzyakov, Y. (2021). Microbial necromass as the source of soil organic carbon in global ecosystems. *Soil Biology and Biochemistry*, *162*, 108422. https://doi.org/10.1016/j.soilbio.2021.108422

Wang, Y., Fan, J., Cao, L., & Liang, Y. (2016). Infiltration and runoff generation under various cropping patterns in the red soil region of China. *Land Degradation & Development*, *27*(1), 83–91.

Wardle, D. A. (2006). The influence of biotic interactions on soil biodiversity. *Ecology Letters*, *9*(7), 870–886. https://doi.org/10.1111/j.1461-0248.2006.00931.x

Wen, S., Wang, J., Li, Y., & Shao, M. A. (2022). Effects of anecic earthworms on runoff and erosion on the slope with soil from the Loess Plateau under a rainfall simulation experiment. *Agricultural Water Management*, *259*, 107230. https://doi.org/10.1016/j.agwat.2021.107230

Whalley, W. R., Riseley, B., Leeds-Harrison, P. B., Bird, N. R. A., Leech, P. K., & Adderley, W. P. (2005). Structural differences between bulk and rhizosphere soil. *European Journal of Soil Science*, *56*(3), 353–360. https://doi.org/10.1111/j.1365-2389.2004.00670.x

Xu, J., Liu, S., Song, S., Guo, H., Tang, J., Yong, J.W., Ma, Y. and Chen, X. (2018). Arbuscular mycorrhizal fungi influence decomposition and the associated soil microbial community under different soil phosphorus availability. *Soil Biology and Biochemistry*, *120*, 181–190.

Zhang, C., Postma, J. A., York, L. M., & Lynch, J. P. (2014). Root foraging elicits niche complementarity-dependent yield advantage in the ancient 'three sisters' (maize/

bean/squash) polyculture. *Annals of Botany*, *114*(8), 1719–1733. https://doi.org/10.1093/aob/mcu191

Zhang, S., Yu, Z., Lin, J. and Zhu, B. (2020). Responses of soil carbon decomposition to drying-rewetting cycles: a meta-analysis. *Geoderma*, *361*, 114069.

Zhang, Z., Liu, K., Zhou, H., Lin, H., Li, D., & Peng, X. (2018). Three dimensional characteristics of biopores and non-biopores in the subsoil respond differently to land use and fertilization. *Plant and Soil*, *428*, 453–467.

Zhang, Y-W. et al. 2021. Changes in soil water holding capacity and water availability following vegetation restoration on the Chinese Loess Plateau. *Scientific Reports* 11: 9692

Zhao, F. J., Knights, J. S., Hu, Z. Y., & McGrath, S. P. (2003a). Stable sulfur isotope ratio indicates long-term changes in sulfur deposition in the broadbalk experiment since 1845. *Journal of Environmental Quality*, *32*(1), 33–39. https://doi.org/10.2134/jeq2003.3300

Zhao, X., Guo, M., Zhang, T., Bai, S., Meng, Y., Tian, Y., Yang, J., & Ma, F. (2023b). Spatiotemporal dynamics of root exudates drive microbial adaptation mechanisms under day-night alterations in constructed wetlands. *Chemical Engineering Journal*, *477*, 147311. https://doi.org/10.1016/j.cej.2023.147311

Zhu, Y., Duan, G., Chen, B., Peng, X., Chen, Z., & Sun, G. (2014). Mineral weathering and element cycling in soil-microorganism-plant system. *Science China Earth Sciences*, *57*(5), 888–896. https://doi.org/10.1007/s11430-014-4861-0

Zwetsloot, M. J., Bongiorno, G., Barel, J. M., di Lonardo, D. P., & Creamer, R. E. (2022). A flexible selection tool for the inclusion of soil biology methods in the assessment of soil multifunctionality. *Soil Biology and Biochemistry*, *166*, 108514. https://doi.org/10.1016/j.soilbio.2021.108514