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The life of soils: Integrating the who and how of multifunctionality

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ABSTRACT

Capturing the complexity of soil life for soil quality assessments is one of the most challenging paradoxes of contemporary soil science. Soil biota perform a plethora of processes that are fundamental to soil quality. As the concept of soil quality developed, so have the attempts to integrate soil biological measurements into monitoring schemes from field to regional scale. To date, however, soil science has not yet succeeded to provide flexible yet objective biological indicator methods to assess soil multifunctionality, customised to the user's context.

We present an integrative framework and elucidate the who and how of soil multifunctionality. The framework encompasses the current scientific understanding of the role of soil biota in supporting the many soil processes that underly soil quality. We specified these relationships for four soil functions (Carbon and Climate Regulation, Water Regulation and Purification, Nutrient Cycling, and Disease and Pest Regulation). We identify challenges often encountered in soil quality assessment and monitoring schemes and discuss how the framework can be applied to provide a flexible selection tool. Soil quality assessments are conducted in different contexts. As assessment objectives range from mechanistic understanding, to functional land management and large spatial scale monitoring so will the practical and logistical constraints for method selection vary.

Biological assessments need to move beyond the quest for a one-size-fits-all minimum dataset, and adopt a more nuanced selection approach founded in soil biology. We stress that biological attributes should not be considered in isolation but alongside soil chemical and physical attributes, as well as management and environmental contextualisation. The presented framework offers a structure to further quantify, understand and communicate the who and how of soil biology in defining multifunctionality.

1. Introduction

Soil biology is paralysed by complexity: as soil biologists, we are continuously being asked by agricultural stakeholders and policy makers alike to define simple indicators of the role of soil biology for soil health/soil quality assessment. However, after decades of research, our failure to agree on biological indicators and unified minimum datasets begs the question: is it possible or even desirable to simplify the complex interactions between soil biota, soil processes, soil functionality and soil quality in such a way that they can be comprehensively described by a small number of parameters? In this paper, we argue that the key to capturing the life of soils does not lie in simplification, but rather in embracing its complexity: we put forward an integrative framework that facilitates the comprehensive understanding of the who and how of soil multifunctionality. This integrative framework will also allow a more flexible selection of soil biological indicator measurements which are pertinent to the function(s) under consideration and customised to the specific objectives of the assessment being conducted. This flexibility for the first time allows us to link biological indicator measurements directly with a functional outcome across a range of scales and applications.

Before we set off on our journey, we must address the terminology of soil quality versus soil health as the two terms that dominate the contemporary public discourse in soil science. The definitions of these concepts have triggered lively debates ever since their introduction, as is extensively described by Bünemann et al. (2018). Recently, Lehmann et al. (2020) argued that the two terms differ in that soil health focusses on broader sustainability goals including planetary health, while soil quality concerns ecosystem services and soil functions from a human perspective. In this, the authors build on the finer nuances voiced earlier (Pankhurst et al., 1997; Doran and Zeiss, 2000), even though these earlier discussions also stated that soil health and soil quality can be used interchangeably (Bünemann et al., 2018; Doran and Zeiss, 2000).

While some scientists argue to use the term soil health as an umbrella

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term encompassing soil quality (Lehmann et al., 2020), others propose that the distinction between these two terms only diverges their value as communication tools (Powlson, 2020). Simultaneously, we are reminded that the utility of a concept, such as soil quality/health, is accomplished by focussing on what we want to achieve with it (Baveye, 2021; Janzen et al., 2021). Amidst these discussions, the general consensus is the recognition that soil quality/health can be quantified by linking its parameters to ecosystem or soil functions as well as the urgent need for a biological perspective. Sidestepping the finer points of this intriguing and ongoing debate on concepts and terminology, for now we use the term soil quality in this paper and treat it as synonymous to the term soil health and define it in its simplest form as "the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals and humans" (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/).

1.1. Historical perspective of inclusion of soil biology in soil quality assessments

Since the concept of soil quality was first introduced by Mausel in 1971, it has been developed and redefined from its initial focus on productivity (Doran and Parkin, 1994) to a wider concept which defines the functional role of soil, both in terms of agricultural productivity and the wider environment (Andrews et al., 2004). Initial attempts at quantifying soil quality led to the development of minimum datasets aimed at capturing overall quality (e.g. Andrews et al., 2004; Doran and Parkin, 1997; Drobnik et al., 2018; Karlen et al., 2003; Powlson, 2020), as described by Bünemann et al. (2018). In short, the concept of minimum dataset collated selected indicators derived from the three classical strands of soil science, bringing together soil physical, chemical and biological parameters for the assessment of soil quality (Norris et al., 2020).

In the late 1990s, in Europe, a scientific and political shift took place, which moved the focus from soil quality per se, to looking at its components in the form of soil threats (Kibblewhite, 2012; EC, 2006). The European Commission defined eight threats of which Decline in Soil Biodiversity primarily concerned soil biology, (EC, 2006). Huber et al. (2008) produced a monitoring framework to assess the impact of these soil threats and derived a minimum dataset of soil and land indicators. A plethora of research followed, but the response of stakeholders to this negative perspective on soil quality was significant and resulted in the withdrawal of the Soil Framework Directive in 2014 (Glæsner et al., 2014). The soil functions approach, originally championed by Doran and Zeiss (2000), was reignited and resulted in the current approach of assessing multifunctionality to support and quantify overall soil quality. However, the term multifunctionality has often been applied to a wide range of assessments pertaining to soil quality, such as the assessment of multiple soil property measurements on individual soil processes (Zheng et al., 2019), rather than the assessment of multiple functions per se. This has introduced some ambiguity around the term multifunctionality, necessitating a more nuanced approach to be defined for its applications to be meaningful. In this context, Bünemann et al. (2018) defined soil functions as soil based ecosystem services, which are generated by bundles of soil processes, that arise from the interactions between physical, chemical and biological properties of the soil (Vogel et al., 2018).

The inclusion of soil biological properties in soil quality assessments started in the late 1980s/beginning of the 1990s, but this did not really find full acceptance until early in the 2000s (Visser and Parkinson, 1992; Doran and Parkin, 1994; Doran and Zeiss, 2000; Bone et al., 2010). Under the designation "Soil Health" Doran and Zeiss (2000) stressed the importance of managing the biological component of soil quality (Schloter et al., 2003; Lehman et al., 2015a; Griffiths et al., 2018) therewith establishing the relevance of soil biological indicators.

Initial biological indicators included into the early minimum datasets encompassed bulk soil activity measurements of microbial biomass, respiration, and keystone organisms such as arbuscular mycorrhizal fungi (Lehman et al., 2015b; Bünemann et al., 2018). Over the years, other measurements such as N mineralisation, microbial diversity, extracellular enzymatic activity and functional guilds of soil fauna were added (Schloter et al., 2003; Brussaard et al., 2004; Lehman et al., 2015a). The emphasis generally remained on microbial measurements as they are associated with a wider range of soil processes (Anderson, 2003; Lehman et al., 2015a). For a comprehensive overview of microbial measurements, their potential and limitations, please see Fierer et al. (2021). Brussaard et al. (2004) convincingly advocated the inclusion of macro- and meso-fauna measurements in soil quality assessments. This spurred an array of indicators being applied in monitoring programs reflecting the complex relationship between soil biota and soil quality, including: earthworms (Morvan et al., 2008; Lima et al., 2013), nematodes (Stone et al., 2016), acari and collembola, enchytraeids and protozoa (Bispo et al., 2009; Rutgers et al., 2009; Cluzeau et al., 2012). However, the selection of biological indicators included in soil quality assessments was often arbitrary and non-scientific, focussing more on standard well known methods, feasibility in general laboratories and cost (Rutgers et al., 2009). This resulted in often poor selection of biological indicators. Bastida et al. (2008) and Lehman et al. (2015b) emphasised that the link between biota identity and functions is the key to understanding and interpreting soil functionality. Meanwhile, emerging molecular tools and technological advances kick-started a new generation of biological methods able to capture biodiversity and better define the relationship with soil processes and functions (Barrios, 2007; Bastida et al., 2008; Lemanceau et al., 2015; Thiele-Bruhn et al., 2020).

1.2. From soil quality to multifunctionality

In 2004, Andrews et al. emphasised that soil quality should be further defined as "the capacity of a soil to function"; functions should include the role of soil in supporting water flow and retention, solute transport and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of potentially toxic materials and maintenance of biodiversity and habitat. Currently, the most prevalent soil functions for an agricultural system are recognized as: Primary Productivity, Nutrient Cycling, Water Regulation and Purification, Carbon and Climate Regulation, Habitat for Biodiversity (Haygarth and Ritz, 2009; Schulte et al., 2014), with a further two functions (pest control and pollutant degradation) proposed by Vogel et al. (2018). The capacity of a soil to supply anyone of the above soil functions is dependent on a combination of the inherent soil properties, geo-physical site conditions, management history and the current management practices being applied (Giuffré et al., 2021).

Zwetsloot et al. (2021) proposed that most agricultural fields can support the supply of at least 3 soil functions at optimal level before trade-offs become apparent between functions. The supply of multiple soil functions is now commonly referred to as multifunctionality and has recently been adopted within the foresight report on soil health and food by the European Commission (Giuffré et al., 2021). While the concept of soil multifunctionality is receiving increased attention, both on a scientific and political basis, it remains limited in application due in part to the many different ways in which it is interpreted (Hölting et al., 2019).

In recent years a number of integrative tools have been established to aid in the quantitative/qualitative assessment and interpretation of soil quality and multifunctionality, including the Cornell Soil Health Test (http://www.css.cornell.edu/extension/soil-health/manual.pdf) and the Biofunctool (https://www.biofunctool.com/) (Thoumazeau et al., 2019). These tools really brought forward the assessment of soil quality in agricultural and forest systems. Both tools utilise a minimum dataset approach that integrates chemical, biological and physical indicators to define soil quality.

Debeljak et al. (2019) were the first to move away from the standard minimum dataset approach with the development of the Soil Navigator Tool (www.soilnavigator.eu). They applied multi-criteria decision

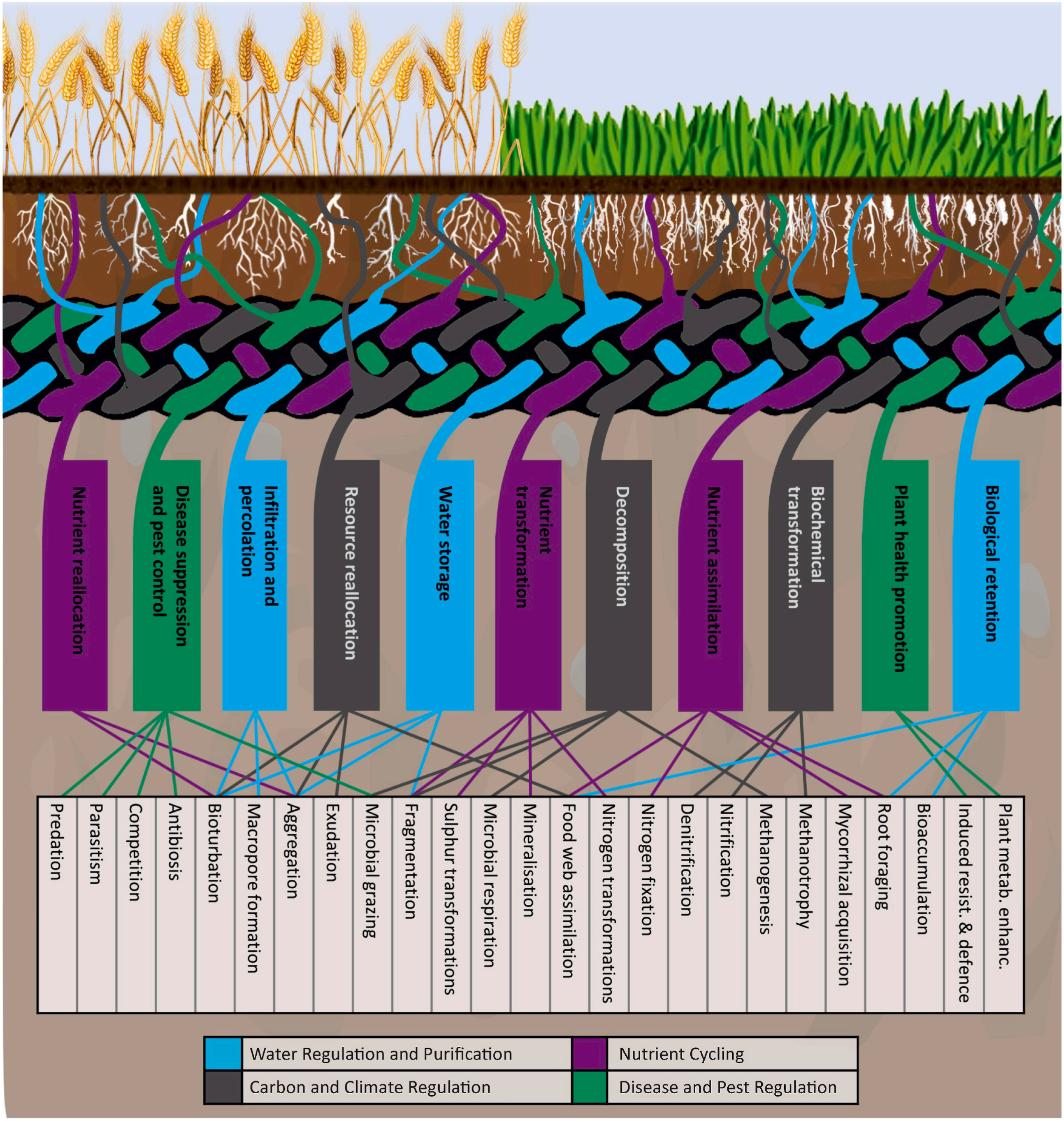


Fig. 1. Conceptual overview of how soil quality is underpinned by multiple soil functions simultaneously, namely Water Regulation and Purification (blue), Nutrient Cycling (purple), Carbon and Climate Regulation (grey) and Disease and Pest Regulation (green). Soil life performs a plethora of processes (beige boxes) which support one or more soil functions (for details see Figs. 2–5). Bundles of related processes, or sub-functions, (coloured boxes) structure the contribution of soil life to each soil function. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

models to define the capacity of a soil to support five soil functions within an agricultural context. These five function models were further integrated to assess overall multifunctionality. In this approach each complex soil function was broken down into less complex sub-functions, defined by the interaction of soil, environmental and managerial attributes (Debeljak et al., 2019). This model framework provided a breakthrough for how soil quality can be assessed and allowed the scientific community to move away from the often misjudged or arbitrary 'indicator' selection. As the Soil Navigator Tool was originally developed with farmers and farm advisors in mind, it purposely relied on input attributes that are readily attainable by the farmer. This resulted in the exclusion of soil biological attributes in four of its five function models (Fig. S1). In the Soil Biodiversity and Habitat model the biological attributes were present, but made optional as this information may not always be available to farmers (greyed out in Fig. S1A).

If we return to the concept that soil quality is defined by the capacity of a soil to function, it is clear that different contexts require different approaches. The Soil Navigator and Cornell Soil Health Test are both tools focussed at the assessment of soil quality by the farmer/land manager and while these tools have been applied for research and monitoring purposes their central focus are at the farm scale. While farmers are primarily interested in functional responses to soil management, research is focused on elucidating the underlying processes, whilst monitoring aims to capture the changing rates of these underlying processes, to allow for early indication and intervention for multifunctionality. Soil biological attributes are often referred to as dynamic attributes as they are responsible for a wide range of soil processes that take place in soil and often respond to changes over time (Ritz et al., 2009); they are also sensitive to impacts associated with agricultural soil management or land use (Bongiorno, 2020).

This leads us to one of the most challenging paradoxes of contemporary soil science: whilst societal interest in soil quality and managing soil as a living resource is growing (Veerman et al., 2020), the sheer complexity of the life of soils has thus far meant that assessments of soil biological measurements that are simultaneously reliable, accessible, affordable and relevant often remain elusive.

It is the aim of this paper to respond to this challenge by formulating an integrative soil function framework that builds on decades of international research to link soil functions to soil processes, and soil processes to soil biota, under temperate climatic conditions. The purpose of this framework is to capture the who and how of the multifunctionality of our soils through a flexible yet objective selection of biological attributes across a range of assessment scales, from detailed mechanistic research to large scale monitoring systems for soil quality. It is not the aim of this paper to include biological attributes for farmers to measure in-situ, but rather provide a scientific basis for assessment of soil quality in research and monitoring.

2. Theory

2.1. An integrative framework for defining the role of soil biota in soil multifunctionality

Our framework responds to the call by Doran and Zeiss (2000) for the inclusion of biological measurements in soil quality assessments, in addition to chemical and physical parameters, to elucidate soil functioning. To achieve this, we first distil the scientific knowledge base of the complex interactions through which soil biota support the many processes that play a role in agricultural systems. Next, we identify how each of these processes contribute to each of the soil functions, this is achieved through the inclusion of sub-functions that cluster bundles of processes which support specific components of the overall function. This builds on the approach of Bünemann et al. (2018), who defined soil functions as bundles of soil processes that underpin the delivery of ecosystem services. The clustering of processes into sub-functions helps to define how the processes support the overall functioning of soils.

Fig. 1 illustrates how sustainable productivity and multifunctionality in agricultural soils is supported by the four soil functions; Carbon and Climate Regulation (CR), Water Regulation and Purification (WR), Nutrient Cycling (NC), and Disease and Pest Regulation (DR). This paper does not include the function of Soil Biodiversity Habitat as it is focussed on the functional role of soil biota. The interweaving of the coloured ribbons signifies that these functions do not exist in isolation, but interact with each other, resulting in both synergistic and antagonistic outcomes (Vazquez et al., 2021; Zwetsloot et al., 2021). We distinguish 11 clusters of these biological processes, referred to as soil 'sub-functions', represented in Fig. 1 by the vertical coloured boxes. Soil processes (vertical beige boxes) may contribute to multiple sub-functions and are regulated by the presence of the soil biota (microbes, micro-, meso- or macro-fauna) (shown later in Figs. 2–6) in conjunction with the availability of resources and edaphic conditions of the soil environment, illustrating the complexity of the soil as a living resource.

2.2. Defining the role of soil biota to the four soil functions

This framework utilises the hierarchical structure of the multi-criteria decision model applied by Debeljak et al. (2019). The framework is made up of four cognitive models (Figs. 2–5), which describe the relationships between soil biota (referred to as biological actors) and processes, based on a thorough review of the scientific literature (for key references see Tables S1a & S1b) and the contribution of these processes to each soil function. Sections 2.2.1 to 2.2.4 provide the definition and scientific underpinning to each of these function cognitive models. The term biological actors refers to a range of soil biota that contribute to the soil processes. These soil biota may take the form of taxonomic family, sub-order, or functional groups, or in specific cases certain species or genera and therefore we apply the broader term 'actor'.

2.2.1. Carbon and Climate Regulation cognitive model

The CR function embodies the capacity of soils to regulate the climate through the (reduction of) emissions of major greenhouse gasses CO_2, CH_4 and N_2O, as well as storage or even sequestration of carbon (C) (Van de Broek et al., 2019). Biological soil processes that support this function can be categorised into three sub-functions: Decomposition, Biochemical transformation, and Resource reallocation (Fig. 2).

Decomposition includes the biological processes controlling the breakdown of organic matter, which results in the production of CO_2 and CH_4. Almost all soil organisms play a role in Decomposition (Hättenschwiler et al., 2005). However, microorganisms in general are responsible for the vast majority of CO_2 respired (Nielsen et al., 2011), while methanogenic archaea specifically are the primary CH_4 producers (Serrano-Silva et al., 2014). The quantity and efficiency of microbial respiration is influenced by micro- and mesofauna that graze on the microbial populations (Eijsackers and Zehnder, 1990; Hättenschwiler et al., 2005). Furthermore, meso- and macrofauna are essential for Decomposition because they mechanically fragment coarse organic material and ingest and partially digest a portion of the litter they process (Frouz, 2018; Nielsen et al., 2011).

Transformations of inorganic molecules that lead to the production of N_2O (nitrification and denitrification), as well as the consumption of CH_4 (methanotrophy) are classified as Biochemical transformations because these processes involve conversions of, rather than breakdown of molecules. Nitrification and denitrification are included here, as well as in the NC model, because they are the most relevant nitrogen (N) cycle processes that control N_2O emissions. All three processes supporting Biochemical transformations are performed by microorganisms.

Rates of processes that underpin Decomposition and Biochemical transformations depend on the availability of resources. Processes that make resources available, unavailable or that displace them, are grouped into the third sub-function: Resource reallocation. This includes mixing and moving soil through bioturbation, occlusion of organic matter by aggregation, allocation of assimilated C and N from plants and microbes into the soil by exudation, and the uptake of C and N by the food web. The flow of C and N through the soil food web can be assessed in more detail by zooming in on the actions of the relevant trophic groups as sub-processes (de Ruiter et al., 1993) (Fig. S2). Most food web sub-processes concern the bottom-up flow of C and N derived from organic matter, with one exception, that of mycorrhizal C translocation, which includes the movement of plant assimilated C directly to their mycorrhizal fungal partner.

2.2.2. Water Regulation and Purification cognitive model

The WR function is defined as "the capacity of the soil to remove harmful compounds, to receive, store and conduct water for subsequent use and as such to prevent droughts, flooding and erosion" (Wall et al., 2020). The WR function is supported by three biologically mediated

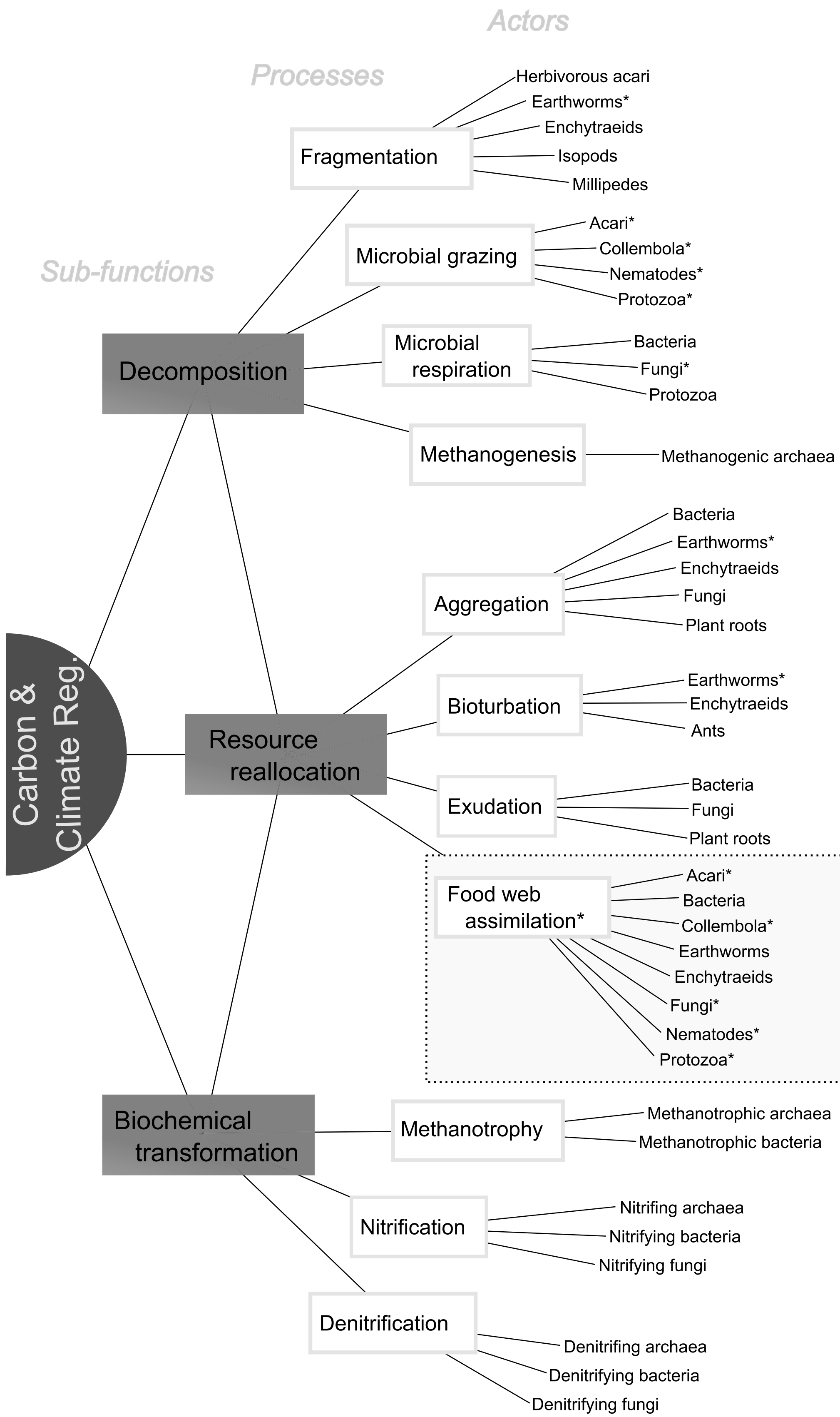


Fig. 2. Cognitive model illustrating how actors (soil organisms) contribute to Carbon and Climate Regulation (CR). By studying the indicated actors and processes, one can assess the capacity of a soil to perform CR, or a specific aspect (sub-function). Food web assimilation can be assessed in more detail by zooming in on sub-processes (See Fig S2). * Marks actors and processes for which particular groups should be considered in relation to the indicated process or sub-function (see Table S1a&b).

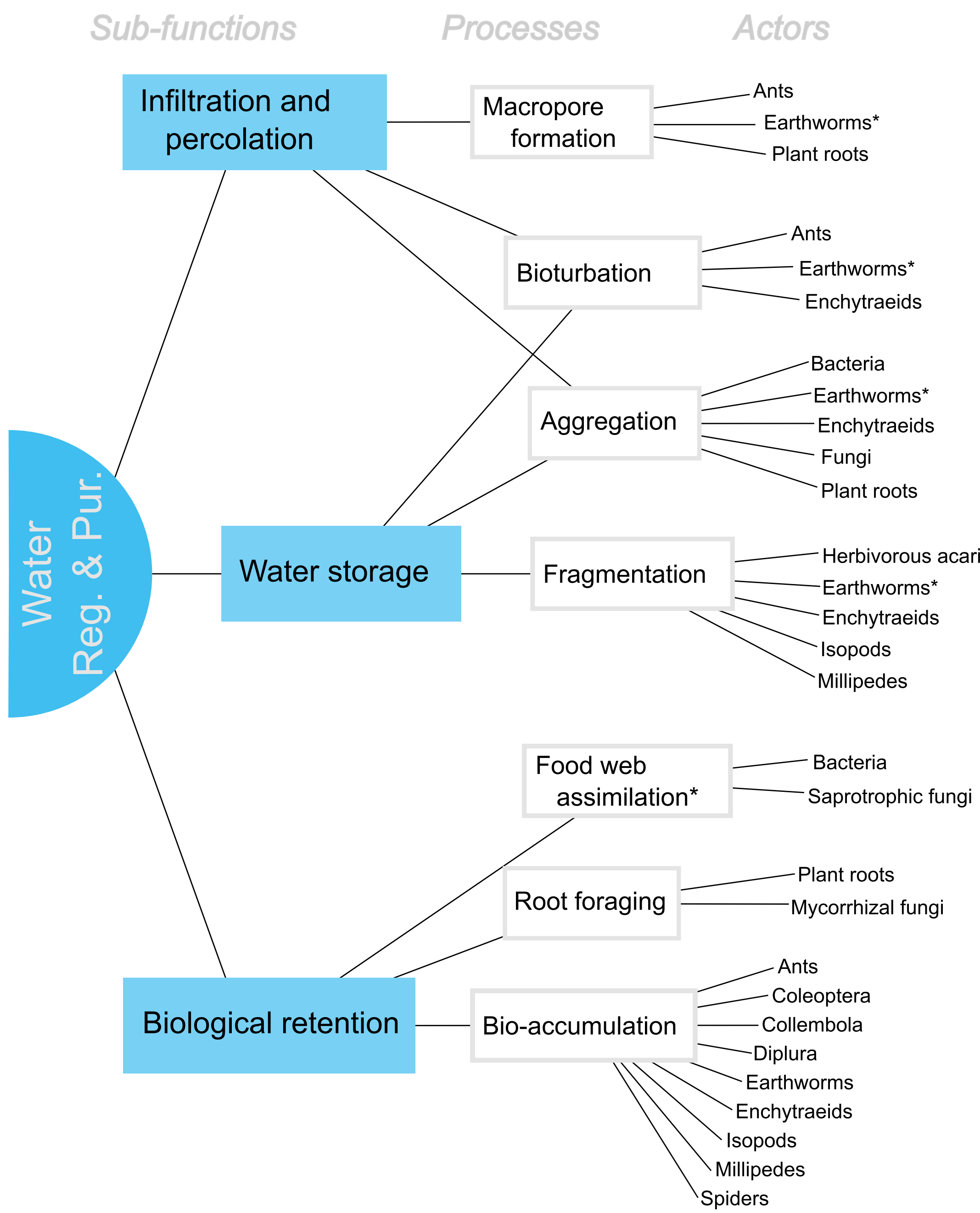


Fig. 3. Cognitive model illustrating how actors (soil organisms) contribute to Water Regulation and Purification (WR) through three sub-functions (bundles of related processes). * Marks actors and processes for which particular groups should be considered in relation to the indicated process or sub-function (see Table S1a&b).

sub-functions which define the overall capacity of the function, these are: Infiltration into, and percolation through the soil, the ability of the soil to store water (Water storage) over time, and the removal of harmful substances through Biological retention (Fig. 3). The sub-functions of Infiltration and percolation and Water storage are maintained through a continuum of bio-physical processes, supported by the soil biota considered as ecosystem engineers (earthworms (Blouin et al., 2013; Taylor et al., 2019), enchytraeids (Dawod and FitzPatrick, 1993), ants (Taylor et al., 2019), fungal hyphae (Rillig and Mummey, 2006), and plant roots (Six et al., 2004)). The processes Bioturbation and Aggregation contribute to both sub-functions through changing soil structure, which in turn supports soil water retention and flow. The sub-function Infiltration and percolation is also dependent upon the presence of macropores, which provide a conduit for water within the soil matrix. Macropore formation is primarily developed through the activity of anecic earthworms (Blouin et al., 2013), ants and roots. The sub-function Water storage further relies on the process of fragmentation in addition to aggregation and bioturbation. Fragmentation involves the physical comminution and partial digestion of plant litter by soil meso- and macrofauna, after which the residues can be decomposed and/or become stabilised (Frouz, 2018) contributing to soil organic matter formation (Lavallee et al., 2019) and Water storage. The sub-function Biological retention relates to the ability of the soil biota in combination with chemical fixation and physical absorption to remove harmful substances from the soil water; these include excess nutrients, metals (Heikens et al., 2001), micro-plastics (Huerta Lwanga et al., 2018) and pesticides (Fierer et al., 2021). However, in the case of pesticides, the metabolic products which are generated during the

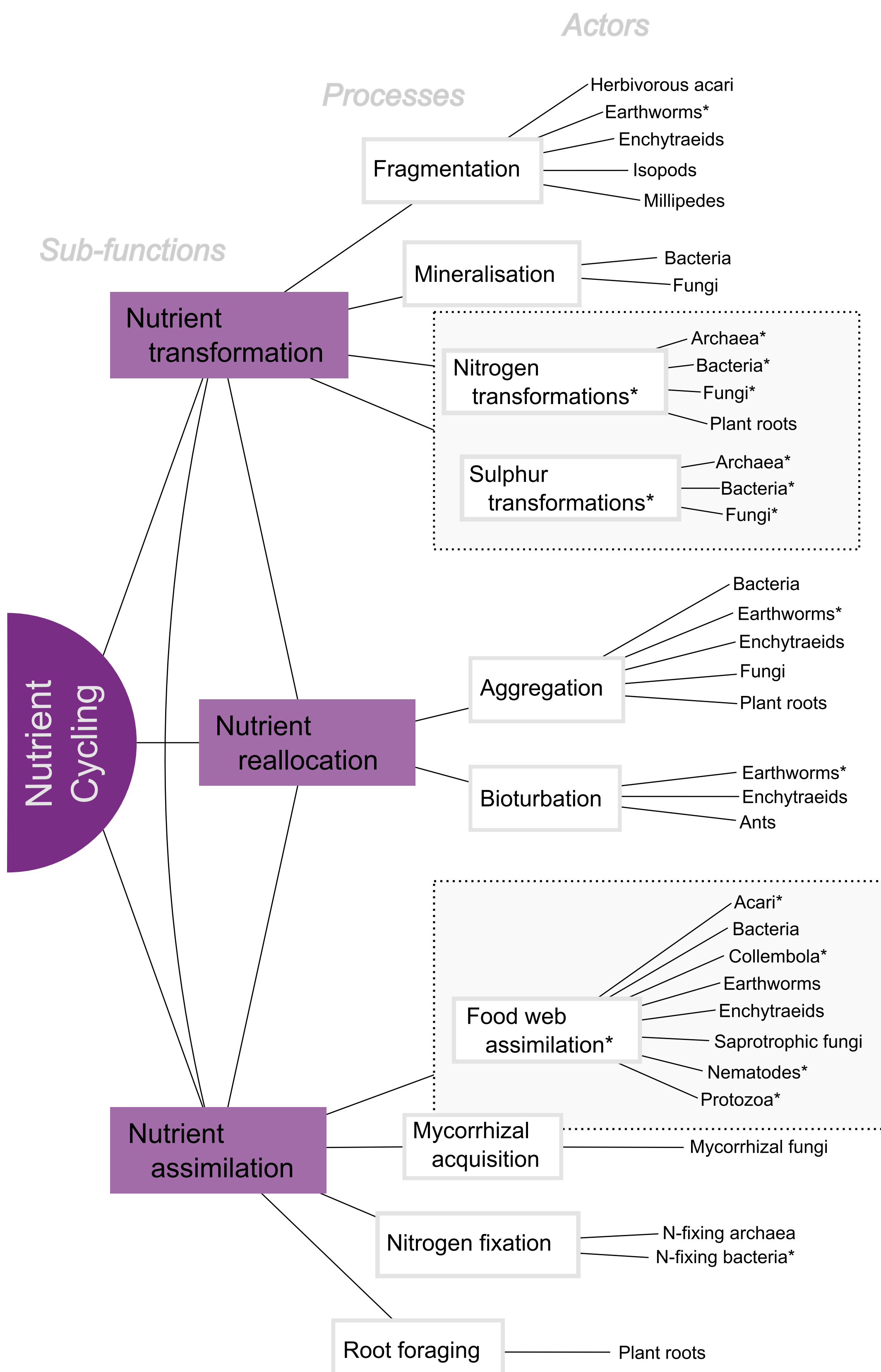


Fig. 4. Cognitive model illustrating how actors (soil organisms) contribute to Nutrient Cycling (NC) through three sub-functions (bundles of related processes). The processes Nitrogen and Sulphur transformations as well as Food web assimilation can be assessed in more detail by zooming in on sub-processes (See Fig S3). * Marks actors and processes for which particular groups should be considered in relation to the indicated process or sub-function (see Table S1a&b).

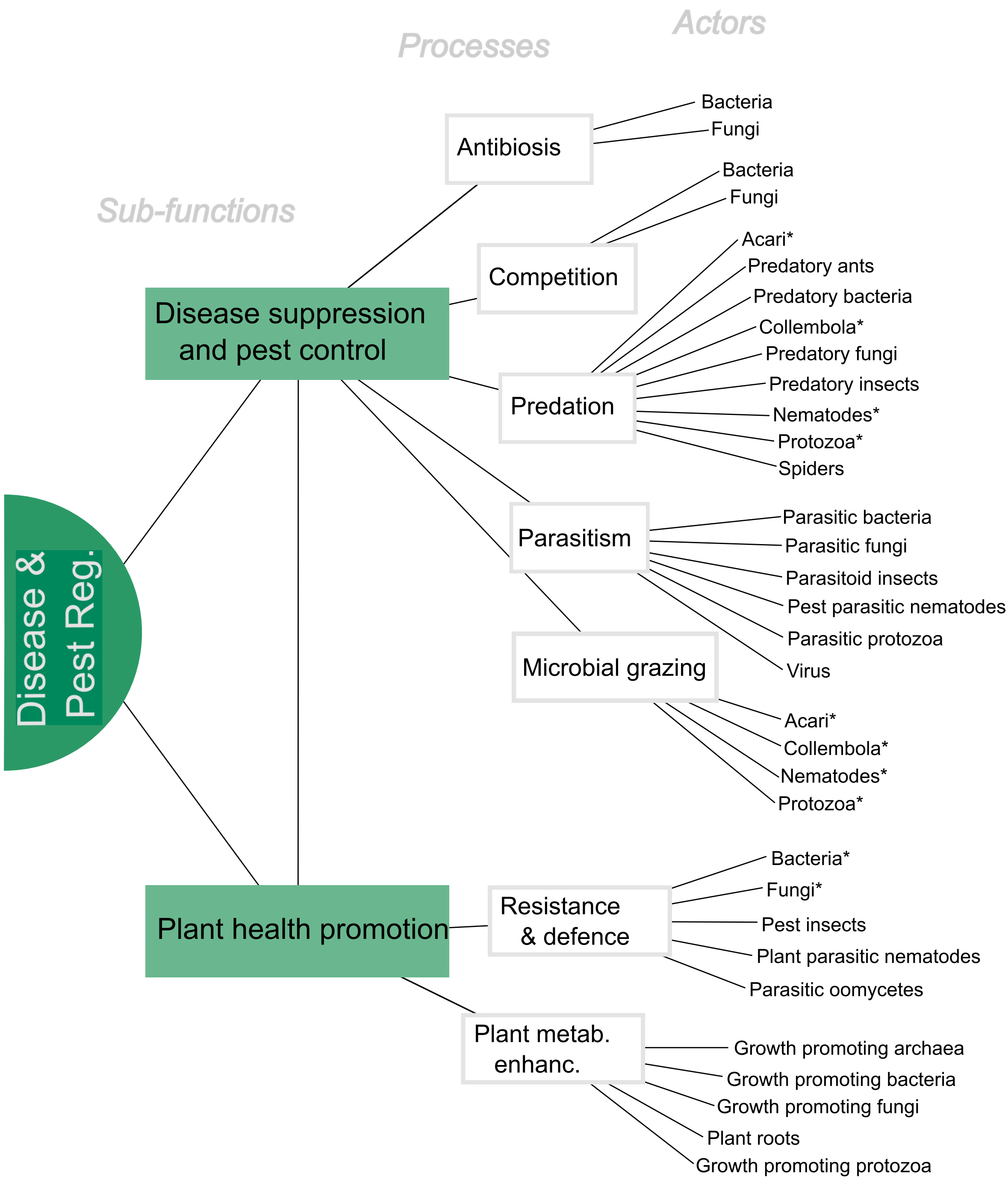


Fig. 5. Cognitive model illustrating how actors (soil organisms) contribute to Disease and Pest Regulation (DR) through two sub-functions (bundles of related processes). * Marks actors for which particular groups should be considered in relation to the indicated process (see Table S1a&b). The process plant metabolism enhancement abbreviated as plant metab. enhanc.

degradation process may in fact be more toxic than the original pesticide applied (Fierer et al., 2021). There are three key biological processes which support this sub-function: food web assimilation, which predominantly entails microbial assimilation of nutrients into microbial biomass, root foraging, which is focussed on the uptake of nutrients for plant growth, and bio-accumulation, which Heikens et al. (2001) related to the feeding strategy of taxonomic groups and the chemical conditions of the soil, such as pH.

2.2.3. Nutrient Cycling cognitive model

The NC function is defined as the capacity of a soil to receive and recycle nutrients from external inputs and to support the acquisition of nutrients from soil minerals, water and air by plants and the soil community (Schröder et al., 2016; Trajanov et al., 2019). The NC model focuses on essential plant macronutrients: nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg) and sulphur (S). The NC function is supported by a number of biological processes and actors which are categorised into three sub-functions: Nutrient transformation, Nutrient reallocation and Nutrient assimilation (Fig. 4).

Nutrient transformation encompasses soil biological processes which lead to changes in the chemical or physical status of nutrient resources (excluding assimilation). These processes are: mineralisation, N transformations, S transformations and fragmentation. Mineralisation involves the transformation of organic nutrients to inorganic form by soil

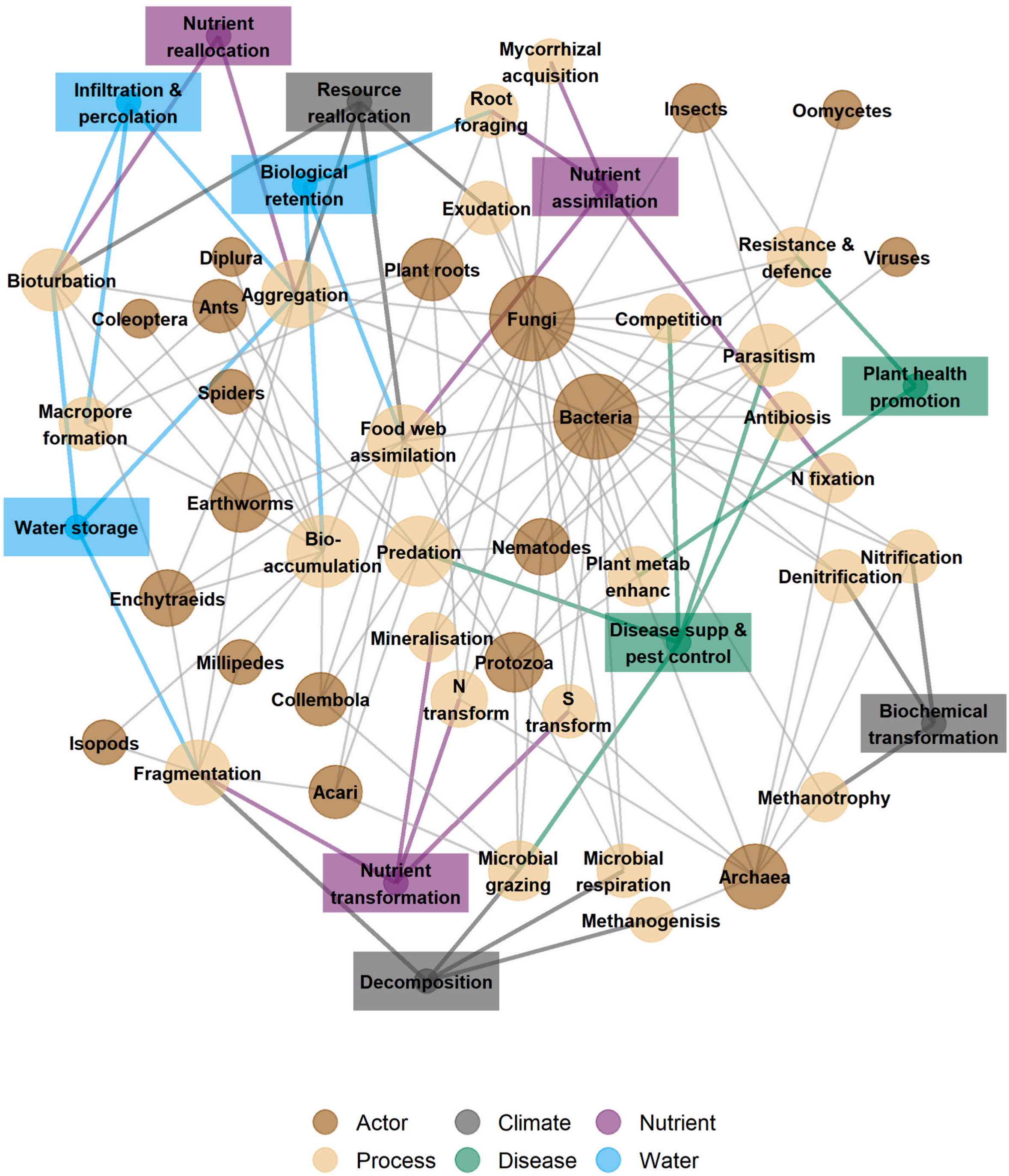


Fig. 6. Network visualisation of the connections between actors, processes and sub-functions. The size of the actor nodes represents the number of processes that they contribute to. The size of the process nodes represents the number of soil functions that they support. Sub-functions are indicated by rectangular boxes and colours refer to the different soil functions: Carbon and Climate Regulation (dark grey), Water Regulation & Purification (blue), Nutrient Cycling (purple) and Disease and Pest Regulation (green). Actor and processes nodes are indicated in dark brown and light brown, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

bacteria and fungi. While the cycling of P, Mg, K and Ca in soil is predominantly governed by chemical processes, soil (micro)biology plays a large role in the transformation of N and S. N transformations include the sub-processes: nitrification, denitrification (Robertson and Groffman, 2007), dissimilatory nitrate reduction to ammonium (DNRA) (Rütting et al., 2011), and anaerobic ammonium oxidation (Anammox) (Hu et al., 2011), which are all performed by microorganisms (Fig. S3). S transformations include the microbial processes sulphur oxidation and sulphate reduction (Brown, 1982). Nutrient reallocation refers to a change in location of and access to nutrient resources and encompasses two processes: bioturbation and aggregation. Nutrient reallocation influences the other sub-functions by controlling the availability and accessibility of resources needed for the biological processes in Nutrient transformation and assimilation. Nutrient assimilation describes the processes controlling nutrient acquisition from the soil and incorporation into biomass by soil biota (food web assimilation), by plants directly (root foraging, Postma et al., 2014; Richardson et al., 2011) or indirectly by plant mutualists; mycorrhizal acquisition (Read and Perez-Moreno, 2003) and N-fixation (Mills, 2019; Reed et al., 2011). Similar to the CR model, the process of food web assimilation is further elaborated into sub-processes, with the exclusion of mycorrhizal C translocation (Fig. S3). Nutrients that are assimilated by soil biota can be mineralized again and cycle through other processes in the Nutrient transformation sub-function; in turn, Nutrient transformations can enhance or reduce the availability of nutrients for assimilation by soil biota and plants.

2.2.4. Disease and Pest Regulation cognitive model

The DR function is the capacity of soils to prevent the establishment and development of soil-borne plant pathogens (microorganisms and microfauna) and pests (meso- and macrofauna) despite their presence in the field, the availability of a susceptible host, and a suitable environment (Cook, 2014; Peterson et al., 2016). The soil biological processes supporting this soil function are bundled in two sub-functions: Disease suppression and pest control, and Plant health promotion (Avis et al., 2008; Mazzola, 2002; Neher and Barbercheck, 2019; Peterson et al., 2016) (Fig. 5).

Disease suppression and pest control entails processes involving the direct biotic interaction between soil organisms and plant pathogens/pests. These include antibiosis, competition, predation, parasitism and microbial grazing (Alabouvette et al., 2009; de Boer et al., 2019; Lemanceau et al., 2006). The microbial community has a prominent role in disease suppression (Bonilla et al., 2012; Gómez Expósito et al., 2017), while both microorganisms and meso- and macro fauna operate in pest control (Pearsons and Tooker, 2017). Historically, disease suppression is differentiated in general and specific disease suppression (Schlatter et al., 2017). 'General' refers to the antagonistic effects of the entire soil microbial community by competition and antibiosis against a range of pathogens/pests. 'Specific suppression' denotes the activity of selected groups of organisms or even individual species and is effective to particular pathogens/pests species. In soils these two aspects are a continuum both contributing to disease suppression (Postma et al., 2008), and are therefore combined in our model.

Plant health promotion results from interactions between soil organisms and plants that trigger induced resistance and defence responses, and enhance plant metabolism. Induced resistance and defence occurs when the interaction with a soil organism activates a plant's defence mechanisms directed against pathogens/pests (Avis et al., 2008; Lemanceau et al., 2006; van Loon et al., 1998), this may be triggered by the pathogen/pest itself or harmless biota. On the other hand, plant metabolism enhancement may be triggered by soil organisms, but it is not directed against a specific pathogen/pest present. Rather, plant metabolism enhancement renders the plant more resistant to pathogens and pests, for examples enhancing plant nutrition via N fixation or producing growth stimulating phytohormones by growth-promoting microorganisms (Berg et al., 2017; Braga et al., 2016; Pascale et al., 2020). The two sub-functions interact with each other. For example, the activity of antagonistic organisms can either activate plants defences (Alabouvette et al., 2009) or select plant growth promoting microorganisms (Curl and Old, 1988; Xiong et al., 2020). When attacked by pests or pathogens, plants can release volatiles or exudate compounds that can attract natural enemies of the pest/pathogen (cry for help) (Berendsen et al., 2012; Liu et al., 2020; Topalovic et al., 2020).

2.3. Disentangling the contribution of soil biota to the delivery of multifunctionality

Having defined the relationships between soil biota and processes for each of the four soil functions, we can now employ network visualisation to trace deterministically how these actors perform soil processes and how these in turn cluster via the sub-functions to define the four functions (Fig. 6) (methodology described in Supplementary information (S3)). This simplified visualisation effectively adds the soil actors from the cognitive function models to Fig. 1 and as such connects the who (actors) and how (processes) of each of the soil functions individually, and indeed of soil multifunctionality in general.

2.3.1. From processes to multifunctionality

In Fig. 6, we observe that most of the processes (19 out of 25) underpin a single function only; their measurement may be relevant as attributes of single functionality. Of the remaining processes, bioturbation, aggregation, food web assimilation and fragmentation each support 3 out of the 4 soil functions (CR, NC and WR), as illustrated by the larger nodes (representing the larger number of out-degrees of those nodes). Measurements of these processes will provide a broader scope for assessing multifunctionality than measurement of aforementioned processes that only contribute to one function. However, in the assessment of multifunctionality it is important that all functions are considered and represented and therefore may also include measurement of single function processes as well (e.g. to also consider the DR function).

2.3.2. From actors to processes

In practice, processes are often difficult to measure in the field, as many processes are represented by rate variables that require a continuous measurement over a certain period of time. Whilst the direct measurement of these rate variables is of great interest to researchers from a mechanistic perspective, most practical monitoring applications are typically constrained by the short time allocated to sampling. Measurements of the actors that perform the processes is therefore a pragmatic alternative to overcome this logistical challenge and are often considered as process indicators or proxies (Rutgers et al., 2012; Griffiths et al., 2018).

Our cognitive models allow us to identify the most relevant biological actors that support each of the soil processes which contribute to each of the soil functions and therefore overall multifunctionality and this was further validated by 40 soil biota experts from across the globe (described in Zwetsloot et al., 2022). Fig. 6 is an illustration of the outcome of these four cognitive models, visualising which biological actors contribute to which processes. For simplicity, we, here, lumped specific actors into broad organismal groups, even though the cognitive models specify processes to be performed by specific actors (Table S1). For example, the bacteria are split up into nitrogen fixers, denitrifiers, methanotrophs etc. in the cognitive models. In this, 19 broad groups of biota were identified to contribute to the four soil functions. Disentangling the pathways through which they contribute to multifunctionality, we find that bacteria, fungi and archaea contribute to the most soil processes (17, 17 and 8 out of the 25 processes, respectively, Table S2) and as such can be considered highly relevant actors for soil multifunctionality. Protozoa, nematodes, enchytraeids, earthworms and plant roots were also important actors contributing to five or more soil processes.

In the interpretation of these results, however, we must caution that this 'headcount' of the 'who' in soil quality assessment in the paragraph above does not necessarily imply that each taxon contributes to functionality in equal measure. In other words, it is not only the number of processes that an actor contributes to that counts, but also the magnitude by which an actor is impacting the process and ultimately ecosystem functioning. In their assessment of the contributions of a range of soil organisms to soil processes, Delgado-baquerizo et al. (2020) found that micro-organisms were important actors in supporting multiple ecosystem functions, but operated at relatively low levels (<50% of their maximum rates). While contrastingly, larger biological actors such as earthworms were found to operate at higher levels of functioning (>75%), while contributing to fewer processes overall.

3. Application

3.1. Limitations to a universal minimum data set

Given the complexity of the life of soils, it should come as no surprise that despite numerous attempts (e.g. Doran and Parkin, 1994; Hanegraaf et al., 2019; Lehmann et al., 2020; Lima et al., 2013; Sharma et al., 2010), the discipline of soil science has thus far failed to agree on one definitive minimum dataset for the assessment of soil quality. Whilst one universal minimum dataset would bring benefits, such as comparability of data across a range of applications, its uniformity would come at the expense of reduced user operability and reduced applicability to the wide range of contexts and scales to which the assessment of soil biology should be included, ranging from research on sustainable soil management at a field scale, to monitoring soil functions over time at continental scale. Put simply: different contexts call for different methods of assessment.

3.2. Which type of assessment is of interest to whom?

Let us elaborate on this and consider three examples of contrasting contexts in which a minimum dataset is commonly applied, as well as their associated practical and logistical constraints (Box 1).

3.2.1. Context 1: mechanistic understanding of multifunctionality

The first context (top row in Box 1) is where we aim to further develop our scientific understanding of the interactions between soil biota and soil processes with the ultimate aim to mechanistically quantify the impact (positive or negative) of specific management practices or edaphic conditions on specific soil functions or multifunctionality, typically at the field scale (e.g. Bongiorno et al., 2019; Sandén et al., 2018). Such assessments are mostly conducted by smaller teams of researchers; as a result, the associated lab analyses and data processing strongly depend on in-house expertise. In this context, reproducibility of the results and cost of analyses are important factors to consider during the selection of the most appropriate soil quality assessment methods, while technical criteria related to sample collection (amount of sample, temporal and spatial sampling designs) may be considered less constraining.

3.2.2. Context 2: optimising sustainable land management

The second context (middle row in Box 1) concerns more applied research focussed on supporting land managers and decision makers to optimise the soil resource for sustainable agricultural production and are interested in the multifunctionality of soils in relation to land management and land-use. Examples include Functional Land Management studies in Europe (e.g. Vazquez et al., 2021; Zwetsloot et al., 2021) and beyond (e.g. Pinillos et al., 2020); however, the role of soil biota in soil multifunctionality has thus far eluded most of these studies. In this second context, soil quality assessment is aimed at optimising the soil resource within a landscape continuum to support decision making, where reliability and reproducibility are important considerations in the selection of assessment methods. Accordingly, experimental methodologies should be applied with caution in this second context, and method selection should focus on the deployment status of the method and the reproducibility of results. Additionally, the assessment of 'functional interactions' tends to be specific to a given landscape or region; as such the regional laboratory infrastructure is an important factor to consider in method selection. Less constraining in this context are the duration of lab analyses, the number of samples to be collected in the field, the amount of sample needed and archivability of the samples.

3.2.3. Context 3: soil quality monitoring over time

Monitoring is the focus of the third context (bottom row of Box 1), with the aim of tracking changes in soil quality and functionality over time in response to market or policy-led incentives. Monitoring requires a simplified set of measurements that can provide proxies for the detailed mechanisms and interactions that we saw being assessed in the first two examples. Monitoring is commonly applied over larger spatial scales at either country scale (e.g. Black et al., 2008; Rutgers et al., 2009; Saby et al., 2015) or continental scale (Fleck et al., 2016; Orgiazzi et al., 2018). At this scale of operation, sample collection criteria such as sample size and short-term repeat visits to a site for process related sampling are constraining. Once in the laboratory, reliability and consistency of methods are highly relevant as selection criteria, as the results of monitoring will inform policy intervention and management actions for years to come. As methodologies develop over the long term, it is important that samples can be stored and archived, to allow for future testing of methodological differences, correlations and biases (van Wesemael et al., 2011).

3.3. From minimum datasets to flexible datasets

We have described three contrasting contexts that each can now include the biological assessment of soil quality; from these descriptions it is self-evident that the answer to the question "which assessments should be applied here?" yields different answers for each of these contexts. In fact, failure to account for any of the practical or logistical constraints may result in inappropriate methods being selected or biological measurements being neglected, as is more-often-than-not the case in country-wide or continental monitoring systems (van Leeuwen et., 2017).

Accordingly, Fierer et al. (2021) call for a change in mindset, to move beyond the quest for a universal minimum dataset to a more nuanced approach which indeed considers the context of the assessment and is tailored to the objectives of the user. Such an approach was the purpose of the 'Soil Management Assessment Framework' (SMAF) originally developed by Andrews et al. (2004), which used a series of decision rules to select the most appropriate assessment methods for inclusion in the minimum dataset from a list of 81 possible methods to measure soil chemical, physical and biological attributes. These contextual decision rules related to land use, land management, and the soil functions of interest to the user.

3.4. BIOSIS: a tool for objective flexible method selection

As a modern-day successor to SMAF (Andrews et al., 2004), Zwetsloot et al. (2022) propose and describe a flexible tool (BIOSIS: Biological Soil Information System) for the context-specific selection of methodologies for assessing the four soil functions described in this paper, as well as overall multifunctionality, specifically for agricultural systems under temperate climatic conditions. Similar to the SMAF framework of Andrews et al. (2004), the new BIOSIS method selection tool is tailored to the context and resources of the user. Based on the cognitive models described in this paper, it defines the pertinence of selected methods to the function(s) under assessment, followed by an expert-opinion based ranking of the relevance of the methods in relation to representing the processes that underpin the functions of interest. User-preferences are evaluated by applying logistical criteria with user-defined weighting factors (as described by Ritz et al., 2009) to constrain the method selection according to the resources available to a given assessment. In total Zwetsloot et al. (2022) identify 191 biological actor-level methods and 98 process-level methods for the assessment of the four soil functions. When we compare this to the nominal bulk soil activity measurements (such as respiration, enzyme activity or nitrogen mineralisation potential) or bulk soil microbial/faunal biomass or diversity measures (Schloter et al., 2003; Brussaard et al., 2004; Lehman et al., 2015a, 2015b; Bünemann et al., 2018), it sheds a dim light on the paucity of methodologies commonly applied in the application of minimum datasets. Our analysis breaks with this tradition and recommends different methodologies for diverse contexts, which at the same time are underpinned by a comprehensive and unified scientific framework. For the assessment of multifunctionality (all four functions) it is prudent to select methodologies which support multiple functions, but in many cases (19 out of 25 processes) only single functions were defined by a process measurement or biological actor measurement. It is therefore key to ensure that the range of methods adopted reflect the four functions.

Box 1
Assessment across scales. Soil functioning can be assessed following one of three approaches.

Mechanistic assessments aim to uncover mechanistic details of relationships between soil biota and soil processes for a range of management practices and edaphic conditions. Typically, mechanistic assessments occur **at field scale** and focus on the contribution of soil biota to one or multiple soil functions.

To assess **functional interactions at a landscape scale** it is important to quantify the optimal delivery of a range of soil functions within a catchment or landscape to achieve multi-functionality across the range of land-uses. Different land-use types will result in a mosaic of biological habitats which enhances the functional capacity of soil biological processes and therefore soil functions.

At the regional scale, monitoring multifunctionality patterns enables the assessment of sustainability in production systems for a given climatic region or societal context. Research at regional scale tests for general patterns and often uses proxy measures to monitor the capacity of soils to supply multiple functions over time on a large number of locations (>100).

3.5. Next steps

This paper has brought together decades of research on the role of soil biology in supporting soil functions, providing a flexible framework for the inclusion of soil biological measurements for the assessment of soil quality. However, this is only the first step in improving the assessment of soil quality and associated functions.

Here we return to our earlier observation that thus far the inclusion of biological methods has lagged behind the inclusion of physical and chemical methods in assessments of soil quality and functionality. Indeed, even a very recent popular publication by the Global Soil Partnership on ‘soil properties’ (FAO, 2021a; 2021b) lists 7 physical attributes, 5 chemical attributes, and only 1 biological attribute: “soil organisms”. This cannot be explained solely by a lack of biological methods, as many novel biological methodologies have been developed in recent decades (Fierer et al., 2021). However the interpretability of such data is considered limited when applied to research questions pertaining to soil quality or multifunctionality as a generic concept (Thomas et al., 2012; Laudadio et al., 2019). Instead, these novel methodologies shed light on one or more biological processes. By linking soil processes to soil functioning, our hierarchical models provide new and concrete utility to these novel methodologies in contributing to our understanding of soil multifunctionality, as a result of which we may expect an expansion of their use in future monitoring schemes.

Secondly while we have emphasised the need to consider biological measurements in assessments, these do not stand in isolation, as the majority of processes which take place in soil result from an interaction of biological, chemical and physical attributes. Lehmann et al. (2020) provide some nice examples of this, for example by elucidating the process of aggregation, in which soil macrofaunal activity results in the mixing and stabilisation of mineral particles: this stabilisation of aggregates is simultaneously determined by chemical and physical attributes such as the quantity and quality of soil organic matter, clay content and mineralogy (Singh et al., 2018). *Vice versa*, soil chemical and physical attributes can also define and shape the habitat in which soil organisms operate, as defined by van Leeuwen et al. (2019), and changes in the chemical or physical conditions of the soil impact on biological processes and rates.

We propose (example provided in Table 1) that any assessment of soil functions is incomplete in absence of managerial and environmental data, as these modulate the biological processes as well as the relationships between soil biology and the physical and chemical conditions (Schröder et al., 2016), and as such define the habitat in which soil life is situated. The next step would be to integrate chemical, physical and biological soil measurements into one selection tool which should also consider the scale of assessment.

4. Concluding remarks

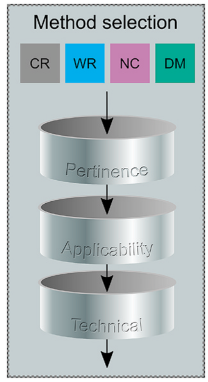
The 2019 Green Deal of the European Commission has given renewed impetus to the role of soil life in agricultural systems, through the sustainable soil management actions underpinning the EU Biodiversity 2030 Strategy, the Farm-to-Fork Strategy and the European Climate Law (Montanarella and Panagos, 2021). The European Soil Observatory (ESO) established in 2020 (Montanarella and Panagos, 2021), provides a first step towards a pan-European assessment of the role of soils in supporting the sustainable development of agricultural systems across Europe envisioned under the proposed Common Agricultural Policy 2021–2027. Now, more than ever, the time is right to replace the commonplace convenience in the choices of methods for the assessment of the who and how of soil functionality, with a robust scientific method selection that brings together and builds on decades of research within Europe and beyond.

In this paper, we have grasped this opportunity and introduced a comprehensive framework to evaluate the role of soil biota in supporting soil multifunctionality. We have elucidated the who and how of multifunctionality by identifying which actors (soil biota) are responsible for driving specific soil processes and how these processes in turn combine to regulate soil functions. This new insight into the life of soils facilitates a more scientific approach to the selection of the most appropriate methods for assessing biological processes and actors for the quantification of soil functionality. The resulting BIOSIS method selection tool (www.biosisplatform.eu) can be applied to a range of user contexts, from applied research to support land managers to policy making, and is flexible in terms of user interoperability, as it has been developed to allow for additional or updated methods, and for new land-use types or assessment approaches to be included over time. This coming decade, we find ourselves at a unique crossroads where the living soil has the attention of farmers, citizens, industry and policy makers alike. As scientists, let us now rise to the challenge to bring the life of soils alive to those on whom the future of our soils depend.

Declaration of interest

None.

Table 1
Example of attributes required for the assessment of soil multifunctionality in temperate agricultural systems.

Chemical	Physical	Biological	Management	Climate/Environment
Cation exchange capacity	Texture		Type of crops	Annual precipitation
Nutrients; N, P, K, Mg pH	Clay content		Crop diversity	Precipitation growing season
Soil organic matter	Bulk density		Crop rotation	Precipitation wet season
Soil organic carbon	Drainage class		% Legumes and Cover crops	Precipitation first growing month
C:N ratio	Soil crusting		No. of crops in rotation	Annual average temperature
Salinity	Groundwater depth		Crop sequence (Expected) yield	Average temperature first growing month
			Net primary productivity	No. of days > 5 °C
			Annual yield harvested by grazing	Altitude
			Crop residues	Slope degree
			Crop failure	
			Tillage type	
			Mineral fertiliser (N,P)	
			Organic fertiliser (N, P)	
			Manure type	
			Other organic inputs	
			Livestock density	
			Pest management	
			Nitrification inhibitors	
			Irrigation rate	
			Irrigation frequency	
			Irrigation type	
			Artificial drainage	

This table provides an example of the chemical, physical, management and climate/environmental information (derived from the Soil Navigator Tool – soilnavigator.eu) in combination with the outputs of the BIOSIS method selection tool (https://biosisplatform.eu/). The BIOSIS method selection tool allows the flexible selection of biological methods based on; 1) pertinence to the function, 2) applicability to the land-use and 3) scores from fifteen technical criteria (see Zwetsloot et al., 2022 (this issue).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.soilbio.2022.108561.

References

Alabouvette, C., Olivain, C., Migheli, Q., Steinberg, C., 2009. Microbiological control of soil-borne phytopathogenic fungi with special emphasis on wilt-inducing Fusarium oxysporum. New Phytologist 184, 529–544. https://doi.org/10.1111/j.1469-8137.2009.03014.x.

Anderson, T.H., 2003. Microbial eco-physiological indicators to asses soil quality. Agriculture, Ecosystems & Environment 98, 285–293. https://doi.org/10.1016/S0167-8809(03)00088-4.

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Science Society of America Journal 68, 1945–1962.

Avis, T.J., Rie Gravel, V., Antoun, H., Tweddell, R.J., 2008. Multifaceted beneficial effects of rhizosphere microorganisms on plant health and productivity. Soil Biology and Biochemistry 40, 1733–1740. https://doi.org/10.1016/j.soilbio.2008.02.013.

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecological Economics 64, 269–285. https://doi.org/10.1016/j.ecolecon.2007.03.004.

Bastida, F., Zsolnay, A., Hernández, T., García, C., 2008. Past, present and future of soil quality indices: a biological perspective. Geoderma 147, 159–171. https://doi.org/10.1016/j.geoderma.2008.08.007.

Baveye, P.C., 2021. Soil health at a crossroad. Soil Use & Management 37 (2), 215–219. https://doi.org/10.1111/SUM.12703.

Berendsen, R.L., Pieterse, C.M.J., Bakker, P.A.H.M., 2012. The rhizosphere microbiome and plant health. Trends in Plant Science 17, 478–486. https://doi.org/10.1016/j.tplants.2012.04.001.

Berg, G., Köberl, M., Rybakova, D., Müller, H., Grosch, R., Smalla, K., 2017. Plant microbial diversity is suggested as the key to future biocontrol and health trends. FEMS Microbiology Ecology 93, 1–9. https://doi.org/10.1093/femsec/fix050.

Bispo, A., Cluzeau, D., Creamer, R., Dombos, M., Graefe, U., Krogh, P.H., Sousa, J.P., Peres, G., Rutgers, M., Winding, A., Römbke, J., 2009. Indicators for monitoring soil biodiversity. Integrated Environmental Assessment and Management 5, 717–719. https://doi.org/10.1897/IEAM_2009-064.1.

Black, H., Bellamy, P., Creamer, R., Elston, D., Emmett, B., Frogbrook, Z., Hudson, G., Jordan, C., Lark, M., Lilly, A., 2008. Design and Operation of a UK Soil Monitoring Network.

Blouin, M., Hodson, M.E., Delgado, E.A., Baker, G., Brussaard, L., Butt, K.R., Dai, J., Dendooven, L., Peres, G., Tondoh, J.E., Cluzeau, D., Brun, J.-J., 2013. A review of earthworm impact on soil function and ecosystem services. European Journal of Soil Science 64, 161–182. https://doi.org/10.1111/ejss.12025.

Bone, J., Head, M., Barraclough, D., Archer, M., Scheib, C., Flight, D., Voulvoulis, N., 2010. Soil quality assessment under emerging regulatory requirements. Environment International 36, 609–622. https://doi.org/10.1016/j.envint.2010.04.010.

Bongiorno, G., Bünemann, E.K., Oguejiofor, C.U., Meier, J., Gort, G., Comans, R., Mäder, P., Brussaard, L., de Goede, R., 2019. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecological Indicators 99, 38–50. https://doi.org/10.1016/j.ecolind.2018.12.008.

Bongiorno, G., 2020. Novel soil quality indicators for the evaluation of agricultural management practices: a biological perspective. Frontiers of Agricultural Science and Engineering 7 (3), 257–274. https://doi.org/10.15302/J-FASE-2020323.

Bonilla, N., Gutiérrez-Barranquero, J.A., De Vicente, A., Cazorla, F.M., 2012. Enhancing soil quality and plant health through suppressive organic amendments. Diversity. https://doi.org/10.3390/d4040475.

Braga, R.M., Dourado, M.N., Araújo, W.L., 2016. Microbial interactions: ecology in a molecular perspective. Brazilian Journal of Microbiology. https://doi.org/10.1016/j.bjm.2016.10.005.

Brown, K.A., 1982. Sulphur in the environment: a review. Environmental Pollution Series B Chemical and Physical 3, 47–80. https://doi.org/10.1016/0143-148X(82)90042-8.

Brussaard, L., Kuyper, T.W., Didden, W.A.M., Goede, R.G.M. de, Bloem, J., 2004. Biological soil quality from biomass to biodiversity - importance and resilience to management stress and disturbance. Managing Soil Quality: Challenges in Modern Agriculture 139–161. https://doi.org/10.1079/9780851996714.0139.

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.

Cluzeau, D., Guernion, M., Chaussod, R., Martin-Laurent, F., Villenave, C., Cortet, J., Ruiz-Camacho, N., Pernin, C., Mateille, T., Philippot, L., Bellido, A., Rougé, L., Arrouays, D., Bispo, A., Pérès, G., 2012. Integration of biodiversity in soil quality monitoring: baselines for microbial and soil fauna parameters for different land-use types. European Journal of Soil Biology 49, 63–72. https://doi.org/10.1016/j.ejsobi.2011.11.003.
Cook, R.J., 2014. Plant Health Management: Pathogen Suppressive Soils, Encyclopedia of Agriculture and Food Systems. Elsevier Ltd. https://doi.org/10.1016/B978-0-444-52512-3.00182-0.
Curl, E.A., Old, K.M., 1988. The role of soil microfauna in plant-disease suppression. Critical Reviews in Plant Sciences 7, 175–196. https://doi.org/10.1080/07352688809382263.
Dawod, V., FitzPatrick, E.A., 1993. Some population sizes and effects of the Enchytraeidae (Oligochaeta) on soil structure in a selection of Scottish soils. Geoderma 56, 173–178. https://doi.org/10.1016/0016-7061(93)90108-W.
de Boer, W., Li, X., Meisner, A., Garbeva, P., 2019. Pathogen suppression by microbial volatile organic compounds in soils. FEMS Microbiology Ecology 95. https://doi.org/10.1093/femsec/fiz105.
de Ruiter, P.C., van Veen, J.A., Moore, J.C., Brussaard, L., Hunt, H.W., 1993. Calculation of nitrogen mineralization in soil food webs. Plant and Soil 157, 263–273. https://doi.org/10.1007/bf00011055.
Debeljak, M., Trajanov, A., Kuzmanovski, V., Schröder, J., Sandén, T., Spiegel, H., Wall, D.P., Van de Broek, M., Rutgers, M., Bampa, F., Creamer, R.E., Henriksen, C.B., 2019. A field-scale decision support system for assessment and management of soil functions. Frontiers in Environmental Science 7, 115. https://doi.org/10.3389/fenvs.2019.00115.
Delgado-baquerizo, M., Reich, P.B., Trivedi, C., Eldridge, D.J., Abades, S., Alfaro, F.D., Bastida, F., Berhe, A.A., Cutler, N.A., Gallardo, A., García-velázquez, L., Hart, S.C., Hayes, P.E., He, J., Hseu, Z., Hu, H., Kirchmair, M., Neuhauser, S., 2020. Ecosystem functions across biomes. Nature Ecology & Evolution 4. https://doi.org/10.1038/s41559-019-1084-y.
Doran, J.W., Parkin, T.B., 1997. Quantitative indicators of soil quality: a minimum data set. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp. 25–37.
Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Defining Soil Quality for a Sustainable Environment. SSSA, Madison, WI, USA, pp. 3–21.
Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15, 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6.
Drobnik, T., Greiner, L., Keller, A., Grêt-Regamey, A., 2018. Soil quality indicators – from soil functions to ecosystem services. Ecological Indicators 94, 151–169. https://doi.org/10.1016/j.ecolind.2018.06.052.
EC, 2006. Proposal for a Directive of the European Parliament and of the Council Establishing a Framework for the Protection of Soils and Amending Directive 2004/35/EC.
Eijsackers, H., Zehnder, A.J.B., 1990. Litter decomposition: a Russian matriochka doll. Biogeochemistry 11, 153–174. https://doi.org/10.1007/BF00004495.
FAO, 2021a. What Are Physical Soil Properties, p. 7a.
FAO, 2021b. What Are Biological and Chemical Sil Properties, p. 7b.
Fierer, N., Wood, S.A., Bueno de Mesquita, C.P., 2021. How microbes can, and cannot, be used to assess soil health. Soil Biology and Biochemistry 153, 108111. https://doi.org/10.1016/j.soilbio.2020.108111.
Fleck, S., Cools, N., De Vos, B., Meesenburg, H., Fischer, R., 2016. The Level II aggregated forest soil condition database links soil physicochemical and hydraulic properties with long-term observations of forest condition in Europe. Annals of Forest Science 73, 945–957.
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.
Glæsner, N., Helming, K., de Vries, W., 2014. Do current European policies prevent soil threats and support soil functions? Sustainability 6, 9538–9563. https://doi.org/10.3390/su6129538.
Gómez Expósito, R., de Bruijn, I., Postma, J., Raaijmakers, J.M., 2017. Current insights into the role of rhizosphere bacteria in disease suppressive soils. Frontiers in Microbiology 8, 2529. https://doi.org/10.3389/fmicb.2017.02529.
Griffiths, B.S., Faber, J., Bloem, J., 2018. Applying Soil Health Indicators to Encourage Sustainable Soil Use : The Transition from Scientific Study to Practical Application, vol. 10. https://doi.org/10.3390/su10093021.
Giuffré, G., Ricci, A., Bisoffi, S., Dönitz, E., Voglhuber-Slavinsky, A., Helming, K., Evgrafova, A., Ratinger, T., Robinson, D.A., 2021. Mission Area: Soil Health and Food Foresight on Demand Brief in Support of the Horizon Europe Mission Board. Publications Office of the European Union 2021, Luxembourg. https://doi.org/10.2777/038626.
Hanegraaf, M.C., van den Elsen, H.G.M., de Haan, J.J., Visser, S.M., 2019. Bbodemkwaliteitsbeoordeling van landbouwgronden in Nederland – indicatorset en systematiek, versie 1.0. https://doi.org/10.18174/498307. Wageningen Research, Rapport WPR-795.
Hättenschwiler, S., Tiunov, A.V., Scheu, S., 2005. Biodiversity and Litter Decomposition in Terrestrial Ecosystems. Annual Review of Ecology, Evolution, and Systematics.
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.
Heikens, A., Peijnenburg, W.J.G.M., Hendriks, A.J., 2001. Bioaccumulation of heavy metals in terrestrial invertebrates. Environmental Pollution 113, 385–393. https://doi.org/10.1016/S0269-7491(00)00179-2.
Hölting, L., Beckmann, M., Volk, M., Cord, A.F., 2019. Multifunctionality assessments – more than assessing multiple ecosystem functions and services? A quantitative literature review. Ecological Indicators 103, 226–235. https://doi.org/10.1016/j.ecolind.2019.04.009.
Hu, B., Shen, L., Xu, X., Zheng, P., 2011. Anaerobic ammonium oxidation (anammox) in different natural ecosystems. Biochemical Society Transactions 39, 1811–1816. https://doi.org/10.1042/BST20110711.
Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones, R.J.A., Kibblewhite, M. G., Lexer, W., Möller, A., Rickson, R.J., Shishkov, T., Stephens, M., Toth, G., Van den Akker, J.J.H., Varallyay, G., Verheijen, F.G.A., Jones, A.R., 2008. Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria. EUR 23490 EN/1. Office for the Official Publications of the European Communities, Luxembourg.
Huerta Lwanga, E., Thapa, B., Yang, X., Gertsen, H., Salánki, T., Geissen, V., Garbeva, P., 2018. Decay of low-density polyethylene by bacteria extracted from earthworm's guts: a potential for soil restoration. The Science of the Total Environment 624, 753–757. https://doi.org/10.1016/j.scitotenv.2017.12.144.
Janzen, H.H., Janzen, D.W., Gregorich, E.G., 2021. The 'soil health' metaphor: illuminating or illusory? Soil Biology and Biochemistry, 108167. https://doi.org/10.1016/j.soilbio.2021.108167.
Karlen, D.L., Ditzler, C.A., Andrews, S.S., 2003. Soil quality: why and how? Geoderma. The Assessment of Soil Quality 114, 145–156. https://doi.org/10.1016/S0016-7061(03)00039-9.
Kibblewhite, M.G., 2012. Definition of priority areas for soil protection at a continental scale. Soil Use & Management 28, 128–133. https://doi.org/10.1111/j.1475-2743.2011.00375.x.
Laudadio, I., Fulci, V., Stronati, L., Carissimi, C., 2019. Next-generation metagenomics: methodological challenges and opportunities. OMICS: A Journal of Integrative Biology 23, 327–333. https://doi.org/10.1089/omi.2019.0073.
Lavallee, J.M., Soong, J.L., Cotrufo, M.F., 2019. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Global Change Biology. https://doi.org/10.1111/gcb.14859, 0.
Lehman, R.M., Acosta-Martinez, V., Buyer, J.S., Cambardella, C.A., Collins, H.P., Ducey, T.F., Halvorson, J.J., Jin, V.L., Johnson, J.M.F., Kremer, R.J., Lundgren, J.G., Manter, D.K., Maul, J.E., Smith, J.L., Stott, D.E., 2015a. Soil biology for resilient, healthy soil. Journal of Soil and Water Conservation 70, 12A–18A. https://doi.org/10.2489/jswc.70.1.12A.
Lehman, R.M., Cambardella, C.A., Stott, D.E., Acosta-Martinez, V., Manter, D.K., Buyer, J.S., Maul, J.E., Smith, J.L., Collins, H.P., Halvorson, J.J., Kremer, R.J., Lundgren, J.G., Ducey, T.F., Jin, V.L., Karlen, D.L., 2015b. Understanding and enhancing soil biological health: the solution for reversing soil degradation. Sustainability. https://doi.org/10.3390/su7010988.
Lehmann, J., Bossio, D.A., Kögel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. Nature Reviews Earth & Environment 1, 544–553. https://doi.org/10.1038/s43017-020-0080-8.
Lemanceau, P., Maron, P.-A., Mazurier, S., Mougel, C., Pivato, B., Plassart, P., Ranjard, L., Revellin, C., Tardy, V., Wipf, D., 2015. Understanding and managing soil biodiversity: a major challenge in agroecology. Agronomy for Sustainable Development 35, 67–81. https://doi.org/10.1007/s13593-014-0247-0.
Lemanceau, P., Maurhofer, M., Défago, G., 2006. Contribution of studies on suppressive soils to the identification of bacterial biocontrol agents and to the knowledge of their modes of action. In: Plant-Associated Bacteria. Springer Netherlands, pp. 231–267. https://doi.org/10.1007/978-1-4020-4538-7_7.
Lima, A.C.R., Brussaard, L., Totola, M.R., Hoogmoed, W.B., de Goede, R.G.M., 2013. A functional evaluation of three indicator sets for assessing soil quality. Applied Soil Ecology 64, 194–200. https://doi.org/10.1016/j.apsoil.2012.12.009.
Liu, H., Brettell, L.E., Qiu, Z., Singh, B.K., 2020. Microbiome-mediated stress resistance in plants. Trends in Plant Science. https://doi.org/10.1016/j.tplants.2020.03.014.
Mausel, P.W., 1971. Soil quality in Illinois—an example of a soils geography resource analysis. The Professional Geographer 23, 127–136.
Mazzola, M., 2002. Mechanisms of Natural Soil Suppressiveness to Soilborne Diseases. Antonie van Leeuwenhoek.
Mills, A.L., 2019. Qualitative and quantitative aspects of the modern nitrogen cycle. In: Hurst, C.J. (Ed.), Understanding Terrestrial Microbial Communities, Advances in Environmental Microbiology. Springer International Publishing, Cham, pp. 31–63.
Montanarella, L., Panagos, P., 2021. The relevance of sustainable soil management within the European Green Deal. Land Use Policy 100, 104950. https://doi.org/10.1016/j.landusepol.2020.104950.
Morvan, X., Saby, N.P.A., Arrouays, D., Le Bas, C., Jones, R.J.A., Verheijen, F.G.A., Bellamy, P.H., Stephens, M., Kibblewhite, M.G., 2008. Soil monitoring in Europe: a review of existing systems and requirements for harmonisation. The Science of the Total Environment 391, 1–12. https://doi.org/10.1016/j.scitotenv.2007.10.046.
Neher, D., Barbercheck, M., 2019. Soil microarthropods and soil health: intersection of decomposition and pest suppression in agroecosystems. Insects 10, 414. https://doi.org/10.3390/insects10120414.
Nielsen, U.N., Ayres, E., Wall, D.H., Bardgett, R.D., 2011. Soil biodiversity and carbon cycling: a review and synthesis of studies examining diversity–function relationships. European Journal of Soil Science 62, 105–116. https://doi.org/10.1111/j.1365-2389.2010.01314.x.
Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., Fernández-Ugalde, O., 2018. LUCAS Soil, the largest expandable soil dataset for Europe: a review. European Journal of Soil Science 69, 140–153. https://doi.org/10.1111/ejss.12499.
Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R., 1997. Biological indicators of soil health: Synthesis. In: Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health. CAB International, pp. 419–435.
Pascale, A., Proietti, S., Pantelides, I.S., Stringlis, I.A., 2020. Modulation of the root microbiome by plant molecules: the basis for targeted disease suppression and plant growth promotion. Frontiers of Plant Science 10, 1741. https://doi.org/10.3389/fpls.2019.01741.

Pearsons, K.A., Tooker, J.F., 2017. In-field habitat management to optimize pest control of novel soil communities in agroecosystems. Insects 8. https://doi.org/10.3390/insects8030082.

Peterson, J.A., Ode, P.J., Oliveira-Hofman, C., Harwood, J.D., 2016. Integration of plant defense traits with biological control of arthropod pests: challenges and opportunities. Frontiers of Plant Science 7, 1–23. https://doi.org/10.3389/fpls.2016.01794.

Pinillos, D., Bianchi, F.J.J.A., Poccard-Chapuis, R., Corbeels, M., Tittonell, P., Schulte, R.P.O., 2020. Understanding landscape multifunctionality in a post-forest frontier: supply and demand of ecosystem services in eastern Amazonia. Frontiers in Environmental Science 7, 206. https://doi.org/10.3389/fenvs.2019.00206.

Postma, J., Schilder, M.T., Bloem, J., Leeuwen-haagsma, W.K. Van, 2008. Soil suppressiveness and functional diversity of the soil microflora in organic farming systems. Soil Biology & Biochemistry 40, 2394–2406. https://doi.org/10.1016/j.soilbio.2008.05.023.

Postma, J.A., Schurr, U., Fiorani, F., 2014. Dynamic root growth and architecture responses to limiting nutrient availability: linking physiological models and experimentation. Biotechnology Advances, Plant Biotechnology 2013: "Green for Good II" 32, 53–65. https://doi.org/10.1016/j.biotechadv.2013.08.019.

Powlson, D.S., 2020. Soil health — useful terminology for communication or meaningless concept ? Or both ? Frontiers of Agricultural Science and Engineering 7, 246–250.

Read, D.J., Perez-Moreno, J., 2003. Mycorrhizas and nutrient cycling in ecosystems - a journey towards relevance? New Phytologist 157, 475–492. https://doi.org/10.1046/j.1469-8137.2003.00704.x.

Reed, S.C., Cleveland, C.C., Townsend, A.R., 2011. Functional ecology of free-living nitrogen fixation: a contemporary perspective. Annual Review of Ecology, Evolution and Systematics 42, 489–512. https://doi.org/10.1146/annurev-ecolsys-102710-145034.

Richardson, A.E., Lynch, J.P., Ryan, P.R., Delhaize, E., Smith, F.A., Smith, S.E., Harvey, P.R., Ryan, M.H., Veneklaas, E.J., Lambers, H., Oberson, A., Culvenor, R.A., Simpson, R.J., 2011. Plant and microbial strategies to improve the phosphorus efficiency of agriculture. Plant and Soil 349, 121–156. https://doi.org/10.1007/s11104-011-0950-4.

Rillig, M.C., Mummey, D.L., 2006. Mycorrhizas and soil structure. New Phytologist 171, 41–53. https://doi.org/10.1111/j.1469-8137.2006.01750.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, 1212–1221. https://doi.org/10.1016/j.ecolind.2009.02.009.

Robertson, G.P., Groffman, P.M., 2007. Nitrogen transformations. In: Paul, E.A. (Ed.), Soil Microbiology, Ecology and Biochemistry, third ed. Academic Press, San Diego, pp. 341–364. https://doi.org/10.1016/B978-0-08-047514-1.50017-2.

Rutgers, M., Schouten, A.J., Bloem, J., Van Eekeren, N., De Goede, R.G.M., Jagersop Akkerhuis, G., Van der Wal, A., Mulder, C., Brussaard, L., Breure, A.M., 2009. Biological measurements in a nationwide soil monitoring network. European Journal of Soil Science 60, 820–832.

Rutgers, M., Wijnen, H.J. Van, Schouten, A.J., Mulder, C., Kuiten, A.M.P., Brussaard, L., Breure, A.M., 2012. A method to assess ecosystem services developed from soil attributes with stakeholders and data of four arable farms. The Science of the Total Environment 415, 39–48. https://doi.org/10.1016/j.scitotenv.2011.04.041.

Rütting, T., Boeckx, P., Müller, C., Klemedtsson, L., 2011. Assessment of the importance of dissimilatory nitrate reduction to ammonium for the terrestrial nitrogen cycle. Biogeosciences 8, 1779–1791. https://doi.org/10.5194/bg-8-1779-2011.

Saby, N., Brus, D.J., Boukir, H., Mulder, V.L., 2015. Approximating the sampling variance of means estimated from systematic random sample data of the French soil monitoring network. Pedometrics. https://hal.inrae.fr/hal-02801717/document.

Sandén, T., Spiegel, H., Stüger, H.-P., Schlatter, N., Haslmayr, H.-P., Zavattaro, L., Grignani, C., Bechini, L., D'Hose, T., Molendijk, L., Pecio, A., Jarosz, Z., Guzmán, G., Vanderlinden, K., Giráldez, J.V., Mallast, J., Berge, H. ten, 2018. European long-term field experiments: knowledge gained about alternative management practices. Soil Use & Management 34, 167–176. https://doi.org/10.1111/sum.12421.

Schlatter, D., Kinkel, L., Thomashow, L., Weller, D., Paulitz, T., 2017. Disease suppressive soils: new insights from the soil microbiome. Phytopathology 107, 1284–1297. https://doi.org/10.1094/PHYTO-03-17-0111-RVW.

Schloter, M., Dilly, O., Munch, J.C., 2003. Indicators for evaluating soil quality. Agriculture, Ecosystems & Environment 98, 255–262. https://doi.org/10.1016/S0167-8809(03)00085-9.

Schröder, J.J., Schulte, R.P.O., Creamer, R.E., Delgado, A., Leeuwen, J. van, Lehtinen, T., Rutgers, M., Spiegel, H., Staes, J., Tóth, G., Wall, D.P., 2016. The elusive role of soil quality in nutrient cycling: a review. Soil Use & Management 32, 476–486. https://doi.org/10.1111/sum.12288.

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. https://doi.org/10.1016/j.envsci.2013.10.002.

Serrano-Silva, N., Sarria-Guzmán, Y., Dendooven, L., Luna-Guido, M., 2014. Methanogenesis and methanotrophy in soil: a review. Pedosphere 24, 291–307. https://doi.org/10.1016/S1002-0160(14)60016-3.

Sharma, S.K., Ramesh, A., Sharma, M.P., Joshi, O.P., Govaerts, B., Steenwerth, K.L., Karlen, D.L., 2010. Microbial Community Structure and Diversity as Indicators for Evaluating Soil Quality, pp. 317–358. https://doi.org/10.1007/978-90-481-9513-8_11.

Singh, M., Sarkar, B., Sarkar, S., Churchman, J., Bolan, N., Mandal, S., Menon, M., Purakayastha, T.J., Beerling, D.J., 2018. Stabilization of soil organic carbon as influenced by clay mineralogy. In: Advances in Agronomy, first ed. Elsevier Inc. https://doi.org/10.1016/bs.agron.2017.11.001.

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, 7–31.

Stone, D., Costa, D., Daniell, T.J., Mitchell, S.M., Topp, C.F.E., Griffiths, B.S., 2016. Using nematode communities to test a European scale soil biological monitoring programme for policy development. Applied Soil Ecology 97, 78–85. https://doi.org/10.1016/j.apsoil.2015.08.017.

Taylor, A.R., Lenoir, L., Vegerfors, B., Persson, T., 2019. Ant and earthworm bioturbation in cold-temperate ecosystems. Ecosystems 22, 981–994.

Thiele-Bruhn, S., Schloter, M., Wilke, B.M., Beaudette, L.A., Martin-Laurent, F., Cheviron, N., Mougin, C., Römbke, J., 2020. Identification of new microbial functional standards for soil quality assessment. Soils 6, 17–34. https://doi.org/10.5194/soil-6-17-2020.

Thomas, T., Gilbert, J., Meyer, F., 2012. Metagenomics - a guide from sampling to data analysis. Microbial Informatics and Experimentation 2, 3. https://doi.org/10.1186/2042-5783-2-3.

Thoumazeau, A., Bessou, C., Renevier, M.-S., Trap, J., Marichal, R., Mareschal, L., Decaëns, T., Bottinelli, N., Jaillard, B., Chevallier, T., Suvannang, N., Sajjaphan, K., Thaler, P., Gay, F., Brauman, A., 2019. Biofunctool®: a new framework to assess the impact of land management on soil quality. Part A: concept and validation of the set of indicators. Ecological Indicators 97, 100–110. https://doi.org/10.1016/j.ecolind.2018.09.023.

Topalovic, O., Hussain, M., Heuer, H., 2020. Plants and associated soil microbiota cooperatively suppress. Plant-Parasitic Nematodes 11, 1–15. https://doi.org/10.3389/fmicb.2020.00313.

Trajanov, A., Schröder, J., Wall, D., Delgado, A., Schulte, R., Debeljak, M., 2019. Assessing the nutrient cycling potential in agricultural soils using decision modelling. In: Proceedings of the 15th International Symposium on Operational Research, SOR 2019. - SLOVENIAN SOCIETY INFORMATIKA (Proceedings of the 15th International Symposium on Operational Research, SOR 2019), pp. 23–27, 9789616165556 - p.

Van de Broek, M., Henriksen, C.B., Ghaley, B.B., Lugato, E., Kuzmanovski, V., Trajanov, A., Debeljak, M., Sandén, T., Spiegel, H., Decock, C., Creamer, R., Six, J., 2019. Assessing the climate regulation potential of agricultural soils using a decision support tool adapted to stakeholders' needs and possibilities. Frontiers in Environmental Science 7, 131.

van Leeuwen, J.P., Creamer, R.E., Cluzeau, D., Debeljak, M., Gatti, F., Henriksen, C.B., Kuzmanovski, V., Menta, C., Pérès, G., Picaud, C., Saby, N.P.A., Trajanov, A., 2019. Modeling of soil functions for assessing soil quality : soil biodiversity and habitat provisioning. Frontiers in Environmental Science 7, 1–13. https://doi.org/10.3389/fenvs.2019.00113.

van Leeuwen, J.P., Saby, N.P.A., Jones, A., Louwagie, G., Micheli, E., Rutgers, M., Schulte, R.P.O., Spiegel, H., Toth, G., Creamer, R.E., 2017. Gap assessment in current soil monitoring networks across Europe for measuring soil functions. Environmental Research Letters 12, 124007. https://doi.org/10.1088/1748-9326/aa9c5c.

van Loon, L.C., Bakker, P.A.H.M., Pieterse, C.M.J., 1998. Systemic resistance induced by rhizhosphere bacteria. Annual Review of Phytopathology 36, 453–483.

van Wesemael, B., Paustian, K., Andrén, O., Cerri, C.E.P., Dodd, M., Etchevers, J., Goidts, E., Grace, P., Kätterer, T., McConkey, B.G., 2011. How can soil monitoring networks be used to improve predictions of organic carbon pool dynamics and CO 2 fluxes in agricultural soils? Plant and Soil 338, 247–259.

Vazquez, C., de Goede, R.G.M., Rutgers, M., de Koeijer, T.J., Creamer, R.E., 2021. Assessing multifunctionality of agricultural soils: reducing the biodiversity trade-off. European Journal of Soil Science 72 (4), 1624–1639. https://doi.org/10.1111/ejss.13019.

Veerman, C., Correia, T.P., Bastioli, C., Biro, B., Bouma, J., Cienciala, E., Emmett, B., Frison, E.A., Grand, A., Filchew, L.H., Kriaučiūnienė, Z., Pogrzeba, M., Soussana, J.-F., Olmo, C.V., Wittkowski, R., 2020. Caring for Soil Is Caring for Life - Ensure 75% of Soils Are Healthy by 2030 for Food, People, Nature and Climate.

Visser, S., Parkinson, D., 1992. Soil biological criteria as indicators of soil quality: soil microorganisms. American Journal of Alternative Agriculture 7 (1–2), 33–37.

Vogel, H.-J., Bartke, S., Daedlow, K., Helming, K., Kögel-Knabner, I., Lang, B., Rabot, E., Russell, D., Stößel, B., Weller, U., 2018. A systemic approach for modeling soil functions. Soils 4, 83.

Wall, D.P., Delgado, A., O'Sullivan, L., Creamer, R.E., Trajanov, A., Kuzmanovski, V., Bugge-Henriksen, C., Debeljak, M., 2020. A decision support model for assessing the water regulation and purification potential of agricultural soils across Europe. Frontiers in Sustainable Food Systems 4. https://doi.org/10.3389/fsufs.2020.00115.

Xiong, W., Song, Y., Yang, K., Gu, Y., Wei, Z., Kowalchuk, G.A., Xu, Y., Jousset, A., Shen, Q., Geisen, S., 2020. Rhizosphere protists are key determinants of plant health. Microbiome 8, 27. https://doi.org/10.1186/s40168-020-00799-9.

Zheng, Q., Hu, Y., Zhang, S., Noll, L., Böckle, T., Dietrich, M., Herbold, C.W., Eichorst, S. A., Woebken, D., Richter, A., Wanek, W., 2019. Soil multifunctionality is affected by the soil environment and by microbial community composition and diversity. Soil Biology and Biochemistry 136. https://doi.org/10.1016/j.soilbio.2019.107521.

Zwetsloot, M.J., Bongiorno, G., Barel, J.M., di Lonardo, P., Creamer, R.E., 2022. A flexible selection tool for the inclusion of soil biology methods in the assessment of soil multi-functionality. Soil Biology and Biochemistry. SBB 108514. In this issue.

Zwetsloot, M.J., van Leeuwen, J.P., Hemerik, L., Martens, H., Simó Josa, I., Van de Broek, M., Debeljak, M., Rutgers, M., Sandén, T., Wall, D.P., Jones, A., Creamer, R.E., 2021. Soil multifunctionality: synergies and trade-offs across European climatic zones and land uses. European Journal of Soil Science 72 (4), 1640–1654. https://doi.org/10.1111/ejss.13051.