



A conceptual framework for soil function evaluation: Towards a common base

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ABSTRACT

The increasing pressure of humans on soils affects their ability to provide key functions and deliver ecosystem services. In the last decades, many methods and tools have been developed to evaluate soil functions, with the aim of providing guidance to land users and policymakers for the sustainable management of soil resources. These methods and tools, however, have been developed in isolation from each other using different conceptual frameworks such as soil health or soil quality, which in turn have evolved over time. This currently results in a diversity of available terminology and definitions to represent the objectives of evaluation and to describe the information on soil functions that is produced in the quantification process. For actors interested in soil function evaluation, this diversity is a source of confusion. In this paper, we develop a conceptual framework to describe the types of information on soil functions that can be searched for and link them with soil functioning and user needs. These concepts are soil function supply, soil dynamic capacity for a function, and soil inherent capacity for a function. The framework is then used with a set of publications on soil function evaluation to identify the information on soil functions they produce and helps rank these publications in terms of objectives and produced information. We highly recommend authors to use our framework to explicitly link their objectives with the information on soil functions that is sought and the method used to obtain this information, in relation to the specific context of the study. The framework also helps to open up a discussion on the fundamentals of monitoring soil functions for the sustainable use of soil resources.

1. Introduction

The contribution of soils to ecosystems and human well-being is being increasingly recognized in national and international initiatives (e.g. FAO and ITPS, 2015; DAW, 2021). At the same time, the awareness of the extent of soil degradation caused by human actions is growing (Kopittke et al., 2019). As a consequence, interest in soil function evaluation is also increasing, notably in environmental assessments (e.g. Garrigues et al., 2012; Jónsson and Davíðsdóttir, 2016) and policy making (e.g. Directorate-General for Environment, 2023). Evaluating soil functions is indeed a necessary first step towards better soil management and soil protection aiming at safeguarding worldwide food production capacities, along with numerous essential soil functions, such as water regulation and purification, nutrient cycling, carbon storage, and the host of biodiversity. Here, the term “soil function” is used in the meaning of soil “roles” according to Baveye et al. (2016). Other meanings of this term are found in the literature (Baveye et al., 2016), such as “process”, i.e. “the transformation of input into outputs” (Dominati et al., 2010). In this paper, soil functions are defined as the outcomes of soil processes, and are expressed with

physical units. For example, the carbon storage function is the amount of CO₂ stored over a period of time. In our framework, the terms “food production”, “water regulation” and the other soil “roles” can gather numerous soil functions and can be designated as categories of soil functions (see 2.1).

Soil function evaluation is a general term to designate any attempt to produce information on soil for decision-making. This implies that its outputs can be understood by the targeted group of stakeholders. Soil function evaluation thus consists in the production of aggregated or summary metrics on soil functions based on primary information on its properties and its environment. These metrics are generally called “indicators” of soil functions. An indicator is calculated for each quantified soil function (Wienhold et al., 2009), and the function indicators can eventually be aggregated into a unique soil index (Doran and Parkin, 1994). Soil function evaluation can be performed in different contexts and for various purposes, such as land planning (e.g. Danner et al., 2003; Lehmann et al., 2013) or farm-scale soil and crop management (e.g. Moebius-Clune et al., 2016; Debeljak et al., 2019). This results in a diversity of conceptual approaches and quantification methods.

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There are three questions at the core of any soil function evaluation: (1) what is the objective of the evaluation?; (2) What information on which soil functions is needed to achieve this objective?; and (3) What method is best suited to obtain this information in the context of the study? The information on soil is at the centre of this questioning, but it is often omitted in publications on soil function evaluation, which results in a gap between objectives and methods. In this paper, we focus on this information that is produced and provide a new conceptual framework designed to help better understand the functioning of soils with a strong focus on the supply of soil functions and identify what information can theoretically be produced on soil functions. We address this framework to any person implied in soil function evaluation as a guide to develop scientifically based evaluation methods suited to their needs and to communicate these methods efficiently. In the framework, we describe as “aspects” (i.e. soil aspect, aspect of a function) the different types of information that can be produced on soil or on soil functions. Given their objectives and contexts, different actors will want to gain knowledge on different aspects of their soils.

Our conceptual framework consists of three pillars:

1. The soil under study. This pillar addresses the following questions: What is a soil, how does it function, and how are “soil functions” defined? Starting from basic definitions allows us to better introduce more complex concepts in the third pillar.
2. The soil users, their interests, and their impacts on soil. There would be no need to evaluate soils if humans did not have an interest in the functions provided by them and if they had no impact on soil functioning. In this pillar, different types of soil users and their links with soil are presented. In the perspective of a soil evaluation, this would help better understand user needs in terms of soil evaluation and better formulate the objectives of the evaluation.
3. The types of information that can be produced from soils, also described as quantification aspects. These aspects can be summarized in three main concepts: function supply, soil dynamic capacity for a function, and soil inherent capacity for a function. They can serve as basis to define soil degradation and the sustainability of a land use.

The following three sections present each pillar of the conceptual framework. Each pillar is complemented by a brief overview of the literature based on a corpus of 36 publications for a total of 33 soil evaluation methods, obtained through a systematic search on the Web of Science Core Collection. More information on paper selection and the building of the corpus can be found in the Supplementary Material. In this review of available methods, the information of importance in the selected papers was: (i) what are the objectives pursued with soil evaluation, (ii) how the authors link their objectives with the evaluation method, (iii) what is the exact soil object under study (i.e. characteristics such as depth, target properties), and (iv) based on the methodology, what information do the produced indicators convey? The important definitions of the conceptual framework are summarized at the end of the framework in [Box 1](#). Note that our framework is purely conceptual. We do not provide any recommendation in terms of methodological choice to assess one or the other aspects. The study of the literature corpus gives an overall idea of the existing methods.

2. Pillar 1: The “soil” under study

Soil functioning is the basis for any reflection on soil evaluation. Basic knowledge on soil is therefore required to understand the different information on soil that we might want to obtain through soil evaluation. We therefore need to introduce what a soil is, how it functions, and define the soil functions on which we want to produce information. This is treated as the first pillar of our conceptual framework and presented in this section.

2.1. Conceptual framework

From a pedological perspective, soil is composed of superimposed horizons that differ from the parent material, extending from the surface to a variable depth. For the purpose of soil evaluation, we propose addressing the question of soil depth by extending the definition of soil to include any material that supports root growth, with a maximum depth of 2 metres, as suggested by the [Soil Survey Staff \(1999\)](#). Thus, soil evaluation consists in assessing the processes occurring below the Earth’s surface, from the surface itself down to the defined soil depth. In [Fig. 1](#), we provide a schematic representation of the soil and its relationship with its environment.

Soil properties refer to the characteristics or components that describe the soil. They can be either measured or qualitatively assessed. Example soil properties are structure, pH, and number of earthworms, which represent physical, chemical, and biological properties, respectively. The pH is related to the concentration of protons and can be quantitatively measured, while soil structure is a physical characteristic that is often qualitatively assessed in the field.

Soil is formed over long periods through the alteration of one or more parent materials. As a consequence, soil properties inherently evolve, although not at the same rate. We define inherent properties as those that remain stable over a human lifetime, provided no extreme events occur; examples are texture, mineralogy, and depth. These properties typically arise from pedogenesis. In contrast, dynamic properties such as carbon content, infiltrability, and microbial biomass are subject to change. Dynamic properties can be further classified based on their short-term variability: some, such as microbial biomass, show significant fluctuations within a year, while others, such as stable organic matter content, show changes that can only be observed over several years.

A soil is intrinsically linked to its environment: lithology (i.e. the geological substrate), hydrogeology (i.e. the proximity to groundwater), topography (e.g. the slope and landscape), vegetation cover and organization in the landscape, and climate. We define environmental factors as natural elements that influence the input and output fluxes in soils. By “fluxes”, we refer to transfers of matter (such as water, organisms, and organic matter) or energy (e.g. temperature). The environmental factors and the fluxes originating from these components are depicted in [Fig. 1](#) in green. The environment of a soil significantly affects its functioning by controlling fluxes at its boundaries.

Transformations occur in soils. Soil processes are defined as the mechanisms and actions that take place within soils, resulting from complex interactions amongst soil physical components (i.e. water, solid matrix, air), chemical properties (e.g. pH, composition of the different phases), and living organisms. For example, water circulation in soils (i.e. a process) is influenced by the structure, texture, and retention properties (i.e. properties) of different horizons, the uptake from plants and organisms (i.e. other processes), and environmental factors such as climate, distance to the saturated zone, and hydraulic conductivity of underlying materials. Soil processes can modify soil properties and lead to output fluxes. These processes control the dynamics of soil properties’ evolution.

Organisms play a key role in soils ([Creamer et al., 2022](#)). They participate in numerous processes, some of which would not be possible without their involvement. This is particularly the case for various physical and chemical processes, such as the physical degradation and mineralization of organic matter. In [Fig. 1](#), we depicted the interaction between soil properties, soil organisms, and soil processes with the feedback loop arrows shown in black.

We define soil functions as the outcomes of soil processes, providing a common definition of soil functions as what soil does, independent of human interests ([Calvaruso et al., 2021](#); [Rabot et al., 2018](#); [Seybold et al., 1998](#)). Soil functions represent fluxes or consequences resulting from processes. For example, during or after a rain event, a portion of the precipitation may leave the soil and percolate deeper towards the

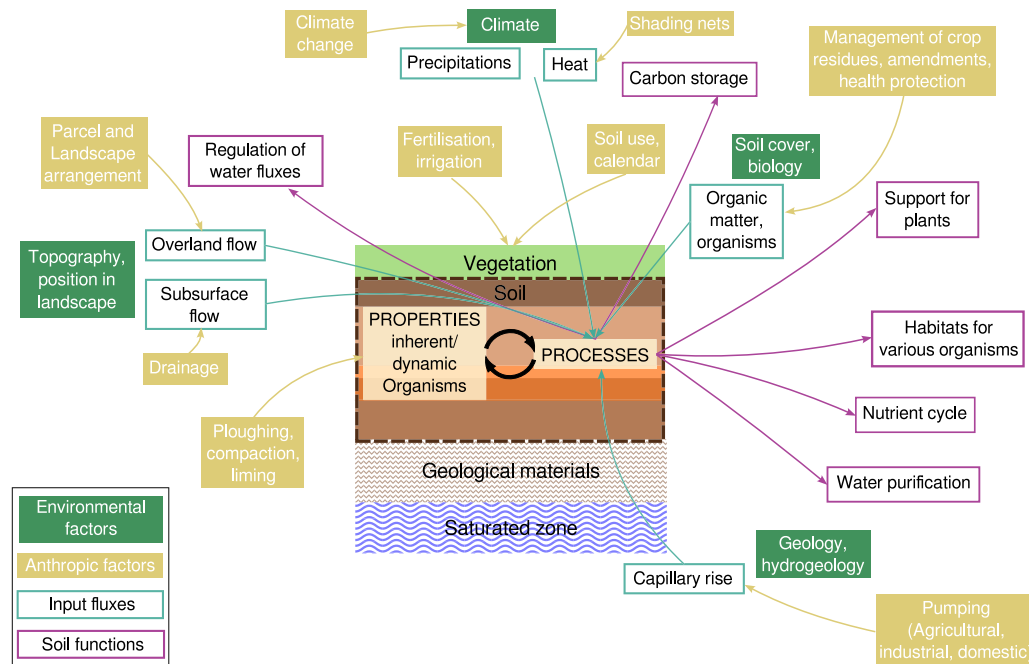


Fig. 1. Soil representation in our conceptual framework. The soil is delimited with dashed black lines, and is surrounded by its environment. Plain boxes represent environmental and anthropogenic factors having an effect on soils. Enclosed boxes represent fluxes. External factors generate input fluxes, and output fluxes are designated as soil functions.

groundwater, with the associated function being groundwater recharge. Another portion of this water may be absorbed by plants through their roots (i.e. a process) and later transpired through stomata. The corresponding function is the supply of water for plants, which represents the flux of water moving from the soil to the plant, and eventually to the atmosphere. If conditions are favourable, a population of organisms may grow and stabilize (i.e. through the process of reproduction). The associated function in this case is the provision of habitat for these organisms, measured by the quantity of births or the renewal rate.

Soils provide multiple functions, some of which are antagonistic while others are synergistic. We refer to soils as multifunctional. Typically, soil functions are grouped into general categories (as depicted in Fig. 1 with purple arrows and boxes). The specific boundaries of these categories can vary among authors, but we commonly include the following: primary productivity (or support for plants), water purification and regulation (or role in the global water cycle), nutrient cycling, carbon storage and climate regulation, and the provision of habitats for organisms.

Processes and functions do not have absolute definitions. Most processes can be decomposed into more elementary processes. For example, the mineralization of a molecule into CO_2 involves several fundamental processes. Another example is soil primary productivity, which results from the supply of water and nutrients from soil to plants, but the supply of water to plants also plays a role in the water purification and regulation function. There is always some overlap between processes and functions.

The constant evolution and complex dynamics of soil properties and environmental factors imply that the provision of soil functions varies over time. Since plants do not require the same amount of water throughout the year, their uptake –and thus the function of supplying water to plants, will also fluctuate. The dynamic nature of soil presents both opportunities and risks for soil users. They have the opportunity to enhance the supply of a function of interest, but they also face the risk of decreasing, sometimes irreversibly, the supply of other interdependent functions that may be less appealing yet vital.

This means that the individual who directly manages the soil might not be the only one who benefits from its functions, and his management decisions could lead to a reduction in the provision of soil functions to other beneficiaries.

2.2. Literature overview

In this first Pillar, we provided a description of soil functioning and defined key notions such as soil processes and soil functions. We see that (i) soil processes are driven by external factors, and (ii) there is a perpetual balance between soil processes and soil properties, with one influencing the other. In soil function evaluation, one or more functions can be quantified. The evaluation can be based on different soil depths, external factors, and types of properties. In this section, we investigate which aspects of our soil description are found in available soil function evaluation methods.

The evaluation of soil function on the entire soil depth might be difficult due to the lack of methods or the lack of available data, depending on the context. Furthermore, for many functions, the upper part of the soil has been shown to be of major importance and the most reactive to soil management (Seaton et al., 2021), as it hosts the majority of microbial activity and is the interface between the soil and the atmosphere. For these reasons, the considered soil depth differs from one study to another. It is straightforward that an indicator computed over the entire soil depth or on part of it will not convey exactly the same information because it relates to different objects. Thus, the depth of evaluation provides a first insight into the “soil” object under study. In our review of available methods, we found that information on the depth interval under study was lacking in almost 20% of the reviewed methods (Fig. 2). About half of the remaining methods evaluate soil functions throughout the entire soil profile, and the other half limited the depth interval under study to 1 meter or less. Twenty-five percent of all methods only considered the topsoil (the first 30 cm).

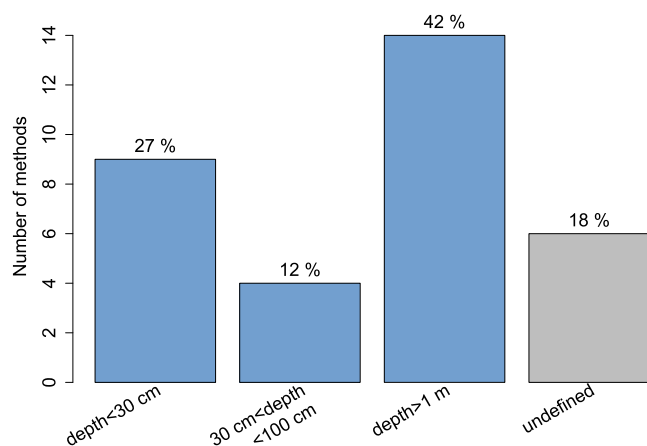


Fig. 2. Soil depth interval under study for the 33 reviewed methods.

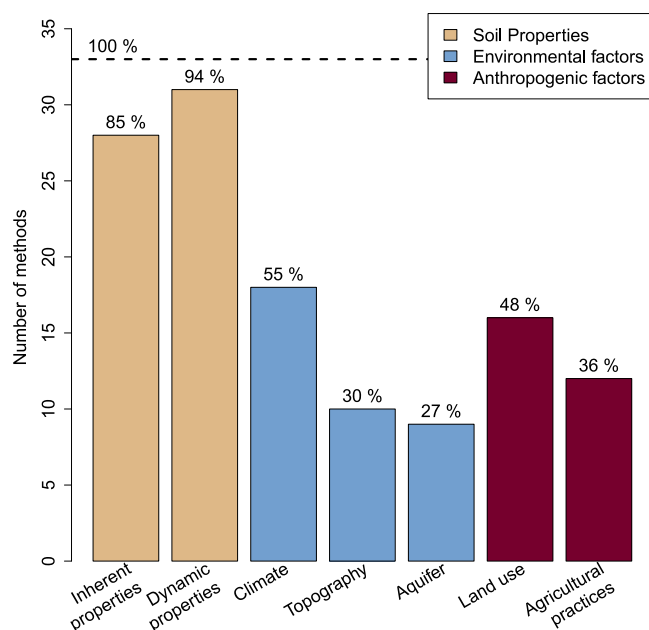


Fig. 3. Bar plot showing the types of soil properties (beige colour) and external factors, which comprise environmental factors in blue colour and anthropogenic factors in red colour. To be counted in a category, a method has to use at least one property belonging to the category.

The properties used in the quantification process depend on the targeted functions and the chosen indicators. However, the use of a given type of property, i.e. dynamic or inherent, can provide insight into the produced information. Out of the 33 reviewed methods, we found that 27 use both inherent and dynamic properties, 4 only use dynamic properties (i.e. [Gonzaga et al., 2016](#); [Rutgers et al., 2012](#); [Thoumazeau et al., 2019b](#); [Kirchmann and Andersson, 2001](#)), and 1 only uses inherent properties (i.e. [Rabot et al., 2022](#)) (Fig. 3). For these 5 methods, the choice to include or exclude one type of property was deliberate and justified. Finally, one method does not rely on any information on soil properties (i.e. [Valujeva et al., 2020](#)), but uses a

soil classification into three classes, along with further information on land use.

In our review, we also took note of the use of a given type of environmental factor, i.e. climate, topography, and hydro-geology, and the use of information on soil management, i.e. land use and agricultural practices (Fig. 3). Similarly to properties, the use of a given type of factor depends on the targeted functions and the chosen indicators. We noticed that no environmental factor was used in 33% of methods, while the three types of factors were used in 18% of the methods. This shows that some methods place more emphasis on the use of environmental factors than others, which eventually indicates that the produced information is different. Similarly, anthropogenic factors are absent in 15 out of 33 cases, while both land use and farming practices are considered in 10 cases. Due to the diversity of evaluation goals and the variety of estimated functions, the review reveals no clear pattern guiding the inclusion of external factors in soil evaluation schemes.

To conclude, we found that due to variations in the considered depth intervals of the soil and in the type of input data used for quantification, the indicators produced by the evaluation schemes do not necessarily convey the same type of information on soil functions. The problem is that there is no established and exhaustive framework to conceptualize and discuss these different types of information. In the literature, this results in situations where the same term is used to designate different things. For example, [Janku et al. \(2022\)](#) and [Gelaw et al. \(2015\)](#) both quantify “soil quality”, yet their conception of this term differs. The former evaluates soil to a depth of 60 cm and includes climate and land cover, while the latter focuses on the top 15 cm and excludes external factors. This is not a problem as soil quality can be declined depending on the context and objectives of the study: the quality in the Czech Republic is not appreciated in the same way as in Ethiopia. However, we would like to give authors and stakeholders tools to identify and simply communicate how they appreciate “soil quality” in relation with soil functioning and why their quantification method provides the targeted information. In the previous sentence, we can replace “soil quality” with any term usually used to describe the objective of soil evaluation (e.g. “soil health”).

3. Pillar 2: Soil users, their interests and their impacts

Humans have an interest in the supply of soil functions. They can influence soil properties and input fluxes to maximize these functions. Therefore, when studying soil functions, it is necessary to consider human soil users. The relationships between soil functioning, human interest, and anthropogenic forcing are depicted on Fig. 4.

3.1. Conceptual framework

Human interest in soil functions can be expressed in terms of ecosystem services, defined as the benefits we obtain from the environment ([Costanza et al., 1997](#)). Hence, soil ecosystem services represent the benefits that we derive from soil functions. They can be valued in monetary terms. For example, soil can retain and degrade organic compounds (i.e. a function), thereby reducing their concentration in groundwater (i.e. a service). It can also infiltrate and store water (i.e. a function), which helps limit the risk of flooding during intense rainfall (i.e. a service). The main difference between a function and a service is that a service must explicitly refer to a human benefit, as depicted in Fig. 4.

Everyone benefits from soil ecosystem services, with advantages associated with each type of soil function. Supporting plants, including nutrient and water storage, allows food production. Water purification prevents, to some extent, the pollution of groundwater or of downstream water. Water regulation helps limit flood events and sediment loads in rivers, while facilitating groundwater recharge. Carbon storage and sequestration play a role in climate regulation. Nutrient cycling is

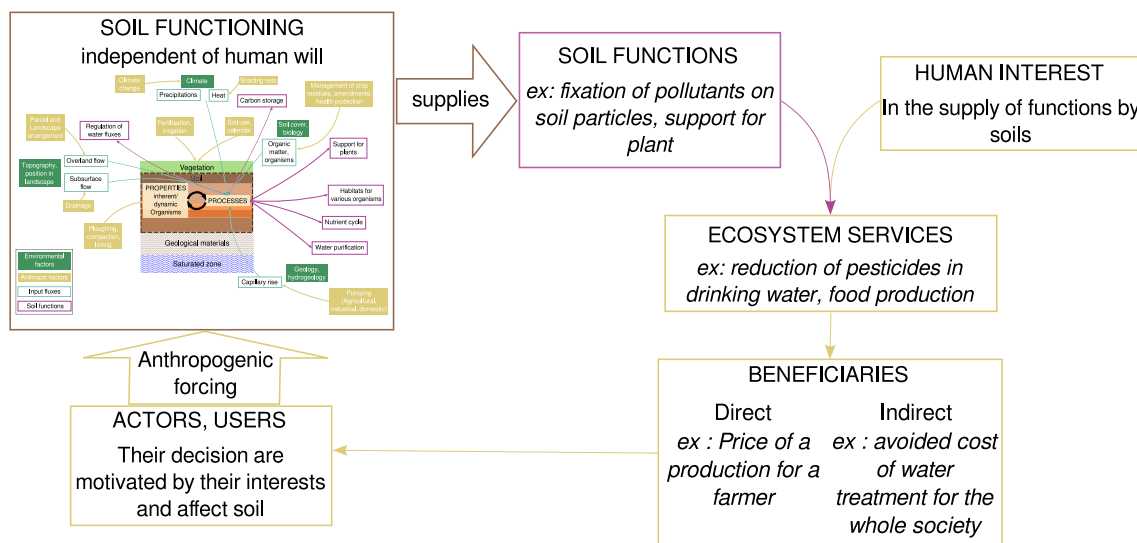


Fig. 4. Graphical representation of the relations between soil, ecosystem services, beneficiaries and actors. Box colours match these of Fig. 1: brown for soil, purple for soil functions, and yellow/gold for all elements related to humans. Smaller arrows show how ecosystem services combine soil functions and human interests, to whom these service benefit, and that some individual designated as soil actors or users apply an anthropogenic forcing on soil to enhance or sustain the delivery of functions of interest.

essential for protecting downstream areas and groundwater from nutrient excess. Finally, the supply of habitats for biodiversity allows soil to serve as a major gene pool for pharmaceutical research (Nannipieri et al., 2017) and to support rare species of cultural interest or species important for crop protection.

Some benefits are direct, while others are indirect (Tibi and Therond, 2018). Farmers benefit directly from the price of their production – partly attributable to soil – whereas users of a water system benefit indirectly from the purification of water by soils, resulting in avoided treatment costs. However, not all of these beneficiaries have a direct impact on soil functioning.

We define stakeholders as individuals who manage soils at various levels and whose decisions and actions influence input and output fluxes, as well as the properties of soils and their environment. Stakeholders typically think in terms of benefits rather than soil functions, exerting anthropogenic pressures on soils (see Fig. 4).

We define soil users as those who act directly on soils and manage them for their own profit. Most soil users are farmers. Among stakeholders, farmers have a unique role: they determine soil cover and farming practices primarily to secure and maximize both the quantity and quality of crop production. We refer to all human interventions on soils as anthropogenic factors. Farmers make decisions regarding land use (e.g. perennial, annual crop, or grasslands) and the temporal succession of different uses. Land use significantly influences soil cover, which plays an important role in the surface properties of soils. Farming practices can affect input fluxes (e.g. organic matter, water, fertilizers, pesticides, heavy metals, and heat), soil properties (e.g. infiltrability, surface structure due to ploughing, density, and pH), and environmental factors (e.g. slope, drainage, hedges, and trenches). These practices can increase the supply of soil functions or even compensate for the absence of supply of certain functions (e.g. irrigation in greenhouses).

In Fig. 1, various anthropogenic factors and their impacts on the environment and soils have been presented (with beige boxes and arrows). Soil properties can be indirectly affected by anthropogenic factors through the feedback loop between properties and processes. Anthropogenic actions can also influence properties or environmental factors that would otherwise be considered inherent in a natural context, such as soil depth affected by erosion or ripping, slope affected

by terracing, and texture (Montagne et al., 2013). Stakeholders do not necessarily control all anthropogenic factors, particularly in the context of climate change. Anthropogenic forcing can also continue to affect soil long after the immediate actions have ceased.

To evaluate soil, it is necessary to identify which stakeholder is requesting the evaluation, to whom the evaluation is addressed, and for what purpose. The direct user of the soil may not be involved or interested in the evaluation process. Instead, a private or public organization, or even a government entity, might seek an evaluation.

3.2. Literature overview

We saw in the previous section that some function evaluation methods use information on anthropogenic factors (e.g. Ellili-Bargaoui et al., 2021; van Leeuwen et al., 2019; Ros et al., 2022; Schwilch et al., 2018), and others do not (e.g. Vogel et al., 2019; Thaumazeau et al., 2019b; Moebius-Clune et al., 2016). This implies that the quantified aspects of soil functions are not the same, and they address two different kinds of questions: (i) How is the soil performing with its current or a projected land use and management practices, or (ii) How is soil performing independently of land use?

Whether anthropogenic factors should be included or not in the computation of soil function indicators depends on the decision that will be made based on these indicators. When proposing a new method for soil function evaluation, this decision should be made explicit in terms of stakeholders and objectives. In the following, we identify and classify the reviewed methods in terms of objectives and targeted stakeholders. It was usually easier to identify the objective than the targeted group of stakeholders.

In the literature, soil function evaluation methods are developed for two main objectives: to provide information for land planning (e.g. Rabot et al., 2022; Valujeva et al., 2020; Danner et al., 2003), or to provide information for crop management at the parcel scale (e.g. Thaumazeau et al., 2019b; Debeljak et al., 2019). Land planning is a broad expression used to designate any decisions and actors linked with land use, land use changes, and policy. In many publications, “land planning” is only mentioned as a possible application of the developed method, without further development on the stakeholders potentially

interested in the evaluation, the scale of decision-making, and the exact type of decision that could be made based on the evaluation (e.g. Rabot et al., 2022; Vrebos et al., 2021; Ellili-Bargaoui et al., 2021; Schwilch et al., 2018). In Danner et al. (2003), case studies are presented to demonstrate how the evaluation method can be applied at the municipality scale, and in Bechler and Toth (2010), it is clearly stated that the method can help identify soils to protect from artificialization. These two publications are actually guidelines for land planners produced by different German Länder, so it is not surprising that their purpose in terms of objective and stakeholders is clearly defined.

Among the publications aimed at producing information for land planning, we can note that there is a diversity of conceptual and methodological approaches. For example, Calzolari et al. (2016) assess the “potential contribution of soil to ecosystem services”, which is “the performance of soil functions based on soil properties regardless of external drivers”. Greiner et al. (2018) quantify “the general capacity of a soil to perform a specific function independent of the land use and of land management practices considering static or slowly changing soil properties”. Both use a methodological approach based on empirical indicators. Finally, Dominati et al. (2014) quantify “the contribution of soils to the whole range of ecosystem services”. Their quantification method differs and relies on a process-based modelling. This illustrates the need for unified concepts for the quantified aspects of soil: one type of method, one type of produced information, that can be useful in different contexts for different objectives.

The other types of studies provide information for crop and soil management. Some tools are designed to be used directly by farmers or by farm advisors to improve soil and crop management at parcel scale for specific objectives (in terms of soil functions) (e.g. Debeljak et al., 2019; Moebius-Clune et al., 2016). Debeljak et al. (2019) also suggest that their tool, the Soil Navigator, can be used “as an educational tool for farmers, farm advisors, and students”. Some studies focus on assessing the impacts of an agricultural practice on soils (e.g. Gonzaga et al., 2016; Lima et al., 2013; Gelaw et al., 2015). The evaluation of soil functions is used to compare soils and determine if a practice has a positive or a negative impact on functions. These publications are more linked with a local context to improve knowledge on farming practices and eventually provide guidelines for farmers and local decision makers. Similarly, Biofunctool® (Thoumazeau et al., 2019a,b) is a tool that evaluates soil functions independently of land use and designed “to make comparative studies at the site scale within similar pedo-climatic conditions”.

Finally, Oberholzer et al. (2012) and Tang et al. (2019) developed tools to include soils in Life Cycle Assessments (LCA), i.e. tools that predict the impacts of land uses and management practices on soils. These can give information for crop management at farm scale (e.g. Oberholzer et al., 2012) or to better evaluate the impacts of human activities on soils at a regional scale or for an economic sector (e.g. rice production in Japan in Tang et al., 2019).

4. Pillar 3: The quantified aspects of soil

4.1. Conceptual framework

4.1.1. Function supply, dynamic and inherent capacities

The key of our conceptual framework is to clearly identify and define three kinds of information (three aspects) on soil functions that can be quantified. These are the supply of a function, the dynamic capacity, and the inherent capacity for a function. No matter the general framework used in the evaluation process (e.g. soil quality, soil health, soil ecosystem services, soil security), all evaluation methods can be ranked within these three aspects, which relate to soil functioning. This makes the identification of the produced information easier. The information carried by supply, dynamic, and inherent capacities is illustrated for four soil functions in Table 1.

The supply of a function refers to the amount of a function that is achieved over a given period, determined by the effective fulfilment of underlying processes during that time. A function supply has a physical unit. We can typically assess the supply of a function over a year, such as crop yields or the amount of purified water. For some functions, supply might be better appreciated on shorter time scales, for example water infiltration in soils during a flood event. The supply of functions is dependent on environmental factors, especially climate. If there is no rain, there will be no infiltration of water in soils. Function supply might also depend on highly variable soil properties. For example, soil surface condition (i.e. a property) influences infiltration and changes cyclically during a cultivation cycle: ploughing, the formation of structural and then sedimentary crust, followed by crust's breakdown as plants emerge (Pare et al., 2011). An intense rainfall on a freshly tilled soil, on a crusted soil, or on a soil covered by vegetation will lead to different levels of infiltration supply.

Measuring the supply of a function cannot rely solely on single evaluation of soil properties but must be based on fluxes too, or on changes observed between two points in time. For example, the supply of the carbon sequestration function over a given period can be estimated by measuring soil carbon at the start and end of that period, and the supply of water infiltration on a catchment during a rain event can be appreciated by analysing the hydrological response at the outlet. The supply of functions reflects what the soil really does considering current land use and management practices. High levels of function supply, especially biomass production, might be sustained by intense farming practices. Therefore, function supply alone does not necessarily provide consistent information on the current state of the soil.

To address this, we introduce the concept of soil capacities. Soil capacity for a function is literally soil's ability to fulfil this function. For a single function, soil capacity can be expressed in different ways and thus convey different information. The capacity for a function can be assessed:

1. Using only inherent soil properties or using both inherent and dynamic soil properties.
2. Independently of land use or considering a given land use.
3. Considering soil and environmental properties or soil properties only.

The first point is essential to understand the notion of soil capacities because the term is used with both significations in the literature, and we therefore recommend to always precise if the used capacity is an inherent (or intrinsic) capacity or a dynamic capacity. The dynamic capacity for a function depends on soil dynamic properties and thus evolves over time depending on the use and the management practices of the soil. The inherent capacity for a function depends on inherent soil properties, and assumes that dynamic properties are in an optimal state for the delivery of the function. This aligns with the definition of capacity in the soil security framework, e.g. capability in McBratney et al. (2014) which was later changed to capacity in Evangelista et al. (2023). The term potential is also sometimes used to designate the inherent capacity as defined here (e.g. Vogel et al., 2019).

To illustrate the second and third points, we introduce an example. The dynamic or inherent capacity of a soil to store water to meet plant needs can be assessed generally (independently of the land use) based on its available water capacity (AWC, a dynamic soil property that can be optimized to assess the inherent capacity) or considering AWC and the type of climate (more or less stable depending on the time horizon). Both are capacities, but the information they convey is slightly different. In the second case, a soil with high AWC in a dry climate could have a lower capacity (inherent and/or dynamic) for the chosen function than a soil with lower AWC in a rainy climate. The two kinds of information can be useful for different objectives. In this example, we could also consider a given land use in the capacity,

Table 1

Examples of soil functions with possible information carried by supply, dynamic and inherent capacities. While dynamic and inherent capacities are together in the same column, the type of assessment for each depends on the types of properties used for their assessment, for example perennial properties for inherent capacity versus dynamic properties for dynamic capacity.

Function	Category of function	Supply	Dynamic/inherent capacity
Water uptake by plants	Biomass production, water regulation	How much water is taken from soil by plants for transpiration over a cropping season?	How much water can be stored in the soil and used for crops? Is there enough rainfall to sustain a sufficient level of water in soils? Can the groundwater contribute to water supply during the dry season?
Carbon storage	Climate mitigation	How much carbon is stored over a period of time? In stable/labile pools?	Given the current land use, can the carbon stock increase by implementing different farming practices? How much additional carbon can be stored considering the current land use or for a change of land use?
Nutrient retention	Nutrient cycling, water purification	What is the quantity of nutrients stored in soil and not lost to groundwater between two cropping seasons?	What is the quantity of nutrients that a soil could store?
Disease regulation	Habitat for microorganisms	How are crop diseases mitigated thanks to soil microorganisms?	Is the soil microorganisms population sufficiently large and diverse to support plants in diseases fighting?

with the objective of assessing whether the soil can store enough water at the beginning of the growth season and the climate provide sufficient water during the growing season to meet plant needs, which is yet another type of information. In this example, depending on the chosen type of capacity (inherent/dynamic, soil properties/soil and environment properties, considering/without considering land use), 6 different informations can be produced. When assessing a capacity, it is thus necessary to specify what is included in it or not, and how these choices relate to the objective of evaluation: does it give valuable information considering the objective?

Indicators of soil inherent or dynamic capacities are constructed based on soil properties and possibly properties of the environment. They rely on an understanding of the relationships between these properties and the processes underlying soil function supply. They can be expressed in physical units or with dimensionless scores (see the following literature overview). It is important to note that the dynamic capacity of a soil is not always linked to the actual supply of a function. Management practices along with inherent variability of certain environmental factors can result in a supply level that deviates from what the dynamic capacity would suggest (also depending on the exact type of capacity that is used). Therefore, dynamic capacity and supply level are distinct and complementary concepts. Similarly, for a given function, a soil may have a high inherent capacity but a low dynamic capacity and supply level compared to another.

The definition of soil inherent capacities implies that, for a given function, there is an optimal state for dynamic properties. Conceptually, soil inherent capacity represents the maximization of soil dynamic capacity for a function as dynamic soil properties vary. However, this optimal state may not be fully achieved or sustained in nature or through human management. Alternatively, soil inherent capacities could be defined in relation with a reference land use, for example an undamaged soil, as suggested in the soil security framework with the genosol reference [Evangelista et al. \(2023\)](#). This reference land use is a proxy of the reference state. Nonetheless, defining this reference soil use can also be challenging, for example because there can be no undamaged soil depending on local past and present human activities. In this regard, the exact signification of soil inherent capacities is a conceptual and methodological choice that should be made explicit, as in the soil security framework.

We propose using the terms soil dynamic and inherent capacities in plural rather than singular, as both are defined for specific functions. A single soil dynamic capacity or inherent capacity cannot be meaningfully defined without aggregating different capacities, which would compromise the objectivity of the concept.

4.1.2. Soil degradation, sustainability of a soil use

In our framework, soil degradation is defined as any reduction in the dynamic or inherent capacity of a soil for a given function. Two types of degradation can be distinguished: reversible and irreversible. Reversible degradation refers to a decrease in dynamic capacity while the inherent capacity remains unchanged. Over time, the dynamic properties affecting this capacity may provoke an improvement, allowing it to return to its initial value or even surpass it. In contrast, irreversible degradation affect the soil inherent capacity, which naturally cannot recover within a human lifetime, but may be restored through massive human intervention. For example, increasing soil depth by ripping can enhance soil inherent capacity for water storage or plant rooting, though this process requires extensive energy and resources (added capital). A reversible degradation, however, has limits: if it also affects the surrounding environment – such as causing biodiversity loss – it may lead to a reduction in potential as well.

The gap between soil inherent and dynamic capacity for a function serves as a measure of the level of degradation or as a margin for improving the soil's dynamic capacity. Certain land uses inevitably result in a reduction of soil dynamic capacity for specific functions (i.e. if dynamic capacity is taken independently of land use). For example, converting permanent grasslands into arable lands may lead to a decline in soil organic matter and a loss of microbial biomass, which in turn reduces the soil's dynamic capacity to produce biomass. In this context, preventing soil degradation cannot be an absolute objective. Instead, the goal should be to maintain soils in a state of easily reversible degradation, allowing natural recovery if human activity ceases or vary. Given that enhancing the dynamic capacity for one function may degrade another, it is also necessary to consider soil multifunctionality and the trade-offs between functions (e.g. as in [Zwetsloot et al., 2021](#)), which affect different beneficiaries — both direct and indirect.

A land use is in consequence considered sustainable if it does not lead to soil degradation. This definition aligns with that of the European environment agency: “Sustainable soil management ensures that (dynamic) soil properties do not decline further” ([European Environment Agency, 2023](#)). Note that a decline in a soil property can also be linked with an increase in the dynamic capacity for a function, the term “deteriorate” is more appropriate in this context. Given the multifunctional nature of soil, the sustainability of a land use can only be appreciated considering all of its functions, provided that such exhaustive list of functions exists.

The literature identifies several major threats to soils that are primary drivers of soil degradation (European Commission, 2002; European Environment Agency, 2023; Huber et al., 2008; Evangelista et al., 2023): erosion, organic matter loss, contamination, sealing, compaction, biodiversity loss, salinization, landslides, acidification and desertification. Salinization, for example, refers to an increase in salt concentrations in the soil, which does not directly alter inherent properties but can considerably affect the surrounding environment, which can in turn impact soil potentials. Erosion, on the other hand, results in the irreversible loss of soil and directly alter its inherent properties.

Box 1: Main definitions of the conceptual framework

Soil: upper part of earth crust composed of superimposed horizons that differ from the parent material or that can support root growth.

Soil properties: characteristics and components that describe the soil and can be measured or qualitatively assessed.

Environmental factors: elements in the soil environment that influence input and output fluxes in soil.

Anthropogenic factors: all human interventions on soils.

Soil processes: all mechanisms and actions taking place in soils.

Soil function: outcome of soil processes, or what soil does independently of human interest.

Soil ecosystem service: a soil function associated to a human benefit.

Soil stakeholders: individuals who manage soils at various levels. Their decisions affect soils.

Aspect of a soil function: any type of information about the soil function that can be sought for. In our framework, we identified three main aspects: supply, capacity, and potential.

Supply of a function: amount of a function achieved over a given period, expressed in physical units.

Dynamic capacity for a function: soil ability to fulfil (or supply) a function considering its properties. Soil dynamic capacity for a function can be evaluated independently of land use or not, and considering environmental factors or not. The exact information conveyed by capacity depends on the type of capacity considered.

Inherent capacity for a function: soil ability to fulfil a function considering only inherent properties, and possible stable environmental factors.

Soil degradation: reduction in the dynamic (i.e. reversible) or inherent (i.e. irreversible) capacities of the soil for a given function.

Soil current state: value of soil inherent and dynamic capacities, and function supply for the soil with current properties, land use, practices, environmental factors.

Soil projected state: value of soil inherent and dynamic capacities, and function supply for the soil with hypothetical values of soil properties, land use, practices, environmental factors.

meaning as in our framework. Dominati et al. (2014) do not use this term but rather “the contribution of soils to the whole range of ecosystem services”. Since function supply and service delivery only differ in the emphasis on human interests in ecosystem services, this sentence can be understood within our framework.

The methods to evaluate supplies are different in each case. Valujeva et al. (2020) use a combination of soil class and land use to evaluate the supply of three functions on a large scale, which constitutes a simplified approach where soils are reduced to a single class and no environmental factors are considered. This method is adapted to the available data and the spatial scale of evaluation. Vrebos et al. (2021) use Bayesian networks trained to assess the supply of four functions based on a set of explaining input variables, including topsoil properties, climatic data, land use, and management practices. Their method is also used at a large scale (country-scale). Finally, Dominati et al. (2010) use a process-based soil-crop model to evaluate the supply of thirteen ecosystem services (i.e. functions with an identified interest for humans) at a farm scale for one soil using soil properties (depth not specified), meteorological data, soil use and practices.

As presented in the framework, soil dynamic capacity for a function can be expressed in different ways. In the literature, it can be challenging to identify what kind of dynamic capacity is being used. In order to understand the exact information conveyed by the produced indicators, it is necessary to dig into the quantification methods. In two cases (i.e. Choquet et al., 2021; Ellili-Bargaoui et al., 2021), physical modelling is used to assess the supply of numerous functions for different soils for a reference state regarding land use and practices. As a result, the outcome is a set of dynamic capacities relative to the specific land use. The quantified supply levels which include environmental factors can be used to compare the dynamic capacities of soils for the reference land use. In the soil navigator (Debeljak et al., 2019; Sandén et al., 2019; Wall et al., 2020; van Leeuwen et al., 2019), the dynamic capacity of the soil considering environmental factors and current land use and practices is assessed using combination rules. Here, the produced capacity can be interpreted as a mean supply value that can be expected on average from this soil with these management practices and this climate.

Two main methods are used to evaluate dynamic and possibly inherent capacities, which use respectively continuous or discrete scoring functions or decision tables. In the scoring function method, properties that influence the selected function are first selected through statistical analysis or expertise, and then scored between 0 and 1 using continuous scoring functions of various shapes (Doran and Parkin, 1994; Karlen and Stott, 1994; Karlen et al., 1997). The scores of individual properties are then weighted and aggregated into a single score indicating soil's capacity for the function. This method is used for example in Tang et al. (2019), Moebius-Clune et al. (2016), Gonzaga et al. (2016), Gelaw et al. (2015), Thoumazeau et al. (2019a) or Lima et al. (2013). This method usually relies on soil properties only (as is the case in the cited papers). The produced information is thus a dynamic capacity independent of land use and environmental factors. The Muencheberg Soil Quality Rating (Mueller et al., 2007) is an exception, as they also consider environmental factors and land use, but the method also stands out by using discrete scoring functions and a particular aggregation method. It is the same type of information as in the soil navigator (but only for the productivity function). In Vogel et al. (2019), the scoring function method is proposed to evaluate both dynamic and inherent capacities, using respectively only dynamic properties or only perennial properties, including environmental properties.

The outputs of the decision table method are also scores for individual functions, but they are usually discrete (e.g. from 1 to 5). For each function, the final score is obtained by combining different properties in decision tables (for example, if $a > x$ and $b < y$, then score = z). This method allows to take into account interactions between properties, as well as environmental and anthropogenic factors. Hence, the type of capacity that is assessed with this type of method can be

4.2. Literature overview

Among the reviewed publications, soil dynamic capacities are evaluated most frequently, although they are not always presented as such. Inherent capacities have been assessed in only two cases out of 33 (i.e. Rabot et al., 2022; Vogel et al., 2019) and function supply in three cases (i.e. Vrebos et al., 2021; Valujeva et al., 2020; Dominati et al., 2014). Vrebos et al. (2021) and Valujeva et al. (2020) use the term “function supply” to designate their quantified aspect with the same

different from one study to another. Danner et al. (2003), Lehmann et al. (2013) and Bechler and Toth (2010) include environmental factors but no information on land use and practices, and thus evaluate the dynamic capacities of soil and its environment independently of land use. In Calzolari et al. (2016), Jost et al. (2021) and Greiner et al. (2018), the same method is used, but land use intervenes in the quantification of the dynamic capacity for some functions (e.g. capacity to host microorganism). Here land use is used as an indicator for the dynamic capacity, as the capacity for some functions are closely related to land use. Contrary to the soil navigator or the Muencheberg Soil Quality rating, the dynamic capacity is evaluated independently of land use, but land use is used as an indicator for capacity as other environmental factors would.

Rabot et al. (2022) quantify soil intrinsic capacities using a set of inherent properties and environmental factors in three land use scenario. They quantify whether soil has the potential to supply functions at a satisfactory level for the considered land use (the “adequacy between indicators and land uses”). Finally, Oberholzer et al. (2012) quantify the “most probable changes in soil quality indicators as a result of on-farm agricultural practices”. These quality indicators are typical indicators of soil dynamic capacities without considering environmental factors. Thus, this tool directly assess soil reversible degradations or improvements.

In the literature, it is common to aggregate individual function scores (for capacities) into a single soil index (e.g. Janku et al., 2022; Fernández et al., 2020; Gonzaga et al., 2016; Thoumazeau et al., 2019a; Ros et al., 2022). This is generally done in studies quantifying dynamic capacities for numerous functions, and the aggregation into a single soil index is done by simply weighting and summing the different function scores. The interpretation of such “soil quality index” (Lima et al., 2013) should thus be done with care. For us, a single score cannot correctly reflect soil multifunctionality. Maybe such scores should be explicitly linked to a soil use and objectives for soil function supply or dynamic capacities set with stakeholders. A high score would indicate that, in this context and with these objectives, the soil could perform the expected functions at a satisfactory level.

In this review, we did not consider: (i) the quantified aspect of soil function seen by authors and (ii) that two similar methods can be applied in two publications for topsoil only or for the whole soil, leading to different kinds of information (this has been discussed in the first pillar of the framework). Concerning the first remark, our framework enables to sort the different approaches in terms of produced information by analysing their methods, and not based on the vocabulary that authors use to communicate (e.g. soil quality, soil health).

5. Discussion

5.1. Linking objectives of evaluation and evaluated aspects

The conceptual framework developed in this study is an attempt to describe soil functioning based on our perception of it as a medium where physical fluxes are modified or produced, some of which are of particular interest to humans. The description of soil provided here helps to better understand how these fluxes originate and how the processes at their core can modify soil properties and functioning over both short and long terms. Based on this understanding of soil functioning, we were able to identify the different types of information (of aspects) that can be searched for on soil functions.

These types of information can be of interest in different contexts and objectives in which an evaluation of soil function is required. We identified these objectives in publications from the scientific literature in Pillar 2 (see Section 3.2). To evaluate the effect of soil and crop management on soils with similar pedology and environmental factors, the information of interest is the dynamic and inherent capacities for different functions (e.g. Thoumazeau et al., 2019b; Gelaw et al., 2015;

Gonzaga et al., 2016). If environmental factors are included in the capacities, they can be compared at larger scales (e.g. regional scale in Greiner et al., 2018). As already stated in Vogel et al. (2019) and Evangelista et al. (2023), the inherent capacity for a function (or potential in Vogel et al., 2019) is a measure of the maximum that we can expect from this function given soil (and environment) inherent properties, and can thus be used to set reasonable goals to improve soil dynamic capacity. However, the methods to evaluate inherent capacities are still few. Finally, the quantification of soil function supply can help evaluate “the contribution of soils to ecosystem services” (Dominati et al., 2014) which can be critical to persuade political actors and other stakeholders of the necessity to preserve soil resources. The quantification of soil function supply with a projected soil use and management practices could also help farmers, farm advisors and land planners to identify the best management practices to reach one’s objectives in the supply of one or more functions, without degrading the supply of other functions (e.g. in the soil navigator, see Debeljak et al., 2019).

We highly recommend to actors involved in soil function evaluation to clearly identify and communicate the context of their studies, their objectives and constraints, and use this information to identify which aspect of soil is best suited to reach their objectives. This would also help justify the methodological choices: include environmental factors or not in a capacity, evaluate soil to a limited depth. Therefore, we summarized the important information to communicate in Box 2. In the publications reviewed in this study, this basic information (i.e. links objectives to the evaluated aspect/searched information on soil functions, and method) was often lacking or was not clearly stated, whereas we stress that it should be clearly explained from the beginning.

Box 2: list of information to provide in the communication of soil function evaluation methods

Objective of the evaluation: what decision will be taken based on the soil evaluation?

Targeted stakeholders: to whom is the evaluation addressed?

Support of evaluation: What is the data support and do we need a change of support for providing the information?

Local constraints: lack of data, for example on soils, context of the evaluation, legal obligations, etc.

Functions of interest: which functions are relevant for the study objectives.

Required information on soil function: what aspect of the functions gives the information needed to achieve the objectives?

Required information on soil for the quantification: quantification depth, included environmental and anthropogenic factors, type of soil properties, etc.

Function indicators and quantification method: do the indicators relate to the targeted aspect?

5.2. Links with other frameworks

Numerous conceptual frameworks for soil function evaluation have been proposed in the literature, including that of soil quality (Doran and Parkin, 1994), soil health (Harris et al., 1996; Lehmann et al., 2020), soil natural capital (Dominati et al., 2010), and soil security (Koch et al., 2013; McBratney et al., 2014; Evangelista et al., 2023). Our goal is not to propose an alternative to those already well-known and used frameworks, but rather to complement them and precise some points. Our main addition is to propose an exhaustive set of aspects on soil functions that can possibly be quantified for different objectives and to link them with objectives and methods. As soil health and soil quality are two fast evolving frameworks with a long history (see e.g.

Bünemann et al., 2018, on the subject), we did not develop the links with our framework. They usually share the concepts of soil dynamic and sometimes inherent capacities.

5.2.1. Soil security

Among the mentioned frameworks, the soil security framework is the most recent and the broader one (Lehmann et al., 2020). It includes five biophysical and socioeconomic dimensions, which are condition, capacity, capital, connectivity and codification (Evangelista et al., 2023). The two biophysical dimensions have direct equivalent in our framework. Condition is defined as the “current state” (Evangelista et al., 2023) and can be associated with the current or dynamic capacity in our framework. Similarly, capacity in the soil security framework is defined as the “optimal biophysical state” (Evangelista et al., 2023) and can be associated with the inherent capacity in our framework. In the soil security framework, a conceptual and methodological choice has been made to evaluate soil condition and soil capacity: the use of a reference soil: “The condition of the soil is concerned with the current state of the soil and refers to the shift in capability [i.e. capacity in latter developments of the framework] compared to the reference state” (McBratney et al., 2014). More information on the methodology to choose a reference soil can be found in the cited papers.

The soil security framework has the ambition to cover all dimensions related to soils to ensure their sustainable management. Our framework is more oriented towards the technical and biophysical evaluation of soil functions, which means that it complements one role of the soil security framework, for the dimensions of capacity and condition. To achieve soil security at regional and global scales, however, social, economic, and legislative dimensions also need to be considered. Adapting the proposed framework to more dimensions, such as connectivity, would certainly be a valuable contribution but it is beyond the scope of this current work.

5.2.2. Soil natural capital

Our view of the soil described in the first pillar and our different concepts introduced in the third one align well with the framework of soil natural capital described by Dominati et al. (2010). The natural capital of soil refers to the “stock of natural assets yielding a flow of either natural resources or ecosystem services”. In our framework, this stock can be characterized by soil inherent and dynamic capacities. Similarly, our definition of soil functions as output fluxes aligns with the idea of a “flow of either natural resources or ecosystem services”. Further, the “formation, maintenance, and degradation” of natural capital can be seen as equivalent to changes in capacities. Ultimately, to enhance the supply of a function of interest, a user may implement a set of practices, which can be viewed as the “added capital” referenced by Dominati et al. (2010).

5.2.3. The term “capacity”

The term “capacity” is frequently used in the literature on soil functions. As this term can have different meanings, we recommend using it carefully, especially by always using the qualifiers dynamic or inherent to avoid confusions. Additionally, we saw in the third pillar that this term can actually mean different things depending on what is included in it. Thus, authors should always precise what they include in a capacity, as it is done by Greiner et al. (2018), who define their capacity as the “general capacity of a soil to fulfil a specific function independent of land use and management, considering static or slowly changing soil properties”. Conversely, we take issue with the application of the term “capacity” in definitions of soil functions, which is found in many publications (e.g. Vrebos et al., 2021; Gelaw et al., 2015; Gonzaga et al., 2016), such as in the soil navigator’s description of primary productivity: “The primary productivity function is the capacity of a soil to supply nutrients and water and to produce plant biomass” (Sandén et al., 2019). In our framework, functions are not capacities but fluxes that can be supplied depending on soil processes and input fluxes.

5.3. A framework to start a fundamental discussion on soil evaluation

This framework facilitates a fundamental discussion about which aspects of soil should be protected and monitored. Indeed, the three concepts of function supply, dynamic, and inherent capacities for a function do not convey the same information. In consequence, building soil protection or monitoring frameworks based on supply or capacities can lead to different outcomes. It is not straightforward to determine which of these concepts to use, as each has its own significance. For soil monitoring, the aim could be to maximize function supply while preserving soil dynamic capacities, or to bring soil dynamic capacities closer to their potentials (i.e. the intrinsic capacities), even if this implies a decrease in function supply. For soil protection, the objective could be to safeguard soils with high potentials, high dynamic capacities, or high supply levels. For sustainable management of soil resources, it is crucial that soil inherent capacities remain at least constant to keep the soil in an “easily” reversible degradation state. However, few methods are available for quantifying soil inherent capacities, as obtaining a reference state for dynamic properties is still a challenging task (see the discussion in Evangelista et al., 2023).

5.4. Shifting focus from soil to soil and their environment

Soil functions have been defined as the output fluxes (or consequences of these fluxes) resulting from soil processes. By evaluating soil functions, we can have information on these fluxes in the monitored soils, usually in cultivated parcels, in forests, or in natural areas. Soil evaluation methods do not consider that, even at a parcel level, there can be a diversity of soil covers and uses (e.g. hedges, ditches, roads), with a specific spatial organization. The fluxes originated from these different components are not necessarily the same, and they can interact. If the end goal of soil evaluation is to maintain a good level of function supply across an area, other elements of the landscape might help to compensate for deficiencies in supply, capacity, or potential of a soil function. In this aspect, our concepts of supply, inherent, and dynamic capacities could be extended to the entire landscape and its various components. From this perspective, degrading a soil’s dynamic capacity or supply level of a function to obtain an important function that no other element of the landscape can provide would be acceptable if this degradation could be counterbalanced by another landscape component. This idea to monitor soils in their environment can also be found in Janzen et al. (2021). An important challenge of soil evaluation is therefore to monitor functions at the landscape level. In this regard, methods to evaluate soils are a pre-requisite but not sufficient in themselves.

6. Conclusion

In this study, we proposed a conceptual framework to enable and facilitate the identification of the information conveyed by indicators of soil functions. In the literature, we found that (i) there is a diversity of announced evaluated aspects, but the used terms are sometimes ambiguous so that it is not always easy to understand which information will be produced, (ii) the “soil” under study in the evaluation differ from one method to another, and is not always clearly defined in terms of considered depth intervals, used properties, and external factors, (iii) we lack concepts to clearly analyse what aspects of soil are evaluated based on the quantification steps. Our framework addresses these issues and will help better design and communicate soil function evaluation method.

The framework introduces three types of information of different nature that can be searched for: the supply of a function, soil’s dynamic capacity for a function, and soil’s inherent capacity for a function. Methods for obtaining these three types of information already exist in the literature, but the vast majority focus only on soil dynamic

capacities. These types of information can be useful for different purposes in different contexts that we also identified in the literature. Thus, the framework makes it easier for future developers to determine which aspect of soil functions is most relevant in their context. The choice of the evaluated aspect should be based on user needs and should result from a discussion with stakeholders, as these questions are beyond the scope of scientists only. The conceptual framework includes all information for stakeholders to understand the interests of these quantities and their links with soil functioning, and to fully grasp the issues around soil monitoring and protection.

CRedit authorship contribution statement

Henri Lechevallier: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Philippe Lagacherie:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Alexandre M.J.-C. Wadoux:** Writing – review & editing, Supervision, Conceptualization.

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 material related to this article can be found online at <https://doi.org/10.1016/j.geoderma.2025.117476>.

Data availability

Data will be made available on request.

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