Soil Quality: towards an indicator system for public policy

Summary of the INRAE study report
Directorate of collective scientific assessment, foresight and advanced studies (DEPE)
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Soils play a crucial role in the functioning of continental ecosystems, on which most human activities are based. These activities create tensions between different land uses (provision of food, materials, energy in various forms, recreational areas, landscapes, areas for housing, infrastructure, manufacturing, waste storage, etc.). Ultimately, they alter the way soils function and even damage it if they are unsuitable, to the extent that ***the European Union (EU) now estimates that 60% of its soils are degraded***[1]*.*

Soils contribute significantly to the major cycles that regulate, in particular, water and greenhouse gas concentrations in the atmosphere. They also help to sustain ecosystems, as they are home to an estimated 60% of the biosphere's species[2]*.* ***Maintaining biodiversity and a viable climate for human societies and biodiversity therefore necessarily involves maintaining and restoring soils to a good ecological condition.***

Growing awareness of the importance of soils for ecosystems has led to a proliferation of policy initiatives. At the international level, these initiatives are often limited to voluntary approaches or symbolic recognition, such as ***the International Year of Soils in 2015****. In the EU, the proposal for a Directive on the Monitoring and Resilience of Soil, published in 2023, reactivates the process of establishing a European framework for soil monitoring. In France, the adoption in 2021 of the Law on Climate and Resilience (No. 1104), which sets a target for limiting the artificialisation of soils, has opened discussions on incorporating the concept of soil functions in the field of land planning.*

The regulation of tensions over land use requires coordination at a global level and decisions at a more local level, all duly supported by sound information. In order to facilitate the governance of soil conservation and restoration, this study seeks to bring together the available scientific resources on how to assess soil quality and health and make them available to decision-makers and stakeholders in the field. It identifies the main proven indicators that can be mobilised and the methods used to assess them. It also highlights the overall system within which indicators are mobilised and the importance of the choices to be made at the different stages of the assessment. Issues such as the distinction between quality and health, the reference situation, the choice of indicators and their possible aggregation or spatialisation are examined.

Scope of the study

Guidelines and recommendations to assess soil quality and soil health exist for each type of use (agricultural, forestry, natural, urban). However, the assessment is seldom done **in a cross-cutting way for all types of land use**. This is the approach favoured in the present study, to deal with the impacts of changes in land use as well as the overall territorial monitoring.

To this end, the **ecological functions** of soils were chosen as the focus of the study. This approach offers a view that is more positive and more stimulating for stakeholders, than that proposed at European level, which focuses on threats leading to soil degradation[1].

This study does not deal with the issue of polluted sites and soils as such, since a specific methodology is applied to those sites in France, with pollution management on a case-by-case basis, based on the assessment of health and environmental risks related to use, rather than on ecological functions.

Similarly, it does not address the general issue of impacts of agricultural, forestry, urban or soil management practices on soils, as the study focuses on indicators and how they are used. Management practices are addressed only insofar as they play a role in the reasoning behind the assessment process. This study does not provide a summary of these practices and their impacts.

The study was carried out by the French National Research Institute for Agriculture, Food and the Environment (INRAE) and co-financed by the French Agency for Ecological Transition (ADEME), the French Office for Biological Diversity (OFB) and the Ministries of the Environment and Agriculture.

Methodological principles

Following the principles formalised for the work of INRAE's Direction de l'Expertise Scientifique Collective, de la Prospective et des Études (DEPE), a DEPE study aims to provide an updated survey and a critical analysis **of current scientific knowledge**. Based on internationally available bibliographical references, it highlights the main lessons to be learned in terms of established knowledge, debates and controversies, uncertainties and knowledge gaps. On this basis, propositions are formulated and tested for relevance by processing existing data. The study does not aim to make public policy recommendations.

The conduct of the study is based on a Scientific Expertise Charter, which sets out the overarching principles of competence, impartiality, plurality and transparency.

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[1] EUSO (European union soil observatory) - https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

[2] Anthony M.A., Bender S.F., van der Heijden M.G.A., 2023. Enumerating soil biodiversity. Colorado state university, 120 (33).

1. Adopting a common language

1.1. Different perceptions of soil quality and soil health

Each type of stakeholder perceives soil quality or soil health based on concerns relevant to their activity. Soil can be viewed as a support area to be shared between human activities (agriculture, manufacturing, housing, recreational activities...), or in terms of its potential to produce food resources, to regulate water resources, to store carbon, as well as for risk management (soil stability, flooding), or even for conservation purposes, for its heritage value.

Within a given category of actors, specificities can be noted. For example, wine growers consider soil characteristics not only in terms of productive potential, but also for their uniqueness as an element of the «terroir» defining the identity of the final product. Differences in perception are also observed between farmers based on their production model (e.g. organic farming, conservation agriculture, conventional farming). Many studies seeking to identify the drivers of these differences in perception have pointed to a link with physical characteristics of farms (size, age of the farmer, technical and economic model). Recent work has emphasised the primacy of social norms and farmers' relationship networks. These differences in perception result in different ways of mobilising and interpreting available soil information, including indicators and their benchmark values. Indicators are not simply transferred from the scientific domain to field applications. They follow **social paths** as illustrated in Figure 1, involving **processes of ownership, transformation and/or co-design**. Indicators are thus the subject of numerous interactions between stakeholders, such as the implementation of joint actions, the development of shared modes of knowledge, and the pooling of representation media.

1.2. Soil quality vs. soil healt

A common language regarding soil quality and soil health needs to be agreed between stakeholders. There is still no consensus in the scientific literature on the differences between these two concepts and the debate is still ongoing. This stems from the proximity of these terms in the definitions published in the late 1990s and early 2000s, the only difference being that the concept of health focuses more explicitly on the **biological dimension of soil functioning**.

Another issue underlying the distinction between quality and health is the need to distinguish between a **mere description of soil characteristics** and a judgemental assessment of its condition as a result of the uses and practices to which it is subjected.

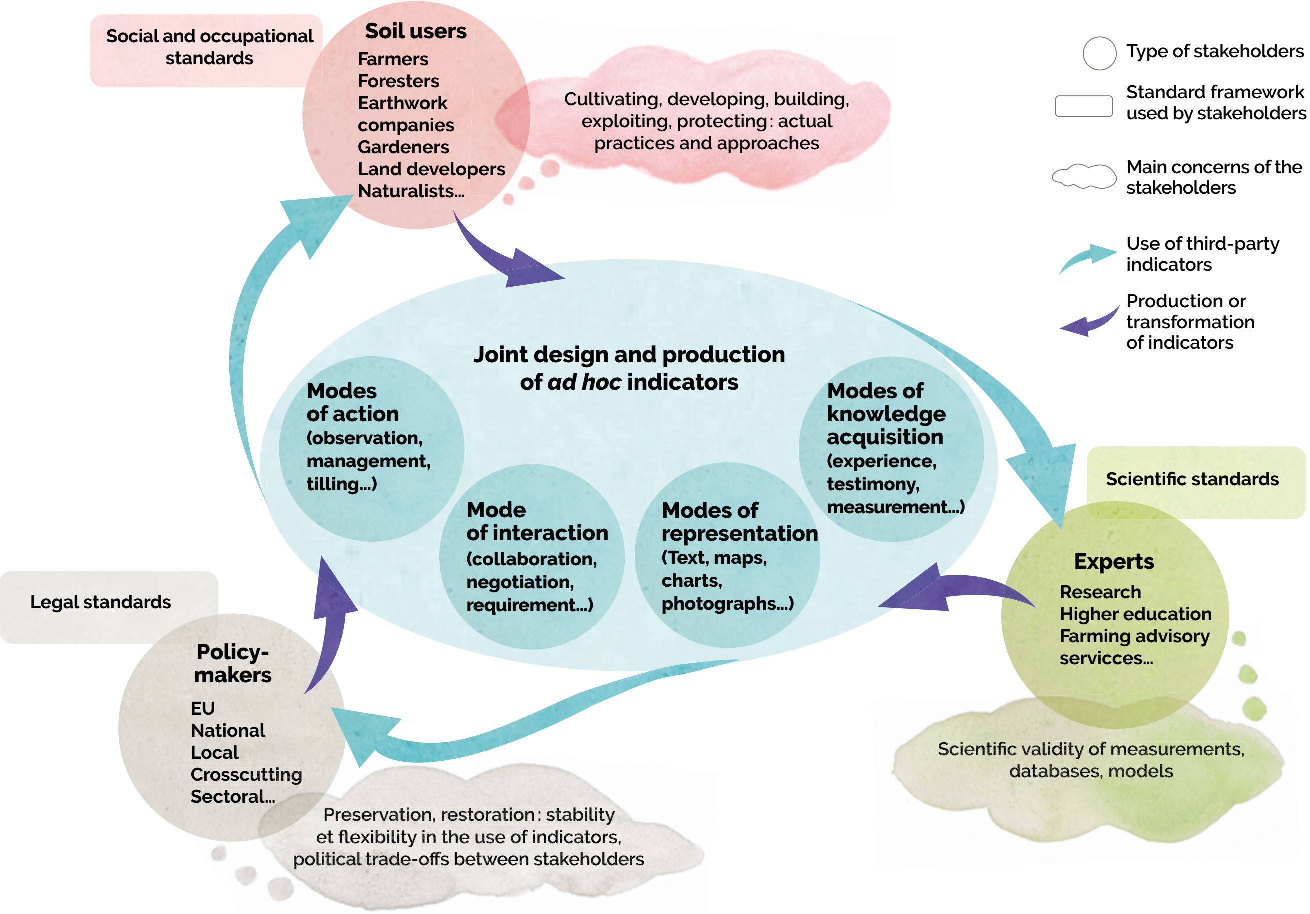


Figure 1. Production and use of soil quality or soil health indicators

From this perspective, the **quality of a given soil** is a description of **what it is or what it does**. For example, soil scientists have developed systems for classifying soil types, the most widely used in France being the Référentiel pédologique (https://www.afes.fr/les-sols). Such descriptions may be based on permanent soil characteristics, i.e. those that are stable over a period of several decades in the absence of human intervention (e.g. texture in the case of sandy or clayey soils), or on characteristics related to functions (e.g. hydromorphic soils in the case of hydrodynamic properties and hydrological functions). The health of a given soil, on the other hand, refers to a judgement of **what the soil is or should be**. TThe good or poor health of the soil corresponds to **the degree to which its potential is realised**. In practice, this potential is generally considered to be the average level of performance observed either in all comparable soils or in a given study area (see Section 2.2). Thus, in Figure 3, Soil B is healthier than Soil A.

1.3. Ecological functions of soils and soil degradation

■ Different dimensions of soil health

TTo assess the health of a given soil, a comparison of observed vs. potential performance (i.e. its quality) can focus on different dimensions. Soil functions and soil degradation can be seen as two symmetrical approaches to soil health.

So far, soil degradation has been monitored by the European Soil Observatory[3]. Soil health is assessed based on eight main threats: anthropisation and, for non-anthropised soils, biodiversity loss, organic carbon loss, pollution, nutrient excess, compaction, salinisation and erosion. Soil is considered degraded when one of these threats reaches a level considered critical. Indeed, its design tends to increase the risk of a negative diagnosis as knowledge of soil degradation develops, which may discourage efforts to improve monitoring and follow-up. Therefore, this study adopted a motivational approach to describing soil health, focusing on the ecological functions provided.

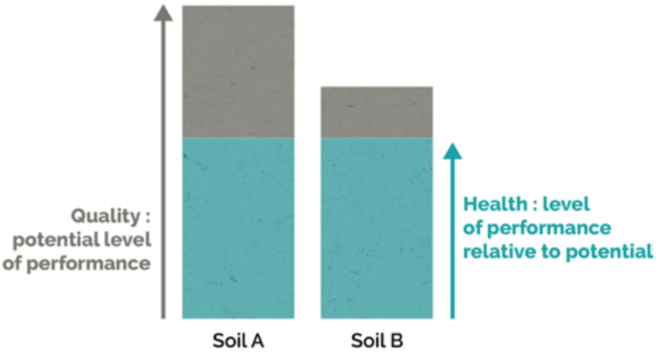


Figure 3. *Soil quality as a potential vs. soil health as a degree of realisation of that potential*

■ Ecological functions of soils

Definitions and identification of soil functions are not yet stabilised in scientific literature. However, there is a broad consensus that a function should be considered as a **combination of biological, physical and chemical processes ensuring an integrated action enabling the soil to function**. The relationships between soil properties, the processes they enable, the functions resulting from the combination of processes, and the ecosystemic services to human societies that derive from them, are classically represented in the form of a cascade. Figure 4 shows a version adapted to the content of this study.

The scope of each function can vary from one source to another, leading to a wide variety of suggested function list.

A textual analysis of the scientific corpus dealing with soil functions revealed that the most frequently used terms designate either objects (e.g. water, nutrients) or actions (e.g. retaining, transferring). Based on this analysis, it was agreed to **define each function as an action on an object** (which could be the soil itself), and the naming of the six functions shown in Figure 5 was composed from the terms most

Sources analysed

The report cites a bibliographic corpus of **1,800 references** from international bibliographic platforms such as the Web of ScienceTM (WoS), supplemented where necessary by French-language literature, as well as reports and works not referenced in these tools. The knowledge sought is applicable to the pedoclimatic context of mainland France.

Articles are selected on the basis of existing syntheses, where relevant to the question under study. The cited corpus is largely multidisciplinary, as shown in Figure 2, which covers the 1,280 sources referenced in WoS. It shows the top 15 WoS categories of journals in which the cited articles were published. It should be noted that the 500 references not included in this analysis of research fields are mainly grey literature and articles from the humanities and social sciences.

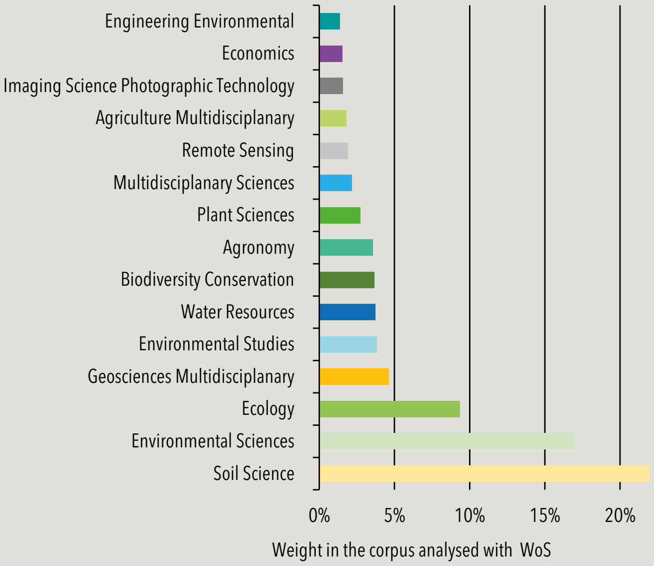
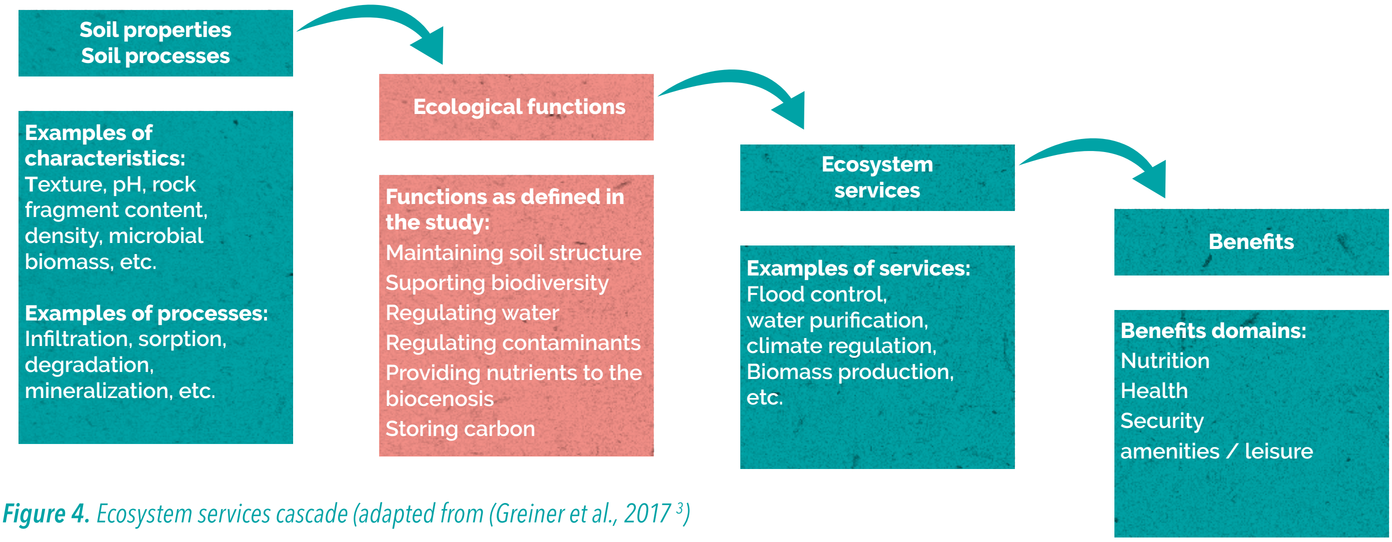


Figure 2. *Research fields of the 1,280 references classified by WoS category (top 15 categories)*



Soil properties
Soil processes

Examples of characteristics: Texture, pH, rock fragment content, density, microbial biomass, etc.

Examples of processes: Infiltration, sorption, degradation, mineralization, etc.

Ecological functions

Functions as defined in the study:
Maintaining soil structure
Suporting biodiversity
Regulating water
Regulating contaminants
Providing nutrients to the biocenosis
Storing carbon

Ecosystem services

Examples of services: Flood control, water purification, climate regulation, Biomass production, etc.

Benefits

Benefits domains:
Nutrition
Health
Security
amenities / leisure

Figure 4. *Ecosystem services cascade (adapted from (Greiner et al., 2017* [3]*)*

frequently found. Certain functions are thus broken down into sub-functions corresponding to different stages of the cycles in which they participate. The delimitation of functions is a conceptual tool to facilitate analysis. However, the multiplicity of processes taking place in the soil, and the interlocking scales at which they are carried out, mean that any outline drawn for each function is always open to question. The challenge of the proposed nomenclature is to cover the whole range of soil functions, while respecting the terminology used in the literature

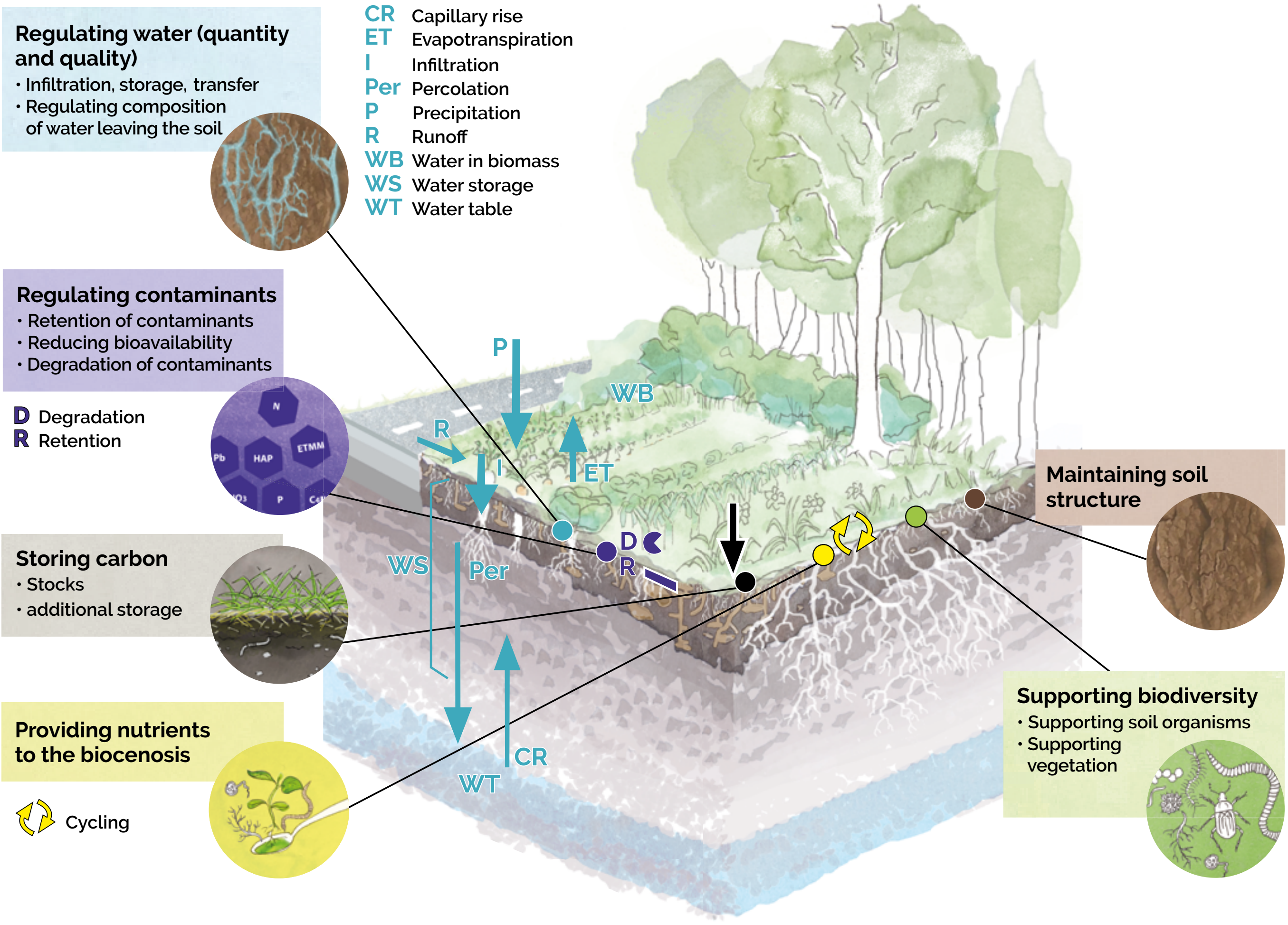


Figure 5. *Scope of the 6 soil functions selected for this study*

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[3] Greiner L., Keller A., Grêt-Regamey A., Papritz A. (2017). Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. Land Use Policy 69 : 224-237. https://doi.org/10.1016/j.landusepol.2017.06.025

1.4. Indicator, reference framework and indication system

An indicator can be defined as a means of obtaining and communicating information about an object or phenomenon of interest, called an *indicandum*. It differs from the mere measurement of a parameter because of the meaning given to it in relation to the object of interest. **Indicators are therefore considered here necessarily as «indicators of something», and not simply as measured or calculated quantities.**

The meaning of an indicator is provided by its interpretative reference framework, i.e. the criteria used to determine whether a given indicator value is low or high, good or bad. **The reference framework thus consists of the indicator, its measurement method and the reference values used to interpret it** (see Section 2.2).

Beyond the interpretation of each indicator, an appropriate strategy must be established to serve the purpose of the evaluation, particularly with regard to the complementarity between the indicators used, their possible weighting, the sampling of measurements, and the statistical and/or cartographic processing of the results (cf. Section 2.3). The combination of all these elements constitutes the **indication system**.

2. Assessing soil quality and soil health: indicators and approach

2.1. The main generic indicators

This study led to the selection of about **fifty indicators considered** relevant for monitoring soil quality and soil health, based on their frequency of occurrence in the scientific corpus on the subject. In particular, we selected those that appear to be the most frequently used for the analysis of soil ecological functions. These indicators cover the physical, chemical and biological components of soils. The main measurement methods and reference values for each indicator have been compiled in the study report. Table 1 presents this selection and places each indicator in relation to the ecological functions and threats presented in Section 1.3. It also indicates the context in which the indicator is assessed (on a soil horizon, a soil profile, or on an entire watershed) and whether it is found in the economic literature.

Indicators are matched with functions (right of the table) and degradations (left) in three ways: as an indicator of the function or degradation, as an optional indicator, and/or as a driver (i.e. a piece of information required to measure or interpret an indicator). For example, the main indicators of the «maintaining soil structure» function are density and structural stability, while grain size and organic carbon content are drivers.

This layout shows that the same indicator can be meaningful for both a function and a threat. For example, the total nitrogen content is an indicator of nutrient excess on the threat side, and of nutrient providing to the biocenosis on the function side. The table also shows that different levels of precision can be chosen. For example, the carbon fractions, which make sense for assessing the degree of stability of carbon stored in the soil, are retained as optional indicators of the «carbon storage» function, but do not appear in the proposed directive. Finally, different strategies may sometimes have been chosen to obtain equivalent information. For example, the analysis of phospholipid fatty acids (PLFA) in the proposed directive can provide an equivalent of the fungus/bacteria ratio appearing on the function side. However, the proposed directive does not include a detailed description of fungal diversity, which is necessary to assess the function of «supporting soil organisms».

2.2. Reference framework for interpretation

The measured or calculated value of an indicator is only meaningful in relation to the interpretation reference framework, specifying the **measurement or calculation method used, and the reference values to which the result must be compared**. These values are, on the one hand, existence values, i.e. the values of the indicator for all comparable soils or soils in a given area, and, on the other hand, threshold and target values, i.e. the critical values that will enable a judgment to be made on the more or less good health of the soil.

■ Existence values

To identify existence values, it is necessary to specify the purpose of the evaluation. For example, if a given soil is assessed in terms of the management practices implemented (e.g. arable land tillage, or inter-row grassing in orchards), the existence values are those of all soils of the same pedoclimatic type and with the same land use type (arable crops or orchards). If the soil is evaluated in terms of possible land use types, the existence values are those of all soils of the same pedoclimatic type, whatever the land use, to which the level of the indicator estimated for each land use is compared.

Different typology systems are available to classify soil types, climates, land use types and management practices, with varying levels of detail. In practice, however, the way in which the available data have been collected and stored strongly determines the typologies used.

■ Threshold and target values

Threshold and target values are used to **assess soil health**. They correspond to the value of the indicator defining a degradation level (threshold value) or the value defining a targeted objective (target value). These thresholds and targets can be broken down into a gradient of more or less healthy classes.

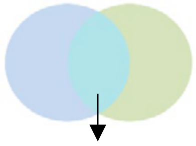
Different strategies are possible for determining these values:

- To start from a policy objective (e.g. to limit the risks to the population from exposure to pollutants), as may be the case when thresholds are set in regulatory frameworks;
- To start with a management objective (e.g. a production objective for a farmer or forester);
- To reach the same state as the equivalent undisturbed soil («natural» soil), even if such a situation is often non-existent, particularly in European territories, given the combination of human activities and ecosystem evolution throughout history. The undisturbed status considered as a standard is therefore very often a situation reconstituted by modelling;

Table 1. Indicators selected to assess the soil functions identified in this study, and indicators mentioned in the proposed Soil Monitoring and Resilience Law (SMRL)

Threats mentioned in *SMLR**

Functions defined in this study

Loss of biodiversity	Loss of soil organic carbon	Soil contamination	Excess nutrient content in soil	S Acidification	Reduced water retention capacity	Subsoil compaction	Topsoil compaction	Salinisation	Erosion	**Indicators**  Indicator common to both appoaches	*Indicator evaluation context*	*Standardised mesure method*	*Operational maturity level*	*Used in economic evaluations*	Supporting soil organisms	Supporting vegetation	Storing carbon	Regulating contaminants	Providing nutrients to the biocenosis	Regulating water quantity	Regulating water quality	Maintaining soil structure
░	▒	▒	▒	▒	░	▒	▒	▒	▒	Depth	⇳		🟢	x	░	░	░		░	░		
									■	Erosion rate	⇔			x	▒	▒	▒	▒	▒	▒	▒	▒
░	░	▒	▒	▒	░	▒	▒	▒	░	Particle-size distribution -- Texture		x	🟢	x	░		░	░		░	░	░
						■ s	■			Bulk density		x	🟢		░	░	░	░		░		■
▒	░	▒	░	▒	░	▒	▒	▒	▒	Rock fragment content			🟡	x			░			░		
▒	░	▒	▒	▒	▒	▒	▒	▒	▒	Structural stability			🟡			░				░	■	■
								■		Electrical conductivity		x	🟢			░		░				
					■	▣ s	▣			Saturated hydraulic conductivity			🟠	x		░		░		■		
					■	▣ s	▣			*Air capacity*					▒	▒	▒	▒	▒	▒	▒	▒
▒	▒	▒	▒	▒	░	▒	▒	▒	▒	Available Water Content (AWC)	⇳		🟢	x		░		░		■		
					■					*Water Holding Capacity* (WHC)	⇔				▒	▒	▒	▒	▒	▒	▒	▒
░				■						pH (water)		x	🟢	x	░	░		░	░			
			░							Cation exchange capacity (CEC)			🟢	x		░		░	░			
			■							Total N content		x	🟢	x	░	░			■			
			■							Available P content		x	🟢	x	░	░			■			
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Available P content		x	🟡	x		░			■			
		■								Total TMM°content			🟢					■				
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Eextractable TMM°content			🟢					■				
		■								Organic polluants content (PAH°)		x	🟡					■				
		■								Organic polluants content (PCB°, dioxins/furans)		x	🟡					■				
		■								Organic polluants content (pesticides and metabolites)		x	🟡					■				
	▣			░	░					Organic carbon content		x	🟢		░	░	■	░		░	░	░
	■ s									Organic carbon/Clay ratio			🟡				▣					
	■									Carbon stock (over 30 cm)			🟢	x			■					
	■									Carbon stock (over 1 m)	⇳		🟡				■					
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Carbon fractions			🟡				▣					
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Oxidizable carbon fraction			🟡				▣					
			■							C/N ratio			🟢		░	░						
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Humus type and composition (including C/N)			🟡		░	░						
■ *										Molecular microbial biomass		x	🟢		■		░		░			
▣ *										Microbial biomass		x	🟡		■ *		░		░			
▣ *										Soil basal respiration		x	🟡		■ *	■			▣			
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	N and C potential mineralisation rate			🟡		■ *	░			░			
■ *										Phospholipid fatty acids (PLFA)					▒	▒	▒	▒	▒	▒	▒	▒
■ *										Soil bacterial diversity			🟢		■ *			░				
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Soil fungal diversity			🟢		■ *			░				
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Fungi/bacteria ratio			🟢		■ *				░			
▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Enchytraeids abundance			🟠		■ *	░						░
■ *										Earthworms abundance		x	🟢	x	■ *	░		■	░	░		░
■ *										Taxonomic composition/functional diversity of earthworms		x	🟢		■ *			■				
■ *										Nematodes abundance		x	🟢		■ *	░						░
■ *										Nematodes diversity		x	🟢		■ *							
■ *										Microarthropods abundance		x	🟡		■ *	░						░
■ *										Taxonomic composition/functional diversity of microarthropods		x	🟡		■ *							
▣ *										Enzymatic activity		x	🟡		■ *			■				
■ *										Abundance of ants					▒	▒	▒	▒	▒	▒	▒	▒
■ *										Diversity of ants					▒	▒	▒	▒	▒	▒	▒	▒

* Version under discussion as of May 24, 2024 -document 2023/0232 (COD) - 10236/24

° TMM: trace metals and metalloids; PAH : polycyclic aromatic hydrocarbons; PCB : polychlorinated biphenyls

■	indicator for a function (right) or for a threat (in SMRL, left)
▣	optional indicator for a function or threat
s	existence of a threshold set by the SMRL
*	One or more indicators can be selected from the column to characterize the function or state of degradation
░	Driver for a function or a threat
▒	Indicator not selected (in study or SMRL)

Indicator operational maturity:

🟢 mature indicator

🟡 still maturing indicator

🟠 indicator under development

⇳ indicator assessed over the entire soil profile

⇔ indicator assessed on a catchment area and/or territory

otherwise, the indicator is to be evaluated on a soil horizon

- Scientifically identify thresholds of change in the «soil ecosystem» state. In a function-based approach, the aim is to identify the ecological tipping points around which these are significantly degraded or improved. This field of research is still largely unexplored and is linked to ecology works on ecosystem dynamics.

In practice, most of the thresholds mentioned in the scientific literature are derived from the distribution of existence values. A soil is considered «healthy» when it falls within the normal range of existing values for all comparable soils

2.3. Choices made by the user of the evaluation

In addition to the indicators and their reference standards for interpretation, the indication system incorporates a series of choices which are largely made by the user of the evaluation, and which need to be spelled out. The co-construction of the system implemented is thus key for its relevance and usability (cf. Section 2.4). The most crucial stages of this involvement are highlighted here, as elements of this system.

■ Defining the purpose of the assessment

Explaining the purpose of the assessment consists in identifying *the indicandum*, i.e. what we want to represent (e.g. a function, or the soil health), and in relation to what we are assessing it (e.g. changes over time, or variations between different uses, or between different practices). This step is crucial, as it **partly determines the selection of indicators to be used, and the choice of the reference values for interpretation**. For example, if the purpose is to assess soil health in relation to the management practices, this requires selecting the indicators most sensitive to the practices in question. This stage in defining the purpose of the assessment can give rise to conflicts, given the differences in perception between stakeholders. It is often overlooked.

■ Spatial and temporal grid

The spatial and temporal monitoring grid and the ad hoc sampling strategy, as well as the choice of reporting format (e.g. dashboard, map, index), including the quantification of uncertainties associated with measurement methods, need to be selected through discussion between stakeholders and experts.

Monitoring grids are chosen based on the **spatial and temporal variability of the object being assessed**. For example, practices such as grazing or returning crop residues to the soil may have a short-term effect on the abundance and composition of microbial communities, a medium-term effect on the degradability of organic matter, and a longer-term effect on the stabilised carbon stock.

■ Aggregation and weighting

Whether approached from the functional or threat angle, soil quality/health is a multi-dimensional object. This raises the question of how to aggregate the various indicators into a single, directly readable result. For example, where functions are considered, aggregation processes are sometimes implemented to produce a soil multifunctionality index from the indicator values obtained for each function.

This approach is controversial, because **although it has the advantage of a very direct readability, it has the disadvantage of concealing the information provided by the evaluation of each function**with the risk of misinterpretation linked, for example, to phenomena of redundancy or compensation between functions. Aggregation also hides the diversity of functions and their evolution dynamics.

Finally and most importantly, the method used must be clearly explained. Two main types of aggregation methods are most commonly used:

- The **downgrading criterion**: if only one of the dimensions of health (e.g. one of several functions) is below the critical threshold, then the soil is considered to be in poor health.
- **Weighting between criteria**: a coefficient is assigned to each criterion to calculate an overall soil quality/health score. This score is then compared with the critical threshold to conclude whether the soil is in good or poor health. Such weighting assumes a hierarchy between functions that the user of the evaluation must take into account. Indeed, while aggregation systems have been proposed in the scientific literature to provide a pragmatic response to the need to assemble information, there is no conceptual basis for ranking the relative importance of different functions.

In any case, attention should be paid to **the diversity of functions performed by soils on a territorial scale**, and not just to the multifunctionality of each soil unit.

2.4. Operationality of indicators

■ Operationality criteria

For an indicator to be effective, the following conditions have been identified and categorised from the scientific literature dealing with indicators in the field of environmental monitoring:

- The **scientific relevance** provided by stabilised conceptual bases and methods;
- The **information value**, i.e. the indicator's ability to answer the questions asked by the users of the assessment, and its relevance for the decisions at hand (e.g. change of land use, adaptation of practices);
- The **legitimacy of** tthe indicator and its appropriation by evaluation users, based in particular on co-construction processes between experts and users;
- The **technical and economic feasibility** of regular monitoring, which requires available consolidated and accessible databases, as well as technical, human and financial resources adapted to the monitoring objectives;
- The **compatibility of** indicators with existing information systems, particularly intergovernmental systems, and with modelling and decision-making tools.

Authors using this classification emphasize the complementarity between **technical operationality**, which has to do with scientific and methodological developments and the databases consolidation, and **practical operationality** - tthe ability of users to take ownership of the indicators and the suitability of the indicators to the issues at hand and the context in which they are implemented. Both aspects must be considered in combination when choosing indicators for a given situation, to ensure a good fit between the degree of precision and technicality and the cost of the system, in relation to the needs, sensitivity and knowledge of users in the field, as well as the resources available.

■ Operationality of selected indicators

This list of operationality criteria was applied to the fifty or so indicators selected as part of the study, with the following results (see Table 1):

- **Nearly half can be considered mature**: their measurement methods are stabilised, or even standardised, and databases have been built based on values measured in a variety of contexts. These indicators benefit from a history of use, or from data acquisition and capitalisation efforts made over the past 20 years. The challenge now is to refine the spatial and temporal grids used to monitor them, in order to gain a better understanding of the causes of variations in their evolution;

- **A quarter are still maturing**, and their use in the field requires support from experts or advisors. Operationality will be facilitated by standardising measurement methods and consolidating reference databases covering the entire territory;
- **A quarter are under development**, still at the research stage. Measurement methods have yet to be developed or stabilised. Most metrics directly quantifying the performance of an ecological function fall into this category.

■ Data availability

The operationality of indicators depends in part on existing data and their accessibility to the user, in particular for identifying reference values and interpreting measurements made in a given context (cf. Section 2.2.).

In France, the available data on soil quality are collected under several programs and consolidated in several databases, including:

- the Donesol database of the Inventaire, Gestion et Conservation des Sols (IGCS) program, which capitalises on all observations made on soils during mapping operations; it also hosts data from the French Soil Quality Monitoring Network (RMQS), whose systematic 16 km resolution grid provides an unbiased estimate of all types of land use/cover on the territory;
- the French Soil Test Database (BDAT), a database of soil analyses on the surface layer horizon of agricultural land;
- the BDSolU database for urban soils, pertaining to the pedogeochemical background in the surface layers of anthropogenic soils that were exposed to diffuse emissions over long periods. It is important to note that the pedogeochemical background of anthropogenic soils provides information on a level of contamination, but should not be considered as a level of pollution. The (BDETM) (Metallic Trace Elements Database) gathers the soil analyses on agricultural land which may receive sewage sludge.

In addition, participatory science and research programmes open possibilities for deploying fine-grained data collection in a variety of contexts, including in private land not easily accessible to research and institutions. Their main weakness lies in the difficulty to control the sampling and measurement methods. This is partly compensated, when the programmes are widely deployed, by the mass of data collected, which enables the application of statistical methods to detect anomalies.

For each indicator selected, the study report lists the reference values obtained from the above-mentioned databases, where available. More occasionally, values are also taken from the literature consulted for the study, or from the proposed European directive on soil monitoring and resilience.

The French system for collecting and managing available soil data is cited in international sources as exemplary. However, if this system is to contribute fully to the operationality of the indicators, **free access to all this data for users still must be ensured**.

3. Mobilising indicators to support public policy on soil quality/health

3.1. Soil quality/health issues have new legal reach

■ Developments in environmental law

In the field of environmental public policy, quality of life and human well-being long took precedence over the ecological quality of environments, sometimes resulting in environmentally nefarious actions, such as the draining of wetlands. From the 1970s onwards, this approach evolved towards a better integration of ecological concepts, as can be seen today in the rules governing the preservation of air, water and natural habitats. For example, the Water Framework Directive (2000), its amendments and implementation legislation show a gradual honing of the assessment of ecological status, which is now divided into five classes for the different types of surface water bodies. To fulfil the initial political objective of preservation and restoration, the indicator system has gradually been articulated to the different levels of governance. It is not yet the case for soils.

■ Evolution of the legal approach to soils

Neither soil nor soil quality have a common legal definition and the legal provisions for their protection are scattered across different codes (e.g. land planning, environment, rural, forestry). The focus is on the soil's capacity to support its use (agriculture, forestry, construction, etc.). **In the absence of objective indicators, urban planning methods take very little account of soil quality**, except in some cases where local authorities are involved in research or support projects (e.g. MUSE[4], UQUALISOL-ZU[5]). Even when the issue of soil quality is addressed by legislation, as in the case for land development operations, it does not play as decisive a role in the final decisions as other aspects such as proximity to urban areas, infrastructure or links with economic sectors. Only in very specific cases (such as certain «Appellation d'Origine Contrôlée» areas) does the economic value of soil incorporate soil quality indicators.

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[4] MUSE offers a method for characterizing, quantifying and mapping soil functions and multifunctionality at the scale of urban planning documents. https://www.cerema.fr/fr/actualites/prendre-compte-multifonctionnalite-sols-amenagement

[5] The UQUALISOL method was used with the municipalities of Gardanne and Rousset (Bouches-du-Rhône), to map an area's soils and the functions and vocations they can fulfil. http://multimedia.ademe.fr/catalogues/CTecosystemes/fiches/methode23p8586.pdf

However, **two recent initiatives reflect the emergence of a more integrated approach to soil quality/health: the Climate and Resilience Act of August 22, 2021 and the proposal for a directive on soil monitoring and resilience** published in 2023 and still under discussion within European bodies.

For a long time, land planning law was based on the objective of saving space and limiting the consumption of natural, agricultural and forest areas, as part of a policy to control urban sprawl. The French land planning code (Art. L. 101-2-1) now fully integrates the objective of combating soil artificialisation, defining it as «a long-lasting alteration of all or part of a soil's ecological functions, in particular its biological, hydric and climatic functions, as well as its agronomic potential, by its occupation or use». A parallel is therefore drawn between the process of artificialisation and its consequence: the degradation of the soil thus artificialised.

The proposed European Directive, at its actual stage, includes a list of indicators designed to provide a comprehensive assessment of soil degradation, regardless of the type of activity (see Section 1.3).

Although it is not yet possible to measure their effects, these recent developments point to a change in approach to soils, taking into account their functionality and adopting a logic of preservation and restoration. But to achieve this, objective information is needed to qualify soils using indicators.

3.2. Indicators in intervention schemes for soil quality/soil health

Soil quality/health indicators are already present in the law or regulation, for example to qualify areas or environments submitted to a specific regime (e.g. wetlands) or in certifying the provision of environmental services (e.g. agri-environmental and climate measures). Soil quality is therefore a useful criterion for the application of a legal regime, with varying degrees of strength depending on the legislation considered.

Most intervention schemes are based on means commitments rather than on the achievement of outcomes (e.g. low carbon labelling). The assumed relationship between the management practices and the soil quality/health that should result, and the expected benefits in terms of ecosystem services is rarely verified. In fact, incentives are mostly calibrated based on measurements taken under experimental conditions, which cannot be generalised to the whole territory. A better understanding of the real impact of these schemes on soil quality and health needs to be developed for each region.

3.3. Restoring degraded soils

■ Diverse paths

Ecosystem restoration has been identified at international level as an effort to repair what has been damaged and is also part of a compensation approach aimed at achieving a zero net degradation situation. It applies to both biodiversity and land. This raises the question of whether this restoration objective recognises the concept of the quality of degraded soils.

French legislation contains a number of concepts with very different degrees of stringency, ranging from the rehabilitation of an area to make it compatible with a particular use, to the ecological restoration of the environment in protected natural areas, to the concept of «renaturation», which is still under construction and may involve a variety of technical processes. With regard to the above-mentioned objective of re-functionalisation, the only explicit reference to it is in the provision on «de-artificialisation» of soils in Article L. 101-2-1 of the French land planning code. At European level, the proposed directive on soil monitoring and resilience sets the objective of «regeneration» and «renaturation», which aims to return soils from a degraded state to a healthy state.

■ Monitoring engineering operations

Changes in a soil's quality/health can be observed over timeframes that can be very short for some aspects (e.g. microbial communities) and very long for others (e.g. carbon stock). As a result, some changes that occur quietly over the long term may already be irreversible by the time they are detected. Conversely, the recolonisation of space by plants and soil organisms is the most accessible and frequently collected observation. However, it is not sufficient in itself to demonstrate that the refunctionalisation of the soil has been achieved, which takes longer.

The scientific literature therefore calls for vigilance, for example with regard to the expectations of an operation aimed at desartificialising the soil, so that the area does not actually suffer a loss of functions. In this sense, the creation of a soil quality/health reference framework will be useful for controlling and monitoring measures to restore degraded soils, regardless of the legal framework in which such action takes place. It will also enable us to influence the alignment of planning documents with the challenges of preserving the areas concerned.

It is therefore crucial to deal with the uncertainty of whether the success of a restoration project is real and sustainable over time, both scientifically (how do we validate the effectiveness of the restoration?) and politically (how do we ensure the long-term preservation of the restored soil?).

If soil quality indicators can be used to monitor and evaluate restoration activities in conjunction with other environmental indicators such as biodiversity, this protocol could be complemented with economic, sociological and cultural indicators. These indicators will play a crucial role in ensuring the sustainability of restoration projects, which can be guaranteed through the use of contractual or land management mechanisms that take soil quality into account.

3.4. Territorial levels of soil quality/soil health governance

Research into the governance of soil quality and health emphasises the importance of a territorial approach to mobilising stakeholders around shared issues. They also highlight different options for delimiting the geographical area and competencies associated with this governance, which can be based on:

- **existing administrative units** (e.g. the Region-SCoT-PLU territorial planning scale), which enables consistency with territorial planning but does not necessarily correspond to the reality of land uses (particularly agricultural and forestry) or of soil quality;
- **homogeneous units in terms of soil type and land use** (the Petites regions agricoles are an example of a compromise between homogeneity of soil types and consideration of uses);
- units relevant to an **integrated approach to environmental issues**, such as watersheds. This issue is also being discussed at the European

level as part of the discussion on the Soil Monitoring and Resilience Directive, which envisages the delimitation of soil districts (for governance) and soil units (for monitoring) within each Member State. At this stage, however, the definition of these units is still very much undetermined.

3.5. Stakeholder involvement

The question posed in this study concerning the reference framework and the indication system cannot be tackled without involving the stakeholders in clarifying the purpose of the assessment. Assessing the quality/health of a region's soils therefore requires a process of reflection involving soil users and scientists, starting with a clear definition of the purpose of the assessment, and defining the indication system accordingly.

Given the complexity of soil functioning and the questions raised by the definition of soil health, the scientific literature emphasises the value of participatory approaches. Involving stakeholders in the design, implementation and interpretation of monitoring programs fosters a shared understanding of soil quality and soil health, and helps to regulate power relationships. The development of inexpensive field teaching kits and manuals, as well as the establishment of nature centers (such as living labs, for example) are needed to develop opportunities for involvement and places for exchange around the soil, its uses and its health.

4. Suggesting areas for future research

4.1. Incentives based on means and/or on outcomes

Public policy incentives for soil conservation are mainly based on means commitments. Theoretical developments promote the implementation of payments for ecosystem services or environmental services, but in practice it is most often the implementation of means, and not the result obtained in terms of soil quality/health, that is contractualised. However, the scientific basis of the relationship between incentives and actual results in terms of soil quality/health is still fragile. In this context, modelling appears a key open field of research.

4.2. Thresholds: concepts, evaluation, benefits and limitations

Thresholds are a crucial element in the interpretation of indicators for monitoring public policy. However, thresholds raise questions. The relevance of using such tools is sometimes questioned because a threshold introduces a break in the interpretation of phenomena that are gradual. For example, two situations that are actually close can be seen as very different (e.g. degraded versus non-degraded) if they are on either side of the threshold. Building on the work carried out in this study on the concept of indicator (definition, role, performance, operationality), the question of thresholds remains to be explored. In particular, this reflection should be linked to ecological knowledge of system dynamics.

4.3. Links between drivers and functions

Similarly, there is still a lack of information in the scientific literature on the relationship between the drivers of functions (to which most of the existing indicators refer) and the actual realisation of functions. The indicators in the works analysed are most often chosen empirically and based on common soil science practices, with no description of the link between the indicator and the process studied. The metrics associated with soil functions therefore remain to be developed and stabilised.

Find out more

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The report, synthesis and summary are available online on the INRAE and GIS Sol websites.

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