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Indicators for preserving soil quality

Isabelle Cousin, Maylis Desrousseaux, Sophie Leenhardt, eds

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Foreword

Over the last decade, growing concerns about soil degradation have been accompanied by a proliferation of proposals for indicators and methods of calculation and implementation, from both public and private actors, with varying degrees of scientific rigor. To facilitate consideration of soil quality in public policy evaluation and implementation, the Scientific Interest Group on Soils (GIS Sol) has emphasised the importance of consolidating the available scientific resources available to characterise soil quality, identify and test key indicators that can be used and associated methods.

GIS Sol's mission is to establish and manage the French soil information system in response to requests from public authorities and society. The group of partners it brings together positions it at the interface between public policy and research. To meet the demand for an overview of soil quality indicators, the French Agency for Ecological Transition (Ademe), the French Office for Biodiversity (OFB), the Ministry of Ecological Transition, Energy, Climate and Risk Prevention (MTEECPR), and the Ministry of Agriculture, Food Sovereignty and Forestry (MASAF) commissioned and funded this study. It was conducted by INRAE's Directorate for Collective Scientific Assessment, Foresight and Advanced Studies (DEPE).

The results are published on the INRAE and GIS Sol websites in three document formats available online. The full scientific report includes the background to the assessment, the study's scientific framework, a description of the method used and the cited bibliography, which includes nearly 1,800 references, the analyses produced by the experts, and the general conclusions drawn from them. This condensed report brings together the main findings of the study report, without referencing the entire scientific corpus used. Consequently, the sources listed in the bibliographic appendix to this condensed report do not represent the entire corpus, which can be found in the extended report (Cousin *et al.*, 2024). The summary briefly presents the main lessons learned from this work. In addition, the results were presented at a public symposium on November 20, 2024, video recordings of which are also available online.

NB: The content of this document regarding the Soil Monitoring and Resilience Law is based on the draft version of Directive (EU) 2025/2360, which was adopted after our report was published.

1. Basis of the study

Context and handling of the study commissioning

Context

Soil quality has been a concern since ancient times, long being perceived by predominantly rural populations as essential to their livelihood. Industrialisation and urbanisation have freed human activities from the characteristics and constraints of the soil. This has led to a distancing from the soil that nourishes us, replaced by retail trade and the neutralisation of this surface by more stable and inert coverings. In agriculture, mechanisation, land development and inputs have mitigated the specific characteristics of cultivated land (drainage of wet soils, irrigation of drying soils, tidal flooding and liming of acidic soils, mineral fertilisation of poor soils, etc.). The cultivation of land and increase in yields has coincided with unprecedented demographic growth and changes in dietary habits.

The impact of human activities on soil is now evident in the form of degradation, with the resilience of the soil system limited or even compromised over a period of several decades. Yet soil is the source of many of the resources used by humans, particularly for food production, so its vulnerability to environmental disruption is a cause for concern. Soils play an important role in mitigating these disturbances, but conversely can contribute significantly to them once certain thresholds are exceeded (greenhouse gas emissions associated with the thawing of permafrost–polar soils–, desertification of Mediterranean soils, etc.). The alert has been raised at every institutional level: the overall estimate of the proportion of land affected by degradation is 20 to 40% (United Nations Convention to Combat Desertification, 2022); within the European Union (EU), the European Soil Observatory (EUSO) has found that 60 to 70% of the EU's land area is affected by at least one soil degradation process[1] (artificialisation, erosion, compaction, pollution, excess nutrients, salinisation, loss of organic matter, loss of biodiversity); and in France, around 20,000 ha of natural, agricultural or forest areas are lost each year.[2] Land use changes have therefore been included in the list of planetary boundaries, the exceeding of which compromises the sustainability of conditions for human development.[3]

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1. EUSO (European Union Soil Observatory), https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard (accessed on 4/11/2024).

2. French Observatory on Land Artificialisation, https://artificialisation.developpement-durable.gouv.fr (accessed on 9/11/2024).

3. "Planetary boundaries define a safe and just development space for humanity, based on intrinsic biophysical processes that regulate the stability of the Earth and marine systems on a global scale. Nine biophysical processes that together regulate this stability: climate change, biodiversity loss, disruption of nitrogen and phosphorus biogeochemical cycles, land use change, ocean acidification, global water use, stratospheric ozone depletion, increased aerosols in the atmosphere, and the introduction of new entities into the biosphere", Steffen *et al.* (2015; https://doi.org/10.1126/ science.1259855), cited by FRB (2023; https://www.fondationbiodiversite.fr/wp-content/uploads/2023/10/FRB_Prospective_2023.pdff, p. 41).

Soil conservation is closely linked to global issues such as climate and biodiversity. In fact, around 60% of known living species (Anthony *et al.*, 2023) reside in the soil, which plays a major role in the hydrobiogeochemical cycles that regulate the atmospheric content of greenhouse gases. Favourable living conditions for biodiversity and human societies inevitably require soil conservation.

Gradually growing awareness of the role of soils in preserving the ecosystems that support human activities and food security has led to political initiatives and the adoption of institutional instruments at international and national levels. The timeline shown in Figure 1.1 shows the main ones. The mid-2010s were notable in this regard, with important partnerships being established under the auspices of the UN around the International Year of Soils in 2015. Major strategies adopted in the early 2020s at the European level (Green Deal and Pact for Healthy Soil in Europe) and at the French level (National Biodiversity Strategy–SNB 2030, which provides in particular for the development of a national soil strategy) laid the foundations for a soil conservation policy.

On a legislative level, initiatives were taken in the early 2020s in France (Climate and Resilience Law setting a target for limiting land artificialisation) and in the EU (proposal for a framework directive on soil monitoring and resilience).

Soil functioning and human activities

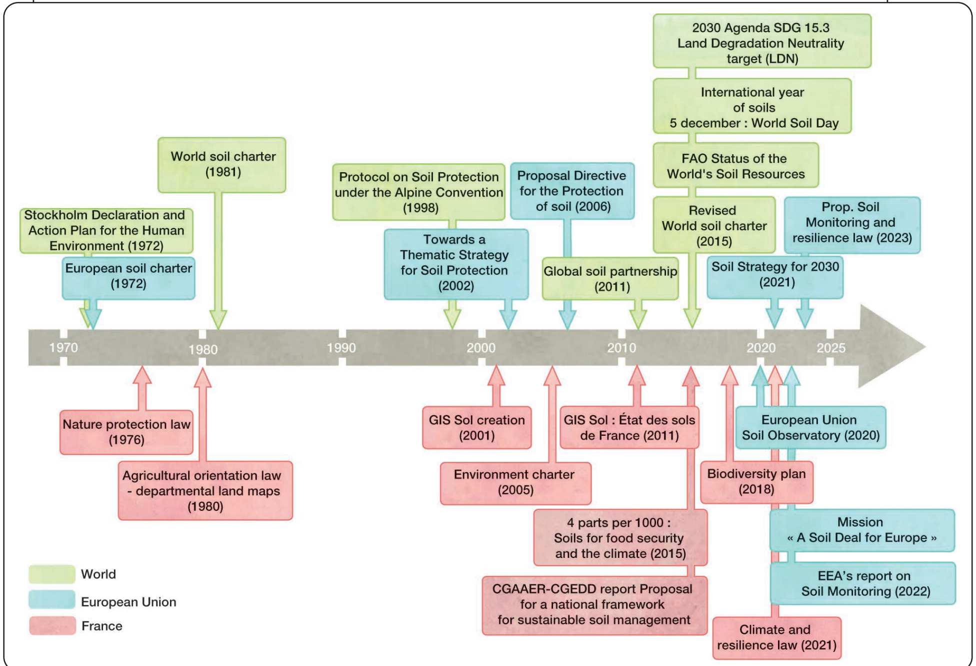
Soils in relation to hydrobiogeochemical cycles and biodiversity

Growing concerns about soil are linked to the fundamental role it plays in the cycles that connect it to the different Earth spheres: the atmosphere, the biosphere, the lithosphere and the hydrosphere. The surface conditions of the soil cover are related to gravity, winds, and the vertical or lateral circulation of water within, below or above the soil cover (surface and deep aquifers, evaporation, evapotranspiration, rainfall, fresh water and sea water). The biosphere influences soils organic matter (decomposing litter, leachate and, above all, roots and soil fauna) as well as by extracting nutrients that the soil makes available to it. In addition to supporting the soil cover, the lithosphere is a source of minerals that are transformed, altered and reorganized through its contributions.

Soil cover is a dynamic flow system. Therefore, it is difficult to discuss soil formation as if soil originated on a specific date (Girard *et al.*, 2023). Some of the processes that govern hydrobiogeochemical cycles constitute inputs to the soil (including weathering of the geological substrate, atmospheric deposits and precipitation, biological activity, and anthropogenic inputs such as fertilisation), while others constitute outputs (including runoff and erosion from the soil surface into watercourses, percolation and leaching into deeper layers, gaseous emissions into the atmosphere, and export through biomass harvesting).

Soils thus play a major role in the cycles of many elements, including carbon, nitrogen, phosphorus and potassium. They are the main global reservoir for some of these elements and the place where they are recycled within organic matter, interacting with microbial, plant and animal organisms. Recent estimates (Friedlingstein *et al.*, 2023) indicate that

Figure 1.1. Timeline of the main institutional initiatives aimed at preserving soil quality, whether directly or indirectly



SDGs: Sustainable Development Goals; FAO: Food and Agriculture Organisation of the United Nations; CGAAER: General Council for Food, Agriculture and Rural Areas; CGEDD: General Council for the Environment and Sustainable Development (currently IGEDD); EEA: European Environment Agency; GIS: Scientific Interest Group.

soils are the largest reservoir of organic carbon, surpassing terrestrial biomass, surface sediments and the ocean. Carbon flows between the soil and the atmosphere are significant and can be positive (sequestration) or negative (CO_2 emissions). Increasing, or at least maintaining, soil carbon stocks is considered essential to limiting or mitigating the predicted increase in atmospheric CO_2 and its consequences in terms of climate change (Brunet and Voltz, 2023).

Globally, continental soils receive an average of 800 mm of rainfall per year (Brunet and Voltz, 2023). For France, this average is 600 mm. Soils retain some of the water that infiltrates during wet seasons, which can then be accessed by plants for growth. This water evaporates, either through vegetation or directly from the soil. Human societies have a decisive influence on how rainwater is distributed between infiltration, runoff and percolation into the soil. In temperate environments, the storage capacity of soils can reach 2/5[e], or even half of the annual rainfall (Brunet and Voltz, 2023). Unstored water passes through the soil to form groundwater, rivers and lakes, eventually ending up in the seas and oceans.

Soil and human activities: ecosystem services, functions and degradation

Human activities depend on and influence these cycles. The conceptual framework of the ecosystem service cascade proposed by Haines-Young and Potschin (2010) enables us to analyse the relationships between soil properties, its functions and the ecosystem services that benefit humans. Figure 1.2 shows an adapted version of the illustration by Greiner *et al.* (2017). Thus, soil properties strongly determine the benefits that can be expected from it.

Conversely, human interventions in land use planning (e.g. levelling, sealing, drainage) or soil management (e.g. tillage, fertilisation) influence these properties to varying degrees and over different timeframes. This results in soil degradation that can be measured as such. This is the approach that has been favoured to date by the European Soil Observatory,[4] as shown in Figure 1.3. Eight main threats are assessed: artificialisation on the one hand, and, for non-artificialised soils on the other, loss of biodiversity, loss of organic carbon, pollution, excess nutrients, compaction, salinisation and erosion.

Soil is considered degraded when it is artificialised, or when one of these threats reaches a level deemed critical. Some of these processes can occur naturally in soil. For instance, certain contaminants are naturally present in concentrations corresponding to what is known as the geochemical background. It is only when these baseline values, observed in undisturbed environments, are exceeded that the level of contamination caused by human activities is considered. The same applies to erosion and salinisation, which are natural processes of soil evolution but which can be significantly accelerated and aggravated by human activities. It is therefore only above a certain threshold that these threats are considered to be degradation.

4. EUSO (European Union Soil Observatory), https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard (accessed on 4/11/2024)

Figure 1.2. The “cascade” pattern of the relationships between properties, processes, functions, ecosystem services and benefits (based on Greiner *et al.*, 2017)

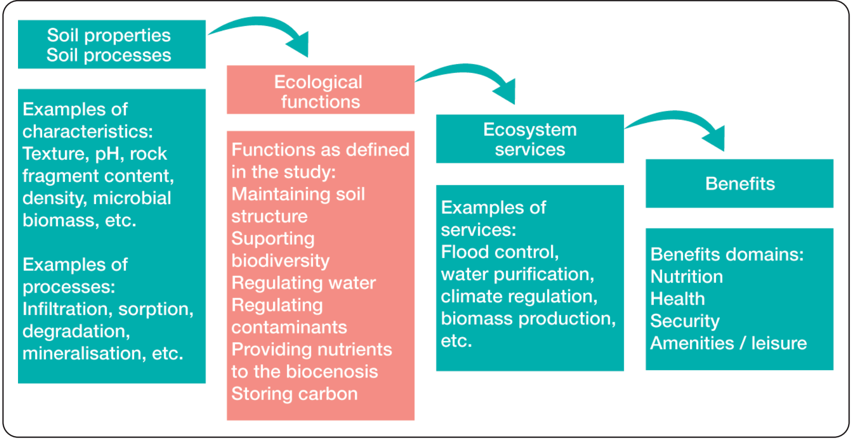
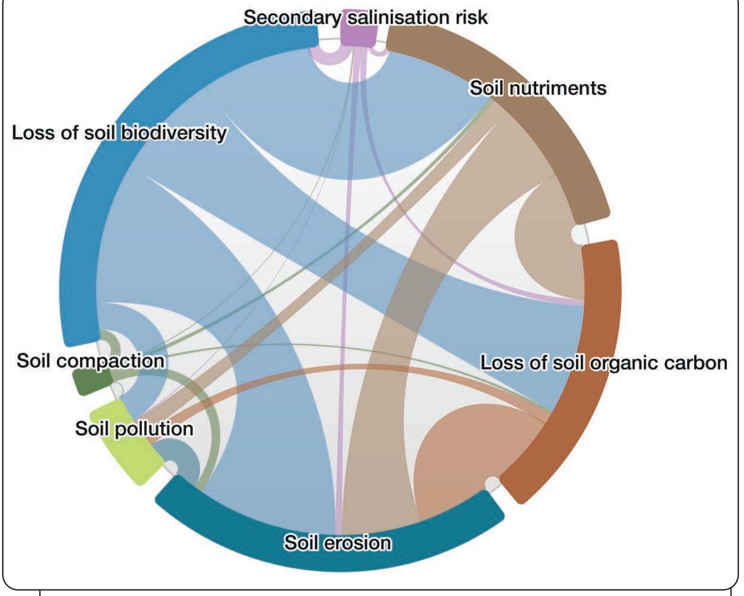


Figure 1.3. Soil degradation in the EU and its coverage.



The size of the area connecting two forms of degradation is proportional to the extent of their overlap in hectares (EUSO, European Union Soil Observatory).

Soil, land and land use

Soil is a component of the ecosystem, which also includes vegetation and terrestrial fauna, as well as the ecosociosystem, which incorporates human activities. Depending on the scope, the French terms "*sol*" (soil), "*terre*" (earth) and "*foncier*" (land) refer to overlapping realities.

"Le Sol" (soil) is defined by the French National Soil Science Society (AFES) as "a volume extending from the Earth's surface to a depth marked by the appearance of hard or loose rock, little altered or little affected by pedogenesis. Soil depth can range from a few centimetres to several tens of metres, or more. Locally, it forms part of the soil cover that extends across the entire surface. It most often comprises several horizons corresponding to a specific organisation of organic and/or mineral constituents. This organisation is the result of pedogenesis and the alteration of the parent material. Soil is the site of intense biological activity (roots, fauna and microorganisms)".[5]

Soil can therefore be analysed as a material, as a compartment of the environment, and as a system capable of performing functions and providing ecosystem services.

"La Terre" is the most polysemic of these three terms. It can refer to the planet Earth itself, the material (e.g. in "*terres excavées*" = excavated soil), soil ("*analyses de terre*" = soil test, "*terres noires*" = black soil), or the geographical and land-related dimension included in the English term "land" ("*terres agricoles*" = agricultural land, "*valeur des terres*" = land value). In agricultural terminology, "terre" has a strong land tenure connotation, whereas "*sol*" is more associated with its characteristics (e.g. deep soils, hydromorphic soils). "*Gestion des terres*" (= land management) can evoke the dynamics of land exchanges, while "*gestion des sols*" (= soil management) refers more to a set of agricultural and forestry practices that are considered together in terms of their consequences for the soil.

"Le foncier" (land) refers to real estate, as well as the way in which space is delimited, fitted out, occupied and subject to rights. The geographical dimension is broader, encompassing both the characteristics of the soil, its uses, and its value. The English term **land** can be understood as covering both the land and geographical dimensions in relation to land use, land degradation, and land consumption in "land take".

Identified needs and scope of the study

Alongside the growing awareness of the importance of soil function for human activities, tensions have intensified between different land uses: food production, extraction of materials, renewable energy, recreational spaces, landscapes, housing, infrastructure, industry, waste storage and, in some cases, purification, flood control, etc. Relationships between these uses call for coordination at a broad level and arbitration at a more local level, based on substantiated information that enables soil quality and suitability for intended use to be assessed. In response to this need and in line with advancing

5. https://www.afes.fr/les-sols/definition-et-enjeux (accessed on 31/10/2024).

knowledge, a multitude of scientific and technical proposals have emerged. Commercial offers for soil quality rating services have also arisen, prompting concerns regarding the scientific validity of the sources and methods used, as well as their transparency.

Initial overview of existing approaches

The diversity of interacting variables within the soil and the range of skills required to analyse them give rise to a wide variety of possible approaches. Table A1, in the appendix, lists the main research projects and institutional observatories that have been implemented over the last decade at various levels of governance. These projects differ mainly in terms of the geographical area covered (world, EU, France, sub-national territories), the types of approaches used (soil health, functions or multifunctionality, ecosystem services), their purpose (monitoring, territorial planning, site/plot management), and sometimes even their specific land use (e.g. forestry, agriculture, urban). With the same aim of taking stock of the situation in France, ADEME published in 2023 a review of research projects on soil multifunctionality that it had supported over the previous 20 years (Vincent and Blanchart, 2023).

The presentation pages of these projects very often state the need for a harmonised and calibrated tool for assessing soil quality. This emphasises the crucial importance of developing a common reference framework for all stakeholders and decision-makers. The framework is expected to align with public policy or private management objectives, to be scientifically sound, and to be operationally practical. However, the proposals available to date remain highly diverse. Soil quality is approached in a variety of ways, with concepts such as quality, health, threats of degradation, safety, functions, ecosystem services and fertility being considered. Projects may focus on specific land uses (agricultural, forestry, urban, natural areas) or they may integrate all uses. The parameters measured almost always cover all areas of physics, chemistry and biology. Some studies on ecosystem services and their assessment process economic data. Projects related to soil artificialisation or forest soil management consider physicochemical data and land use data as *proxies* for soil functionality (e.g. FOR-EVAL, Observatoire national de l'artificialisation (French National Observatory on Land Artificialisation), ARTISOLS and DESTISOL). Recognising the importance of biodiversity and the difficulty of assessing it, some projects have focused more specifically on this dimension (e.g. EJP Soil MINOTAUR, ECOFINDERS and Bio-indicators of soil quality).

A common approach to soil quality for all land uses

It is in this context that the present study was conducted, with the aim of clarifying the scientific basis currently available for supporting soil quality assessment. Notably, the study is aligned with the comprehensive perspective promoted by two ongoing public policy initiatives: the Climate and Resilience Law adopted in France in 2021 and introducing restrictions on soil artificialisation, and the European *Soil Monitoring and Resilience* Directive (proposal published in July 2023) providing for the harmonisation of soil degradation monitoring across the EU as a key step towards soil preservation.

These two initiatives address soil quality in a way that is not specific to each use or type of space (natural, agricultural, forest or urban). With this in mind, the assessment carried out here focuses on scientific resources that are suitable for all uses. Work dealing more specifically with the quality required for agricultural or forestry production, for example, has not been targeted. The aim is to produce a shared overview that can be used by all stakeholders to address the effects of changes in land use and for territorial monitoring.

Polluted sites and soils

This study has not examined the legal framework of polluted sites and soils. The principles underpinning the French policy for managing polluted sites and soils are set out in the texts describing the methodology developed in 2007 (Circular of February 8, 2007) and updated in 2017.[6] The current approach to managing polluted sites is based on assessing health and environmental risks according to how the sites are used. Attention is given to the compatibility of the state of the environment with current and future uses. The need to restore this compatibility in order to control health and environmental risks after site rehabilitation is also taken into account. The management plan focuses on treating sources of pollution, particularly concentrated pollution, and controlling residual pollution, while taking remediation techniques and their costs into account.

Pollution indicators were considered and compiled where relevant for an integrated assessment of soil quality and functions. However, the extensive literature specific to polluted sites and soils was not reviewed.

Expert group involved

The working group was set up and the study was conducted in accordance with the Principles for conducting collective scientific assessments and studies at INRAE (Donnars *et al.*, 2021), which are summarised in Box 1.1.

Isabelle Cousin from INRAE and Maylis Desrousseaux from the Paris School of Urban Planning were responsible for the scientific coordination of the study. A committee of scientific experts comprising 19 researchers and research professors from the public sector (including the pilots) was formed.

Participants were identified based on their disciplinary expertise and publications on the study topics. As illustrated in Figure 1.4, the assembled committee is highly multidisciplinary. Two major areas are represented: soil sciences and human and social sciences. In addition to soil ecology, expertise in ecology was sought to consider concepts and reference frameworks developed for other environments that could be relevant to soils. Finally, skills in data processing and information systems management were also mobilised.

6. https://ssp-infoterre.brgm.fr/fr/methodologie/methodologie-nationale-gestion-ssp (accessed on 31/10/2024).

Box 1.1. Study principles.

This study is based on a critical analysis of the available worldwide scientific knowledge on the various aspects of soil quality. This literature was analysed by a panel of scientific experts from public research or higher education institutions. As well as summarising perceptions and definitions of soil quality, the study identifies the main stages in assessing soil quality, selecting the key indicators and methods for evaluating soil functions. It also highlights areas of concern, controversial issues, and the dynamics of innovation in this field. By updating the scope of acquired knowledge, and identifying areas of uncertainty, controversy, and knowledge gaps, this work aims to inform various stakeholders' reflections on considering soil quality in public policy. It thus contributes to the mission of research institutes to support public policy.

Experts are selected based on their publications in peer-reviewed scientific journals. Attention is given to the diversity of links of interest (e.g., funding, intellectual affinities and collaborative links), which are inevitable in applied research. Cases of conflict of interest are excluded. Transparency is ensured by describing the sources used and the method used in the study report.

The study is conducted in consultation with the funders (the monitoring committee) and the main parties involved in the subject (the advisory committee of stakeholders).

Figure 1.4. Disciplinary fields of the 19 experts in the study according to the INRAE reference framework (up to 3 macro-disciplines per expert).

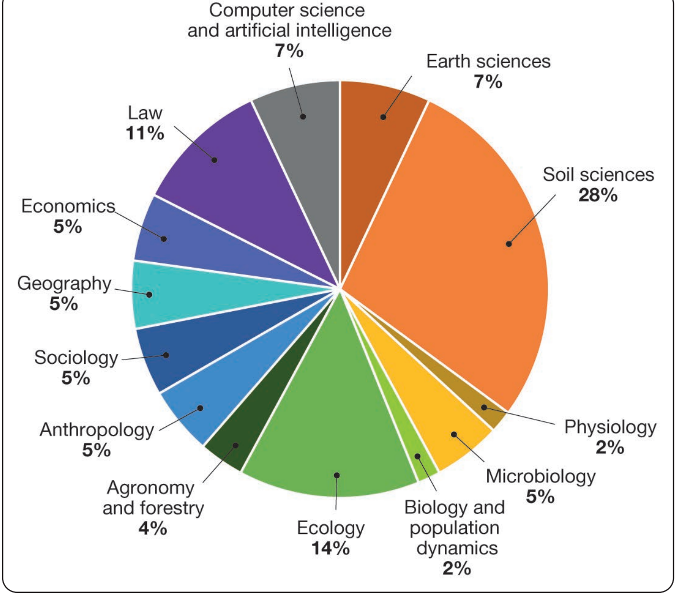
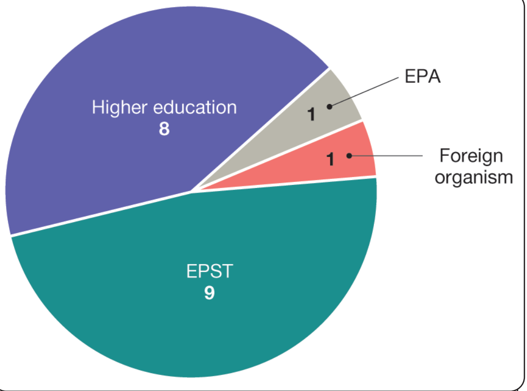


Figure 1.5. Affiliation of the 19 study experts by type of organisation.



EPST: *établissement public à caractère scientifique et technique* – Public Scientific and Technical Establishment; EPA: *établissement public à caractère administratif* – Public Administrative Institution.

The members of the expert committee hail from 10 research and higher education organisations. Their affiliations demonstrate significant diversity (Figure 1.5): only 26% of experts are affiliated with INRAE. A substantial proportion (41%) are from higher education institutions. Notably, there is only one non-French expert.

Occasional contributors were consulted on specific issues and acted under the responsibility of the expert who requested their input. While they are not members of the scientific expert committee, they are part of the working group and are among the report's authors.

Literature analysed

The complete report cites a bibliographic corpus of nearly 1,800 references. This has been compiled from international bibliographic platforms such as Web of Science (WoS) and Scopus, and has been supplemented where necessary by French-language literature, reports, books, and articles that are not referenced on these platforms.

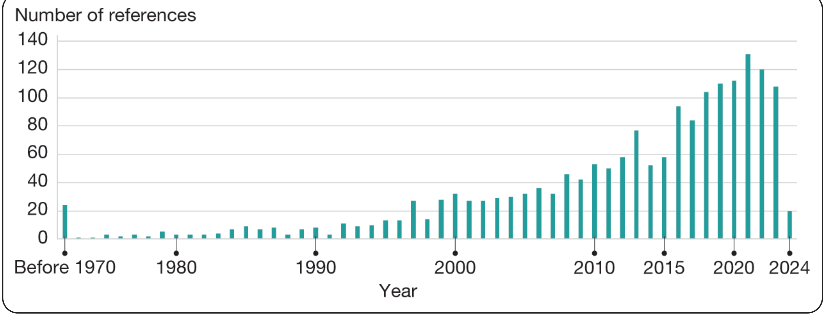
The targeted knowledge is applicable to the soil and climate contexts in mainland France. Articles were selected with a focus on existing literature reviews when they were relevant to the issue under study (Table 1.1).

For the most part (95%), the cited literature dates from after 1990. Older references were also used to trace changes in stakeholders' perceptions and to draw on certain older methodological sources that remain relevant today. Nevertheless, over half of the corpus was published within the last 10 years (Figure 1.6).

Table 1.1 Types of documents from the corpus cited in the study report.

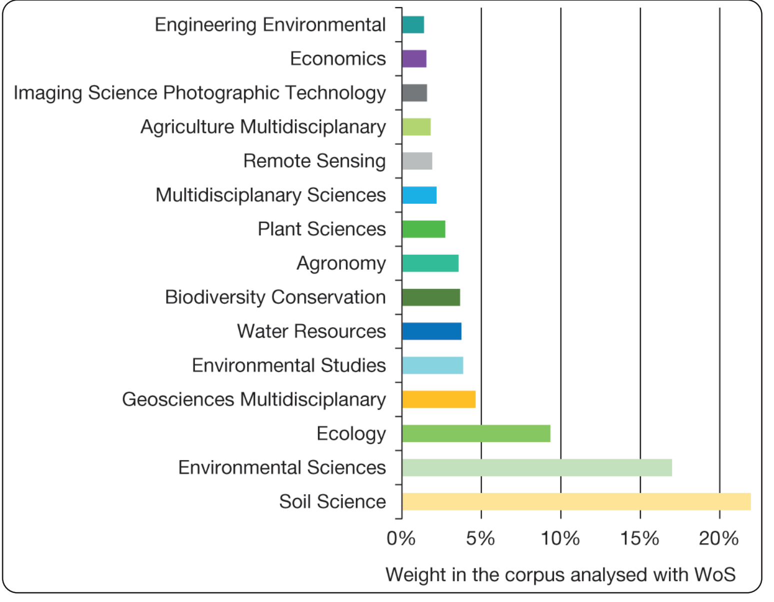
Type of documents	Number of references	% of the report's corpus
Article	1,500	84%
including literature review	257	14%
Book or book chapter	164	9%
Report	81	5%
Conference proceedings or paper	28	2%
Thesis	13	1%
Other (e.g., dataset, map)	9	1%
TOTAL	1,795	100%
Number of references in at least one database (WoS or Scopus)	1,366	76%
Number of references in WoS	1,278	71%
Number of references in Scopus	1,341	73%

Figure 1.6 Temporal distribution of the corpus cited in the study report (n = 1795)



The broad multidisciplinary nature of the corpus is represented in Figure 1.7, which is based on the 1,280 sources referenced in the WoS. The top 15 WoS categories to which the journals publishing the cited articles belong are shown, bearing in mind that the 500 references not included in this WoS category classification mainly relate to grey literature and articles in the humanities and social sciences. The figure also illustrates the core disciplines of the analysed sources in the fields of soil, earth and environmental sciences. In addition to these fields, a broader perspective is provided by ecological studies related to soil functions, and sustainable resource management (water, biodiversity and agriculture; forests, not shown here, appear at a more detailed level).

Figure 1.7. Research areas of the 1,280 references classified in the WoS categories (top 15 categories).



Certain measurement methods based on technologies, identified more specifically by the WoS, are also included such as remote sensing and imaging.

The relative weight of the countries where the authors' affiliated organisations are located (Figure 1.8), reveals the general predominance of the most dynamic geographical areas in terms of scientific production (United States, EU, China). However, it also highlights France's relatively important position, which is linked not only to the selection criteria for sources researched for their applicability in a French context, but also to the historically developed investment in French research on soils. Other countries known for their significant investment in this area are also present in this figure, such as Australia, Canada, Switzerland and Brazil.

Reading guide and terminology used in this condensed report

Reading guide

The bibliographic corpus thus compiled reveals the great heterogeneity of the conceptual frameworks and terminologies used. Soil quality appears to be studied from a variety of angles, including soil condition and properties, threats to its integrity, degradation dynamics, vulnerability, resilience, health, value, safety, ecosystem processes, functions