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An operational definition of absolute soil quality and soil health, and why we need both in practice

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Abstract. (200 words)
The concept of soil health is becoming increasingly popular. Yet, the way to measure it remains unclear, which hinders its effective consideration in decision-making processes. We propose a general framework to interpret soil data, including the scoring of *absolute soil quality* (the state of an indicator representative of a soil function regarding an absolute maximum) and (ii) the scoring of *soil health* (the relative level of an indicator with respect to soil intrinsic potential). We underline that the scoring of soil quality and potential quality is central in land planning and excavated soil reemployment (i.e., matching land future use with soil capabilities) whereas soil health, as the mirror of soil degradation, is essential for soil restoration and sustainable management. We illustrate the approach with saturated hydraulic conductivity as an indicator of soil infiltration capacity for 42 measurements from contrasting soil types and uses, and demonstrate that the approach can be generalized to other soil indicators and functions. Overall, we outline the need to refine target or threshold values for the scoring of both soil quality and soil health, thereby better equipping stakeholders for sustainable soil management and land planning.

1 An operational definition of soil quality and soil health

The concept of soil health is becoming increasingly popular. Yet, the way to measure it remains unclear. Initially defined as "the continued capacity of a soil to function as a vital living system" (Doran and Zeiss, 2000), the concept of soil health has evolved into a deeper integration of soil biology (which has long been the neglected pillar of soil quality) and the capacity of soil to provide ecosystem services in line with sustainability goals (Kibblewhite et al., 2008; Faber et al., 2022). Recently, the Soil Monitoring Law (EU, 2025) defined soil health as "*the physical, chemical and biological condition of soil, determining its capacity to function as a vital living system and to provide ecosystem services*". These services include: (i) food and other biomass production; (ii) regulation of water fluxes and quality; (iii) climate regulation; (iv) habitat for biodiversity; (v) material provision; (vi) support for human infrastructures and activities; and (vii) heritage conservation. Nevertheless, this conceptual definition doesn't fully solve the issue of soil health's practical assessment (Lehmann et al., 2020; Weninger et al., 2024). The lack of an operational definition prevents objective quantification, which discourages stakeholders from incorporating soil health into management plans (e.g., land planning, construction, forestry and agriculture). Vogel et al. (2019) proposed to distinguish the soil intrinsic potential to fulfil a function—determined by its inherent properties—from its current state, thereby identifying the scope for improvement. Faber et al. (2022) and Cousin et al. (2025) followed a similar logic, defining soil health as the current condition of the soil compared to its potential (referred to as "soil quality", conditioned by soil intrinsic properties as well as climate and land use). By positioning soil current state regarding an achievable potential in ideal conditions, soil health reflects the degree of soil degradation. Its measurement is essential for restoration purposes, helping to identify which management practice can best restore soil functioning.

Although the concept of soil health is defined in a relatively consensual way, its scoring does not solve all issues faced by practitioners. The scoring of both the current state of the soil and its achievable potential (if soil is managed ideally for a given soil use) are central for land planning issues and require a proper scoring approach. This is essential to match land (future) use with soil capabilities, which are not necessarily reflected by soil health scores. For instance, a healthy sandy soil will generally have a smaller water holding capacity than a degraded silt loam soil; conversely, a degraded sandy soil may drain water more efficiently than a healthy heavy clay soil. Interestingly, the FAO distinguishes the *absolute soil health*, defined as the deviation of the actual soil from an ideal one, from the *relative soil health*, consisting in a relative rating depending on the suitability of the soil for its actual use. The *absolute soil health* concept of the FAO offers a solution to appreciate the current state of the soil in absolute terms, regardless of soil potential. This approach, while effective for fertility and biomass production, has yet to be extended to other soil ecosystem services.

Consistent with these definitions and to meet the needs of practitioners, we propose a general framework to interpret soil data including (i) the scoring of *absolute soil quality*, defined as the state of an indicator representative of a soil function regarding an absolute maximum; and (ii) the scoring of *soil health*, defined as the relative level of an indicator with respect to soil potential, with soil potential defined as the best achievable value for a given soil (Fig. 1). Our definition of *absolute soil quality* and the *absolute soil health* concept of the FAO converge, however they differ in terminology. For the sake of clarity, we prefer to refer to *absolute soil quality*, since "soil health", to our point, implies a relative state regarding an intrinsic potential, just like for human health.

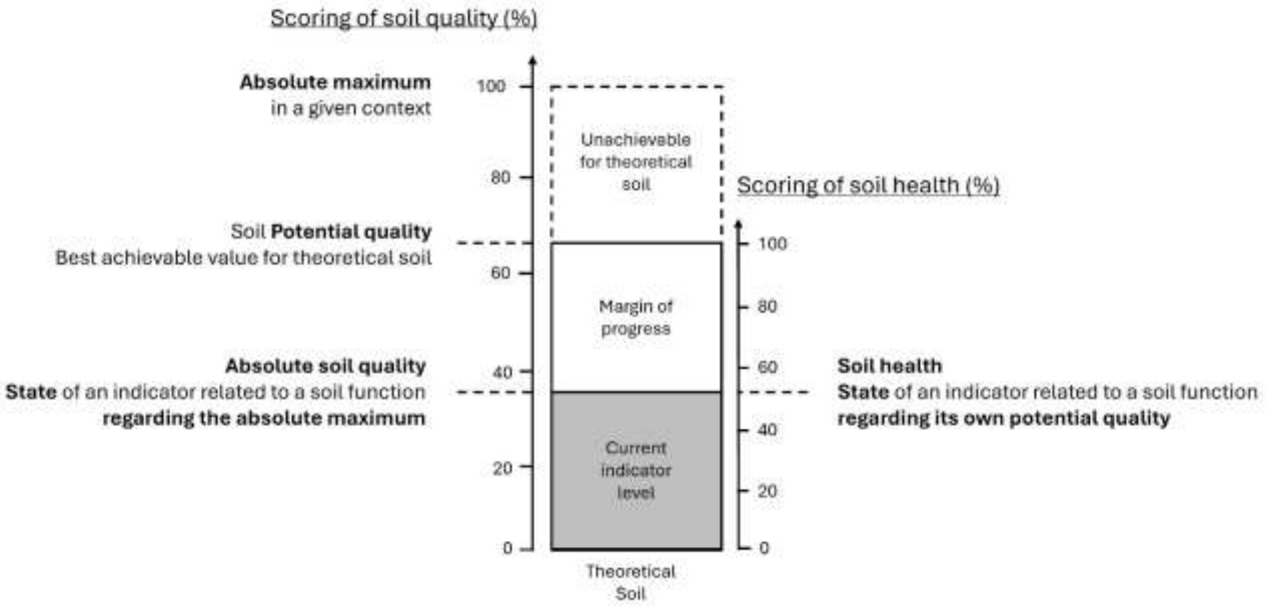

Figure 1. Conceptual representation of soil quality (State of an indicator related to a soil function regarding the absolute maximum), soil potential (best achievable value of an indicator for a given soil) and soil health (State of an indicator related to a soil function regarding soil potential).

In the above conceptual approach, the operational definition of soil quality and soil health relies on the scoring of indicators related to soil functions. This contrasts with the definition of the Soil Monitoring Law (EU, 2025), relating soil health to the provision of ecosystem services. To implement an operational scoring system, the use of soil functions as a reference level is appropriate for several reasons. First, soil ecosystem services may relate to several soil functions (e.g., biomass production depends on water supply, nutrient supply and soil structure), which challenges the direct interpretation of soil indicators in terms of ecosystem services. Second, a conflictual interpretation of one soil indicator may arise if it relates to two or more soil functions, and that these functions are not considered separately (e.g., a high level of available phosphorus favors crop production but hinders soil biodiversity; a high bulk density limits biomass production but improves the bearing capacity of the soil) (Vogel et al., 2019; Lehmann et al., 2020; Baveye, 2021). Third, the aggregation of several indicators into a score for soil functions independent from one another solves the challenge of redundancy (multiple collinearity) between soil indicators, a common issue in soil modelling. This step decreases the risk of a biased interpretation occurring when multiple collinear indicators are interpreted individually. Therefore, soil indicators must be interpreted considering the soil functions they represent. They can then be aggregated to score soil functions, which can be used alone or in combination to evaluate soil ecosystem services, in line with the definition of the Soil Monitoring Law. In a further step, the soil's capability to support a given land use may be evaluated by looking at the priority functions and services for the intended use.

2 Scoring in practice : illustration with the soil saturated hydraulic conductivity

To illustrate the concepts, saturated hydraulic conductivity (Ksat) was chosen as an indicator of soil infiltration capacity. Ksat was measured for 42 soils in Wallonia (Belgium) with contrasting properties and of various soil uses (forest, agricultural, urban, natural and industrial). Ksat were determined from *in situ* measurements with a constant head permeability test (Porchet, 1935; Appendix 1). Infiltration capacity of soils was interpreted from the Ksat measurements based on permeability classes defined by O'Geen, (2013), corresponding to determined Ksat ranges (Table 1). For the quantification of soil quality from Ksat values, the minimal and maximal thresholds of each permeability were positioned on scale from 0 to 5 (Table 1), to develop a scoring function by linear interpolation between discrete values (Fig. 2a), a common approach in soil quality assessment (Vogel et al., 2019; Séré et al., 2024). In parallel, textural classes associated to the permeability ranges of O'Geen, (2013) were used to score soil health (Table 1; O'Geen, 2013). One scoring function was calibrated for each of the five aggregated textural classes (Fig. 2b), with the maximum value of the Ksat range considered as an achievable maximum (Table 1). Therefore, five linear functions were calibrated between 0 and the maximum value of the textural class, corresponding to a 100 % soil health. Accordingly, the finer the texture, the more the scoring function is shifted to the left of the graph (Fig. 2b), which means that the maximum soil health is reached with a lower hydraulic conductivity.

Table 1 : Permeability classes and their corresponding saturated hydraulic conductivity (Ksat) values as defined by O'Geen (2013), and the soil quality score given by the scoring function. Each value range is typical for a given textural class.

Permeability class	Ksat (mm h^{-1})	Scoring (-)	Textural class
Very slow to slow	0 – 5	[0-1]	Clay, sandy clay, silty clay
Moderately slow	5 – 20	[1-2]	Clay loam, sandy clay loam, silty clay loam
Moderate	20 – 63	[2-3]	Very fine sandy loam, loam, silt loam, silty clay loam, silt
Moderately rapid	63 – 127	[3-4]	Sandy loam, fine sandy loam
Rapid to very rapid	127 – 254	[4-5]	Sand, loamy sand and coarse sand

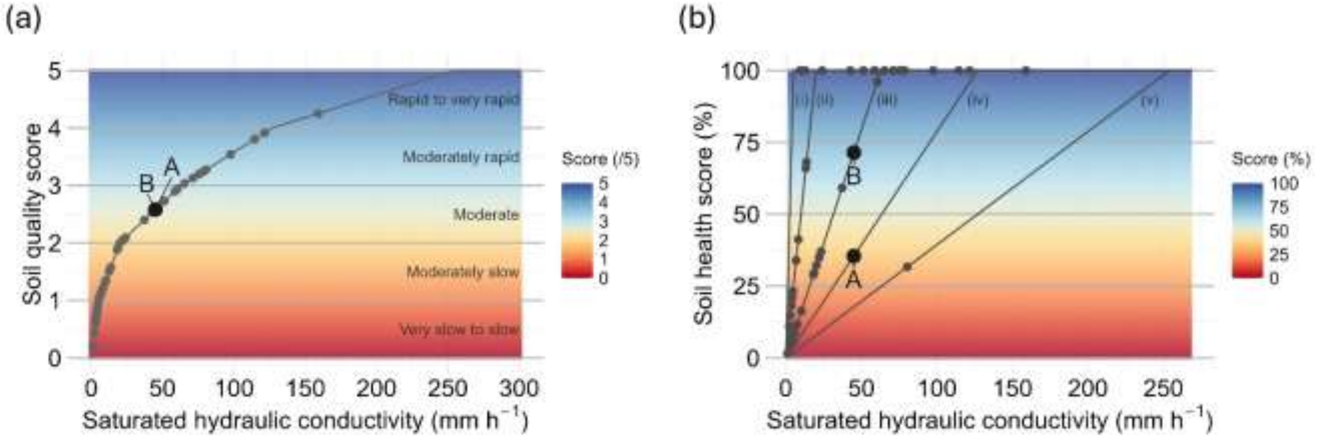

Figure 2. (a) Scoring function (grey line) assigning a quality score to soil infiltration from Ksat values; (b) Scoring functions assigning a soil health score to soil infiltration from Ksat values, according to aggregated soil textural classes (*from left to right: (i) Clay, sandy clay, silty clay; (ii) Clay loam, sandy clay loam, silty clay loam; (iii) Very fine sandy loam, loam, silt loam, silty clay loam, silt; (iv) Sandy loam,*

fine sandy loam; and (v) Sand, loamy sand, coarse sand) point. The grey points are the 42 measurements from this study. In bold are drawn two theoretical soils having similar absolute soil qualities (30 mmh h^{-1}) but distinct soil health scores due to distinct textural classes.

To highlight the complementarity between the soil quality and soil health scoring, two hypothetical soils, having a similar Ksat of 30 mm h^{-1} but a distinct soil texture (Soil A, sandy loam and Soil B, silt loam) were drawn on Fig. 2. Since soil texture defines here soil potential (90 mm h^{-1} for Soil A and 40 mm/h for SoilB) the two soils have a similar absolute quality score but they significatively differ in soil health (30/90 = 33 % for Soil A and 30/40 =75 % for Soil B). This outlines that in a soil health approach (Fig. 2b), for which results are expressed relatively to soil-specific potential, soils rank quite differently than in a quality-based assessment, considering soil indicator values in absolute terms. This emphasizes that soil health reflects soil degradation, representing a decline in the capacity of soil to provide ecosystem services relative to an optimal state (undegraded soil is 100% healthy). This is consistent with the Soil Monitoring Law (EU, 2025) focusing primarily on degradation metrics to monitor soil health (e.g., erosion rates, nutrient excess, bulk density thresholds by textural class for compaction, organic carbon to clay ratio for structural instability).

Ksat values of the 42 Walloon soils were positioned on both graphs, too (Fig. 2a, b). The results spread across the entire range of soil quality classes (Fig. 2a), which gives confidence in the adequacy of the threshold values used for interpreting the data. For the scoring of soil health (Fig. 2b), about half of the soils have reached the maximum score of 100%, which means that they meet or even exceed the optimal value defined for their textural class. They include a majority of forest, urban and industrial soils, with some of them having an important natural or artificial stone load potentially affecting soil infiltration beyond soil texture. This outlines that defining soil achievable potential for a given indicator is often not straightforward and remains a major challenge to implement robust soil health scoring systems.

3 Generalization of the scoring framework

The distinction between soil quality and soil health and the respective scoring approaches can be extended to other soil indicators and functions. For example, regarding the ‘nutrient supply’ function of soil, available nutrient content can be interpreted in absolute terms (absolute soil quality) or normalized to the cation exchange capacity, which modulates the soil’s potential for nutrient retention (soil health). Similarly, alpha diversity (i.e., local species richness) serves as a soil quality indicator for the ‘biodiversity habitat’ function of soil, whereas soil health can be evaluated by comparing observed diversity to the expected value predicted from environmental parameters (Terrat et al., 2017). Given the multiplicity and diversity of existing soil indicators, we are convinced that the concept can be extended to each of the main soil functions, for a quantitative evaluation of all key dimensions of soil quality and health.

However, it is important to note that all soil indicators do not perfectly match this framework. For instance, some soil indicators may have target values that are not soil-type specific. In this case, soil quality and soil health concepts converge, because they range on a similar scale. This is true for instance for the VESS indicator (Visual Evaluation of Soil Structure; Guimarães et al., 2011), an indicator aiming to score structural quality and ranging from 1 to 5 regardless of soil type. In this case, the

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indicator remains relevant in evaluation schemes of both soil quality and soil health, even though the two concepts overlap. In contrast, soil 'determinants' (e.g. stone load, soil texture and mineralogy) are properties that do not vary (or to a very limited extent) naturally in soils over human timescales. These indicators that intrinsically define the soil and its achievable potential can hardly be integrated in soil health scoring schemes because they are not (or poorly) affected by degradation processes and can hardly be improved by human intervention. However, they absolute soil quality scoring may have an interest.

4 Conclusions and perspectives

In conclusion, a comprehensive interpretation of soil indicators requires two distinct types of reference systems: (i) absolute soil quality reference values to answer the questions: "How is a given soil performing in absolute terms? Is this soil inherently superior to another for a specific function?" This information is key for land-use planning and for excavated soil reemployment; and (ii) soil health reference values (i.e., target or threshold values specific to a soil type or condition) to answer the questions: "Is the soil performing close to its potential? Is there room for improvement?" This information is crucial for restoration and sustainable management purposes. We believe that the concept developed here has a universal character and can be extended to other soil functions and indicators. We also highlight that the development of adapted benchmarks is key to improving the interpretation of soil data. Particularly, the determination of soil achievable potential is challenging and critical, because its determination is necessary to assess soil health. Therefore, we strongly encourage the soil science community to establish refined target or threshold values to improve scoring systems for both soil quality and soil health indicators. This will contribute to equip stakeholders with the necessary tools to better take soil functionality into account in decision-making processes, which is key for sustainable soil management and land planning in the future.

Appendix A – Experimental methods and data

In the framework of the Walloon Soil Quality Index (IQSW) project, 42 soils from various land uses (forest, agricultural, urban, natural and industrial) have been sampled and analysed from March to October 2025 in Wallonia, Belgium. The goal was to measure a number of physical, chemical and biological parameters to evaluate soil quality and health. Sampling and field measurements were conducted in two phases, with 32 sites visited from March to June 2025 and 10 of the 32 sites revisited in October 2025, to test the seasonal variability of the parameters. At each site, a homogeneous zone has been determined from cartographic data and field observations prior to sampling based on soil type, topography, land cover, management practices and historical data. Measurements and sampling were located within a circle of 10 m in diameter in the homogenous zone.

Among the measured parameters, saturated hydraulic conductivity (Ksat) was determined *in situ* using a constant head permeability test adapted from the Porchet method (Porchet, 1935) following the protocol established by Brussels Environment in Belgium (https://document.environnement.brussels/opac_css/elecfile/O015_-_Fiche_n4_-_Essai_Porchet_Tube_FR.pdf).

This method consists in monitoring for 30 minutes the water flow rate in a borehole dug in the surface horizon (diameter of 15 cm and approximately 20 cm in depth). After one hour of pre-saturation, a constant head is maintained in the borehole with a graduated cylinder vertically inserted into the borehole and filled with water (Fig. A1). The cylinder is perforated at 15 cm from the bottom to let water flow to the borehole and maintain the constant load. The test is initiated when air begins to enter the cylinder, indicating that the water level in the borehole has reached the perforation height. The decrease in water height within the cylinder is recorded at regular time intervals (first, every minute, then every 5 minutes) for 30 minutes or until the cylinder is empty. These values are then used to deduct the mean Ksat value following equation (1).

$$Ksat = \mu(K(T)) = \mu\left(\frac{d^2}{(4\,H\,D) + D^2}\,\frac{\Delta h}{\Delta T}\right) \qquad (1)$$

Where $\mu(K(T))$ is the mean of conductivity values deduced for each increment of time; d, the cylinder diameter; H, the water height in the borehole; D, the borehole diameter; T, the time increment; and h, the height of the water column in the cylinder. For each site, four permeability tests were conducted in the homogeneous zone. The result presented in Table A1 is the mean of these four tests.

Figure A1: Field set up for the permeability test. A cylinder prealably filled with water is inserted into a borehole (15 cm diameter, around 20 cm in depth) and the water flow rate is measured to calculate Ksat.

At each site, a composite sample was bulked from ten cores sampled with an auger (0-30 cm). Laboratory analysis was subcontracted to an accredited laboratory (Centre de l'agriculture et de la ruralité in La Hulpe, Belgium) and included soil texture (protocol derived from ISO 11277), organic carbon (ISO 10694) and pH in a 1M KCl solution (ISO 10390).

Table A1 describes the 42 individual measures in terms of soil use, texture, organic carbon content, pH in KCl and Ksat.

Table A1: Description of the 42 analysed soils in Wallonia, Belgium. ID with a letter in suffix refers to the results of the second revisit (October 2025) of a same site. The textural class was determined from the laboratory analysis (protocol derived from ISO 11277). Ksat is the mean value of the four replicates values measured on each site.

ID	Soil use	Texture	Organic carbon (%)	pH KCl (/)	Ksat (mm.h^{-1})
01	Industrial	Loam	1.81	6.60	6.78
02	Urban	Loam	1.91	7.80	13.20
03	Urban	Silt loam	2.45	8.10	23.33
04	Industrial	Silt loam	0.49	8.10	3.16
05	Agricultural	Loam	0.94	6.00	24.00
06	Agricultural	Silty clay	6.07	7.00	97.49
07	Urban	Loam	2.98	5.50	13.64
08	Urban	Silt loam	5.23	5.90	60.49
09	Forest	Loamy sand	3.03	3.30	30.00
10	Forest	Silty clay	5.78	3.60	114.47
11	Agricultural	Loam	1.80	4.20	3.65
12	Agricultural	Silt loam	1.31	6.40	18.69
13	Agricultural	Silt loam	1.17	6.70	5.84
14	Agricultural	Silty clay	3.91	7.50	71.07
15	Agricultural	Silty clay	3.72	7.10	75.43
16	Agricultural	Silt loam	3.21	6.30	1.02
17	Forest	Clay	1.79	3.90	78.60
18	Forest	Silty clay	2.76	3.80	51.34
19	Urban	Silt loam	1.61	6.00	5.29
20	Urban	Silt loam	4.65	7.10	22.05
21	Urban	Silt loam	0.69	7.20	7.34
22	Agricultural	Loam	1.75	5.80	2.97
23	Urban	Silt loam	25.27	7.30	121.60
24	Industrial	Silt loam	2.71	5.80	30.00
25	Industrial	Loam	3.58	5.00	4.64
26	Urban	Silty clay	6.54	7.50	58.52
27	Urban	Silty clay	6.89	6.20	12.62
28	Natural	Clay	4.07	7.10	158.98
29	Agricultural	Silty clay	0.56	6.80	9.52
30	Agricultural	Silty clay	3.21	6.20	42.68
31	Agricultural	Silt loam	2.31	5.60	18.21
32	Agricultural	Silt loam	2.24	5.30	65.26
05-b	Agricultural	Loam	1.03	6.20	8.25
08-b	Agricultural	Loam	1.02	6.30	58.88
09-b	Forest	Loamy sand	1.97	3.20	80.46
11-b	Agricultural	Loam	1.80	4.40	4.21
20-b	Urban	Silt loam	4.39	7.40	10.31
21-b	Urban	Silt loam	0.61	7.40	3.90
22-b	Agricultural	Loam	1.75	6.00	2.20
23-b	Agricultural	Silt loam	1.33	5.20	3.54
27-b	Urban	Silt loam	6.36	7.50	37.26
32-b	Agricultural	Silt loam	2.05	5.00	20.34

Code, data, or code and data availability

The core data used in this manuscript is available in Appendix A, where Ksat values are averaged per site. The code was developed to design an original numerical tool, to automatically interpret soil data (absolute soil quality and soil health) through a web application. Both data and code are the property of the funder. Please contact the authors if you would like to access the information. Author contributions

All authors contributed to the overall discussion surrounding the concept of soil quality and health, their operational definition and practical implementation. All authors designed the field work for the measurement of Ksat values; CV created the scoring functions and analysed the data; BH formalized the concepts and drafted the manuscript, which was revised and improved by all authors.

Competing interests

The authors declare that they have not been subject to any conflict of interest.

Disclaimer

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Short summary

The concept of soil health is becoming increasingly popular. Yet, the way to measure it remains unclear. We developed a general framework to measure not only soil health (the relative level of an indicator with respect to soil intrinsic potential), which central for sustainable soil management, but also absolute soil quality (the state of an indicator representative of a soil function regarding an absolute maximum), which is necessary in land planning, to match land use with soil capabilities.