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Fundamental conditions "indicators" should meet to be objective and to guide practice reliably

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Abstract. Over the last 2 decades, a significant body of research has been devoted to finding parameters that could serve as "indicators" of a range of soil properties of interest, including soil health and the many functions/services of soils. Even though the topic had been the object of a sustained debate among ecologists between 2001 and 2010, no one seems to have looked so far into conditions soil indicators should satisfy to be objective, nor is it made clear to users and policy makers which ones are objective and which ones are value-laden and therefore subjective. In the present article, we identify the conditions a soil parameter A needs to satisfy in order to be an objective indicator of another property B. We argue that in addition to A and B being measurable and not merely quantifiable approximately, a testable mechanistic theory needs to exist, which causally relates A and B. In most contexts in which soil indicators are currently used, such a theory appears to be entirely lacking, leading us to call for a significant research effort focusing on theory development.

1 Introduction

Over the last two decades, the use of "indicators" has become ubiquitous in many disciplines dealing with ecology or the environment. In the context of soils, indicators are used routinely to assess, quantify, and map the various ecosystem services (ES) they provide to human populations (e.g., Rillig et al., 2023; Lechevallier et al., 2025; Wadoux et al., 2026a,b) or to assess their "quality", "health", or "security" (e.g., Liptzin et al., 2022; Bagnall et al., 2023; Sharma et al., 2023; Jia et al., 2025; Evangelista et al., 2025; Dynarski et al., 2026; Wieser et al., 2026) and thereby, purportedly, guide farmers and land owners toward the most appropriate soil management practices. On soils alone, thousands of articles have dealt with one or more indicators. Consistently absent from this remarkably large body of literature published recently is any in-depth analysis of the conditions a given parameter has to satisfy to be considered as an indicator of a property one is interested in.

There was a time when this aspect of indicators attracted attention and was actively debated in the ecology literature. Twenty-five years ago, Dale and Beyeler (2001) pointed out that the use of ecological indicators as resource management tools was hampered by the fact that "management and monitoring programs often lack scientific rigor because of their failure to use a defined protocol for identifying ecological indicators". They added further that "until standard methods are established for selecting and using indicators, interpretation of their change through space and time remains speculative […].

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The creation and use of standard procedures for the selection of ecological indicators allow repeatability, avoid bias, and impose discipline upon the selection process". In contrast to that perspective, at about the same time, other authors recommended that ecological indicators should involve other, less strictly science-based perspectives. Hyatt (2001) considered that the use of ecological indicators, to balance socio-economic and ecological aspects in decision making, should be improved, a view echoed by Robertson and Hull's (2001), who complained that ecological indicators "are too often defined only by scientists".

In the decade that followed, a sustained debate took place on the nature and meaning of ecological indicators (e.g., Smyth et al., 2007; Niemeijer and De Groot, 2008; Heink and Kowarik, 2010; Syrbe and Walz, 2012; Müller and Burkhard, 2012). At the science-based end of the spectrum of views expressed in this debate, Niemeijer and de Groot (2008) pointed out that "often, no formal criteria are applied regarding an indicator's analytical utility within the total constellation of a selected set of indicators. As a result, the indicator selection process is subject to more or less arbitrary decisions, and reports dealing with a similar subject matter or similar geographical entities may use widely different indicators and consequently paint different pictures of the environment." To alleviate this problem, Niemeijer and de Groot (2008) recommended that identification of the most relevant indicators in a given situation should be based on the concept of "causal network". Turnhout et al. (2007), on the contrary, were interested in "ecological indicators that attempt to measure the ecological quality of ecosystems and that can be or are specifically developed to be used as instruments to evaluate the effects of policies on nature." They claimed that these indicators, "although they are highly dependent on scientific knowledge, cannot be solely science-based, due to the complexity of ecosystems and the normative aspects involved in assessing ecosystem quality", and they argue that the inclusion of stakeholders' perspectives is essential in the development of ecological indicators, which are situated "in a fuzzy area between science and policy". For Müller and Burkhard (2012), ecological indicators should not be science-based either but should instead be "management-relevant" communication tools that "facilitate a simplification of the high complexity in human-environmental systems."

In the overview they provide of the then existing definitions of ecological indicators, Heink and Kowarik (2010) distinguished between ecological indicators described as, alternatively, descriptive measures, normative measures, hybrid measures, parameter values in hybrid concepts, descriptive components, and hybrid components. They concluded their overview with the impression that "the indicator term is a profoundly ambiguous term that has different meanings in different contexts. […] The intermingling of descriptive and normative concepts in the use of indicators is rife in [the] conservation literature. There are many articles that make use of indicators for soil quality, sustainability, ecosystem health, or biodiversity value […], while leaving the normative justification for the selection of the respective indicators mostly unclear. This implies that normative values can be measured *objectively*, which is certainly not true. Thus, implicit values are insinuated to the reader, a situation which has to be avoided […]. *To distinguish empirical science from normative settings or even personal viewpoints with doubtful acceptability, it is very helpful to separate descriptive from normative indicators*" (emphasis added).

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Since the publication of this article by Heink and Kowarik (2010), the debate among ecologists on the meaning of ecological indicators appears to have been put on a back burner. The nomenclature of ecological indicators proposed by Heink and Kowarik (2010) is often cited, but in practice, authors rarely specify whether the indicators they consider are by definition objective, i.e., independent of the value system of whoever evaluates them, or are value-laden, and hence necessarily subjective. The impression that the ecology literature gives at this point is that ecologists have pretty much given up trying to make ecological indicators objective, or even carefully distinguishing the few that are from the many that are not. As the editor of an ecology journal explained to us recently, researchers in that discipline "are far from understanding all the complex relationships between the variables involved in ecological indication" and focus their attention instead on addressing the needs of "users of ecological indication for the necessary applications that can be developed and applied to real-life problems even if knowledge is tainted by the confounding of complexity", and, one might add, by subjectivity.

To be sure, soils are no less complicated to describe than the ecosystems considered by ecologists. Therefore, if complexity explains why ecologists feel forced to accept that some of the indicators they use be subjective, there might conceivably be equally as many reasons to do so in soils. However, just as it makes sense to question the usefulness of the concept of ecosystem when dealing with the functions/services provided by soils (e.g., Baveye et al., 2018), it is useful to enquire whether subjective indicators like those defined by ecologists are really appropriate for the management of soils. The risk in that context, which in many ways is already materializing now, is that farmers and soil managers might get bombarded with biased and contradictory "indicators" designed to meet the needs of particular economic or specific interest groups, e.g., the fertilizer industry or organisations focused on the maintenance of biodiversity or on promoting soil health, so much so that it would create confusion as to what course of action to adopt. If, for some reason, subjective soil indicators need to be used (for example, in relation to cultural services of soils), it would seem desirable, following Heink and Kowarik (2010), to clearly label them as such, so as not to confuse or amalgamate them with objective, science-based indicators. Policy makers, in particular, need to be made aware clearly of which is which in the information they receive, so that they can make rational, unbiased decisions.

In this general context, the key objective of the present forum piece is to identify the minimum set of conditions that any kind of indicator, and in particular soil indicators, need to meet in order to be considered objective, i.e., a priori free from bias that may be associated with the value system of the observer. Our hope is that the following reflection with stimulate a constructive debate on the topic, and ultimately result in more robust information provided to the public and to policy makers.

2 Conditions of objectivity

A starting point toward addressing this issue of objectivity is to consider that in order for property A of a soil to potentially serve as an indicator for property B, at the very least A should be measurable. That would seem entirely obvious, and yet in various contexts, practitioners have sometimes put forth concepts that do not lend themselves at all to measurement. An example is the amount of "cosmic influence" contributed to a vineyard as part of so-called "biodynamic" practices that are

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popular in most wine-producing regions around the world (e.g., Baveye, 2022). Beyond this imperative that property A be measurable, opinions seem to differ on how rigorously one should require property B to also be measurable. Indicators have been proposed in the past for soil properties that are so vaguely defined that it is not clear how one would go about measuring them unambiguously. A good example in that context is the metaphor of "soil health", which has been the object of an intense debate over the last decade, in particular on how to define it, whether a precise definition of it is really needed, and whether it can be measured in practice or is "immeasurable" as some have qualified it (e.g., Lehmann et al., 2020; Baveye, 2021, 2025; Janzen et al., 2021; Powlson, 2021; Wade et al., 2022; Harris et al., 2022; Maaz et al., 2023). The fact that these questions have not been satisfactorily resolved to date has not discouraged some researchers from developing a whole panoply of soil health indicators (e.g., Janvier et al., 2007; Cardoso et al., 2013; Bagnall et al., 2023).

Strict adherence to the scientific method clearly mandates that properties of systems we are trying to describe be precisely defined and measurable. William Thomson (Lord Kelvin) aptly noted more than a century ago that "when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be" (Thomson, 1889). Over the years, various authors, apparently heeding that advice, have argued that significant effort should be made to develop accurate and practical methods for quantifying the ecosystem services (ES) that soils provide to human populations (e.g., Daily et al., 2009; Crossman et al., 2013; Boyanova et al., 2014; Greiner et al., 2017). However, their statements refer to "quantifying", which is not at all the same as what Lord Kelvin was referring to. He was definitely writing about the ability to *measure*.

The difference is clear in an example from the literature, discussed by Baveye et al. (2016). In this example (Figure 1), the authors mapped 18 ecological parameters —16 ecosystem services and 2 biodiversity metrics — in the French Alps, and explored their co-occurrence patterns underpinning the supply of multiple ecosystem services. They produced "self-organizing maps" encompassing five clusters of ecosystem services, represented graphically by wind-rose- or spider-like diagrams, which the authors argue could be very valuable tools in support of land use planning. However, close inspection shows that none of the normalized values displayed in the wind roses was actually *measured*. Some, related to hunting data, were approximated by disaggregation into 1 by 1 km grid cells of public statistics gathered at much larger spatial scales, which in itself is a very questionable process, without any theoretical justification. Most other parameter values resulted from expert opinion or were obtained via modelling, in the absence of any local data suitable to ascertain how well, or how poorly, the models performed in the selected region.

Half a century ago, after the publication of a landmark article by Westman (1977), the absence of data, and the virtual impossibility to come up with any kind of objective monetary valuation, caused the precursor of the ecosystem services framework to fall out of grace among scientists (e.g., Baveye et al., 2013; Baveye, 2017), and one could argue that the same fundamental problem has hampered the widespread adoption of the concept of ecosystem service since its re-emergence 30 years ago (e.g., Eigenbrod et al., 2013; Petter et al., 2013; Vrebos et al., 2015; Baveye et al., 2016; Baveye, 2017; Rova et

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al., 2018; Lautenbach et al., 2019; Mengist et al., 2020; Pereira et al., 2025). Some progress has been achieved in the actual measurement of some functions and services provided by soils, and in their reliable quantification through the use of heavily-tested models (Chalhoub et al., 2020, 2025; Choquet et al., 2021; Scammacca et al., 2023; Montagne et al., 2025), but this work remains so far limited to a particular type of soil configuration, which makes these endeavours feasible. In the overwhelming majority of articles dealing with ecosystem services, the properties that are targeted in the elaboration of indicators are routinely "guesstimated" by individual experts or panels of experts, or via a crude form of modelling as in Figure 1, and are therefore intrinsically subjective, yet are reported as if they were unquestionably objective (e.g., Grima et al., 2023; Peng et al., 2023; Marali et al., 2025; Yahdjian et al., 2026; Wadoux et al., 2026a,b).

Even if, in attempts to determine whether a soil property A could serve as an indicator for a property B, one were in the situation where both A and B are measurable, would that be sufficient to proceed with using A as an indicator? Clearly, the answer to that question is negative. There has to be more than that. Measurability of both A and B is definitely required, but is not sufficient. A and B would also have to be somehow closely connected to each other. In that respect, one might argue that as long as there is a statistical correlation between the two, that should work. To a large extent, this is the premise on which the application of artificial intelligence to the identification of indicators is based. But a fundamental, and well-known, problem with correlations is that they do not imply causation (e.g., Ives, 2022; Byrnes and Dee, 2025; Yurchenko, 2026). Two properties can be correlated by chance without there being really any connection between them other than a spurious one, for example if both properties happen to be causally connected simultaneously to a third one. As an example, large sea-going ships tend to carry heavy cargo loads and are typically commanded by older, experienced captains. However, there is no causal relationships between the age of the captains and the size of the cargo their ships carry.

In order for the link between properties A and B to be based on causation, and not mere correlation, a testable *theory* —ultimately implemented in a computer model in most cases—is needed that links the two properties *mechanistically*. The development of such a theory requires answers to a number of questions. For example, if one wants a theory linking the biodiversity within an ecosystem to some property of the latter, as some have done for soil "ecosystem" services (e.g., Pulleman et al., 2012; Liu et al., 2023; Fan et al., 2023; Eldridge et al, 2023), one needs to first determine which biodiversity, taxonomic, structural, or functional (Lausch et al., 2016), appears to be most relevant. Then the spatial as well as temporal scales at which the theory is meant to apply need to be considered carefully. Finally, the precise mechanisms by which the ecosystem property of interest results from the characteristics and behaviour of the biodiverse flora or fauna need to be elucidated and described mathematically. Research along those lines for the purpose of defining effective indicators appears to have been virtually non-existent over the last few decades. It seems from the literature that the very understandable desire to see biodiversity preserved around the world has encouraged many researchers to postulate *ex cathedra* that maintaining biodiversity is crucial to sustaining a wide range of ecosystem properties. However, beyond mere words, the link between biodiversity and these ecosystem properties remains elusive in the absence of any underlying mechanistic theory (Baveye et al., 2016b).

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Over the last few years, several authors have argued that a significant effort toward theory development is direly needed, in particular to determine what we should measure in the field (e.g., Neal, 2021; Neal et al., 2020; Harris et al., 2022; Baveye, 2025). This question is particularly timely at the moment, not just for the research on soils but in ecology in general, as researchers who are enthusiastic about the potential of artificial intelligence (AI) advocate for the accumulation of massive amounts of data to feed into the AI algorithms. Theories are required to ensure that data that one collects are actually meaningful. A side benefit of the theory development effort that one hopes will rapidly unfold in that context is that it will also provide a much-needed, strong foundation on which to base the identification of indicators.

4 Take-home message

The key message of the present article is that it is important, when talking about a given "indicator", to make clear whether it is objectively defined and measurable, or whether it encapsulates opinions, influenced by personal beliefs and values. Users, and in particular policy makers, should be told explicitly which is which, to avoid confusion and, worse, disinformation. We offer a blueprint for how to determine if a given soil indicator can be considered objective. This does not at all imply that only soil indicators that objectively relate to soil properties are of interest in practice. Normative indicators, as defined by Heink and Kowarik's (2010) nomenclature, are also useful in specific contexts, for example when dealing with the (often neglected) cultural aspects of soils, and should therefore not be ignored. All that is needed, when developing and promoting such indicators, is a reminder that they are not based on a mechanistic theory, but are the reflection of their author(s) personal beliefs. This should go a long way toward sanitizing any debate in which these indicators are involved.

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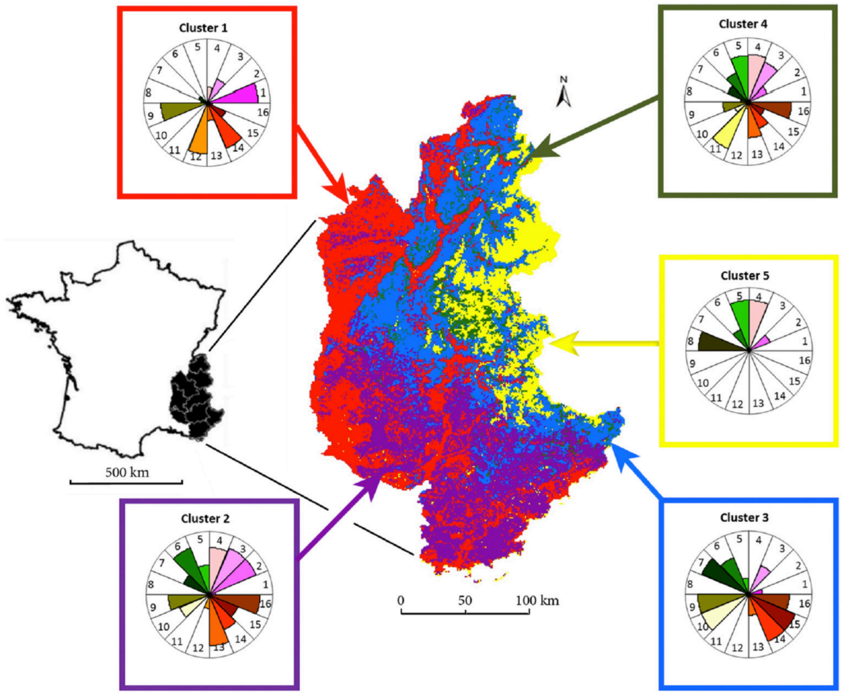

Figure 1: Illustrative example of the quantification and mapping of 16 ecosystem services in the French Alps. The reported values (normalized to 0–1) give the impression that these services were measured and therefore relatively objective, when in fact they were merely "guesstimated" and largely subjective (Reprinted from Baveye et al., 2016).

References

Bagnall, D. K., Rieke, E. L., Morgan, C. L., Liptzin, D. L., Cappellazzi, S. B., & Honeycutt, C. W. (2023). A minimum suite of soil health indicators for North American agriculture. *Soil Security*, *10*, 100084.

Baveye, P. (2017). Quantification of ecosystem services: Beyond all the "guesstimates", how do we get real data?. *Ecosystem Services*, *24*, 47-49.

Baveye, P. C. (2021). Soil health at a crossroad. *Soil Use and Management*, *37*(2), 215-219.

Baveye, P. C. (2022). Support for "we" visions and for broadening the scope in the debate on alternative forms of agriculture. *Outlook on Agriculture*, *51*(3), 313-322.

Baveye, P. C. (2025). Why a mechanistic theory of soils is crucially important: Another line of supportive argument exists, seldom invoked in soil science. *Soil*, *11*(2), 1131-1140.

https://doi.org/10.5194/egusphere-2026-3485
Preprint. Discussion started: 2 July 2026

Baveye, P. C., Baveye, J., & Gowdy, J. (2013). Monetary valuation of ecosystem services: It matters to get the timeline right. *Ecological Economics*, *95*, 231-235.

Baveye, P. C., Baveye, J., & Gowdy, J. (2016a). Soil "ecosystem" services and natural capital: Critical appraisal of research on uncertain ground. *Frontiers in Environmental Science*, *4*, 41.

Baveye, P. C., Berthelin, J., & Munch, J. C. (2016b). Too much or not enough: Reflection on two contrasting perspectives on soil biodiversity. *Soil Biology and Biochemistry*, *103*, 320-326.

Baveye, P. C., Chalhoub, M., Choquet, P., & Montagne, D. (2018). Is the focus on "ecosystems" a liability in the research on nature's services?. *Frontiers in Ecology and Evolution*, *6*, 226.

Boyanova, K., Nedkov, S., & Burkhard, B. (2014). Quantification and mapping of flood regulating ecosystem services in different watersheds – Case Studies in Bulgaria and Arizona, USA. In T. Bandrova, M. Konecny & S. Zlatanova (Eds.), Thematic Cartography for the Society (pp. 237-255): Springer International Publishing. https://doi.org/10.1007/978-3-319-08180-9_1

Byrnes, J. E., & Dee, L. E. (2025). Causal inference with observational data and unobserved confounding variables. *Ecology Letters*, *28*(1), e70023.

Cardoso, E. J. B. N., Vasconcellos, R. L. F., Bini, D., Miyauchi, M. Y. H., Santos, C. A. D., Alves, P. R. L., ... & Nogueira, M. A. (2013). Soil health: Looking for suitable indicators. What should be considered to assess the effects of use and management on soil health?. *Scientia Agricola*, *70*, 274-289.

Chalhoub, M., Gabrielle, B., Tournebize, J., Chaumont, C., Maugis, P., Girardin, C., ... & Garnier, P. (2020). Direct measurement of selected soil services in a drained agricultural field: Methodology development and case study in Saclay (France). *Ecosystem Services*, *42*, 101088.

Chalhoub, M., Garnier, P., Coquet, Y., Montagne, D., & Baveye, P. C. (2025). Assessment of future soil ecosystem services of a drained soil under different climate change scenarios. *European Journal of Soil Science*, *76*(3), e70144.

Choquet, P., Gabrielle, B., Chalhoub, M., Michelin, J., Sauzet, O., Scammacca, O., ... & Montagne, D. (2021). Comparison of empirical and process-based modelling to quantify soil-supported ecosystem services on the Saclay plateau (France). *Ecosystem Services*, *50*, 101332.

Crossman, N. D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I. . . . Maes, J. (2013). A blueprint for mapping and modelling ecosystem services. Ecosystem Services, 4, 4-14. https://doi.org/http://dx.doi.org/10.1016/j.ecoser.2013.02.001

Daily, G. C., Polasky, S., Goldstein, J., Kareiva, P. M., Mooney, H. A., Pejchar, L., Shallenberger, R. (2009). Ecosystem services in decision making: Time to deliver. Frontiers in Ecology and the Environment, 7(1), 21-28. https://doi.org/10.1890/080025

Dale, V. H., & Beyeler, S. C. (2001). Challenges in the development and use of ecological indicators. *Ecological indicators*, *1*(1), 3-10.

https://doi.org/10.5194/egusphere-2026-3485
Preprint. Discussion started: 2 July 2026

Dynarski, K. A., Adeleke, E., Baumhardt, R. L., Burke, J., Carter, T., DeLaune, P., ... & Wills, S. A. (2026). Soil health indicator variability and management sensitivity across soils, bioregions, and agricultural systems. *Agriculture, Ecosystems & Environment*, *399*, 110203.

Eigenbrod, F., Armsworth, P. R., Anderson, B. J., Heinemeyer, A., Gillings, S., Roy, D. B., ... & Gaston, K. J. (2010). The impact of proxy-based methods on mapping the distribution of ecosystem services. *Journal of Applied Ecology*, *47*(2), 377-385.

Eldridge, D. J., Guirado, E., Reich, P. B., Ochoa-Hueso, R., Berdugo, M., Sáez-Sandino, T., ... & Delgado-Baquerizo, M. (2023). The global contribution of soil mosses to ecosystem services. *Nature Geoscience*, *16*(5), 430-438.

Evangelista, S. J., Francos, N., Sharififar, A., Ng, W., Minasny, B., & McBratney, A. B. (2025). Advancing soil security with soil spectroscopy: The efficient estimation of indicators. *Soil Security*, *21*, 100211.

Fan, K., Chu, H., Eldridge, D. J., Gaitan, J. J., Liu, Y. R., Sokoya, B., ... & Delgado-Baquerizo, M. (2023). Soil biodiversity supports the delivery of multiple ecosystem functions in urban greenspaces. *Nature Ecology & Evolution*, *7*(1), 113-126.

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.

Grima, N., Jutras-Perreault, M. C., Gobakken, T., Ørka, H. O., & Vacik, H. (2023). Systematic review for a set of indicators supporting the Common International Classification of Ecosystem Services. *Ecological Indicators*, *147*, 109978.

Harris, J. A., Evans, D. L., & Mooney, S. J. (2022). A new theory for soil health. *European Journal of Soil Science*, *73*(4), e13292.

Heink, U., & Kowarik, I. (2010). What are indicators? On the definition of indicators in ecology and environmental planning. *Ecological indicators*, *10*(3), 584-593.

Popp, J., Hoag, D., & Hyatt, D. E. (2001). Sustainability indices with multiple objectives. *Ecological Indicators*, *1*(1), 37-47.

Ives, A. R. (2022). Random errors are neither: On the interpretation of correlated data. *Methods in Ecology and Evolution*, *13*(10), 2092-2105.

Janvier, C., Villeneuve, F., Alabouvette, C., Edel-Hermann, V., Mateille, T., & Steinberg, C. (2007). Soil health through soil disease suppression: which strategy from descriptors to indicators?. *Soil biology and Biochemistry*, *39*(1), 1-23.

Janzen, H. H., Janzen, D. W., & Gregorich, E. G. (2021). The ‘soil health’ metaphor: Illuminating or illusory?. *Soil Biology and Biochemistry*, *159*, 108167.

Jia, J., de Goede, R., Li, Y., Zhang, J., Wang, G., Zhang, J., & Creamer, R. (2025). Unlocking soil health: Are microbial functional genes effective indicators?. *Soil Biology and Biochemistry*, *204*, 109768.

Lausch, A., Bannehr, L., Beckmann, M., Boehm, C., Feilhauer, H., Hacker, J. M., ... & Cord, A. F. (2016). Linking Earth Observation and taxonomic, structural and functional biodiversity: Local to ecosystem perspectives. *Ecological Indicators*, *70*, 317-339.

Lautenbach, S., Mupepele, A. C., Dormann, C. F., Lee, H., Schmidt, S., Scholte, S. S., ... & Volk, M. (2019). Blind spots in ecosystem services research and challenges for implementation. *Regional Environmental Change*, *19*(8), 2151-2172.

https://doi.org/10.5194/egusphere-2026-3485
Preprint. Discussion started: 2 July 2026

Lechevallier, H., Lagacherie, P., & Wadoux, A. M. C. (2025). A conceptual framework for soil function evaluation: Towards a common base. *Geoderma*, *461*, 117476.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544-553.

Liptzin, D., Norris, C. E., Cappellazzi, S. B., Mac Bean, G., Cope, M., Greub, K. L., ... & Honeycutt, C. W. (2022). An evaluation of carbon indicators of soil health in long-term agricultural experiments. *Soil Biology and Biochemistry*, *172*, 108708.

Liu, S., Plaza, C., Ochoa-Hueso, R., Trivedi, C., Wang, J., Trivedi, P., ... & Delgado-Baquerizo, M. (2023). Litter and soil biodiversity jointly drive ecosystem functions. *Global Change Biology*, *29*(22), 6276-6285.

Maaz, T. M., Heck, R. H., Glazer, C. T., Loo, M. K., Zayas, J. R., Krenz, A., ... & Deenik, J. L. (2023). Measuring the immeasurable: A structural equation modeling approach to assessing soil health. *Science of the Total Environment*, *870*, 161900.

Marali, K., Chiles, R. M., Kaye, J. P., Kirchhoff, C. J., Wainger, L., & Cibin, R. (2025). A systematic review of ecosystem services modeling for environmental health assessment. *Ecological Indicators*, *172*, 113245.

Mengist, W., Soromessa, T., & Feyisa, G. L. (2020). A global view of regulatory ecosystem services: Existed knowledge, trends, and research gaps. *Ecological processes*, *9*(1), 40.

Montagne, D., Scammacca, O., Walter, C., Cousin, I., Coquet, Y., & Michelin, J. (2025). The concept of ecosystem services and its application to soil: Between promises and reality. pp. 161-209, in Yves Coquet and Joël Michelin *(eds), Agricultural Soil Science: Sustainable Management of Agricultural Soils*, Wiley, London, U.K. Doi: 10.1002/9781394361809.ch7

Müller, F., & Burkhard, B. (2012). The indicator side of ecosystem services. *Ecosystem Services*, *1*(1), 26-30.

Neal, A. (2021). The theory of soil, AWE International, https://www.awe.international/article/1841384/theory-soil (last access: February 6, 2026).

Neal, A. L., Bacq-Labreuil, A., Zhang, X., Clark, I. M., Coleman, K., Mooney, S. J., ... & Crawford, J. W. (2020). Soil as an extended composite phenotype of the microbial metagenome. *Scientific Reports*, *10*(1), 10649.

Niemeijer, D., & De Groot, R. S. (2008). A conceptual framework for selecting environmental indicator sets. *Ecological indicators*, *8*(1), 14-25.

Peng, Y., Welden, N., & Renaud, F. G. (2023). A framework for integrating ecosystem services indicators into vulnerability and risk assessments of deltaic social-ecological systems. *Journal of Environmental Management*, *326*, 116682.

Pereira, P., Inacio, M., Barcelo, D., & Zhao, W. (2025). Ecosystem services mapping and modelling. Where is the validation?. *Geography and Sustainability*, *6*(3), 100286.

Petter, M., Mooney, S., Maynard, S. M., Davidson, A., Cox, M., & Horosak, I. (2013). A methodology to map ecosystem functions to support ecosystem services assessments. *Ecology and Society*, *18*(1).

Powlson, D. S. (2021). Is 'soil health' meaningful as a scientific concept or as terminology. *Soil Use and Management*, *37*(3), 403-405.

https://doi.org/10.5194/egusphere-2026-3485
Preprint. Discussion started: 2 July 2026

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Peres, G., & Rutgers, M. (2012). Soil biodiversity, biological indicators and soil ecosystem services—an overview of European approaches. *Current Opinion in Environmental Sustainability*, *4*(5), 529-538.

Rillig, M. C., Van der Heijden, M. G., Berdugo, M., Liu, Y. R., Riedo, J., Sanz-Lazaro, C., ... & Delgado-Baquerizo, M. (2023). Increasing the number of stressors reduces soil ecosystem services worldwide. *Nature Climate Change*, *13*(5), 478-483.

Robertson, D. P., & Hull, R. B. (2001). Beyond biology: toward a more public ecology for conservation. *Conservation Biology*, *15*(4), 970-979.

Rova, S., Pastres, R., Zucchetta, M., & Pranovi, F. (2018). Ecosystem services' mapping in data-poor coastal areas: Which are the monitoring priorities?. *Ocean & Coastal Management*, *153*, 168-175.

Scammacca, O., Sauzet, O., Michelin, J., Choquet, P., Garnier, P., Gabrielle, B., ... & Montagne, D. (2023). Effect of spatial scale of soil data on estimates of soil ecosystem services: Case study in 100 km^2 area in France. *European Journal of Soil Science*, *74*(2), e13359.

Sharma, S., Lishika, B., & Kaushal, S. (2023). Soil quality indicators: A comprehensive review. *International Journal of Plant & Soil Science*, *35*(22), 315-325.

Smyth, R. L., Watzin, M. C., & Manning, R. E. (2007). Defining acceptable levels for ecological indicators: an approach for considering social values. *Environmental management*, *39*(3), 301-315.

Syrbe, R. U., & Walz, U. (2012). Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics. *Ecological indicators*, *21*, 80-88.

Thomson, W. (1889). *Lecture on electrical units of measurement* (3 May 1883), Popular Lectures Vol. I, p. 73, McMillan and Co.

Turnhout, E., Hisschemöller, M., & Eijsackers, H. (2007). Ecological indicators: between the two fires of science and policy. *Ecological indicators*, *7*(2), 215-228.

Vrebos, D., Staes, J., Vandenbroucke, T., Johnston, R., Muhumuza, M., Kasabeke, C., & Meire, P. (2015). Mapping ecosystem service flows with land cover scoring maps for data-scarce regions. *Ecosystem services*, *13*, 28-40.

Wade, J., Culman, S. W., Gasch, C. K., Lazcano, C., Maltais-Landry, G., Margenot, A. J., ... & Wallenstein, M. D. (2022). Rigorous, empirical, and quantitative: a proposed pipeline for soil health assessments. *Soil Biology and Biochemistry*, *170*, 108710.

Wadoux, A. M. C., Debeljak, M., Lagacherie, P., & Creamer, R. E. (2026a). Synergies and trade-offs between soil functions differ with land-use intensity. *Agriculture, Ecosystems & Environment*, *397*, 110112.

Wadoux, A. M. C., Debeljak, M., Lagacherie, P., & Creamer, R. E. (2026b). Spatial hotspots and bundles of soil functions across Europe. *Ecological Indicators*, *182*, 114481.

Westman, W. (1977). How much are nature's services worth? *Science* 197, 960–964.

https://doi.org/10.5194/egusphere-2026-3485
Preprint. Discussion started: 2 July 2026

Wieser, S., Keiblinger, K., Mayer, H., Rosinger, C., Mentler, A., Wriessnig, K., ... & Bodner, G. (2026). Energy matters: Soil organic carbon fractions as soil health indicator or characterizing ecosystem property. *Soil and Tillage Research*, *257*, 106927.

Yahdjian, L., Campana, S., Tognetti, P. M., Alberti, J., Graff, P., Molina, C., ... & Virtanen, R. (2026). Insights on global rangeland ecosystem services shaped by grazing and fertilization. *Frontiers in Ecology and the Environment*, e70022.

Yurchenko, S. B. (2026). On a physical theory of causation in multiscale analysis of biological systems. *Acta Biotheoretica*, *74*(1), 2.