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The definition of soil science from a geographical perspective

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ABSTRACT

This paper proposes a revised definition of “soil science” through the lens of geography, emphasizing the critical role of spatial dimensions and landscape relationships in shaping soil systems. While traditional definitions often neglect the geographical context, soil properties, formation processes, and functions are inherently influenced by spatial variability and environmental interactions. By examining the historical evolution of soil science, existing definitions, core geographical principles, and advancements in soil mapping, this paper proposes a refined definition of soil science that explicitly integrates geographical perspectives. This revised definition conceptualizes soil as a spatially heterogeneous and temporally dynamic system, governed by its geographical setting and spatial configuration. Incorporating this perspective not only deepens the theoretical foundations of soil science but also enhances its relevance to land use planning, environmental management, and sustainable agricultural practices.

1. Introduction

Soil science is an interdisciplinary field that integrates concepts from geology, ecology, environmental science, and foundational sciences including mathematics, physics, chemistry, and biology to understand soils as dynamic, living systems. This holistic approach highlights the interconnectedness of soil with global biogeochemical cycles and ecological processes that sustain life on Earth. When applied to the moon and other planets the principles of soil science as practiced on Earth have been adapted to studying the surface of these bodies, in a subdiscipline known as “Astropedology” (Retallack 2025).

Recently Hartemink and McBratney (2025) surveyed the various historical definitions of the term “soil science” and concluded that it is inadequately defined. They then proposed a shorter definition: “Soil science is the study of planetary soil, using evolving theories and knowledge to understand its role in sustaining ecosystems and tackling environmental challenges” and an expanded definition: “Soil science is the study of the soil of the Earth and other planets, using evolving theories and knowledge to understand its role in sustaining ecosystem functioning, tackling environmental challenges, and supporting humanity.” Both definitions take the term “soil” as elsewhere defined, but including other planets (implied in the first definition, explicit in the second). Both use the phrase “using evolving theories and knowledge to understand its role.”

Already this definition has attracted responses. Ghezzehei and Berhe (2025) point out that “[this] definition inadvertently constrains the discipline’s scope by emphasizing its applied aspects over the pursuit of fundamental knowledge. This utilitarian focus risks diminishing soil science’s capacity to generate the transformative insights”, and propose the definition “the multidisciplinary natural science that studies the Earth’s porous surface layer - its formation, composition, properties, processes, and evolution across scales.”

Neither of these definitions explicitly mention the geographic dimension of soil – the fact that soils occur in space and time, over the landscape. This is the geographical perspective, which we would like to include explicitly in the definition of “soil science”. Perhaps “soil of the Earth” or “Earth’s porous surface layer” imply that geography should be considered, and perhaps “across scales” implies geographic scale, but these inferences are doubtful. Both definitions imply, to us, that the soil is to be studied pointwise, as a soil “individual” participating in Earth surface processes, but not as geographic entities with spatial and temporal extent, beyond that of the scale of observations.

Soils are not uniform entities but rather exhibit remarkable spatial variability at all scales across the landscape, and further form distinct

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spatial patterns at these scales. The properties, formation processes, and functions of soil are intrinsically linked to their geographical context, including topography, climate, and spatial relationships with other landscape elements. This spatial dimension is fundamental to understanding soil as a natural resource and environmental component.

Many studies of soils have concentrated on the behaviour at the scale of a soil individual, sometimes called a pedon or elementary volume. A typical example is lysimeter studies. However, soil geography has been part of soil science since the days of Doukachaev (Rusakova et al. 2022) and maps of soil classes as holistic expressions of soil behavior have been created since Doukachaev, for example since 1899 in the USA (Brevik et al. 2016). Perhaps the study of soil geography is not considered as fundamental as detailed studies of soil processes. However, as Miller and Schaetzl (2016) point out in their historical review, the study of soil geography has evolved alongside advancements in mapping technologies and methodologies, reflecting the growing recognition of the importance of spatial context in understanding soil systems. Advances in technology, along with increased appreciation of environmental sciences, has brought soil geography renewed prominence.

Therefore, this paper aims to examine the role of geography in soil science. From that we propose a revised definition of soil science that incorporates the geographical perspective. By integrating geographical principles into the definition of soil science, we can better capture the spatial dimensions and landscape relationships essential to understanding soil as a complex, dynamic system. This geographical perspective not only enhances our theoretical understanding of soil science but also links soil roles for land use planning, environmental management, and sustainable agriculture.

2. Current definitions of soil science

The definition of soil science has evolved over time, reflecting changes in our understanding of soil systems and the methodologies used to study them (Hartemink and McBratney, 2025). The definitions from these authors and Ghezzehei and Berhe (2025) were given above. Their definitions focus primarily on the functional roles of soil rather than its spatial characteristics and relationships. Only the Hartemink and McBratney (2025) definition mentions the moon and other planets, so the following definitions apply to Earth only. This is natural because humans live (so far) only on Earth and are thus mostly concerned with its soils.

Other contemporary definitions of soil science similarly tend to emphasize functional aspects, while giving less attention to spatial dimensions. For instance, the Soil Science Society of America defines soil science as "the discipline that deals with soils as a natural resource on the surface of the earth including soil formation, classification, and mapping; physical, chemical, biological, and fertility properties of soils; and these properties in relation to the use and management of soils" (SSSA, 2008). While this definition mentions soil mapping, suggesting some recognition of spatial aspects, it does not explicitly emphasise the geographical nature of soil systems or the importance of spatial context in understanding soil properties and processes.

Similarly, many textbook definitions focus on soil as a medium for plant growth, a component of ecosystems, or a natural resource, without adequately addressing its geographical dimensions. These definitions often describe soil science as the study of soil properties, processes, and management, but fail to highlight the spatial variability of these properties and processes or the influence of geographical context on soil formation and function. At best, these point out different soil environments (e.g., deserts, mountains, river bank, estuary, swamp, arid, semi-arid, and humid tropic) and some of the typical soils found in each, but these are considered pointwise, not as a continuum. An example is the outstanding text on tropical soil fertility by Sánchez (2019).

The exceptions are textbooks on soil genesis and classification, which emphasize the geographic factors that influence pedogenesis. A good example is Buol et al. (2011) that proposed a conceptual continuum of space and time for soil. This concept explains the space-time continuum, in which soils at a fixed geographical location may change over time. This model also considers landform changes within the same timeframe as the formation of pedogenic features. Space-time models can be constructed to better understand the spatial distribution of soils across any landscape.

Richer-de-Forges et al. (2024) argue that soil science intersects with multiple disciplines, and definitions often blur between explaining what soil is, what it does, and why it matters. While these authors recognise soil as a three-phase volume (solid, liquid, gaseous), extending from the Earth's surface to where weathered rocks appear, they still do not adequately address the fact that soil properties and processes vary significantly across space.

These limitations suggest a need for a more geographically-informed definition of soil science that explicitly recognizes the spatial dimensions of soil systems and the importance of geographical context in understanding soil properties, processes, and management.

Brevik and Arnold (2015) reference the concept of soil as a geographic body in their proposal to redefine soil in the modern context, aligning closely with the principles of Soil Geography. Although the term "Soil Geography" is not explicitly emphasized, their focus on soil variability, locality, and spatial distribution reflects its core ideas. They argue that soils are unique, mappable entities shaped by environmental conditions and landscape position—key concerns of geographic analysis. The authors also highlight the increasing role of human activity in soil formation, particularly in the Anthropocene, which is a growing focus in Soil Geography. Furthermore, their call for interdisciplinary integration across fields such as engineering, geology, and environmental science mirrors Soil Geography's bridging role between natural and social sciences. By advocating for a broader, more inclusive definition of soil that incorporates spatial and anthropogenic dimensions, Brevik and Arnold contribute significantly to the evolving framework and relevance of Soil Geography.

3. Geographical principles in soil science

The integration of geographical perspectives into the definition of soil science is not merely a semantic exercise but has practical implications for how soil is studied, managed, and conserved. As Miller and Schaetzl (2016) argue, understanding the spatial variability of soils at different scales is crucial for accurate soil management and conservation practices. A beautiful example of considering soils as landscape elements is by Ruellan and Dosso (1993). Another example is the extensive set of block diagrams produced by the NRCS in the United States, which show the conceptual relation between soil bodies. This goes back to the pioneering work on "soilscape fabrics" from the soilscape analysis of Hole (1978) and the "soil combinations" of Fridland (1974) – soils were considered as natural bodies at nested spatial scales, with soil-forming factors also considered at these scales.

The integration of geographical principles into soil science provides a framework for understanding the spatial dimensions of soil systems. These principles help explain how and why soil properties vary across landscapes and provide tools for analyzing and predicting these spatial patterns. Next, we examine key geographical principles relevant to soil science and their implications for defining the field.

3.1. Spatial distribution and variability of soils

A fundamental geographical principle in soil science is the recognition that soil properties vary both vertically (within the soil profile) and laterally (across the landscape). Soil bodies are not just the top 30 cm and do not exist in isolation, rather, they are a component of broader landscape systems, with properties and processes influenced by their geographical context. As Miller and Flores (2023) note, soil properties or characteristics are a response to their location, with soil forming processes occurring differently across the landscape. These processes have geographical extent, and therefore so do the soils. This spatial variability exists at multiple scales, from microscopic variations in soil structure to global patterns in soil types (Lin et al., 2005). This variability is not random but exhibits patterns and relationships that can be analyzed and predicted using geographical principles and methods.

The spatiotemporal variability of soil is the result of different forming factors, weathering rates, time of development, and human intervention. Understanding this variability is essential for effective land management, as it allows for matching land use and management practices to the specific capabilities of soils in different locations. This principle underscores the importance of a geographical perspective in soil science, as it recognizes that soil properties cannot be fully understood without considering their spatial context.

3.2. Geographic "Laws"

There are three well-known geographic principles which are somewhat loosely called "laws". The first is Tobler's First Law of Geography which states that "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). This is not a law in the sense of physical laws, since there are many exceptions, especially for soils where soil-forming factors may vary in close proximity. Still, within some range, depending on context, soil properties exhibit spatial autocorrelation, meaning that locations close to each other are more likely to have similar soil properties than locations far apart. This is the basis for classical soil survey, which attempts to partition the soil landscape into more or less homogeneous units. This first "law" forms the basis for local spatial analysis techniques used in soil mapping, such as interpolation by kriging. This depends on variogram analysis and modelling of the local spatial dependence. This allows the prediction of soil properties at unsampled locations, based on measurements at nearby points, taking advantage of the spatial relationships between soil properties, with nearby locations tending to have more similar properties than distant locations, (Ma et al., 2019).

The second so-called law is due to Goodchild and Janelle (2004), who states that geographic properties are inherently non-stationary, that is, as context changes, so do both property values and the local spatial structure. This implies that models of spatial structure have inherent instability as the context changes. Either the relations between soil properties and environment change functional form, or at least if the same form can be used, the parameters vary. This links to the first law: the form and/or parameters of a variogram model of a soil property cannot be expected to be the same over large geographic extents. This also applies to models based on the third "law" (see next).

The second law has significant implications for soil science, particularly in spatial prediction and modelling. Soils are influenced by complex, variable environmental factors (e.g., parent material, topography, climate), meaning that spatial relationships and covariate effects often change across space and scales. This violates the stationarity assumption (i.e., assuming that spatial autocorrelation and covariate relationships are constant over space), especially in large or diverse landscapes. This is why machine-learning methods such a tree-based methods and artificial neural networks are used in soil mapping, rather than local methods such as kriging. Moving-window kriging (Harris et al., 2010; Minasny et al. 2005) also results from recognizing this law: local spatial structure varies over space. Certainly studying these relationships and their causes must be included in the concept of soil science.

The third so-called law is due to Zhu et al. (2018). This uses the concept of similarity in feature (attribute) space, as that relates to similarity in geographic space. That is, the more similar the geographic configurations of two locations (e.g., landforms, land use history, hydrology, climate over the period of soil formation), the more similar the values (or processes) of a target variable at those locations. In soil science, the Third Law is implicitly used when modelling soil properties based on environmental covariates (e.g., climate, geology, topography, vegetation, and time) from sampled (training) areas and then applying these models to predict the properties over areas with similar geographic configurations. This can be with machine-learning methods such as regression or classification forests, or by similarity-based methods as advocated by Zhu, for a recent example see Zhao et al. (2025). Again, soil science is intimately involved here, to build models based on principles from soil genesis, either using knowledge-based methods directly, or selecting environmental covariates for machine-learning models within the SCORPAN framework (McBratney et al., 2003) that best relate to soil formation.

3.3. The catena concept

The catena concept, developed by Geoffrey Milne, represents a key geographical principle in soil science. Milne defined catena as "the regular repetition of soil profiles in association with certain topography" (Milne, 1935). This concept captures the systematic variation of soils along hillslopes, reflecting the influence of topography on material and energy transfers as soil formation processes (Odgers et al., 2008).

Topography affects soil properties through its impact on water movement, erosion, and microclimate. Slope gradient controls erosion and deposition, with steeper slopes promoting erosion and gentler slopes favouring accumulation. Slope shape determines material redistribution, with convex slopes losing and concave slopes gaining soil particles and nutrients. Slope position shapes infiltration and sedimentation patterns; upper slopes are more eroded and coarse-textured, while lower slopes accumulate finer materials and nutrients. This framework is essential for soil mapping, as it allows for the identification of systematic relationships between landscape position and soil properties. Slope orientation affects solar exposure, influencing soil temperature, moisture, and biological activity. However, even similar slope aspects show varied biological activity depending on latitude or global location. This highlights the need to consider both microclimatic and geographic factors when evaluating soil processes across different spatial scales.

3.4. Scale considerations

Scale is a critical geographical principle in soil science, influencing how soil properties are observed, analyzed, and managed. Different soil phenomena are observable at different scales (Lin et al., 2005). For example, microscopic soil structures may be relevant for understanding soil porosity and water movement, while landscape-scale patterns are important for land use planning and watershed management. The appropriate scale of observation depends on the specific soil properties or processes being studied and the management objectives (Caniego et al., 2005). This is also true for modelling soil processes, as explained by Hoosbeek and Bryant (1992), in their well-known three-axis classification of models. Their principal axis is scale, from soil region (e.g. global phenomena) into molecular interaction (e.g. Ion exchange phenomena).

Scale considerations also affect soil classification and mapping. Larger-scale maps allow for more detailed observations and classifications, while smaller-scale maps provide broader overviews and associations of soils with defined landscape relations within the mapping unit. The choice of mapping scale influences the level of detail that can be represented and the types of soil patterns that can be detected (Malone et al., 2013).

Understanding scale relationships is also essential for effective soil management. Management decisions often need to integrate information from multiple scales, from detailed field-level soil properties to broader landscape patterns.

3.5. Geographic technologies in soil science

Geographic technologies have revolutionized soil science by providing new tools for observing, analyzing, and visualizing soil patterns. These technologies include:

1. Geographic Information Systems (GIS): GIS allows for the integration, analysis, and visualization of spatial soil data, enabling complex spatial analyses and the creation of detailed soil maps (Burrough, 2001). Many soil information systems are now based on GIS platforms, e.g., Gobezie et al. (2025), Díaz-Guadarrama et al. (2024).
2. Remote sensing: Satellite and aerial imagery provide data on land cover, vegetation patterns, and surface characteristics that can be used to infer soil properties and map soil types across large areas, including a very specific soil like peat soil (land) or acid sulfate soils (Dematte et al., 2020; Demattê et al., 2025; Widyatmanti & Sammut, 2017; Minasny *et al.*, 2019).
3. Global Positioning Systems (GPS): GPS enables the precise location of soil sampling points and field observations, improving the accuracy of soil maps and spatial analyses, especially machine-learning predictive models.
4. Digital soil mapping: This approach combines traditional soil science knowledge with digital spatial data and statistical methods to predict soil properties at unsampled locations (MacBratney et al., 2003; Ma et al., 2019, Minasny et al., 2024).
5. Geostatistical methods: Techniques such as kriging, co-kriging, and spatial regression allow for the analysis of spatial patterns in soil properties and the prediction of soil characteristics based on spatial relationships (Lark, 2012).

These technologies have significantly enhanced our ability to study and manage soils from a geographical perspective. They allow for more detailed and accurate soil mapping, improved understanding of spatial soil patterns, and more effective integration of soil information into land management decisions. Their development and use must be part of the definition of soil science.

4. Proposed definition of soil science from a geographical perspective

Building upon the historical development, current definitions, geographical principles, technological developments and soil mapping approaches discussed in previous sections, we here propose a definition of soil science that explicitly incorporates the geographical perspective. This definition aims to capture the spatial dimensions and landscape relationships that are essential to understanding soil as a complex, dynamic system.

A geographically informed definition of soil science must include several key principles:

- Spatial variability: Recognition that soil properties vary across space at multiple scales, from microscopic to global.
- Landscape relationships: Acknowledgment of the connections between soil and other landscape elements, such as topography, hydrology, and vegetation patterns.
- Scale considerations: Awareness of the importance of scale in soil study, including relationships between observation scale, process scale, and management scale.
- Geographical principles: Incorporation of fundamental geographical concepts, such as the three “Laws” of Geography and the catena concept.
- Spatial technologies: Recognition of the role of geographic technologies, such as GIS, remote sensing, and spatial statistics, in advancing soil science.

Based on these principles, we propose the following definition of soil science from a geographical perspective:

Soil science is the study of the spatially-variable and temporally-dynamic soil system of Earth and other planetary bodies, using evolving theories, geographical principles, and advanced technologies to understand soil formation, distribution, properties, and functions across landscapes and scales. When applied to the Earth, soil science recognizes soil as an integral component of the Earth's systems, with properties and processes influenced by geographical context and spatial relationships, and seeks to apply this understanding to sustain ecosystems, address environmental challenges, and support human well-being."

This explicitly-geographical definition of soil science promotes a holistic approach that considers soil as part of broader landscape and environmental systems. It recognizes the interconnections between soil and other components of the Earth system. This holistic view aligns with contemporary perspectives that view soil not as a discrete entity but as a dynamic component of the Earth system (Hartemink & McBratney, 2025). It acknowledges that soil processes influence and are influenced by processes in other Earth system components, creating complex feedback loops and interactions. The mention of “other planetary bodies” recognizes that the basic principles of soil physics and chemistry apply on the surfaces of these bodies. The limitation to Earth for “sustain ecosystems” etc. restricts these aspects to where they are relevant, while still including other planetary bodies as soils to be studied.

5. Conclusion

This paper has examined the definition of soil science from a geographical perspective, highlighting the importance of spatial dimensions and landscape relationships in understanding soil systems. A geographical perspective is not merely an addition to soil science but an essential dimension that enhances our understanding of soil as a complex, spatially variable, and temporally dynamic system. By explicitly incorporating this perspective into the definition and practice of soil science, we can better address the major challenges facing modern society which is essential for developing resilient strategies in the face of rapid environmental and societal change. The geographical perspective in soil science opens several promising directions for future research and practice:

1. Advanced spatial modelling: Continued development of spatial modelling approaches that can capture the complex relationships between soil properties and environmental factors across multiple scales.
2. Integration of temporal dynamics: Enhanced methods for modelling and predicting changes in soil properties over time, considering both natural processes and human influences.
3. Multiscale approaches: Development of frameworks and tools for integrating soil information across scales, from microscopic soil structures to global soil patterns.
4. Interdisciplinary collaboration: Strengthened collaboration between soil scientists, geographers, ecologists, hydrologists, and other researchers to better understand the role of soil in broader Earth systems.
5. Participatory mapping: Engagement of local communities and stakeholders in soil mapping (Rossiter et al., 2015) and assessment, incorporating traditional and local knowledge into scientific understanding of soil patterns (Mason et al., 2024, Paltseva 2025, Wadoux et al., 2023).
6. Policy integration: Enhanced incorporation of spatially explicit soil information into policy and decision-making at multiple levels, from farm management to national land use planning (Bouma, 2025).

CRediT authorship contribution statement

Wirastuti Widyatmanti: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **David G. Rossiter:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Destika Cahyana:** Writing – original draft, Resources, Investigation, Data curation.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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