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Soil Profiles: A Window Into Soil Genesis and Degradation

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ABSTRACT

In this commentary, we argue that the soil profile represents an indispensable window into the soil system. The soil profile is a vertical section of the soil body that represents a pattern in the landscape. The description and interpretation of the layers and horizons from the surface to the parent material or bedrock is the language of soil scientists to record and communicate the story of the soil. The story tells the evolution (genesis) of the soil and explains the resulting physical, chemical, and biological properties. The exposed profile can therefore help in determining the soil's potential to provide ecosystem services as well as its suitability for different land-use applications. Efforts to classify soils globally across different climates and land management by soil profiling have contributed extensively to soil mapping and have enabled stakeholders to make informed decisions for sustainable land management. Despite its utility and significance, the soil profile has almost become a "lost language" within soil science. Pedology, as a subject within which soil profiling was once vehemently instructed and practiced, has notably declined in the past decade. The number of fully trained pedologists has dwindled, and investment in training the next generation in the art of profiling has declined. The trained pedologist may represent something of an endangered profession, yet soil profiling has allowed and continues to allow vital discoveries to be made about the soil system. This commentary traces the progress and trends on the study of soils over the century, considering their genesis, functions, and degradation captured by a profile. We chart the transformative contributions of remote and proximal sensing to advance soil science in the past decades, and how these findings have been used to ensure more sustainable and resilient land management practices. Furthermore, in chronicling the evolution of soil profiling, we aim to set out an inspiring roadmap for the next generation of pedologists to motivate them to "pick up the shovel" and engage with profiling without fear. Profile characterization is not only science but also literacy. Now that soil degradation has become a priority concern, careful observation and description of the profile are more important than ever, not only for diagnostic purposes but also as a historical record of the current, unique state of the soil.

1 | Introduction

Soil description and profiling techniques existed in Europe well before the recognition of soil sciences in the late 19th century (Warkentin 2006). In the 1500s, Bernard Palissy (1510–1590) invented the soil sampling auger. Georges-Louis Leclerc de Buffon (1707–1788) provided detailed soil descriptions and observations of pedological features like ferro-manganese concretions, linking them to geochemical cycles. Albrecht Daniel Thaer (1752–1828) designed the methodology for sampling, description, and mapping of soil variability in cultivated areas. Charles Darwin (1809–1882) made detailed drawings of soil profiles (hereafter referred to as SP), and P.E. Müller (1835–1915) was considered a key forerunner of pedology due to his detailed descriptions of the SP and associations with a pedogenetical approach (Hartemink 2009).

The characterization and understanding of SPs are vital for assessing soil quality and fertility, and for informing sustainable land management practices (Herrick 2000). An accurate description of the SP, including its morphological properties, provides a comprehensive understanding of the soil's condition and behavior (Lehmann et al. 2020; Reichert et al. 2022). This information is crucial for predicting soil performance under different land-uses and management practices, thereby supporting informed decision-making in agriculture, environmental management, and land development.

One key concept is pedodiversity, which refers to the diversity of soil types, properties, and horizon development within a specific region or landscape. This diversity results from different soil formation factors such as parent material, climate, topography, the role of organisms, and time (Jenny 1941; Hartemink and Bockheim 2013). Just as biodiversity is crucial for ecosystem resilience, pedodiversity plays a fundamental role in supporting plant productivity, ecological stability, and environmental sustainability (Laliberté et al. 2013; Mikhailova et al. 2021). It underlines essential functions, including nutrient cycling and water regulation, both of which are crucial for maintaining healthy ecosystems and promoting effective land-use (Lehmann et al. 2020).

Sustainable land management requires effective soil conservation strategies that are specifically adapted to the pedodiversity of the region, helping to sustain long-term agricultural productivity and protect vital resources. SPs are vital for characterizing soil variability and the implications for agricultural productivity and environmental sustainability.

Pedology has declined markedly over the past decade. Although invaluable to our understanding of soils, the SP has, in many ways, become a "lost language" within Pedology. The pool of fully trained pedologists has dwindled, and investment in training the next generation in this essential skill has all but disappeared. The pedologist now risks becoming an endangered professional figure, even though SP setting and description has long enabled, and continues to enable, fundamental discoveries about the soil system.

In this commentary, to mark the 75th Anniversary of the European Journal of Soil Science, we reflect on over one century of pedology and soil profiling key issues across diverse environments and land covers. We examine some limiting factors that are assessed through SPs, the main pillars of pedology literacy such as soil monolith production, museums and data collection for national and continental scale examples. We highlight the transformative contributions that SPs have made to advancing soil science and literacy, shaping sustainable land management practices. By tracing the evolution of profiling, we aim to provide a compelling roadmap for the next generation of pedologists.

1.1 | Soil Genesis, Functions, and Degradation Captured by a Soil Profile

Exposing a SP is a key skill in pedology, building on the foundational work of pioneers like Dokuchaev (Richter Jr. 2007), who recognized the importance of understanding soil composition and classification. Only by opening a SP can one begin to explore and understand pedogenic horizons, and the context in which the SP sits along a catena. The term "catena" comes from the Latin word for "chain", and it refers to the idea that the soils in a catena are linked together in a sequence, with each soil type grading into the next (Brevik and Hartemink 2010). A soil catena typically consists of a series of soils that develop in response to the topographic position, with remarkable differences between the top of the slope from those at the bottom. The soils in a catena may differ in terms of their texture, structure, pH, and nutrient content, among other characteristics. The concept of soil catena was first introduced by G. Milne who coined the term in the 1930s to describe the recurring patterns of soil sequences found along a hillslope in East Africa (Milne 1935a, 1935b). Soil catena was originally formulated for savannahs but is now applied in all biomes (Borden et al. 2020). The study of pedogenesis and soil classification has been further advanced by researchers like Duchaufour (2008), who provided comprehensive overviews

Key Points

- Soil profiles reveal functions and processes beyond surface sampling.
- Decline in pedology threatens soil knowledge and future expertise.
- Subsoil constraints, critically control roots, water and fertility.
- Sensors and ML enhance profiling but need field validation.

of the processes that shape SPs. Other notable pedologist like K.G. Glinka (1867–1927) developed the concept of “soil genesis”, G.D. Smith developed the concept of “soil morphology”, and M.G. Cline developed the concept of “soil-landscape relationships”.

In pedology the concept of soil diagnostic horizon is paramount for classification into the existing systems (e.g., USDA Soil Taxonomy—Soil Survey Staff 2022, and World Reference Base (hereafter WRB 2022))—IUSS Working Group WRB (2022). A diagnostic horizon can be a surface or a subsoil part of the SP that exhibit peculiar features that can be recognized in the field or by laboratory analyses. Often, several diagnostic horizons can be displayed in a single profile and contribute to the attribution to different qualifiers of the soil type.

The objective of the field description of a SP is to identify a wide range of diagnostic features that are critical for classifying soils, for evaluating their agricultural capability and ecological functions. These characteristics include, but are not limited to depth, color, texture, structure, stone content, consistency, and many other features of pedogenic or management significance such as coatings, redoximorphic features, concentrations, cementation, porosity, and biological activity (D'Amico et al. 2025; Dokuchaev 1967). By systematically recording these observations, pedologists can capture both qualitative and quantitative data that are essential for understanding the diversity of soils across the globe. Furthermore, it provides a foundation for monitoring soil functions, such as carbon sequestration, water filtration and storage, and biodiversity support, which are critical for maintaining ecosystem services, promoting sustainable development, and addressing global challenges such as soil degradation, climate change, and food security. In the context of pedodiversity, the description of a SP is a crucial tool for characterizing and understanding soils in different environments and regions. Clearly, there has always been a need for a systematic framework. Several national and international classification systems exist. In this contribution, we have used the WRB for Soil Resources (for consistency).

1.2 | Limiting Factors in Soils Observed Through the Characterization of Soil Profiles

By studying SPs, several limiting (or positive) factors that affect plant growth and soil management can be observed. These aspects would otherwise be ignored if sampling only the top 20 or 30 cm, which is often the focus of surface-level soil assessments. Additionally, most soil types are defined by taking into consideration subsoil diagnostic horizons, which are important indicators of their functioning in their respective ecosystems. Some of these evidence the existence of severely limiting chemical conditions, such as the damaging acidity of thionic horizons, which would not be detected if sampling is limited to the topsoil (at least seasonally, e.g., D'Amico et al. (2024), Figure 1a). Many of these subsurface features are major constraints to root growth and water infiltration. For example, natric horizons (Figure 1b), often present at depths greater than 30 cm, pose very strong limitations for plant growth; sodium ions cause clay dispersion and migration to deeper layers, where it can clog pores, and create impermeable and very dense horizons, less penetrable by roots (Figure 1b). Fragic horizons are dense, brittle, and almost impermeable horizons that can form at depths of 30–100 cm, and are characterized by a high bulk density, low porosity, and a lack of roots and other biological activity. They restrict water and air movement, leading to waterlogging in the horizons above and reduced aeration (Figure 1c). Cemented horizons (Figure 1d), such as duripans, petrocalcic or ortstein/placic ones, are also significant constraints to root development, overall soil productivity and water availability.

Regardless of their position, some diagnostic horizons, such as mollic or umbric dark surface horizons with high organic matter content, can be indicators of potentially high fertility. In weathered ferralic horizons, possibly high levels of phosphorus are adsorbed on iron oxides and not easily available for plants, and their presence requires specific agronomic management to keep them fertile. The presence of argic, vertic, or natric subsurface horizons may also require comprehensive SP characterization to accurately identify and understand the complex interactions between soil properties and processes. By continuing research and current monitoring of SPs, we can obtain a detailed picture of the factors that influence soil behavior, fertility, and overall ecosystem function, and contextually inform more effective land management and conservation strategies.

1.3 | Soil Monoliths and Museums

1.3.1 | Soil Monoliths

Soil monoliths were first collected in Russia during the last decades of the 19th century. Soil monoliths are undisturbed vertical sections taken from the SP wall that preserve the original horizons and morphological features. The methods of removing the monoliths from the profile and the materials used to preserve them may vary in required skills and resources but generally result in valuable tools to visualize the soil body. Collections of preserved SPs are useful visual aids in teaching pedology. A SP may be taken from the field preserved as a lacquer peel or as a monolith, which is subsequently prepared in the workshop so that its features are shown. A monolith shows the natural, undisturbed structure of a soil and the sequence of horizons. Monoliths are prepared with glue so that they are preserved for a long time. They are the best alternative to viewing soil in a pit in the field and are therefore an important educational resource. Hence, preserved SPs are an aid in soil advocacy and promoting literacy. A collection of SPs that represent diversity in geographic regions, landscape elements or

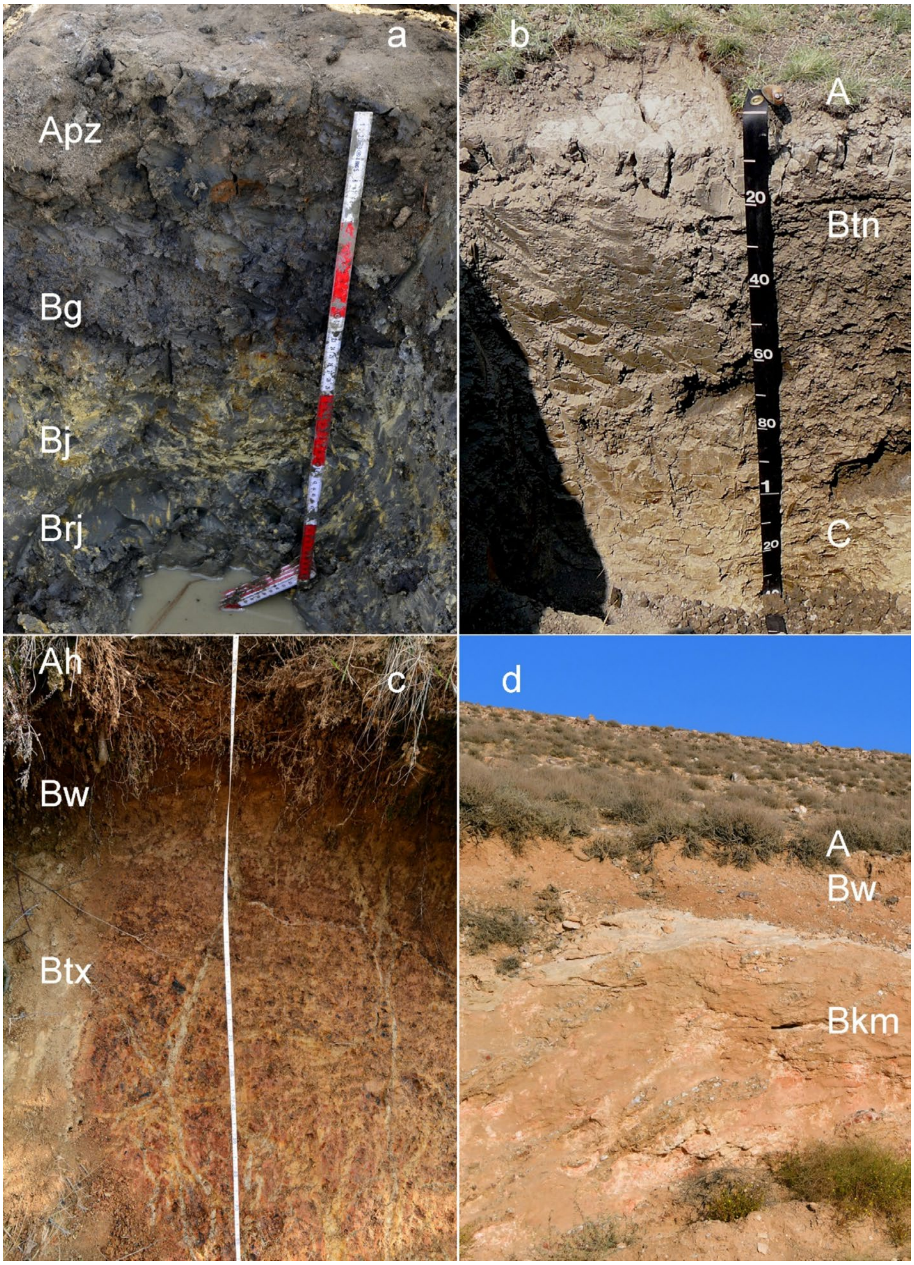

FIGURE 1 | (a) Thionic Gleysol in Guinea Bissau, the yellow jarosite concentrations in the thionic horizon (Bj) evidence production of sulfuric acid in deep horizons (photo M.E. D'Amico); (b) Solonetz in Romania, in which the natric horizon (Btn), poses limitations to water percolation and root growth (Photo E. Michéli); (c) dense fragic horizon (Btx) limiting root growth at depth in a Fragic Luvisol in NW Italy (photo M.E. D'Amico); (d) petrocalcic horizon visibly limiting root growth in a Petric Calcisol in Jordan (photo M.E. D'Amico).

land management practices may be used for comparative studies, especially if soil sampling material is available from the profiles. Preserved SPs, or soil monoliths, make the unseen visible. Seeing multiple profiles together raises awareness of the fact that soils vary across the landscape, across regions and continents, and that soils can be impacted by humans.

1.3.2 | Soil Museums

In natural history museums, or in the curricula of schools, soil is a rare topic. The unfamiliarity with the subject is a limitation for real engagement with, and appreciation for, soils. Soil museums and exhibitions are places where people are introduced to pedodiversity and soil functions. Some museums focus on soil as a system, in the context of the wider environment (e.g., geology, ecology, biodiversity).

An inventory was made of soil museums and exhibitions in the world (Reichert et al. 2022). The review identified 38 museums specifically dedicated to soils, 34 permanent exhibitions, 32 collections that are accessible by appointment, and 3 virtual museums. The number of soil museums worldwide is low and geographical distribution uneven, compared to museums devoted to other collections or topics. All continents, however, have at least two soil museums or permanent exhibitions. This survey revealed that soil museums receive between 1000 and 10,000 visitors annually.

Russia has various soil museums (Moscow and St. Petersburg) that have large collections of soils from all over Russia and the former Soviet Union. Indeed, the museum that presented the first collection of soils, the "Central Soil Museum of Dokuchaev" in St. Petersburg Russia, opened in 1902. This museum continues to function today. Other well-known museums are in Thailand (Bangkok), which exhibits all soil series of Thailand and uses its profiles for workshops with farmers. Similarly, the soil museum of the Emirates in Dubai is linked to desert and dryland research. The United States has various soil monolith exhibitions, including permanent expositions at the University of Wisconsin-Madison and the University of California, Davis. The World Soil Museum in Wageningen (NL) has arguably the most diverse collection of soils, and to the best of our knowledge it is the only museum exhibiting soils from around the globe. The reference collection of the World Soil Museum, of which the larger part has been described with a single (evolving) international field protocol and has been analyzed in certified laboratories with in most cases the same methodology, provides a scientific reference for the FAO-UNESCO Soil Map of the World and the WRB classification system. Several universities have broad monolith collections for teaching purposes for students and interested visitors at public events. The importance of collections and museums is well reflected by the recent proposal for a new working group of the International Union of Soil Sciences (IUSS) for global coordination of soil museums and digital repositories of profile images.

Teaching soil classification and diagnostic features has often been the prime purpose of exhibiting SPs. It is no surprise perhaps that many soil museums are commonly connected to, or part of, an academic institute. These serve to provide training opportunities, not least for higher education students, who may not be able to study particular SPs in the field. Outside of formal education, the challenge for soil museums is to capture and sustain the interest of the public. Museum collections need to be put into a broader perspective than soil classification alone, using an approach that is designed for different user groups. Visitors with no education or prior knowledge of soil need to be introduced to it in multiple ways, such as storytelling. Gamification, the use of the senses, the stimulation of curiosity-driven exploration, and the use of digital media are other ways of enticing the visitors to soil museums to engage with the soils (Figure 2).

2 | Soil Sensing

Soil sensing refers to the inference of physical, chemical, and biological properties of soil from electrical signals measured using various platforms (Viscarra Rossel and Bouma 2016). Sensing platforms differ in their distance to the soil surface (i.e., proximal (< 2 m), aerial, and satellite-based) and the sensing technology (e.g., reflectance, conductivity). Whereas aerial and satellite platforms allow for quantifying lateral variation of soils, they are restricted to a shallow detection depth (Babaeian et al. 2019; Chen et al. 2022). Here, we will focus on the technologies that can be employed to study SPs. Therefore, we will specifically address advances in proximal soil sensing (PSS) that can, together with SP mapping, provide a quantitative estimate of profile properties and their variation (Hartemink and Minasny 2014; Minasny and McBratney 2016).

FIGURE 2 | (a) Hungarian University of Agriculture and Life Science, Gödöllő, soil monolith corner. (b) ISRIC soil museum 1 wall overview of soil monoliths that represent the interaction between land and climate. (c) A visitor in the JRC soil awareness corner at the Ispra Site.

Each of the commonly used proximal soil sensors, such as visible near-infrared (vis–NIR), mid-infrared spectroscopy, X-ray fluorescence (XRF), and electromagnetic induction (EMI), is suitable for quantifying specific soil characteristics. As a result, recent advancements lie in their integrated use and the development of novel sensor technologies (Breure et al. 2022; Ludwig et al. 2023; Schmidinger et al. 2024; Xue et al. 2023). This multi-sensor approach addresses the limitations of individual technologies, providing a more robust characterization of soil along its vertical profile (Wang, Zhao, et al. 2022; Wang, Ma, et al. 2022; Grunwald et al. 2024). The fusion of data from multiple sensors enables more accurate and comprehensive assessments of soil properties. Examples include the combination of XRF with EMI to quantify soil properties such as texture, nutrient content, and depth (Chatterjee et al. 2021), or XRF with vis–NIR to determine particle size, major elements and soil organic carbon (SOC), as well as to develop composite quality indexes (Gozukara et al. 2022). Additionally, the development of portable and low-cost spectrometers facilitates SP descriptions in the field, such as soil horizon delineation by use of a digital camera (Zhang and Hartemink 2019).

Another transformative development is the increased application of machine learning (ML) with PSS data (Minasny and McBratney 2025; Wadoux 2025). ML, including ensemble modeling and deep learning, is increasingly employed to analyze the large and complex datasets generated by soil sensors (Chen et al. 2023; Padarian et al. 2022; Viscarra Rossel et al. 2024). There is a wide variety of ML algorithms, each developed for a specific purpose that may have an application in SP description. For example, convolutional neural networks can take 2D or 3D arrays as inputs, rendering them especially suitable for SP descriptions. ML therefore allows for integrating various sensor data to quantify differences in color, texture, structure, coarse fragments, mottles, and other redoximorphic features that are generally used to characterize soil horizons (Hartemink and Minasny 2014).

These technologies are now central to comprehensive soil monitoring, SOC sequestration assessment, and detecting contamination (Dai et al. 2024; Sanderman et al. 2021; Wang et al. 2024). Despite the limited detection depth, a growing emphasis is being placed on integrating PSS data with aerial and satellite data (Chen et al. 2023; Demattê, Minasny, and Hartemink 2025; Demattê, Rizzo, et al. 2025; Minasny et al. 2024). Recently, the integration with aerial and satellite data has been shown to allow more optimal planning of pedological field surveys (Behrens et al. 2024), reducing subjectivity in locations to describe SPs and more effective resource allocation. Future research could focus on the use of spectral libraries for characterizing SP horizons, the quantification of errors for the various sensors used in SP description, visualization techniques of digital profiles, and integrating digital SP data into databases akin to spectral libraries (Pham et al. 2021).

3 | Soil Profiling for Global, Continental and National Scales Monitoring

Soil sampling is a core practice for monitoring soil functional properties, guiding sustainable land use, and supporting environmental and agricultural policies. It provides essential data on a wide range of indicators, including SOM, nutrient status, texture, structure, pH, contamination, salinity, and biodiversity, that reflect the condition and functionality of soils. At global, continental, and national levels, soil sampling informs scientific research, environmental governance, and regulatory compliance. Increasingly, it is embedded in standardized measurement, reporting and verification (MRV) frameworks that enable consistent and credible soil monitoring across jurisdictions. Existing governmental repositories, such as the European Soil Data Centre (ESDAC), offer a wealth of standardized profile-level data that can support this harmonization (European Commission, Joint Research Centre 2023b).

While current approaches are largely standardized, they have evolved from earlier models of soil surveying and classification. Historically, soil information was derived primarily from excavated profile pits, with morphological descriptions (e.g., horizon boundaries, color, structure, porosity, and presence of diagnostic features) used to inform classification and mapping. SP remains essential for understanding soil genesis, long-term transformation processes, and subsoil functionality that is still not captured by surface-only sampling strategies or remote sensing technologies. However, SPs require much longer times and much higher costs than topsoil sampling, and most large-scale monitoring systems cannot afford such high costs nor the time required. But it is necessary to not forget the huge amount of information that only SPs can deliver.

3.1 | Global Level

Globally, soil sampling supports international goals related to land degradation neutrality, biodiversity protection, sustainable agriculture, and climate resilience. Global initiatives such as the FAO's Global Soil Partnership and the World Soil Information Service (WoSIS) promote harmonized sampling protocols and data-sharing frameworks (FAO, ISRIC). Sampling typically follows stratified random or grid-based approaches and encompasses both surface and subsoil layers to capture the vertical heterogeneity of SP properties. Core indicators are assessed using consistent analytical methods, and the data contribute to global models and policy frameworks. The Harmonized World Soil Database (HWSD) is a global dataset that provides comprehensive and harmonized soil information, playing a crucial role in SOC stock estimates and IPCC major soil type mapping (Sinitambirivoutin et al. 2024). The latest update to HWSD version 2.0 incorporates new data sources, improved classification systems, and enhanced spatial resolution, enabling more accurate and reliable SOC stock estimates and IPCC major soil type mapping (Schiettecatte et al. 2025). Also, the Soil atlases represent valid contribution to the continental SP knowledge, (Jones et al. 2010). These initiatives represent a significant evolution from early global data efforts, which were often project-based and lacked methodological coherence. The current generation of global soil datasets benefits from high-resolution spatial frameworks, standardized metadata, and the integration of pedogenic indicators and mineralogical properties. While surface (e.g., 0–30 cm) composite samples dominate these datasets, the inclusion of deep horizons and full profile descriptions remains limited, posing a challenge to certain tasks such as modeling deep carbon pools or assessing soil functioning at ecosystem scale.

3.2 | Continental Level

Continental initiatives adapt global goals to regional conditions. For instance, the European Union's proposed Soil Monitoring Law introduces a common framework for soil monitoring across all member states (European Commission 2023, Alblas et al. 2025). This law includes a defined set of soil descriptors (i.e., SOC, nutrient balance, contamination, compaction, salinity, erosion, and biodiversity) that must be monitored regularly. Pioneering in this the SP Analytical Database for Europe (SPADE) including over 10,000 SPs in a harmonized database, representing a wide range of soil types (https://esdac.jrc.ec.europa.eu/resource-type/soil-point-data). The European Soil Regional Types (EUSR5000) project was completed in 2005, and it provides a comprehensive classification of soil regions in Europe. The project was carried out by the Federal Institute for Geosciences and Natural Resources (BGR) in Germany, in cooperation with the European Commission's Joint Research Centre (JRC). The EUSR5000 project aimed to create a harmonized soil classification system for Europe, which would facilitate the exchange of soil data and expertise among European countries. The project resulted in the creation of a soil regional types of maps, which covers the entire European continent at a scale of 1:5,000,000. The EUSR5000 map identifies 32 distinct soil regions in Europe, each with its own unique characteristics and properties. These soil regions are based on a combination of factors, including climate, geology, topography, and WRB reference soil groups RSG. In contrast, LUCAS Soil module operationalize these ambitions through harmonized sampling campaigns using fixed depths (e.g., 0–20 cm from survey undergoing between 2009 and 2018, recently extended to 0–30 cm in 2022) (European Commission, Joint Research Centre 2023a; 2023b, 2018; Fernández-Ugalde et al. 2020). LUCAS exemplifies an approach that combines methodological standardization with scalability. However, its reliance on auger-based surface samples, though suitable for comparative assessments, is often insufficient for characterizing pedogenic horizons, clay illuviation, root barriers, or drainage parameters that are observable only in full profile excavations.

3.3 | National Level

At national level, soil sampling is used to support land-use planning, agricultural advice, and compliance with environmental and climate commitments. National monitoring networks are usually built around 1000 of geo-referenced plots, sampled at regular intervals (e.g., every 5–10 years). Multi-depth sampling, commonly in increments such as 0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm (Chen et al. 2022), is now standard for certain purposes, for example assessing SOC stocks and SOC sequestration over time. Auger-based composite sampling offers practical coverage across diverse landscapes, while profile pit sampling is used at benchmark sites where a more detailed understanding of soil function is required. Sampling is typically supported by GIS-based site selection, field classification, and rigorous archiving of samples for future use.

A representative example is Ireland, where soil monitoring has gained increasing national importance in the context of climate policy, agri-environmental schemes, and EU compliance. In recent years, agronomic topsoil sampling has been a central component of national monitoring efforts. The Soil Sampling and Analysis Programme (SSAP), developed under Ireland's Agri-Climate Rural Environment Scheme (ACRES), reflects this shift toward harmonized and MRV-aligned monitoring systems (Department of Agriculture, Food and the Marine 2022). The SSAP involves widespread composite sampling, typically at 0–10 cm, designed to inform farm-level nutrient management planning and support broader environmental objectives. This surface-focused sampling is efficient and scalable and provides essential information on soil fertility, pH, organic matter, and nutrient balances.

At the same time, Ireland's soil monitoring system builds on a longer history of national projects that established the country's National Soil Database in the early 2000s (Creamer et al. 2014, Teagasc 2008). This database was based on geo-referenced samples from over 1300 locations, designed to cover all major soil types. Importantly, these national projects combined different sampling methods: full SP descriptions and morphological observations at selected sites (e.g., using pits), and auger-based sampling at many others. This generated a layered dataset that ranges from high-resolution profile-level information, capturing horizonation, texture transitions, drainage class, and rooting depth, to broader, landscape-scale assessments based on auger or composite core data.

In Spain, around 16,000 soil samples were taken in 2024 for monitoring carbon storage by following the same sampling procedure described in the LUCAS topsoil survey. This dataset offers precise information about the cultivated areas in Spain, the yields achieved, including yield comparisons across different crops and regions, and various descriptive aspects of agricultural activities, including soil management techniques and the types of irrigation used.

4 | Soil Profiles for Landscape Reconstruction and Geoarchaeology

The role of soil as an indicator for geomorphic processes and their use in landscape reconstruction and geoarchaeology is documented in scientific literature with many 1000 of research articles in SCOPUS. Soil profiling constitutes a foundational method in geoarchaeology. It enables the translation of geomorphic processes and human action into coherent narratives of landscape transformation. Landscape is conceived as a dynamic system, as defined by Zinck et al. (2023), in which soils are examined in relation to their geomorphic context. SPs serve as diagnostic units for interpreting phases of erosion, deposition, transport, or stability. However, it is the spatial distribution of SPs, expressed through a soil catena that allows for the broader interpretation of process dynamics at the landscape-scale (Maerker et al. 2019). Soils can reveal aspects of landscape transformation when assessed through chronosequences, providing a temporal framework for understanding.

By contrast, the geoarchaeological dimension of soil science approaches, SPs primarily as archives of human activity (Targulian and Bronnikova 2019). Initial conceptualizations emphasized the ability of soils to record environmental information, a phenomenon widely known as "soil memory". This concept was first coined by Nikiforoff (1953) and is echoed in Dokuchaev's famous phrase "Soil is a mirror of the landscape". Traditionally, this memory was associated with the solid phase of soils, focusing mainly on soil properties and embedded artefacts (Targulian and Bronnikova 2019). More recent approaches have broadened this notion to include the soil pore system as a medium of memory as well (Pogosyan et al. 2024). Furthermore, contemporary scholars have proposed soil memory not only as an interpretative metaphor but as a methodological and epistemic framework in paleopedology (Nascimento and Bernardes Ladeira 2025), with further applicability for landscape reconstruction and geoarchaeology.

While soil memory is often associated with landscape stability, the loss of this memory has been identified as a valuable indicator of landscape instability (Bettoni et al. 2022, Monger and Bronnikova 2025) and erosion. In this sense, soils are seen as active witnesses of geomorphic changes and human activity, from discrete events (e.g., burning, trampling, and volcanic eruptions) to structural modifications (e.g., farming, building, climate change). SPs at archaeological and historical sites are typically polygenetic, with cultural layers interwoven among soil horizons, offering a context-rich archive of complex socioecological interactions. Some examples include soil formation in Eastern Mediterranean states (Sedov et al. 2017; Itkin et al. 2018), ancient agricultural terraces (Itkin et al. 2022), and fields heavily affected by warfare.

Epistemologically, comparing geopedology and geoarchaeology as frameworks poses challenges, particularly in terms of how each discipline conceptualizes its objects of study. In geopedology, the landscape is interpreted as the archive, while the pedon (through the SP) serves as the analytical unit. In geoarchaeology, the pedon is often regarded as the primary archive, and its properties are considered the primary units of analysis. In this regard, the language of soil profiling serves as a translator between the two disciplines, providing a shared narrative of geomorphic processes and human agency.

5 | Concluding Remarks

SP description remains fundamental for understanding soil genesis, spatial variability, and land management implications. The use of classification systems such as Soil Taxonomy and WRB provides an essential common language for describing and communicating soil information across regions and disciplines. Through diagnostic horizons, properties and materials, these frameworks enable the integration of field observations with broader soil mapping and monitoring efforts. Across soil science domains, researchers have consistently emphasized that detailed SPs description is indispensable for interpreting soil functioning and managing soils sustainably. At the same time, advances in quantitative pedology (pedometrics) have expanded our capacity to analyse and synthesize SP data, revealing patterns and functional relationships that would otherwise remain hidden. These digital developments complement rather than replace field-based expertise.

However, there is a growing concern that the practice and transmission of SP description skills are declining. Fewer trained pedologists, reduced field-based curricula and limited institutional investment risk weakening the foundational knowledge required to interpret soils as dynamic landscape archives. This trend is alarming in a context where soils are central to climate mitigation, food security, biodiversity conservation and land degradation neutrality. Encouragingly, several initiatives aim to revitalize the field pedology and soil, to address these challenges, promoting soil literacy and advocating for the importance of pedology is essential. Within this context, the IUSS promotes some initiatives, for example, of the "Soil judging" competition (BSSS, IUSS) to revive SP description skills for the next generation. Similar initiatives to the IUSS Soil Judging activities exist at a national scale across Europe and include field-based pedological training and SP description exercises organized by national soil science societies. These initiatives provide hands-on training, intergenerational knowledge exchange and renewed visibility for field-based soil expertise. The collective experience of the soil science community demonstrates that maintaining strong SP description skills is essential for linking classification, monitoring, modeling and implementation of policy. Strengthening soil literacy and reinvesting in field pedology are therefore not nostalgic exercises but strategic necessities. By combining rigorous field observation with quantitative and digital technologies, the next generation of soil scientists can ensure that SP remains the "window of the landscape", which is critical for the foundation for promoting sustainable soil management and environmental stewardship.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Alblas, E., A. Edlinger, J. Helfenstein, et al. 2025. "Bridging Law and Soil Science to Promote Soil Health." *European Journal of Soil Science* 76, no. 4: e70127.

Babaeian, E., M. Sadeghi, S. B. Jones, C. Montzka, H. Vereecken, and M. Tuller. 2019. "Ground, Proximal, and Satellite Remote Sensing of Soil Moisture." *Reviews of Geophysics* 57, no. 2: 530–616.

Behrens, T., K. Schmidt, F. Stumpf, et al. 2024. "Operationalizing Fine-Scale Soil Property Mapping With Spectroscopy and Spatial Machine Learning." *EGU Sphere*: 1–28. https://doi.org/10.5194/egusphere-2024-2810.

Bettoni, M., M. Maerker, A. Bosino, C. Schillaci, and S. Vogel. 2022. "Bibliometric Analysis of Soil and Landscape Stability, Sensitivity and Resistivity." *Land* 11: 1328.

Borden, R. W., I. C. Baillie, and S. H. Hallett. 2020. "The East African Contribution to the Formalisation of the Soil Catena Concept." *Catena* 185: 104291.

Breure, T. S., J. M. Prout, S. M. Haefele, et al. 2022. "Comparing the Effect of Different Sample Conditions and Spectral Libraries on the Prediction Accuracy of Soil Properties From Near-And Mid-Infrared Spectra at the Field-Scale." *Soil and Tillage Research* 215: 105196.

Brevik, E. C., and A. E. Hartemink. 2010. "Early Soil Knowledge and the Birth and Development of Soil Science." *Catena* 83: 23–33.

Chatterjee, S., A. E. Hartemink, J. Triantafilis, et al. 2021. "Characterization of Field-Scale Soil Variation Using a Stepwise Multi-Sensor Fusion Approach and a Cost-Benefit Analysis." *Catena* 201: 105190.

Chen, S., D. Arrouays, V. L. Mulder, et al. 2022. "Digital Mapping of GlobalSoilMap Soil Properties at a Broad Scale: A Review." *Geoderma* 409: 115567.

Chen, S., N. P. Saby, M. P. Martin, et al. 2023. "Integrating Additional Spectroscopically Inferred Soil Data Improves the Accuracy of Digital Soil Mapping." *Geoderma* 433: 116467.

Creamer, R. E., I. Simo, B. Reidy, et al. 2014. *Irish Soil Information System – Synthesis Report (2007-S-CD-1-S1)*. Teagasc.

Dai, L., J. Xue, R. Lu, et al. 2024. "In-Situ Prediction of Soil Organic Carbon Contents in Wheat-Rice Rotation Fields via Visible Near-Infrared Spectroscopy." *Soil and Environmental Health* 2, no. 4: 100113.

D'Amico, M. E., M. Barbieri, and D. A. E. Khair. 2024. "Mangrove Rice Productivity and Pedogenic Trends in Guinea Bissau, West Africa." *Journal of Soils and Sediments* 24: 244–258.

D'Amico, M. E., E. Pintaldi, C. Colombero, et al. 2025. "Large-Scale Cryostructures and Pedogenesis in Blockstreams in the Ligurian Alps (NW Italy): Pleistocene Paleoclimate Implications." *Catena* 249: 108676.

Demattê, J. A., B. Minasny, and A. E. Hartemink. 2025. "Vital for Sustainable Agriculture: Pedological Knowledge and Mapping." *European Journal of Soil Science* 76, no. 1: e70040.

Demattê, J. A., R. Rizzo, N. A. Rosin, et al. 2025. "A Global Soil Spectral Grid Based on Space Sensing." *Science of the Total Environment* 968: 178791.

Department of Agriculture, Food and the Marine. 2022. "Soil Sampling and Analysis Programme (SSAP). Government of Ireland." https://www.gov.ie/en/publication/d4c7f-soil-sampling-and-analysis-programme/.

Dokuchaev, V. V. 1967. *Russian Chernozem Selected Works of V.V. Dokuchaev, Vol. 1*, edited by S. Monson. Jerusalem.

Duchaufour, R. 2008. *Pedology: Pedogenesis and Classification*, 236–269. Springer Netherlands.

European Commission. 2023. Proposal for a Directive Soil Monitoring Law. https://environment.ec.europa.eu/publications/proposal-directive-soil-monitoring-and-resilience_en.

European Commission, Joint Research Centre. 2023a. *LUCAS 2022 Topsoil Data*. European Soil Data Centre (ESDAC). https://esdac.jrc.ec.europa.eu/content/lucas-2022-topsoil-data.

European Commission, Joint Research Centre. 2023b. *Soil Profile Database (SPD)*. European Soil Data Centre (ESDAC). https://esdac.jrc.ec.europa.eu/resource-type/datasets.

Fernández-Ugalde, O., A. Jones, and R. G. Meuli. 2020. "Comparison of Sampling With a Spade and Gouge Auger for Topsoil Monitoring at the Continental Scale." *European Journal of Soil Science* 71, no. 2: 137–150.

Gozukara, G., M. Acar, E. Ozlu, O. Dengiz, A. E. Hartemink, and Y. Zhang. 2022. "A Soil Quality Index Using Vis-NIR and pXRF Spectra of a Soil Profile." *Catena* 211: 105954.

Grunwald, S., M. O. F. Murad, S. Farrington, W. Wallace, and D. Rooney. 2024. "Multi-Sensor Soil Probe and Machine Learning Modeling for Predicting Soil Properties." *Sensors* 24, no. 21: 6855.

Hartemink, A. E. 2009. "The Depiction of Soil Profiles Since the Late 1700s." *Catena* 79, no. 2: 113–127.

Hartemink, A. E., and J. G. Bockheim. 2013. "Soil Genesis and Classification." *Catena* 104: 251–256.

Hartemink, A. E., and B. Minasny. 2014. "Towards Digital Soil Morphometrics." *Geoderma* 230: 305–317.

Herrick, J. E. 2000. "Soil Quality: An Indicator of Sustainable Land Management?" *Applied Soil Ecology* 15: 75–83.

Itkin, D., O. Crouvi, H. C. Monger, U. Shaanan, and H. Goldfus. 2018. "Pedology of Archaeological Soils in Tells of the Judean Foothills, Israel." *Catena* 168: 47–61.

Itkin, D., R. Poch, C. Monger, et al. 2022. "Pedology of Archaeological Stone-Wall Bench Terraces." *Geoderma* 428: 116129.

IUSS Working Group WRB. 2022. "World Reference Base for Soil Resources." In *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed. International Union of Soil Sciences.

Jenny, H. 1941. *Factors of Soil Formation: A System of Quantitative Pedology*, 281. Dover Publications.

Jones, A., V. Stolbovoy, C. Tarnocai, G. Broll, O. Spaargaren, and L. Montanarella. 2010. *Soil Atlas of the Northern Circumpolar Region*, 144. European Commission, Publications Office of the European Union.

Laliberté, E., J. B. Grace, M. A. Huston, et al. 2013. "How Does Pedogenesis Drive Plant Diversity?" *Trends in Ecology and Evolution* 28: 331–340.

Lehmann, J., D. A. Bossio, I. Kögel-Knabner, and M. C. Rillig. 2020. "The Concept and Future Prospects of Soil Health." *Nature Reviews Earth and Environment* 1: 544–553.

Ludwig, B., I. Greenberg, M. Vohland, and K. Michel. 2023. "Optimised Use of Data Fusion and Memory-Based Learning With an Austrian Soil

Library for Predictions With Infrared Data." *European Journal of Soil Science* 74, no. 4: e13394.

Maerker, M., C. Schillaci, R. T. Melis, et al. 2019. "Geomorphological Processes, Forms and Features in the Surroundings of the Melka Kunture Palaeolithic Site Ethiopia." *Journal of Maps* 15, no. 2: 797–806.

Mikhailova, E. A., H. A. Zurqani, C. J. Post, M. A. Schlautman, and G. C. Post. 2021. "Soil Diversity (Pedodiversity) and Ecosystem Services." *Land* 10: 288. https://doi.org/10.3390/land10030288.

Milne, G. 1935a. "Some Suggested Units of Classification and Mapping Particularly for East African Soils. Soil Research–Bodenkundliche Forschung, Supplement to the Proceedings of the International Union of Soil Science IV, 183-198."

Milne, G. 1935b. "Composite Units for the Mapping of Complex Soil Associations." *Transactions of the 3rd International Congress of Soil Science* 1: 345–347.

Minasny, B., T. Bandai, T. A. Ghezzehei, et al. 2024. "Soil Science-Informed Machine Learning." *Geoderma* 452: 117094.

Minasny, B., and A. B. McBratney. 2016. "Digital Soil Mapping: A Brief History and Some Lessons." *Geoderma* 264: 301–311.

Minasny, B., and A. B. McBratney. 2025. "Machine Learning and Artificial Intelligence Applications in Soil Science." *European Journal of Soil Science* 76, no. 2: e70093.

Monger, C., and M. Bronnikova. 2025. "Soil Memory of Bioclimatic Changes in the Northern Chihuahuan Desert, USA." *Catena* 254: 108944. https://doi.org/10.1016/j.catena.2025.108944.

Nascimento, D. L., and F. S. Bernardes Ladeira. 2025. "Memories of the Deep Past: The Importance of the Soil Memory Concept for Paleopedology Studies." *Catena* 254: 108945.

Nikiforoff, C. C. 1953. "Pedogenic Criteria of Climatic Changes." In *Climatic Change: Evidence, Causes, and Effects*, edited by H. Shapely, 189–200. Harvard University Press.

Padarian, J., B. Minasny, and A. B. McBratney. 2022. "Assessing the Uncertainty of Deep Learning Soil Spectral Models Using Monte Carlo Dropout." *Geoderma* 425: 116063.

Pham, V., D. C. Weindorf, and T. Dang. 2021. "Soil Profile Analysis Using Interactive Visualizations, Machine Learning, and Deep Learning." *Computers and Electronics in Agriculture* 191: 106539.

Pogosyan, L., K. Abrosimov, and S. Sedov. 2024. "Pore Space Memory of the Tlalpan Pedosedimentary Sequence as an Indicator of Paleopedogenesis." *Journal of Plant Nutrition and Soil Science* 187: 816–825. https://doi.org/10.1002/jpln.202300444.

Reichert, J. M., P. I. Gubiani, D. Rheinheimer dos Santos, D. J. Reinert, C. Aita, and S. J. Giacomini. 2022. "Soil Properties Characterization for Land-Use Planning and Soil Management in Watersheds Under Family Farming." *International Soil and Water Conservation Research* 10, no. 1: 119–128.

Richter, D., Jr. 2007. "Humanity's Transformation of Earth's Soil: Pedology's New Frontier." *Soil Science* 172: 957–967.

Sanderman, J., J. A. Baldock, S. R. Dangal, et al. 2021. "Soil Organic Carbon Fractions in the Great Plains of the United States: An Application of Mid-Infrared Spectroscopy." *Biogeochemistry* 156, no. 1: 97–114.

Schiettecatte, L. S., I. Tzamtzis, J. L. Chotte, et al. 2025. "Assessment of Soil Integration in Nationally Determined Contributions and Guidance for Quantifying Ex-Ante Soil Organic Carbon Stock Changes in National Policies Using IPCC Default Methodologies." *Catena* 252: 108805.

Schmidinger, J., V. Barkov, H. Tavakoli, et al. 2024. "Which and How Many Soil Sensors Are Ideal to Predict Key Soil Properties: A Case Study With Seven Sensors." *Geoderma* 450: 117017.

Sedov, S. N., A. L. Aleksandrovskii, M. Benz, et al. 2017. "Anthropogenic Sediments and Soils of Tells of the Balkans and Anatolia: Composition, Genesis, and Relationships With the History of Landscape and Human Occupation." *Eurasian Soil Science* 50: 373–386.

Sinitambirivoutin, M., E. Milne, L. S. Schiettecatte, et al. 2024. "An Updated IPCC Major Soil Types Map Derived From the Harmonized World Soil Database v2.0." *Catena* 244: 108258.

Soil Survey Staff. 2022. *Keys to Soil Taxonomy*. 13th ed. USDA-Natural Resources Conservation Service.

Targulian, V. O., and M. A. Bronnikova. 2019. "Soil Memory: Theoretical Basics of the Concept, Its Current State, and Prospects for Development." *Eurasian Soil Science* 52: 229–243. https://doi.org/10.1134/S1064229319030116.

Teagasc. 2008–2014. *Soil Maps–National Soil Survey of an Foras Talúntais (County-Scale Maps)*. Teagasc. https://teagasc.ie/environment/soil/soil-maps/.

Viscarra Rossel, R. A., and J. Bouma. 2016. "Soil Sensing: A New Paradigm for Agriculture." *Agricultural Systems* 148: 71–74.

Viscarra Rossel, R. A., Z. Shen, L. R. Lopez, et al. 2024. "An Imperative for Soil Spectroscopic Modelling Is to Think Global but Fit Local With Transfer Learning." *Earth-Science Reviews* 254: 104797.

Wadoux, A. M. J. C. 2025. "Artificial Intelligence in Soil Science." *European Journal of Soil Science* 76: e70080.

Wang, J., X. Zhao, K. E. Deuss, D. R. Cohen, and J. Triantafilis. 2022. "Proximal and Remote Sensor Data Fusion for 3D Imaging of Infertile and Acidic Soil." *Geoderma* 424: 115972.

Wang, L., Y. Cheng, I. M. Meftaul, et al. 2024. "Advancing Soil Health: Challenges and Opportunities in Integrating Digital Imaging, Spectroscopy, and Machine Learning for Bioindicator Analysis." *Analytical Chemistry* 96, no. 20: 8109–8123.

Wang, Z., Y. Ma, Y. Zhang, and J. Shang. 2022. "Review of Remote Sensing Applications in Grassland Monitoring." *Remote Sensing* 14, no. 12: 12.

Warkentin, B. P. 2006. *Footprints in the Soil: People and Ideas in Soil History*. Elsevier.

WRB. 2022. "World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps." In *International Union of Soil Sciences (IUSS)*, 4th ed. IUSS.

Xue, J., X. Zhang, S. Chen, et al. 2023. "The Validity Domain of Sensor Fusion in Sensing Soil Quality Indicators." *Geoderma* 438: 116657.

Zhang, Y., and A. E. Hartemink. 2019. "Digital Mapping of a Soil Profile." *European Journal of Soil Science* 70, no. 1: 27–41.

Zinck, J. A., G. Metternicht, H. F. del Valle, and M. Angelini. 2023. *Geopedology. An Integration of Geomorphology and Pedology for Soil and Landscape Studies*. Springer.