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Soil Diversity and Climate: An Overview of Profile Data and Acquisition With the WoSIS Global Legacy Dataset

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ABSTRACT

Soil profiles are the primary field evidence from which pedogenesis, soil classification and land-use effects are interpreted, yet their availability remains uneven across climates and land-cover contexts. Here, we analyse the World Soil Information Service (WoSIS) 2023 snapshot together with Copernicus Global Land Cover 2015 and the global biome delineations to assess the distribution, classification status and temporal coverage of legacy soil-profile observations. Cropland is the most represented land-cover class, with 67,370 profiles (29.5%), followed by herbaceous vegetation with 40,277 profiles (17.7%), whereas wetlands, mangroves, tundra and several forested or arid systems remain rather underrepresented. The temporal distribution of profiles with recorded sampling dates increases markedly from the mid-twentieth century to the 1980s and declines after 1990, suggesting a possible shift away from field-based profile description and towards mapping, modelling and remotely sensed approaches. The review of forest, volcanic, cold-region, arid, wetland, cropland, grassland, urban and Mediterranean soils further shows that profile description remains essential for interpreting soil functions, diagnostic horizons, degradation processes and land-management constraints. This work provides a repeatable workflow for future WoSIS releases and other harmonised soil databases, and highlights the need to recover, standardize and publish legacy soil-profile information while training a new generation of pedologists able to combine field description with digital soil science.

1 | Introduction

The pedosphere, a critical component of the Earth's ecosystem, exhibits significant variability across different climates and land-use systems (Smith et al. 2024). The discipline of pedology and soil classification has undergone significant advancements over the last 20–30 years, driven by technological innovations, increased understanding of soil processes, and the need for more accurate and detailed soil information for environmental management and sustainability (Hartemink et al. 2008; McBratney et al. 2003; Minasny et al. 2013). This progress has been marked by the emergence of new concepts and trends, including a greater emphasis on understanding soil genesis and the application of digital mapping techniques (Lagacherie et al. 2013; Dobos et al. 2017). Continental and global soil monitoring systems are essential to capture the spatial and temporal variability of soil properties across heterogeneous landscapes. At the European scale, repeated soil surveys reveal inconsistencies in trends of soil organic carbon (SOC) contents and stocks due to fragmented data and

For affiliations refer to page 19.

Highlights

- Cropland accounts for 29.5% of soil profiles since 1950.
- Forested areas have ~32.4% of soil profiles in Temperate Broadleaf and Mixed Forests.
- Soil profiles increased by 400% from 1950 to 1980.
- Soil profiles declined after 1990 due to reduced sampling.
- Tundra and Montane Grasslands have less than 1% of soil profiles.
- Global soil profile data are strongly biased across biomes and land covers.
- Cropland dominates sampling (29.5%), skewing pedological inference.
- Temperate forests (32.4%) overshadow arid and cold soil systems.
- WoSIS–LC–biome integration exposes structural gaps in global datasets.
- Post-1990 decline signals erosion of field-based pedological expertise.

non-harmonized methodologies (Harbo et al. 2026), highlighting the need for coordinated frameworks. Changes in soil conditions are due to a mixture of natural and anthropogenic processes, as well as methodological artefacts (conditions, sampling procedure, processing, analytical method, etc.). Multi-scale approaches are therefore required to integrate local observations into consistent continental assessments, ensuring comparability and supporting policy-relevant soil health evaluations (Campbell et al. 2025).

The foundation of soil science lies in the understanding of soil formation and classification, which is rooted in Hans Jenny's equation (Jenny 1941). This equation considers soil as a function of climate, organisms, relief, parent material, and time, and has been influential in pedology (Buol et al. 2011). The equation ($S = f$ (cl, o, r, p, t)) highlights the complex interactions that shape soil properties and has been widely used to understand soil formation and classification (Jenny 1941; Buol et al. 2011). The SCORPAN model, an extension of Jenny's work, incorporates space and other soil properties as additional factors to predict soil properties and classes (McBratney et al. 2003). This model has been widely used for digital soil mapping, leveraging geographic information systems (GIS), geostatistics, and machine learning techniques to predict and map soil types and properties across landscapes (Lagacherie et al. 2013; Kempen et al. 2015).

Soil classification systems, such as U.S. Soil Taxonomy (Soil Survey Staff 2022) and the World Reference Base for Soil Resources (IUSS Working Group WRB 2022), have evolved to incorporate new concepts and diagnostic criteria. These systems recognise the importance of soil catenas, that is, sequences of soils developed from broadly similar parent material under similar climatic conditions but differentiated by topographic position and associated hydrological and geomorphic processes (Milne 1935; Zinke et al. 1984). Although neither U.S. Soil Taxonomy nor WRB explicitly uses the catena concept as a hierarchical classification level, both recognise the role of relief and landscape position in shaping soil properties and horizon differentiation. The study of soil catenas is crucial for understanding the spatial distribution of soils within a landscape (Dominati et al. 2010; Hartemink et al. 2008). Both the U.S. Soil Taxonomy and WRB, for example, classify soils based on their properties and horizons, and although they do not explicitly use the catena concept in their classification hierarchy, they acknowledge the role of topography in shaping soil characteristics.

The decision on where to take a soil profile is critical for understanding soil genesis, classification, and catenary relationships (Hole 1961). Soil Profiles (hereafter SPs) should ideally be taken in areas representative of the dominant soil type and landscape position to capture the full range of soil properties and horizons (Soil Survey Staff 2022). Natural “in situ” SPs, which have developed without significant human disturbance, are particularly valuable for research and classification purposes (Hartemink et al. 2008; Minasny et al. 2013). They provide a window into the long-term processes that have shaped the soil and its position within the landscape (Zinke et al. 1984; Dobos et al. 2017). The study of such profiles can reveal detailed information about soil formation, erosion, and deposition processes, and how these factors influence the soil catena (Hartemink et al. 2008; Minasny et al. 2013). In Europe, this information is also presented in soil atlases, which illustrate the complex inter-linkages between soil degradation processes by describing and mapping major soil functions (Jones et al. 2005).

The soil unit concept, which refers to the basic mapping units of soil classification, is also an important aspect of soil science. The soil unit concept can range from very detailed (series) to broad (orders) categories, and the dominant soil type within a landscape or region dictates the overall soil characteristics and functions, influencing ecosystem services such as water storage and filtration, SOC sequestration, and biodiversity support (Dominati et al. 2010; Hartemink et al. 2008).

This work aims to provide an overview of the SP distribution across climate and land-use contexts using WoSIS (World Soil Information Service; Batjes et al. 2024), the largest openly available legacy SP datasets available, and to discuss the implications for the continued development of pedology. This includes innovative techniques such as inventorying the legacy soil database that contains profiles, and using proximal sensing to build digital soil libraries. The work draws on benchmark research articles, reviews and the references therein to summarise SP descriptions and their connections with other domains of soil science (Smith et al. 2024; Ma et al. 2023; Dobos et al. 2017; Kempen et al. 2015; Minasny et al. 2013).

We examine contrasting soilscapes, including those widely represented in Europe and circum-Mediterranean environments, together with other major soil types in their respective bioclimatic settings. Our objective is to highlight the synergy between SP description, soil classification and digital archiving, and to show how pedological knowledge can support land managers, researchers and policy stakeholders.

2 | Overview of the Soil Profiles Availability at Global Scale From the World Soil Information System (WoSIS)

In this section we summarized the dataset used, including: (i) the number of available point profiles, (ii) the ratio between topsoil and full profile data, and (iii) the type of classification reported. To ensure transparency while avoiding excessive detail in the manuscript, the original data sources underpinning the analysis are explicitly reported. Soil information was derived from the WoSIS snapshot 2023, which provides quality-assessed and standardized profile data to support global soil mapping and modelling (Batjes et al. 2024). Land cover information was obtained from the Copernicus Global Land Cover Layers (2015), offering consistent, high-resolution classification of land use and land cover at the global scale (Buchhorn et al. 2020). The WoSIS profiles have been taken over the course of a long time-period. Potential discrepancy between the Land cover data at the time of surveying might have occurred. For example, deforestation from the original SP surveying/description. This information can also emphasize the value of WoSiS as a legacy reporting tool for the soil conditions before land use change.

In addition, biome delineation was based on a global ecoregion framework, enabling the stratification of results across major ecological zones and supporting the interpretation of soil processes within broader environmental contexts (Dinerstein et al. 2017). Together, these datasets ensure a harmonised and reproducible basis for the analysis while maintaining a concise presentation of the methodology.

According to WoSIS data availability, we performed a comprehensive analysis of SPs overlaid with COPERNICUS land cover 2015 (Figures 1 and 2). This revealed a diverse distribution of SPs within land cover types. The data shows that cultivated and managed vegetation/agriculture (cropland) has the largest share of WoSIS profiles, accounting for 29.5%, with 67,370 profiles. Herbaceous vegetation is the second most sampled land cover type, covering 17.7% of the total, with 40,277 profiles. Open forest, and shrubs also have a significant number of samples worldwide, accounting for 12.6% and 8.0% of total profiles, respectively. The data also highlights the importance of forested areas, with closed forest, evergreen broadleaf, and closed forest, deciduous broadleaf, representing 6.3% and 6.1% of total profiles, respectively. Urban/built-up areas account for 3.8% of total profiles, while bare/sparse vegetation, open forest, mixed, and

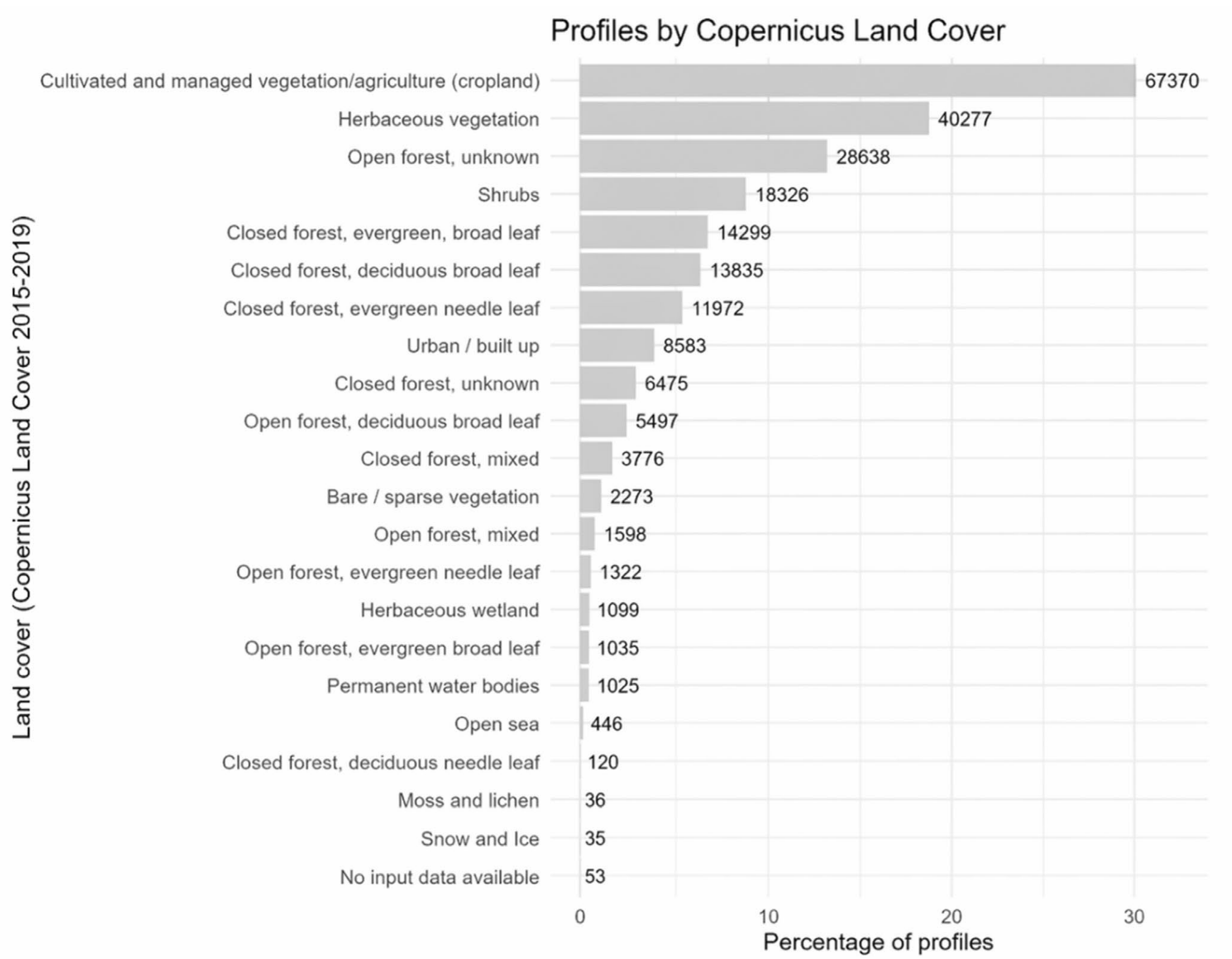

FIGURE 1 | Distribution of WoSIS soil profiles across Copernicus land-cover classes.

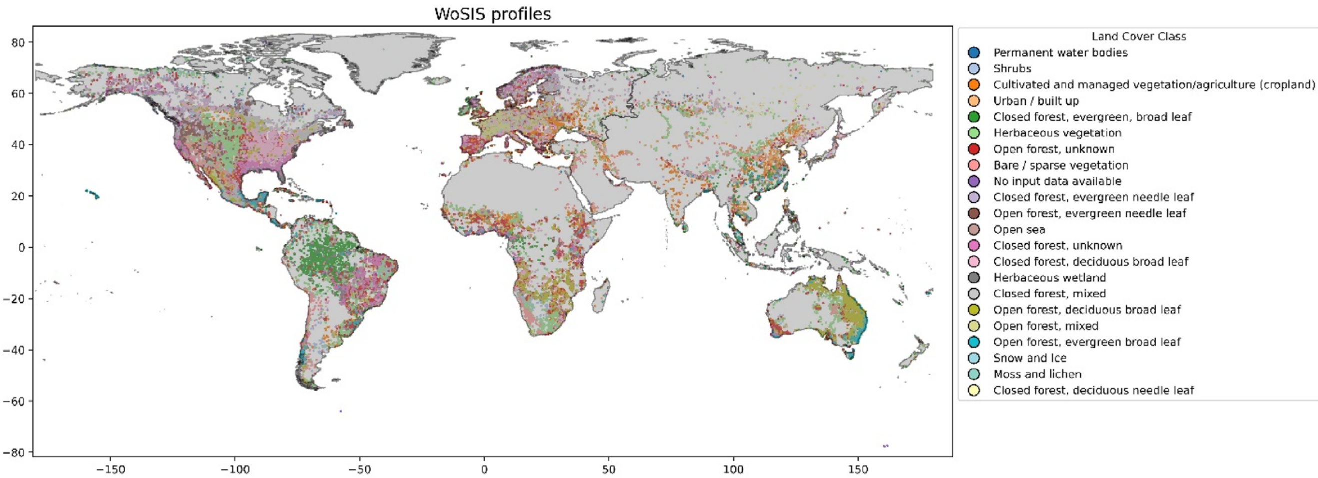

FIGURE 2 | Map of WOSIS soil profiles within Land cover classes.

herbaceous wetland cover smaller percentages, ranging from 1.0% to 0.5%. The data also shows that permanent water bodies, open sea, and snow and ice cover very small percentages, ranging from 0.4% to 0.03%.

This analysis provides valuable insights into the distribution of land cover types and their associated SPs, which can inform strategies for soil conservation and agricultural management. It also identifies environmental systems for which denser pedological information is needed. The coverage and density of SPs vary greatly depending on the region, country, and specific soil type.

The same dataset overlaid with Global Biomes (Dinerstein et al. 2017) reveals a diverse distribution of SPs in the biomes across the globe. The global biome dataset spatially defines 14 terrestrial biomes. Vegetation cover is forested in half of them. The plant communities that are found in the same biome can appear similar in structure but contain very different sets of species. The data (Figures 3 and 4) shows that the Temperate Broadleaf & Mixed Forests biome dominates, accounting for 32.4% of total SPs (73,635). Tropical & Subtropical Grasslands, Savannas & Shrublands follow closely, covering 17.1% of the total, with 38,958 profiles. Temperate Grasslands, Savannas & Shrublands and Mediterranean Forests, Woodlands & Scrub also have a significant presence, accounting for 11.7% and 10.9% of total profiles, respectively. The tropical regions are less well-represented, with Tropical & Subtropical Moist Broadleaf Forests covering 7.8% of the total, and Tropical & Subtropical Dry Broadleaf Forests and Tropical & Subtropical Coniferous Forests accounting for 2.3% and 1% of total profiles, respectively. The data also highlights the importance of other biomes, such as Deserts & Xeric Shrublands, Temperate Conifer Forests, and Boreal Forests/Taiga, which cover 5.7%, 5.6%, and 2.9% of total profiles, respectively. The less represented biomes, including Tundra, Montane Grasslands & Shrublands, Flooded Grasslands & Savannas, and Mangroves account for 0.9%, 0.8%, 0.4%, and 0.3% of total profiles, respectively.

By intersecting the WoSIS SP locations with COPERNICUS land cover and Global Biomes, the 10 land cover × biome combinations with the largest share of SPs are reported in Table 1. The data shows that cultivated and managed vegetation/agriculture (cropland) is the most prominent land cover type, with a substantial presence in Temperate Broadleaf & Mixed Forests (11.6% of total profiles), Temperate Grasslands, Savannas & Shrublands (5.1%), and Mediterranean Forests, Woodlands & Scrub (4.9%). Herbaceous vegetation is also widespread, particularly in Temperate Broadleaf & Mixed Forests (4.5%) and Tropical & Subtropical Grasslands, Savannas & Shrublands (4.2%). Closed forest, deciduous broadleaf, and open forest, unknown, are also notable in Temperate Broadleaf & Mixed Forests, covering 4.2% and 4.0% of total profiles, respectively. Additionally, closed forest, evergreen, broad leaf, is prominent in Tropical & Subtropical Moist Broadleaf Forests (2.9%), while shrubs are common in Deserts & Xeric Shrublands (2.8%).

One of the most notable observations is the high number of SPs in cropland within the Temperate Broadleaf biome, with 26,437 profiles accounting for 11.6% of the total. This is an evidence that large surfaces within this biome have been transformed into cropland, and that agricultural production has driven soil surveys in these areas more intensively than in other natural ecosystems.

Furthermore, the overlap between cropland and natural biome boundaries reflects the widespread conversion of areas within several ecoregions, including temperate broadleaf forests, temperate grasslands, and Mediterranean forests. This pattern should not be interpreted as ongoing encroachment without independent land-use change data, but it does indicate that agricultural land use has strongly shaped the distribution of available soil-profile observations.

The data also suggests that certain biomes are overrepresented in the dataset, with Temperate Broadleaf & Mixed Forests and Temperate Grasslands, Savannas & Shrublands accounting for 32.4% and 11.7% of the total profiles, respectively. In contrast, other biomes like Tropical & Subtropical Moist Broadleaf Forests and Deserts & Xeric Shrublands have relatively fewer profiles (Tables 2 and 3). This disparity in representation may indicate that the dataset is biased towards certain regions or biomes, which could impact the accuracy of any analyses or conclusions drawn from the data.

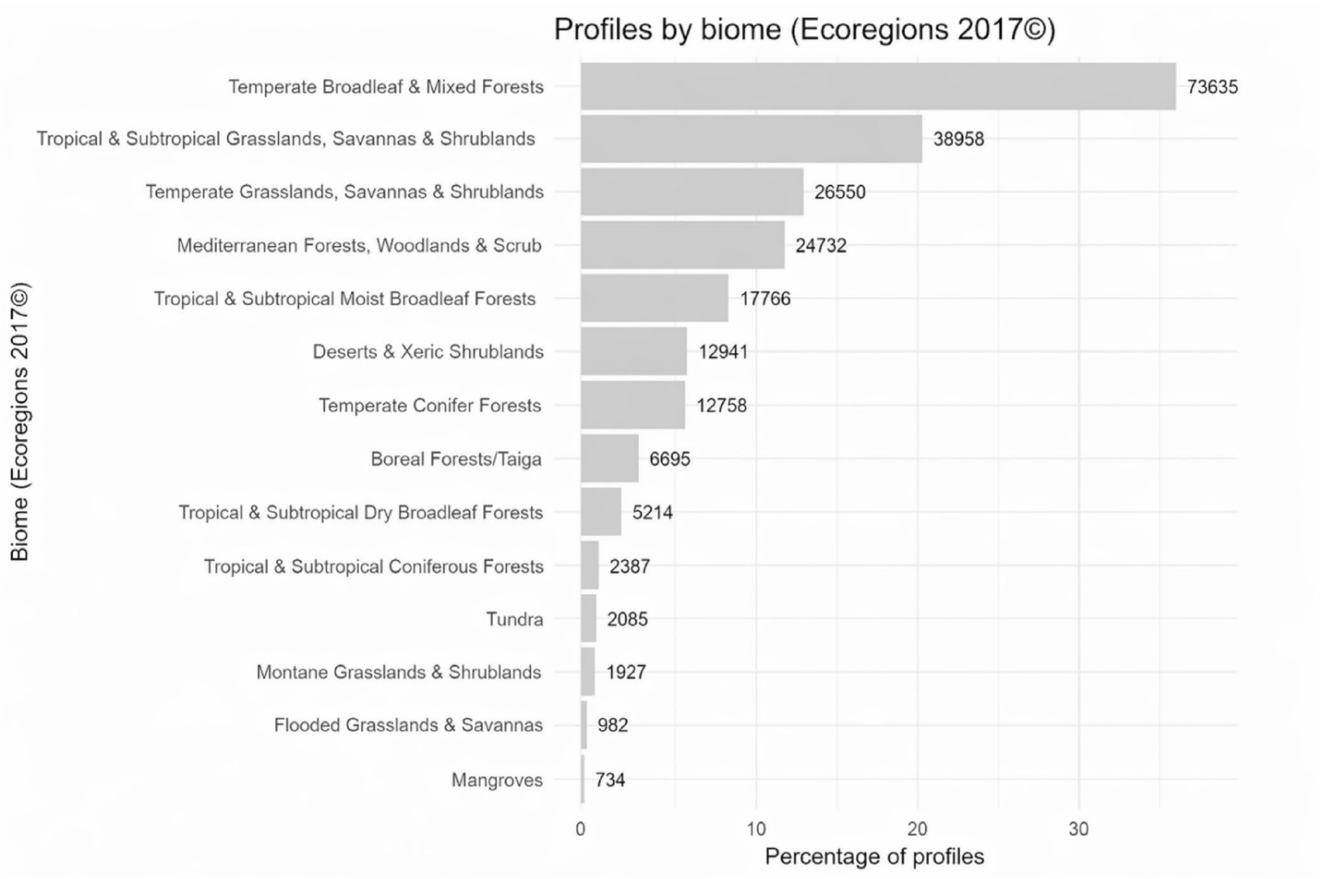

FIGURE 3 | Distribution of WOSIS soil profiles in global Biomes.

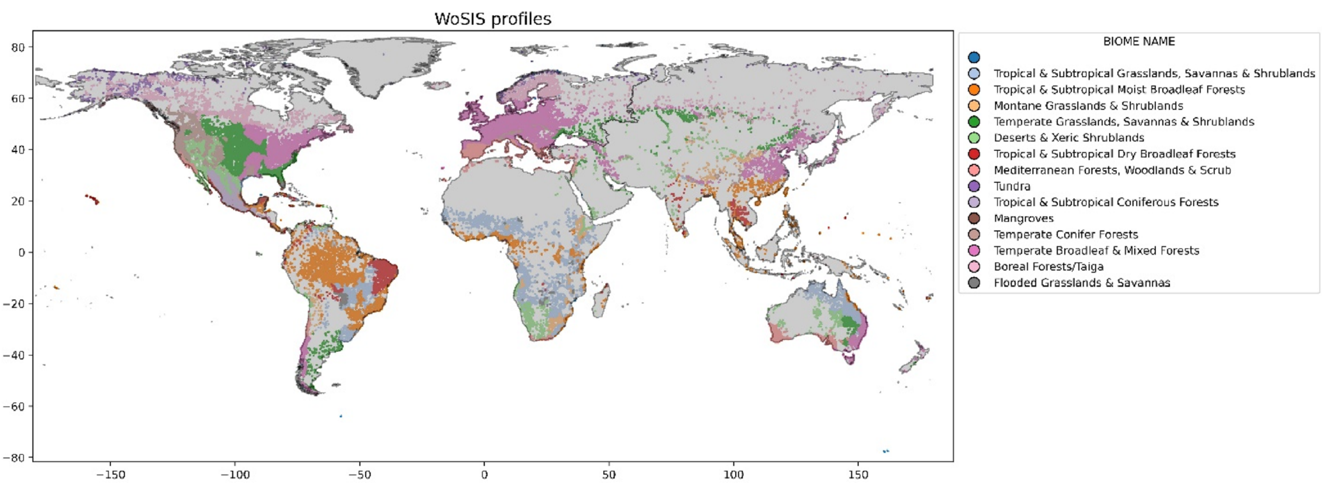

FIGURE 4 | Map of WOSIS soil profiles in global Biomes.

Additionally, the lack of SPs in certain biomes is also noteworthy. For example, Tundra, Montane Grasslands, and Flooded Grasslands have relatively few profiles, which suggests that these biomes are underrepresented in the dataset or that they are more difficult to sample. This could be due to a variety of factors, including the remoteness of these biomes, the difficulty of accessing them, or the lack of research focus on these areas. Regardless of the reason, the underrepresentation of these biomes in the dataset may limit our understanding of the soil processes and ecosystem characteristics in these regions.

Globally, WoSIS SPs with recorded sampling dates increase markedly from the mid-twentieth century to the 1980–1989 decade, followed by a decline after 1990 (Figure 5). G. A decline in the period 1990 onwards is also found in many other continents. The dataset contains almost 220.000 profiles with survey date distributed across six continents, with North America being the most represented continent (n = 79,250, 34.98%), followed by Oceania (n = 42,293, 18.67%), Europe (n = 38,569, 17.02%), South America (n = 25,123, 11.09%), Africa (n = 32,193, 14,21%), and Asia being the least represented (n = 8588, 3.79%), Antarctica (n = 24, 0.01%).

TABLE 1 | Distribution of the 10 land cover × biome combinations with the largest share of soil profiles.

Land cover	Biome	Number profiles	Share
Cultivated and managed vegetation/ agriculture (cropland)	Temperate Broadleaf & Mixed Forests	26,437	11.6%
Cultivated and managed vegetation/ agriculture (cropland)	Temperate Grasslands, Savannas & Shrublands	11,667	5.1%
Cultivated and managed vegetation/ agriculture (cropland)	Mediterranean Forests, Woodlands & Scrub	11,262	4.9%
Herbaceous vegetation	Temperate Broadleaf & Mixed Forests	10,229	4.5%
Herbaceous vegetation	Tropical & Subtropical Grasslands, Savannas & Shrublands	9656	4.2%
Closed forest, deciduous broad leaf	Temperate Broadleaf & Mixed Forests	9553	4.2%
Cultivated and managed vegetation/ agriculture (cropland)	Tropical & Subtropical Grasslands, Savannas & Shrublands	9381	4.1%
Open forest, unknown	Temperate Broadleaf & Mixed Forests	9034	4.0%
Closed forest, evergreen, broad leaf	Tropical & Subtropical Moist Broadleaf Forests	6682	2.9%
Shrubs	Deserts & Xeric Shrublands	6408	2.8%

The observed decline in the number of documented SPs may be attributed to multiple factors, although these are often difficult to trace back systematically. For instance, shifts in research priorities towards large-scale national or continental soil mapping initiatives may have reduced the emphasis on field-based profile description. A further hypothesis relates to the increasing reliance on modelling approaches in soil science. In recent years, a growing proportion of soil scientists and pedologists have focused on digital soil mapping and predictive modelling, potentially with limited direct engagement in field-based SP observation. Within this context, it may be informative to explore trends in scientific literature, for example, by analysing the temporal evolution in the number of publications employing modelling approaches relative to those based on field SP data. Such an analysis could provide indirect evidence of a broader shift in methodological paradigms within the discipline.

3 | Soil Profiles Across Climate and Land-Use Types

We use WRB terminology throughout the text (IUSS Working Group WRB 2022). The following chapter includes some of the most widespread soils in land covers, this includes: (i) Distribution and environmental context (climate and land use), (ii) Some typical SP features and diagnostic horizons (linked to WRB RSGs), (iii) Key functional properties (e.g., physicochemical and biological properties, hydrological behaviour), (iv) reference to their representation in WoSIS legacy snapshot 2023 where relevant (not necessarily following this order).

3.1 | Forest Soils

Approximately one-third of the Earth's soils developed under forest cover (Torreano 2004). Forest soils are defined by their capacity to support forest vegetation across different climates. Forests influence soil formation through microclimate buffering, deep rooting, litter input and nutrient cycling (Torreano 2004). As soil and vegetation co-evolve, digging and interpreting SPs is essential for understanding forest ecology, nutrient cycling, and soil functions in general (De Feudis et al. 2016). Common soil types include Luvisols and Planosols, which commonly have moderate to high base saturation, and Umbrisols, which occur in humid and perhumid mountain forests. Acrisols and Alisols, with low base saturation, are found in some temperate deciduous forests in Asia and South America. Podzols, often associated with coniferous forests, are acidic and nutrient-poor soils with a bleached eluviated horizon. In warm and humid forests, strongly weathered soils such as Acrisols, Alisols, Ferralsols, Nitisols and Plinthosols may occur; Ferralsols, Nitisols and Plinthosols are particularly common in tropical rainforest regions and are generally rich in iron (Fe) and aluminium (Al) oxides but poor in readily available nutrients. Histosols, found in wet, boggy forest areas, are made mostly of organic material and are waterlogged and anoxic. Despite the different soil types, the organic horizons serve as distinct and defining features and indicate different decomposition pathways and nutrient cycles (Zanella et al. 2018). This layer forms due to the continuous accumulation of leaf litter, twigs, bark, and other plant materials unique to forest environments. In contrast to grasslands, deserts, or agricultural fields, the forest floor allows organic matter to accumulate and decompose gradually, often creating a visible, well-developed organic horizon. Its presence reflects the dense vegetation and slow decomposition processes typical of forests, making it a unique and essential component of forest soils. Preserving the organic horizons is key to preventing degradation in vulnerable ecosystems (De Feudis et al. 2021). While temperate deciduous forests usually grow on nutrient-rich soils, tropical forests often grow over highly weathered and nutrient-poor soils (Figure 6a) formed under intense desilication (Osman 2013). Thick and dark surface horizons are rare, except in anthropogenic cases as in

TABLE 2 | WoSIS profiles available classified according to FAO, WRB or USDA systems, and profile density by biome.

	Soil classification					Density of soil profiles		
Biome name	FAO	USDA	WRB	Not classified	Total per biome	Area in km^2	n_profile	One location each × km
NA	5	16	46	575	726		726	
Tropical & Subtropical Moist Broadleaf Forests	469	395	529	11,395	17,766	20920087.93	17,766	1177.54
Tropical & Subtropical Dry Broadleaf Forests	565	64	647	1880	5214	4024625.71	5214	771.89
Tropical & Subtropical Coniferous Forests	694	4	558	46	2387	721046.73	2387	302.07
Temperate Broadleaf & Mixed Forests	341	9197	516	58,794	73,635	12886937.20	73,635	175.01
Temperate Conifer Forests	36	2320	105	10,006	12,758	3880921.90	12,758	304.20
Boreal Forests/Taiga		182	3	6038	6695	16586848.68	6695	2477.50
Tropical & Subtropical Grasslands, Savannas & Shrublands	58	379	308	25,373	38,958	22189375.69	38,958	569.57
Temperate Grasslands, Savannas & Shrublands	3	10,013	309	15,039	26,550	10935436.14	26,550	411.88
Flooded Grasslands & Savannas		124		351	982	1178928.50	982	1200.54
Montane Grasslands & Shrublands		11		678	1927	5043759.15	1927	2617.42
Tundra		130		1832	2085	22889475.42	2085	10978.17
Mediterranean Forests, Woodlands & Scrub	100	342	317	23,321	24,732	3542032.52	24,732	143.22
Deserts & Xeric Shrublands	1597	1094	1411	4434	12,941	26969881.40	12,941	2084.06
Mangroves	52	31	59	414	734	334730.04	734	456.04
	3920	**24,302**	**4808**	**160,176**	**228,090**	152104087.00	228,090	1690.65

Note: Classification categories are not mutually exclusive because some profiles contain more than one classification entry; therefore, row-wise sums may differ from the total number of profiles per biome.

Amazonian Dark Earths, enriched by long-term management (Macedo et al. 2017) (Figure 6b). In such systems, fertility is forest-dependent, and disturbance may trigger degradation and savannization (Flores et al. 2024).

By contrast, boreal forests develop on acidic, low-nutrient Podzols, shaped by slow decomposition and strong leaching (Osman 2013). Soil biological communities also vary across forest systems: macrofauna often play a major role in tropical forests, whereas microbial (Weston and Whittaker 2004) and fungal pathways tend to be especially important in temperate and acidic podzolic systems.

In forest environments, SPs reveal functional variability critical to forest productivity and composition (Torreano 2004). Their analysis informs assessments of water retention, rooting capacity, nutrient and organic matter cycling pathways and vulnerability to erosion, key for forest conservation and sustainable land use. However, in many areas, soil profiling in forest ecosystems faces significant challenges related to steep slopes, dense vegetation and limited accessibility. Forested areas are often located in remote areas that pose logistical challenges. Steep terrain and dense vegetation limit the ability to conduct extensive soil sampling or use heavy equipment. In addition, traditional SP description requires manual excavation and skilled interpretation of horizons, textures, colours, and other features. This process is expensive and time-consuming.

To face these issues, in the last decades, advanced tools such as improved laboratory standards and proximal sensing tools have been developed (Schillaci et al. 2026). The use of proximal sensors such as portable X-ray fluorescence and Vis–NIR visible

TABLE 3 | Number of locations with full soil profiles versus locations with topsoil-only data.

BIOME NAME	Full soil profile	Only topsoil	Total result
NA	534	192	726
Tropical & Subtropical Moist Broadleaf Forests	14,415	3351	17,766
Tropical & Subtropical Dry Broadleaf Forests	4368	846	5214
Tropical & Subtropical Coniferous Forests	2003	384	2387
Temperate Broadleaf & Mixed Forests	55,450	18,185	73,635
Temperate Conifer Forests	10,368	2390	12,758
Boreal Forests/Taiga	5252	1443	6695
Tropical & Subtropical Grasslands, Savannas & Shrublands	31,838	7120	38,958
Temperate Grasslands, Savannas & Shrublands	24,980	1570	26,550
Flooded Grasslands & Savannas	862	120	982
Montane Grasslands & Shrublands	1616	311	1927
Tundra	1566	519	2085
Mediterranean Forests, Woodlands & Scrub	8994	15,738	24,732
Deserts & Xeric Shrublands	10,210	2731	12,941
Mangroves	644	90	734
	173,100	**54,990**	**228,090**

and near-infrared spectroscopy to analyze soil has gained favour because they offer a rapid means of quantifying elemental concentrations for data collection from the SPs (Pham et al. 2021). Electro-magnetic induction instruments, acquiring georeferenced measurements of apparent electrical conductivity, allow mapping of soil spatial variability and, after appropriate calibrations through laboratory soil analysis, enable inferring related soil properties (El-Naggar et al. 2021). Additionally, portable soil testing kits have brought laboratory capabilities into the field. Modern kits can quickly assess pH, density, texture, and even microbial activity, reducing the need for extensive sample transport and processing. Combined with mobile apps and cloud-based data platforms, these kits enable real-time data collection, analysis, and sharing. However, the recent large use of high-tech solutions for soil profiling is becoming a future challenge for forest pedologists. Forest soils account for ~30%–35% of WoSIS locations, reflecting strong sampling intensity in temperate and boreal regions, although this proportion is influenced by land cover attribution and potential uncertainties due to land use change.

3.2 | Volcanic Soils

The study of SPs developed from volcanic materials represents a topic of critical scientific, agricultural, and environmental relevance. Volcanic settings, characterized by the deposition of fresh pyroclastic materials like ash, pumice, and lava flows, foster the development of the unique soil chemical and physical properties of Andosols (IUSS Working Group WRB 2022). Historically, these fertile soils have been the bedrock of thriving civilizations, including the ancient rice cultivation on Java's volcanic soils in Indonesia (Fiantis et al. 2017), the vineyards and orchards flourishing on Mount Vesuvius's slopes in Italy, and the population of the Early Bronze age in the Campania plain (southern Italy) (Vingiani et al. 2018) thanks to their nutrient-rich and well-drained nature.

Early soil scientists, including Dokuchaev (1883) and Marbut (1921), recognized the distinct characteristics of volcanic soils, observing their rapid horizon development, high porosity, and unique mineralogical properties. The fast pedogenetic development makes volcanic soils a natural laboratory for understanding soil-forming processes driven by parent material, climate, biological activity, topography, and time. Furthermore, volcanic eruptions act as chronological markers, enabling researchers to date soil layers and reconstruct past environmental and climatic conditions. Today, the study of volcanic SPs remains crucial for agriculture, natural land degradation processes such as landslides (Vingiani et al. 2015; Terribile et al. 2007), land restoration, and climate change research, particularly due to their high capacity for SOC sequestration and their role in the global carbon cycle. In Italian non-volcanic mountain ecosystems (> 600 m a.s.l.), characterized by gentle slopes (< 21%) and vigorous green biomass activity, high Normalized Difference Vegetation Index (NDVI) values, the widespread occurrence of andic soils has been documented (Mileti et al. 2017). These soils exhibit distinctive physical and hydrological properties, including low bulk density and exceptionally high-water retention. Notably, evidence has been provided that such soils can influence ecosystem functioning by accelerating the timescale of photosynthetic activity, as inferred from NDVI measurements (Terribile et al. 2018). Despite their numerous potentials, Andosols are highly susceptible to land degradation processes, primarily due to their limited capacity to recover following disturbance (i.e., their low resilience). Several cases have documented the relationship between Andosols and landslide events (Scognamiglio et al. 2019), particularly those involving rapid debris flows. These types of landslides pose serious threats to human populations and infrastructure, as they typically occur without clear precursory signs.

Andosols exhibit a diverse range of morphological features (Shoji et al. 1993; Nanzyo et al. 1993; FAO 2001; Oskarsson 2007), particularly in their horizon development. Based on IUSS Working group WRB (2022), common profile

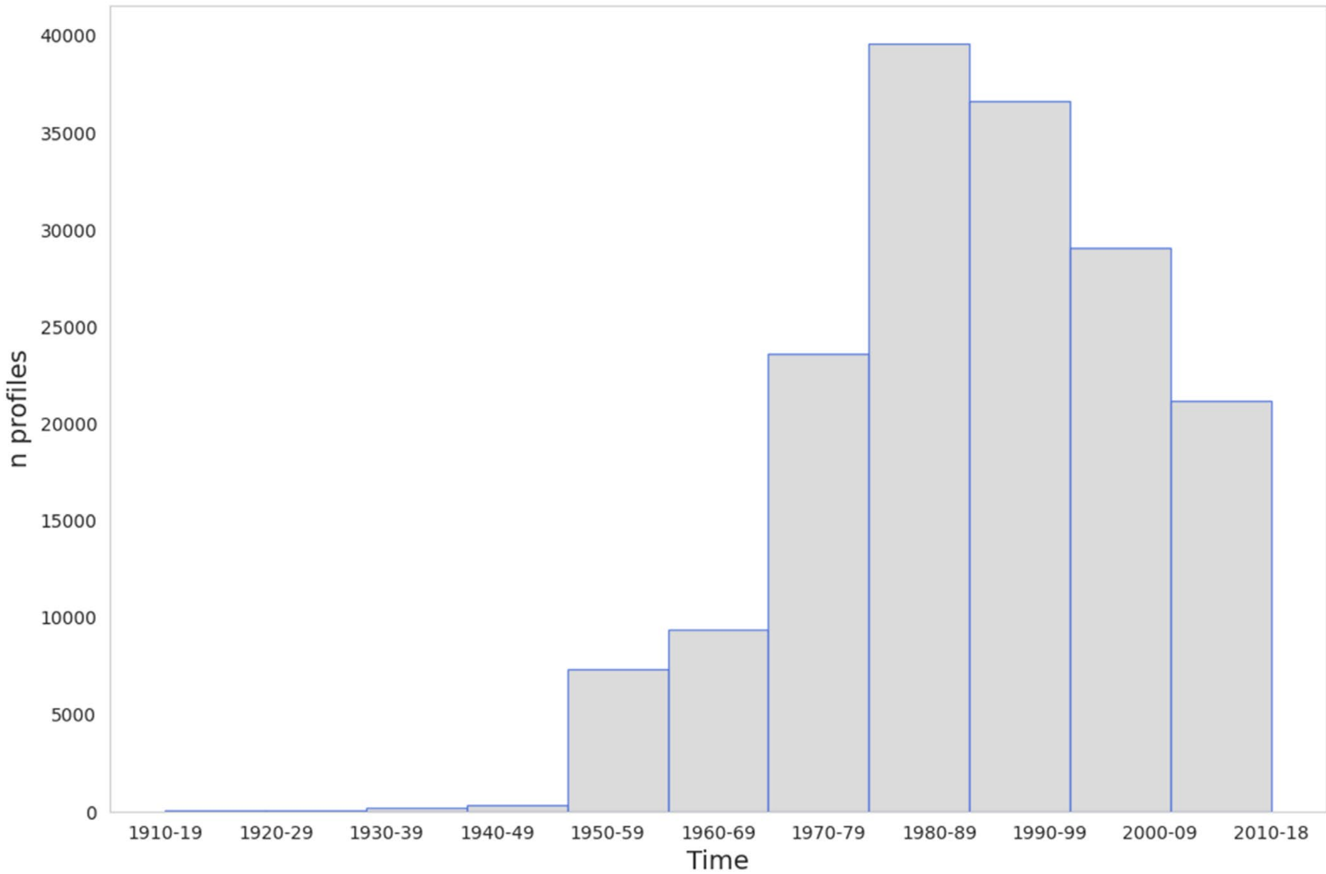

FIGURE 5 | Number of WoSIS soil profiles in the last 11 decades.

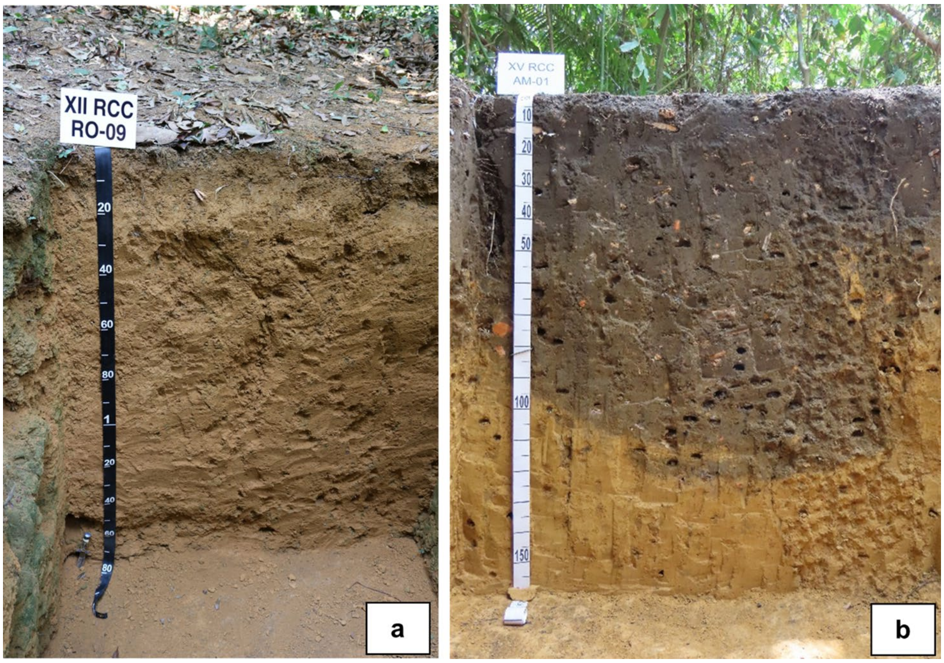

FIGURE 6 | Forest soil profiles in the Brazilian Amazon. (a) Ferralsol (−9.39977 S; −62.01636 W); (b) Anthrosol—Amazonian Dark Earths (−3.25319 S; −60.22853 W). *Source:* G.B. Alves.

types include (i) Vitric Andosols: young volcanic soils having, within 100 cm of the soil surface, vitric properties (i.e., $\geq 5\%$ by grain count of volcanic glasses and related materials, and containing a limited amount of short-range-order minerals and/or organo-metallic complexes), formed from thick deposits of ash, pumice, or scoria, and characterized by low water retention capacity (e.g., 1500 kPa) and limited content of SRO minerals (including allophane, imogolite and ferrihydrite); (ii) Silandic and Aluandic Andosols, featuring andic properties: silandic are dominated by SRO minerals, strongly acid to neutral soil reaction, and show a bit lighter colour than aluandic, which typically exhibit Al-humus complexes, extremely acid to acid reaction and a blackish colour.

A crucial aspect of studying Andosol profiles is the potential for misidentification. For example, a C horizon characterized by light-colored ash can easily be confused with an E horizon dominated by claric materials, and differentiating a Bs horizon from a buried A horizon (i.e., spodic vs. panpaic horizon) requires careful observation (Figure 7a). The ratios of pyrophosphate-extractable carbon to organic carbon, and fulvic acid carbon to pyrophosphate-extractable carbon are suggested for a differentiation (IUSS Working Group WRB 2022). However, the presence of volcanic glasses, allophane, and imogolite, as well as the soil's morphology and mineral composition are also important. The colour of Andosols (Figure 7b,c) is a complex interplay of (i) the original tephra type; (ii) the amount and characteristics of the soil organic matter (SOM) present; and (iii) the composition of the weathering products. While fresh tephra ranges are white to black, weathering of low SOM horizons can lead to yellow or reddish hues due to the formation of Fe (hydr) oxides such as goethite, ferrihydrite, or hematite. Soil texture in Andosols exhibits wide variations, being influenced by tephra type, particle size, and degree of weathering. A significant challenge in its study is the discrepancy between field and laboratory texture determination. This is largely due to SRO minerals and associated SOM, which inhibit the dispersion of mineral particles during mechanical analysis, leading to a relevant underestimation of the clay fraction content of these soils and to the need for specific methods for determining soil texture (Bartoli et al. 2007).

The abundance of SRO minerals in Andosols profoundly impacts their consistency, contributing to excellent physical properties beneficial for cultivation and plant root growth. These soils often exhibit smeariness, reflecting thixotropic properties, and have a low bulk density, attributable to their high content of SRO minerals and SOM. Surface horizons commonly display granular or subangular blocky structure, whose size and grade can vary with the specific soil material, cultivation practices, and climatic conditions, while subsurface horizons often show larger, weaker subangular blocky structures, though young Andosols derived from coarse tephra may be single-grained, lacking distinct structure. This unique structure, coupled with high water retention, large total porosity, and good drainage, creates exceptionally favorable conditions for plant root growth. The high anion exchange capacity of these soils, resulting from variable charges of the minerals present and their isoelectric point in the alkaline range, affects agriculture, particularly phosphate mobility. Volcanic soils (e.g., Andosols) constitute about 3%–5% of profiles, reflecting their restricted spatial distribution and the uncertainty associated with linking soil type to environmental context.

3.3 | Cold Region Soils

Many soil types can be observed by soil profiling in cold climates, which are mostly affected by freezing and thawing (Jones et al. 2010). Cryosols form in permafrost regions, where ground remains at or below 0°C for two or more consecutive years below a seasonally thawed "active layer". The active layer is where most soil genesis occurs. Cryosols. Cryosols are found in Arctic and sub-Arctic regions, as well as in many high-elevation mountain areas. Perennially frozen ground at shallow depths strongly limits water percolation and root growth, and large quantities of SOC and gases are found in these layers. When permafrost is not present, or deeper than 2 m, soils may still be characterized by deep freezing and thawing (and cryoturbation) but are classified differently.

A key feature of Cryosols is the presence of a gelic (or cryic) horizon. It is often characterized by a mixture of soil, ice, and SOM, and is often found in the lower layers of the SP. Above the gelic horizons, the soil material shows evidence of cryoturbation, such as mixing of soil materials, disrupted soil horizons, involutions, organic intrusions, separation of coarse fragments

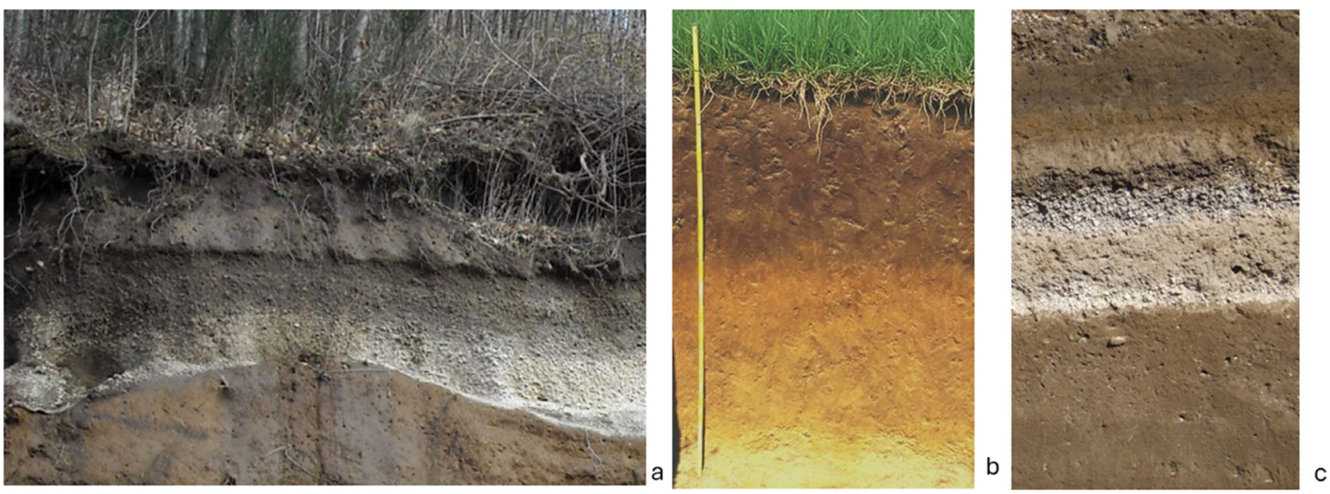

FIGURE 7 | Sequences of pyroclastic deposits and volcanic soils from southern Italy: (a) Vitric Andosol (Loamic) over Silandic Eutric Andosol (Siltic) at Monteforte Irpino (province of Avellino), (b) Vitric Hypereutric Andosol (Loamic) at Parete (province of Caserta), (c) Silandic Eutric Andosol (Loamic) at Sarno (province of Salerno).

from fine earth, cracks. Ground landforms (hummocks, sorted or unsorted circles, stripes, nets and polygons) are common (Figure 8). Cryoturbation thus leads to the development of highly complex soils and geomorphic features, characterized by high variability of edaphic properties across just a few meters (e.g., D'Amico et al. 2015).

The uppermost permafrost in sedimentary deposits is often rich in ice and SOM, and permafrost thaw may lead to the production of CO_2 or CH_4 as microbial action on this material is accelerated when the ground temperature rises above 0°C (Figure 8) (Schuur et al. 2015). Throughout most of the Holocene, permafrost soils have sequestered SOM and now contain 1035 ± 150 Pg SOC (1 Pg = 1 billion tonnes) in their uppermost 3 m (Hugelius et al. 2014). This represents 33% of the soil total C in the Northern Hemisphere, although the permafrost land area is only 15%–25% of the hemisphere's land area. Soils of cold regions (boreal and tundra) comprise roughly 10%–15% of SPs, although their representation remains limited relative to their global extent. It is a highly studied domain, and due to global warming is increasing in importance.

3.4 | Soils in Arid and Desert Environments

Arid lands are commonly defined as areas with an aridity index, calculated as the ratio of mean annual precipitation to mean annual potential evapotranspiration, between 0.05 and 0.20;

a

b

FIGURE 8 | (a) active cryoturbation creating irregular horizons, caused by shallow freezing and thawing, in an Albic Podzol in a periglacial hummock in the Italian Alps (Mortirolo Pass, Sondrio; photo M.E. D'Amico 2017); (b) ancient, large-scale cryoturbation associated with Pleistocene permafrost thaw in an Umbric Albic Ortsteinic Podzol observed in a temperate montane beech forest (Garessio, Cuneo, Italian Alps; Photo M.E. D'Amico 2018; characterized in D'Amico et al. 2019). When describing a SP in cold regions, it is crucial to note the presence of horizons such as an organic-rich zone at depth, which is formed through the subduction of SOM by cryoturbation. The distribution of SOM with depth in the SPe is a key variable that influences projections of C emissions from Cryosols.

hyper-arid regions have values below 0.05, whereas semi-arid regions have higher values (UNEP 1992). These areas, frequently located near and around major deserts (hyper-arid regions), are characterized by low and irregular precipitation and high evaporation rates. Low moisture availability limits vegetation growth, reduces biological activity, and constrains the formation of stable organo-mineral complexes, ultimately resulting in limited SOM inputs, shallow profiles and weak horizon differentiation (e.g., Cui et al. 2020; Fayyadh and Ismail 2021).

On the other hand, soil development in arid environments is influenced by episodic and sometimes intense rainfall events followed by surface runoff feeding ephemeral channel networks and water bodies, and by water infiltration through preferential pathways, leading to the redistribution and concentration of soluble compounds and to heterogeneous patterns of eluviation and illuviation (Lu et al. 2023). These processes are influenced by the landforms and by the bedrock perviousness and composition.

Common soil types are typically Leptosols, Regosols, and Arenosols, when very shallow or poorly developed, or developed from sand deposits, and as Solonchaks (Figure 9b), Solonetz, Calcisols, Gyspisols (Figure 9a), and Durisols when marked by redistribution and accumulation of soluble salts, sodium ions, carbonates, gypsum, and silica. Kastanozems are also common in arid steppe lands. Calcisols and Solonchaks are frequent soil types within Mediterranean arid environments. Calcisols are rich in secondary calcium carbonate and defined by a calcic or petrocalcic horizon, whilst Solonchaks are saline soils that develop in poorly drained depressions (sebkhas, chotts) and coastal zones. Solonetz are peculiar soils, as the Btn horizon produced by clays dispersed by abundant sodium ions in the soil solution is extremely dense and impervious to roots and water percolation.

Because of the vastness, inaccessibility and very low population density of many arid regions, limited soil survey and mapping activities have been conducted in the past, often limited to localized agriculture development areas (e.g., oases and land reclamation zones). Only generalized regional soil maps are available (e.g., Soil map of Africa by European Commission, Joint Research Centre 2013). Moreover, many legacy SPs data lack georeferencing or consistent horizon descriptions, which limit their usability for modern applications such as digital soil mapping or environmental modeling. Many national or regional maps have been produced in past decades and are not available in digital format.

Today, there is a growing demand for survey-based soil data in arid regions driven by climate change and desertification mitigation targets. In addition, there is increasing pressure on marginal lands for agriculture and urban expansion. In the WoSIS dataset, there is a shortage of well-documented, georeferenced, and standardized SP data from arid regions, particularly in developing countries. Linked to this is the lack of specialized training in soil surveying. Looking ahead, future pedologists must develop innovative approaches tailored to the complexities of arid and semiarid soils. This includes coupling traditional soil survey knowledge with new technologies such as proximal sensing, remote sensing, machine learning, and portable spectrometry for high-throughput SP characterization.

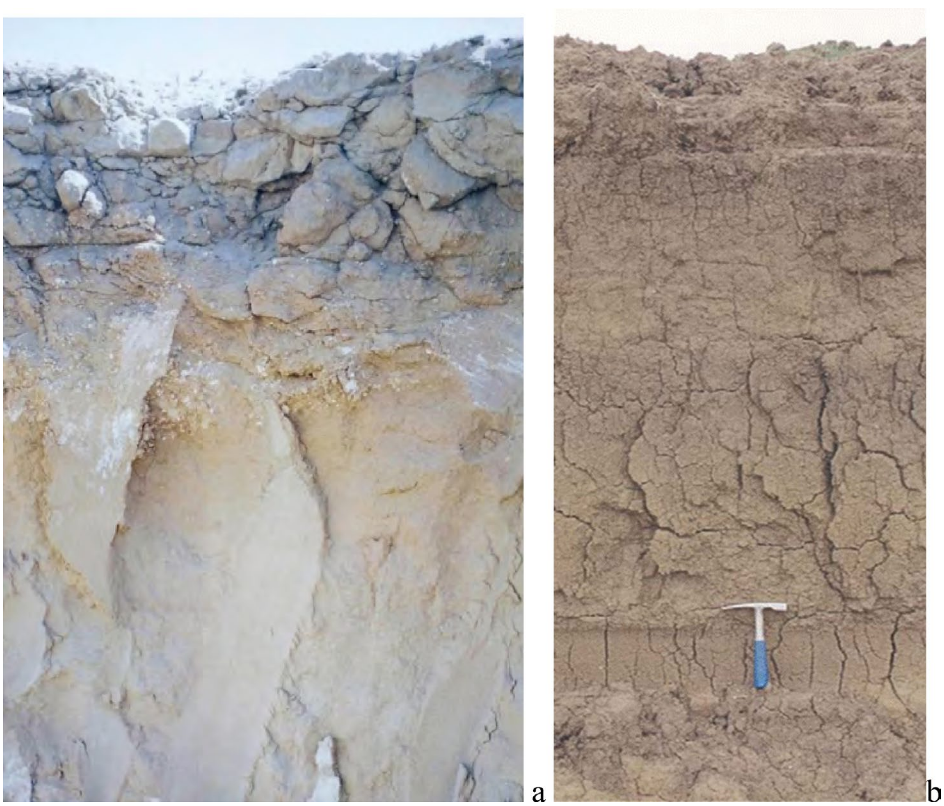

FIGURE 9 | (a) Petric Gypsisol in northwestern Kuwait. The surface has a well-developed angular to subangular blocky structure followed by a sandy layer to 70 cm depth where a Petrogypsic horizon was identified. *Source:* Soil Atlas of Asia. (b) Solonchak in Kairouan, Tunisia (photo I. Dridi).

Arid and desert soils account for ~5%–10% of profiles, indicating underrepresentation likely linked to sampling constraints and therefore low pedodiversity.

3.5 | Soils in Wetlands

Wetlands occur in the transition areas between aquatic and dry habitats, where the soil is continuously or momentarily saturated by groundwater or stagnation (Neue et al. 1997). Covering about 6% of the Earth's surface (Zhang et al. 2016), wetlands occur in a vast range of climates, from the permanently frozen lands at the high latitudes to the tropics, inland and on coasts. Water saturation decelerates SOM decomposition, often resulting in SOM accumulation at the soil surface, and in the formation of organic soils. For this reason, wetland soils are considered a major carbon sink and, although the decomposition dynamics differ in different climates and wetland types (Amendola et al. 2018), they are considered extremely vulnerable ecosystems whose mismanagement can lead to enormous quantities of greenhouse gases being released into the atmosphere (Gilet et al. 2025). While providing countless ecosystem services, wetlands are among the most threatened and degraded systems as their use may involve drainage (e.g., to obtain agriculturally usable land (Joel and Glina 2025), as the natural vegetation may be destroyed to establish rice paddies (D'Amico et al. 2024)), or peat may be harvested (Gilet et al. 2024).

The swift change in soil moisture regime in the transition between aquatic and dry areas, and the consequent vegetation shifts, cause great variability in wetland soils along short distances (Demas and Rabenhorst 2001; Vittori Antisari et al. 2017; Ferronato et al. 2016, 2019), or major changes in soil properties when the moisture regime is artificially changed (Joel and Glina 2025). This variability, together with the strong influence of water excess on physical, chemical and biological soil properties, explains why wetland soils receive particular attention in classification: several WRB Reference Soil Groups are commonly associated with hydromorphic, redoximorphic or periodically saturated conditions, and Gleyic and Stagnic are principal qualifiers for many RSGs (IUSS Working Group WRB 2022).

The study of wetland soil is often limited by the high groundwater level, and investigated depths rarely exceed 1 m. In fact, sampling in this condition can require specific tools such as core samplers (Figure 10d). The most recognizable feature of wetland soils is the presence of redoximorphic features (Figure 10a), which originate from Fe oxidation/reduction under oxic or anoxic conditions, respectively (Erebara et al. 2025; Salvucci et al. 2025). Reductimorphic features have a greyish or bluish colour (hue of N, 10Y, 5Y, 2.5 Y, GY, G, BG, B, or PB, and/or chroma ≤ 2) and are associated with Fe depletions, while oximorphic features are reddish or black, often with a high chroma, and are associated with concentrations of Fe oxides. The position where these color patterns occur, indicating the origin of the water saturation: reductimorphic features around biopores and in the outer parts of the aggregates, and/or oximorphic features inside the aggregates indicate stagnic conditions, which occur when saturation is caused by stagnant water (Figure 10a); the opposite indicates gleyic conditions, where saturation is caused by groundwater (Figure 10b).

Several soil properties are impacted by the quality and residence time of water. In the case of saline water, the soil can become enriched in sodium or soluble salts (Ferronato et al. 2016; Salvucci et al. 2025; Jiménez-Ballesta et al. 2024) and thus be classified as Gleyic/Stagnic Solonetz or Solonchak, respectively. When soil submergence increases and redox potentials become more negative, sulfur is reduced and precipitates with reduced Fe (Hartley and Dickinson 2010), resulting in blackish-blueish colors at depth because of microcristalline pyrite. When water saturation subsides (or the soil is artificially drained), the sulfides are oxidized, forming the Thionic horizon (IUSS Working Group WRB 2022) with bright yellow jarosite mottles (D'Amico et al. 2024), sulfuric acid, extreme soil acidification, potentially impacting water quality, ecosystems and infrastructure (Sullivan et al. 2018; Fitzpatrick et al. 2025).

Buried horizons are common in wetland soils and are often associated with fluctuating water levels and alluvial deposition during periods of inundation. This may cause an irregular decrease in SOC contents with depth, as is typical of periodically flooded soils. In horizon designation, common suffixes include b, d, g, j, l, r, v and z (IUSS Working Group WRB 2022), although less developed A/AC/C horizonations are also common (e.g., Ferronato et al. 2018, 2019).

Wetland soils represent ~3%–5% of profiles, despite their ecological importance, and are likely underestimated due to their mapping and classification challenges.

3.6 | Soils in Cropland and Grasslands

In Europe, agricultural land occupies a large share of the total land area, with cropland representing a major component (FAO 2022). Croplands often display reduced biodiversity and limited ecosystem functioning; recent findings revealed at the EU level an higher variety of pathogens and viruses (Labouyrie et al. 2023). Despite its productivity, cropland represents the largest and most uncertain biospheric source of SOC loss in Europe (Smith 2004). It can also contribute substantially to greenhouse gas (GHG) emissions, nutrient loss, biodiversity decline, and water pollution when managed with excessive fertilizers inputs, intensive tillage, inadequate irrigation and drainage strategies, and a lack of ground cover (Carlson et al. 2017; Craswell 2021; Porwollik et al. 2022).

Grasslands comprise a wide range of landscapes dominated by grasses, forbs, and shrubs, and are primarily used for grazing ruminants and supporting rural livelihoods (Motta-Delgado et al. 2019). In Europe, these systems cover roughly 17% of the land area and play a key role in C storage and cycling (Lisec et al. 2024). However, overgrazing can lead to soil compaction, which reduces water infiltration and increases erosion risk (Avondo et al. 2013; Greenwood and McKenzie 2001). Inappropriate livestock management may also shift grassland from C sinks (when they are in this condition) into GHG sources (Karaca et al. 2021).

In European and Mediterranean croplands, the most common soil types include Luvisols, Cambisols, and Chernozems. In Mediterranean semi-arid zones, fertile Kastanozems, Calcisols,

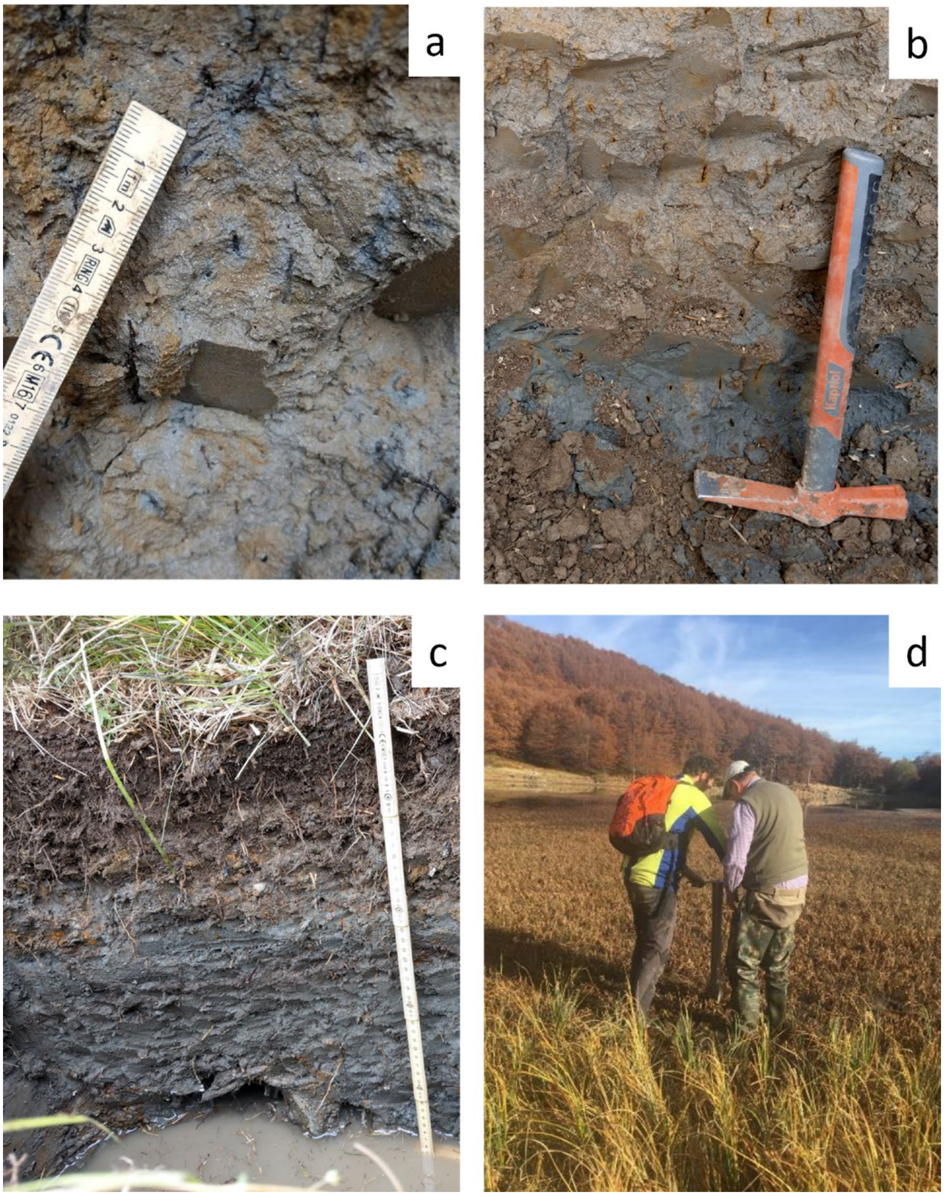

FIGURE 10 | Redoximorphic features: (a) gley colours inside biopores indicating stagnic conditions; (b) reddish colours inside biopores and a gley-coloured matrix at the bottom of the profile indicating gleyic conditions; (c) groundwater saturation inducing gleyification at the bottom of this Mollic Gleysol by a glacial lake in the Northern Apennines, Italy; (d) pedologist using a core sampler to study the soil of a perilacustrine wetland in the Northern Apennines, Italy. Photo: W. Trenti.

Vertisols, and Fluvisols are also widespread (Tóth et al. 2020). Analysis of the LUCAS database revealed considerable variation in soil texture across European croplands. Coarse-textured soils dominate the Boreal and Boreal-to-Temperate biomes, while medium-textured soils are more common in other climate zones. Topsoil SOC contents are significantly higher in the Boreal and Boreal-to-Temperate biomes, with a mean of 27 g/kg in annual croplands, compared with a mean of 15–20 g/kg in other biomes. Climate and soil type were also identified as key drivers of variation in soil pH, cation exchange capacity, total nitrogen, and nutrient content (Tóth, Jones, and Montanarella 2013).

European grasslands are commonly associated with Phaeozems, Kastanozems, Luvisols, Planosols, and Cambisols in regions characterized by extensive grazing, while Calcisols, Gypsisols, and Regosols are more typical in low-intensity production systems (Tóth et al. 2008). Coarse to medium-sized soil textures are most prevalent, although fine-textured soils are also found in the Euro-Mediterranean mountain biomes (Figure 11). Soil properties vary considerably across grasslands, with mean topsoil SOC contents ranging from 17 to 40 g/kg across the nine climate zones within the LUCAS dataset (Tóth, Jones, and Montanarella 2013). The difference in average SOC contents between cropland and grassland aligns with the notion that converting grassland to cropland often degrades soil structure, causes C losses, and reduces the soil's capacity for water infiltration and retention (Strock et al. 2022).

In both cropland and grassland systems, SPs reflect long-term interactions among land use and management, and other non-anthropogenic soil forming factors (Kuzyakov and Zamanian 2019). Soil profiling, grounded in core pedological

FIGURE 11 | Examples of cropland and grassland soils. (a) Luvisol with an argic horizon developed on glacial deposits near Ballymoon, east of Muine Bheag Co. Carlow, Ireland. *Source:* https://esdac.jrc.ec.europa.eu/projects/SoilImaGes/Images/isric_00089.jpg. (b) Eutric Gleysol on alluvium near the Ellebach valley, adjacent to Hambacher Wald, Nordrhein-Westfalen, Germany. Source: https://esdac.jrc.ec.europa.eu/projects/SoilImaGes/Images/isric_00063.jpg. (c) Pellic Vertisol in pasture in Uganda; limited mechanisation can constrain the agricultural use of these soils because of shrink–swell behaviour and high subsoil bulk density. Photo: M.E. D'Amico et al. 2015.

principles, offers critical insight into the vertical distribution of soil properties shaped by these factors, helping to address a common limitation of soil sampling campaigns that tend to over emphasize surface layers (Demattê et al. 2025). This approach is particularly valuable for assessing the impacts of management practices, as disturbances such as tillage, fertilizer placement, and livestock grazing can lead to pronounced stratification of layers with different bulk densities within the SP (Kay and VandenBygaart 2002; Zhang et al. 2022; Souza et al. 2023). Moreover, deep-rooted crops often extend beyond surface depths and alter subsurface soil characteristics, influencing key soil functions that must be considered when evaluating ecosystem outcomes (Pierret et al. 2016).

Soil profiling also enables direct observation of soil horizon depths and the presence of restrictive layers such as hardpans, which often develop from intensive tillage in croplands or soil compaction caused by overgrazing in grasslands (Daniel et al. 2002; Tlili et al. 2025; Zeng et al. 2017). It also reveals signs of clay illuviation through changes in texture or the formation of argic horizons, as well as features like mottling, gleying, or coloration that signal fluctuating water tables and redox processes, thereby informing site-specific water management (Heck et al. 2022). Accumulations of salts, carbonates, or Fe oxides that affect plant growth, along with variations in soil structure, porosity, bioturbation evidence, and root penetration, can also be observed and used to guide land management decisions (de Soto et al. 2017). Excavated SPs allow more detailed assessment of soil texture, SOC, pH, nutrient status, aggregate stability, biological activity, and other soil monitoring indicators across depth intervals.

Traditional in situ or excavated soil profiling is limited in both spatial and temporal resolution. However, innovative sensing technologies still face limitations, especially in their ability to represent deeper soil layers and to detect fine-scale processes such as those governed by microbial activity (Feldman et al. 2023; Chen et al. 2024). Key management variables, such as fertilizers application rates and livestock movement patterns, can be estimated using sensor-based monitoring systems, but these estimates often need local calibration and can introduce uncertainty when used as inputs in soil models (Sharma et al. 2025).

Cropland and grassland soils represent about 25%–30% of profiles, highlighting the historical focus on agricultural soils, while acknowledging potential overlap with other land-use categories; for instance, the urban soils to land take issues.

3.7 | Soils in Urban Environments

In urban environments, SPs remain a revealing "window" into soil function, just as in natural landscapes, but what they uncover is a layered archive of human intervention. Urban soils are frequently disturbed by excavation for foundations, utilities, and backfill, leading to the truncation, mixing, or burial of natural horizons beneath technogenic layers (Figure 12). The WRB acknowledges this complexity by defining "soil" as any material within 2 m of the surface, including paved areas, industrial grounds, and even rooftop substrates (IUSS Working Group WRB 2022). Among its 32 Reference Soil Groups, the WRB designates Technosols for soils containing a continuous technic hard layer or substantial amounts of artefacts, such as rubble, slag, or plastics, within the upper meter. These are further refined using qualifiers like *Urbic*, *Garbic*, or *Thyric*, which specify the origin or engineering of the anthropogenic material. However, considering artefacts in soil taxonomy is only the first step in addressing the full complexity of urban pedogenesis.

Mapping urban soils presents major challenges. Until the early 2000s, they were typically represented as blanked-out areas on soil maps, labelled simply as 'urban' with no further detail. In effect, traditional soil maps depicted a continuous soilscape interrupted by voids, blank spaces corresponding to built-up environments. However, attempts to characterize these indistinct areas began much earlier. The Russian soil scientist S.S. Sobolev was arguably the first to frame urban soils within the context of Dokuchaev's legacy. In his foundational 1949 publication, Sobolev included a section on Dokuchaev's investigations of Moscow soils. This early

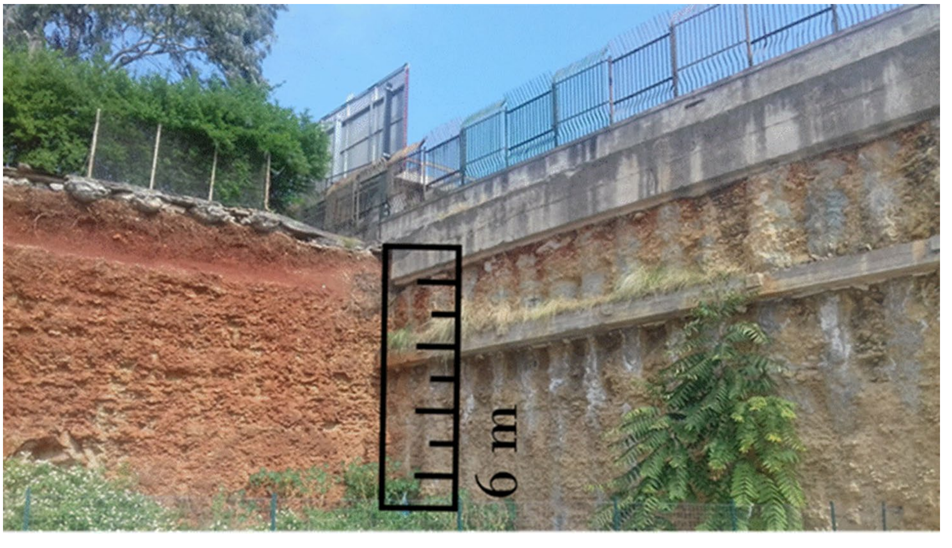

FIGURE 12 | Traditional approaches used in natural or managed ecosystems often fall short when applied to urban environments. The classical concept of the *pedon*—as a representative slice of a continuous soilscape—is frequently inadequate for describing and mapping urban soils. Instead, these soils form a patchwork of distinct terrigenous layers and geomembranes, each reflecting different anthropogenic histories. In this example (38°06′8.51″N, 13°20′53.74″E), the profile on the left tells a different story than the one on the right. Although both are *Technosols*, they display entirely different sequences of properties and materials, including *Urbic, Relocatic* (*Transportic*), *Ekranic, Thyric, Transportic*, and *Technic hard*. Urban soils account for < 1%–2% of profiles, revealing a substantial gap in global soil datasets and potential misclassification.

contribution laid the groundwork for viewing urban soils as a distinct category, highlighting their anthropogenic layers, debris content, and structural alterations resulting from human activity. It was Zemlyanitskiy (1963), however, who first systematically described "soils in the cities", showing that intensive human disturbance often obliterated natural horizons and warranted the recognition of a new soil class. Similar insights followed shortly thereafter in the United States (Pettry and Coleman 1973) and Europe (Blume 1975). Building on these developments, Craul (1985) later offered a comprehensive analysis of the unique challenges posed by urban soils, outlining field identification methods and proposing strategies for their management and remediation. Short et al. (1986) mapped 20 profiles along Washington D.C.'s National Mall, revealing up to ~6 mof mixed fill, abrupt lithologic breaks in 95% of pits, and surface lead concentrations near 184 $mg\,kg^{-1}$. In Europe, Blume (1989) proposed a dedicated classification for urban soils, distinguishing sealed surfaces, modified natural soils, and soils developed on anthropogenic deposits, while in Asia, Jim (1998) documented roadside soils in Hong Kong with bulk densities > 1.6 $g\,cm^{-3}$ and topsoil OM content below 10 $g\,kg^{-1}$, underscoring severe compaction and nutrient depletion. More recently, several urban soils of Moscow, among the earliest to receive systematic attention, were comprehensively examined by Prokofeva and Gerasimova (2018), who provided detailed taxonomic and diagnostic descriptions in accordance with WRB standards. A parallel effort was undertaken by Huot et al. (2017) in New York City, applying both WRB and the U.S. Soil Taxonomy frameworks to characterize urban profiles.

Traditional survey techniques that extrapolate between auger points often prove inadequate in urban settings, where demolition debris, heterogeneous fill layers, and impervious surfaces disrupt lateral continuity. Standard grid-based sampling may also overlook entire functional zones within the urban mosaic. A more flexible, multi-dimensional descriptive approach, integrating physical and chemical properties with land use, ownership, aesthetic value, and historical context, would more effectively address the complex questions posed by planners, ecologists, and citizens (Ajmone-Marsan et al. 2016).

Interpreting urban SPs requires expertise that extends beyond conventional horizon identification. Pedologists must recognize contact zones where imported fill interfaces with native substrata, distinguish compacted or sheared pan fragments beneath pavements, and interpret redox mottles left by formerly saturated conditions. While classical features such as argic or mollic horizons may still be present, they often coexist with technogenic indicators such as Organotechnic materials (characterized by high artefact content), Technic hard materials (relatively continuous consolidated layers resulting from industrial processes), and Urbic properties (also marked by high artefact content).

These complex profiles are not a limitation but a strength: they document the evolving histories of urban land, from wetland to market garden, from industrial site to community park (Certini and Scalenghe 2021). Such narratives are critical for guiding redevelopment, restoration, and conservation efforts. Yet, as soil science curricula continue to shift away from field-based training (Brevik et al. 2022), the ability to "read" these profiles is diminishing. Without this interpretive literacy, urban soil management risks defaulting to generic engineering templates or one-size-fits-all remediation strategies.

Revitalizing field-based profiling, now supported by the WRB's expanded lexicon and a multidimensional interpretive framework, offers a path toward integrating geotechnical, ecological, and cultural perspectives. Such an integrated approach is essential for resilient urban planning, especially as cities expand and transform soilscapes at an unprecedented pace. A recent example of how such integrative thinking can be operationalized is Destisol, the decision-support model developed by Séré et al. (2024). Destisol translates 20 readily measurable soil indicators into scores for 15 soil functions, checks their compatibility with 13 land-cover types, and evaluates 18 ecosystem-service bundles, enabling planners to align existing soil conditions with proposed urban uses.

3.8 | Soils in Mediterranean Environments

Mediterranean soils have been documented in southern Spain (Andalusia) already in the 12th century by Ibn al-'Awwām in his seminal treatise *Kitāb al-filāḥa* ('Book of Agriculture' Clément-Mullet 1864; Olson and Helen 1943). Up until the mid-20th century, Mediterranean soils were mostly referred to as 'terra rossa' or other 'red Mediterranean soils' (Cereceda 1922; Neustruev 1927; Joffe 1949), reflecting the dominance of Rhodic Luvisols that typically develop on the karst ecosystems in northern and eastern Mediterranean (Figure 13a). However, the broader concept of 'Mediterranean soil' as any soil in any Mediterranean climatic zone began with the major advance in Mediterranean pedology around the early 1950s (e.g., Reifenberg 1952) and gradually expanded through the late 20th century (Bruin 1970).

Mediterranean soils are now broadly recognized as occurring in Köppen's Cs climatic zones (temperate warm and hot dry summers with wet winters; Torrent 1995), characterized by a predominance of evergreen sclerophyllous shrubs and trees (Castri and Mooney 1973), and covering ~2.4% of the global land area (Flores et al. 2024). These soils are highly diverse, reflecting varied parent materials, topography and biota.

Soils in Mediterranean areas are mostly Leptosols, Vertisols, Solonchaks, Kastanozems, Phaeozems (Figure 13b), Calcisols, Luvisols (Figure 13c,d), Cambisols (Figure 3f), Fluvisols, Arenosols, and Regosols (Torrent et al. 2023). The occurrence of Andosols (especially in Italy and Greece) is another testimony to the great diversity of Mediterranean soils. Gypsisols are common in the driest Mediterranean areas (e.g., Spain, Tunisia). Other than soils with little or no profile differentiation (IUSS Working Group WRB 2022), the characteristics of most Mediterranean soils are A-C or A-B-C profile, mass additions and losses, low organic matter inputs, leaching and redistribution of calcite and/or silica, clay translocation, rubefaction, and development of vertic features (Torrent et al. 2023).

Soils in the Mediterranean support the extensive cultivation of olives, grapes, citrus fruits, figs, almonds, and a wide variety

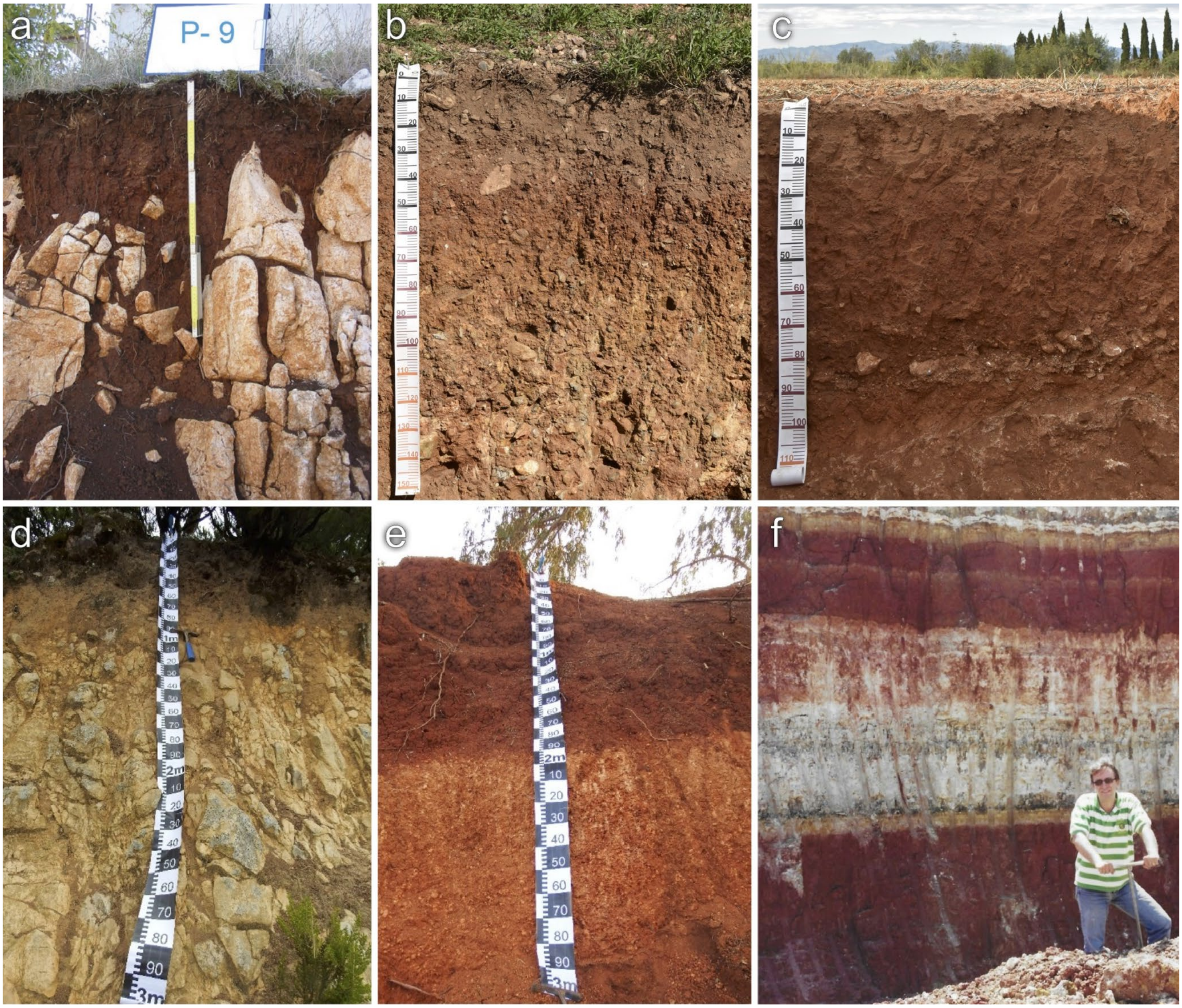

FIGURE 13 | Example profiles of Mediterranean soils: (a) Shallow terra rossa overlying bioclastic floatstone in a karst terrain in Western Herzegovina, Bosnia and Herzegovina (after Durn et al. 2014). (b) Phaeozem developed from old deltaic deposits in Catalonia, Spain (Boixadera and Poch 2023; photo courtesy: Marcin Świtoniak). (c) Luvisol developed from alluvial-colluvial foothill deposits, modified to agricultural bench terraces in Catalonia, Spain (Boixadera and Poch 2023; photo courtesy: Marcin Świtoniak). (d) Luvisol on sandstone in hilly terrain in the Balta region, Tunisia (photo courtesy: Ahlem Tlili). (e) Cambisol overlying limestone rock in a gently sloping plain in the Oued Zarga region, Tunisia (photo courtesy: Ahlem Tlili). (f) Terra rossa in the Apulia region, south-eastern Italy. A sequence of buried red soils serves as a testament to a long pedogenesis process. Alternating layers of limestone and red soils as a result of tectonic movements and soil formation over different periods (photo courtesy: Alessandra Pezzuto).

of cereals and legumes. Irrigation farming is also widespread (Figure 13e,f). Soil is vulnerable to erosion and salinization, particularly in areas with intensive agriculture and human pressures (Panagos et al. 2015, 2016, 2020, 2021), while soil sealing is extensive in coastal areas, reflecting demands from tourism. In addition to the strong influence of millennial anthropogenic action (Anthrosols and Technosols; Monger et al. 2015), these soils are also characterized by a significant supply of aeolian dust (Yaalon 1997).

Common characteristics of Mediterranean soils are (i) dominant colours of 5YR to 10YR that express a rubefaction (Fedoroff and Courty 2013); (ii) aeolian dust that contributes to substantial accumulation of silt calcite and quartz (Yaalon 1997); (iii) Ap/Apu and buried Ap/Apu horizons that express modern and past anthropogenic influence; (iv) mollic A horizons and epipedons, although many Mediterranean soils have low organic material content; (v) Bw and Bt horizons, commonly with subangular or angular blocky structure and distinct clay coatings following clay translocation, or Bk horizons (Bruin 1970; Torrent 1995); and (vi) soil degradation due to salinization and sodification (Zdruli et al. 2011; Itkin et al. 2022; Dridi and Gueddari 2019; Boixadera and Poch 2023; Tlili et al. 2025), as well as whole-profile charred matter distribution due to anthroturbation (Itkin et al. 2022).

Since the publication of the FAO Soil Maps of the World (FAO–UNESCO, 1971–1981), only a few northern African countries, such as Tunisia, have updated their soil information through their National Soil Institutions (Jones et al., 2013; Tóth, Jones, and Montanarella 2013). A full inventory of soils is therefore needed to produce national WRB soil maps that are comparable with those of highly surveyed countries in terms of scale, resolution and information content. As with previous soil atlases (Panagos et al. 2024), the visualization of Mediterranean soils in a specific soil atlas is expected to raise soil awareness, support soil policies and decision making, and express their distinctness and facilitate future research on these soils. Thus, there is an urgent need to embark on new soil surveys by providing an accurate description of the SP, and updating obsolete soil data that hampers sustainable soil management, while contributing to improved soil health.

There are many challenges for future 'Mediterranean pedologists'. Reviving pedology by establishing it as an educational tool in schools and academia is key, as is strengthening the bond of pedology with sustainable management practices (Tlili et al. 2025) and providing practical solutions for agriculture, environmental aspects, ecology, and engineering. Pedologists need to remain relevant in times of rapid technological change. In spite of the many potential advantages, future integration of artificial intelligence (AI) in pedology should consider the associated risks (Wadoux 2025).

Mediterranean soils represent around 5%–8% of profiles, although their delineation is subject to overlap with both forested and agricultural systems.

4 | Conclusions

In this work, we combined the largest global legacy soil-profile dataset, WoSIS, with Copernicus Global Land Cover 2015 and global biome data to derive zonal statistics on SP availability by land use and environmental setting. The analysis shows that soil-profile availability varies strongly across land-cover classes, biomes, and their intersections. Croplands and grasslands are comparatively well represented, whereas wetlands, tundra, mangroves, and several arid or forested systems remain underrepresented.

With this contribution, pedological information available on a global scale with WoSIS database was highlighted and a methodology for zonal statistics on the abundance of classified SPs over the major climate and land-use types was proposed. This contribution highlights the value of globally available pedological information in WoSIS and proposes a reproducible workflow for evaluating the abundance of classified SPs across major climate and land-use types. The results underscore the importance of expanding harmonised soil-profile datasets to underrepresented regions and environments. Such expansion would support soil conservation, stakeholder engagement, data sharing and interoperability. However, the availability of harmonised profile descriptions linked to visual documentation and chemical and physical analyses remains limited, constraining both soil-science interpretation and the development of effective soil-management strategies.

Further research should prioritize the recovery, standardization, and publication of legacy SP data, including site metadata, horizon descriptions, photographs, and laboratory analyses. Addressing these gaps would strengthen pedological interpretation, improve digital soil mapping, and support targeted soil-management and conservation strategies. The continued integration of field pedology with digital tools is essential for the sustainable use and protection of soil resources. We encourage other researchers to build on our findings and continue to advance our understanding of soil science, and we look forward to seeing the impact of this research on the development of more sustainable soil management practices.

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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 in WOSIS 2023 snapshot at https://data.isric.org/geonetwork/srv/api/records/e50f84e1-aa5b-49cb-bd6b-cd581232a2ec. These data were derived from the following resources available in the public domain: WOSIS 2023 snapshot, https://data.isric.org/geonetwork/srv/api/records/e50f84e1-aa5b-49cb-bd6b-cd581232a2ec.

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