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RECEIVED 07 February 2026

REVISED 11 April 2026

ACCEPTED 16 April 2026

PUBLISHED 14 May 2026

CITATION

Madeira M, Guerreiro S, Arsénio P and Florentino V (2026) Converting the genetic-based national soil classification to the World Reference Base: a challenge for updating soil mapping in Portugal. *Span. J. Soil Sci.* 16:16368. doi: 10.3389/sjss.2026.16368

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Converting the genetic-based national soil classification to the World Reference Base: a challenge for updating soil mapping in Portugal

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The diversity of soil classification systems makes correlation between them challenging. The World Reference Base for Soil Resources (WRB) stands as a reference framework for international correlation of soils. In Portugal, soil mapping remains heterogeneous, as 55.3% of the mainland was mapped at a scale of 1:25,000 using the Classification of the Soils of Portugal (CSP), while the remaining area was mapped at a scale of 1:100,000 using the WRB system. Converting these legacy maps into a unified national 1:100,000 soil map in the WRB system requires the reinterpretation and remapping of the outdated 1:25,000 soil map. The present study discusses the categorical levels of the genetic-based CSP dating from 1974, their correspondence with WRB, and the relevance of updating this classification. The majority of CSP categorical levels show limited correspondence with WRB Reference Soil Groups, since CSP definitions lack the quantitative diagnostic criteria and thresholds required by the WRB. Exceptions include the “*Barros*” order (83% Vertisols), and the suborders *Colluvial soils* (100% Regosols) and *Humic Litholic soils* (78% Umbrisols). Overall correspondence improves when considering soil-forming factors such as lithology, relief, and climate, allowing for a better estimation of dominant and codominant RSGs within mapping units, as well as improved assignment of principal and supplementary WRB qualifiers. The proposed methodology supports the updating and harmonization of soil mapping in Portugal, but, to be successful, it requires the collection of new soil data to refine mapping units. New soil data would also be of great usefulness for revising and modernizing the CSP and improving the use of the WRB system.

KEYWORDS

diagnostic approach, geographic information systems, legacy soil data, Portuguese soil classification, soil classification conversion

Introduction

Accurate and relevant knowledge of the soil cover in landscapes plays a crucial role in supporting soil governance, policymaking, and management of soil resources (Bruyn and Prager, 2024; Demattê et al., 2025; Lagacherie, 2025). Soil maps based on harmonized terminologies are indispensable to capture spatial variations in soil cover (Demattê et al.,

2025) and to ensure effective communication and the integration of national standards into international frameworks (Sousa et al., 2004). In the past few decades, the understanding of the global nature of environmental issues has created a need for international, updated, and harmonized soil maps and databases. These are indispensable for effective land use planning and the sustainable management of natural resources (Lagacherie, 2025). As soil surveys in the majority of European countries were conducted independently, the current challenge lies in converting the national legends into a global classification system (Sládková, 2010; Dondeyne et al., 2014; Hughes et al., 2017; Dobos et al., 2019; IUSS Working Group WRB, 2022). The World Reference Base for Soil Resources (WRB) represents an ongoing attempt at consensus and does not seek to eliminate or replace other classifications; rather, it serves as a frame of reference for the international correlation of soils (Mantel et al., 2023). Because national soil classifications have different principles and definitions, a straightforward one-to-one conversion of national soil units to a universal system is difficult or not possible (Michéli et al., 2019). However, correlation can still be achieved by using legacy soil data, combined with expert knowledge (Hendriks et al., 2019; Michéli et al., 2019; Bruyn and Prager, 2024).

The updating and harmonization of soil mapping in Portugal is crucial to supporting harmonized land suitability evaluations and land use planning and ensuring alignment with EU-wide soil data harmonization efforts. This process is currently hindered by the heterogeneity of soil classification systems, and the outdated Classification of the Soils of Portugal (CSP; IDRHa, SPCS, 2004). The CSP dates back to 1958, when soil mapping was started to give an overview of the nation's mainland soil resources (Cardoso, 1965); its last update occurred in 1974 (Cardoso, 1974) and was adopted for the environmental settings in regions south of the Tagus river and the Coastal Center region (Figure 1). The CSP followed the development of systematic soil mapping in Portugal, at a scale of 1:25,000, encompassing approximately 55.3% of the mainland territory. In the 1980s, when mapping at a scale of 1:25,000 covered approximately half of the territory, regional and national authorities determined to develop soil maps at a scale of 1:100,000, for the north (Agroconsultores, 1991; Agroconsultores, 1995) and part of the central region (Agroconsultores, 2004). These maps, comprising approximately 44.7% of mainland Portugal (Figure 1) and currently harmonized in a digital format, used the Revised Legend of the Soil Map of the World (FAO/UNESCO, 1987; 1988) and the World Reference Base for Soil Resources (WRB) (FAO, 1998). Currently, these maps are being harmonized by using the WRB (IUSS Working Group WRB, 2022), which is the current international soil classification system adopted by the European Union for the development of harmonized soil information products, and related publications (ESDAC, 2004; Jones et al., 2005; Terres et al., 2016; Mantel et al., 2023).

Both 1:25,000 and 1:100,000 soil maps have recently been made available online as open-access vector data (DGADR-SNIS, 2022). This highly heterogeneous soil information regarding classification systems, scale, and mapping methodologies is a major source for agricultural and environmental policymaking and nature and soil conservation. In order to update and harmonize soil mapping in the mainland, the outdated 1:25,000 soil map completed during the 1980s should be remapped in the short term to a 1:100,000 soil map

using the WRB system. Nonetheless, defining a methodology to convert the CSP legend to the WRB, as it has been done in other countries or regions to update their legacy soil survey data (Sládková, 2010; Dondeyne et al., 2014; Dobos et al., 2019), remains a major challenge. The great difficulty is primarily related to the 1:25,000 soil map, in which the spatial patterns of the soil types in the genetic-based Classification of the Soils of Portugal rely on scarce and non-georeferenced reference soil profiles data (SROA-Serviço de Reconhecimento e Ordenamento Agrário, 1973; DGADR-SNIS, 2022).

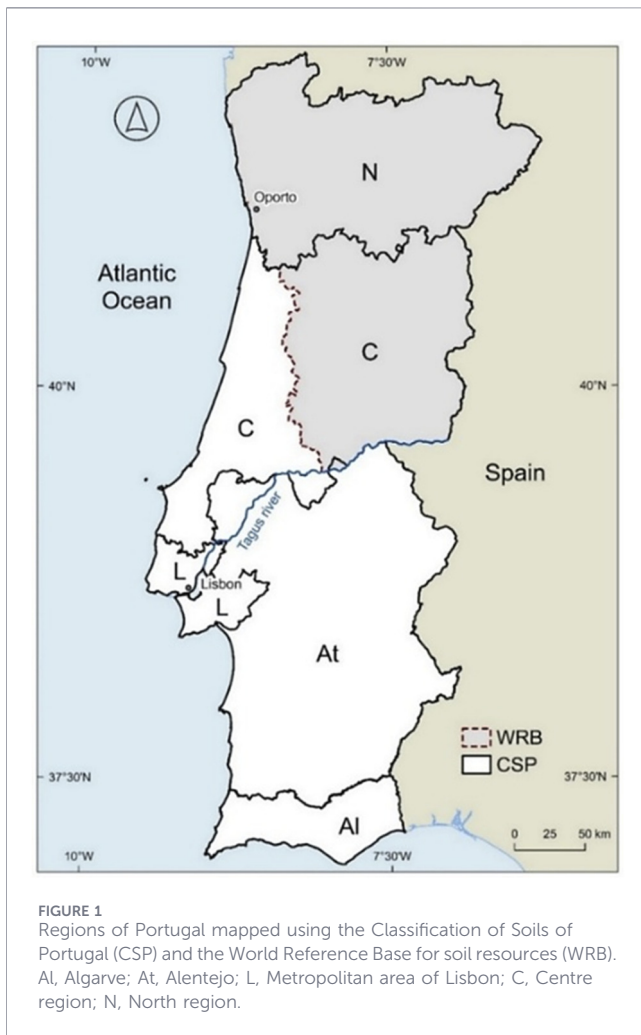
The concept and soil units of the CSP were developed before sufficient data and modern data processing tools became available. Accordingly, it is essential to evaluate their correspondence with the WRB and evaluate the feasibility of updating the CSP. An approximation of a Soil Map of Portugal (1:1,000,000) was created (Cardoso et al., 1973) as a contribution to the Soil Map of Europe, at a 1:5,000,000 scale, using the legend, rules, and instructions adopted for the European Soil Map (FAO/UNESCO, 1974), a basis for the distribution of soil types within the European Union (Tóth et al., 2008), but no correlation between this legend and the CSP was provided. A proviso attempting simple reviews and expert knowledge was made by Sousa et al. (2004) to establish correspondence between soil suborders of the CSP and the Reference Soil Groups (FAO, 1998).

It is essential, then, to identify and discuss the correspondence between the categorical levels of the CSP (Cardoso, 1974) and WRB soil units, to support the updating and harmonization of soil information and data exchange at the national and international levels. Because no funding is available for new sampling or fieldwork, soil map updating should be developed by using legacy soil information (Hendriks et al., 2019; Lagacherie, 2025). Making the most out of existing data, the proposed re-mapping goes beyond a mere soil correspondence exercise, as it requires the development of an entirely new legend (Bui and Moran, 2003). This study addresses four main questions: (i) what is the correspondence between the CSP categorical levels and WRB Reference Soil Groups (RSGs); (ii) how to convert the legend of the 1:25,000 soil map, based on the genetic-based CSP, to WRB RSGs; (iii) how to identify the principal and supplementary qualifiers associated with different RSGs; and (iv) what is the relevance of maintaining the use of the CSP both in the legacy soil maps and in future mapping efforts? Given that in a Mediterranean climate (semiarid and dry subhumid) weathering intensity and soil formation rate are relatively low (Verheye and de la Rosa, 2005), we hypothesize that exploring the relationships between legacy soil data and environmental variables (e.g., lithology and relief), supported by digital mapping techniques, may aid in the conversion process and improve the spatial prediction of soil types across the landscape.

Materials and methods

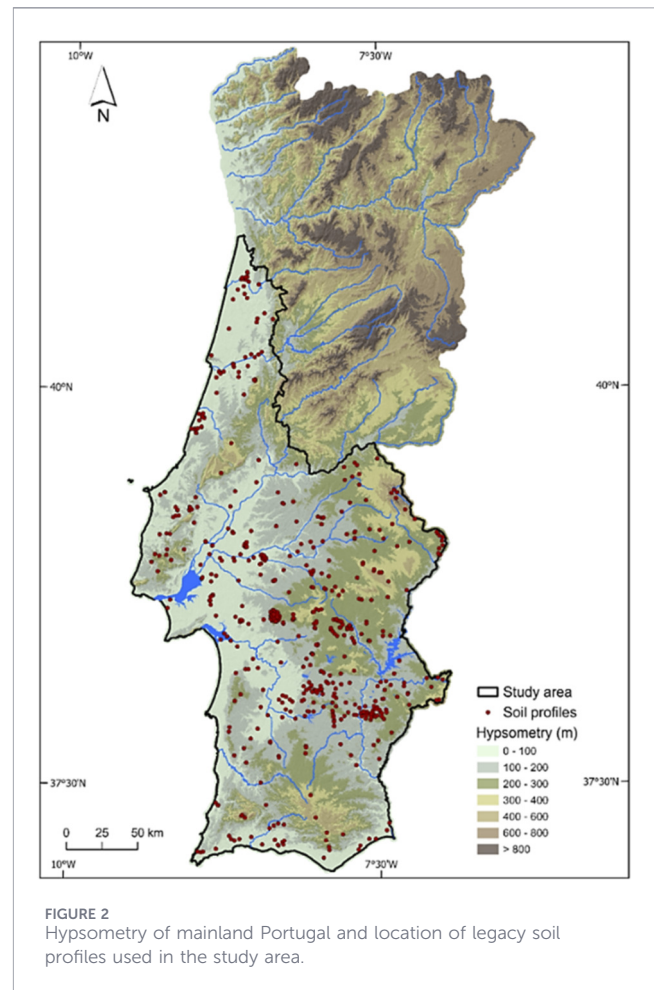
Study area

The study area covers approximately 47,555 km² (36°57'41" and 40°59'42" N; 6°56'16" and 9°29'56" W), and includes the Algarve, Alentejo, and Lisbon metropolitan area of the Lisbon region, along



with part of the Central region (Figure 1). Its altitude ranges between 0 and 1,000 m above sea level, and the climate is primarily of the Csa subtype, characterized by hot, dry summers and mild, wet winters, while in areas closer to the ocean, it is of the Csb subtype. Although climate exhibits internal variations (with an annual mean rainfall and temperature range of 400–1,000 mm and 12.5 °C–17.5 °C, respectively), it can be considered relatively homogeneous (characterized by semi-arid and dry subhumid conditions) when compared to regions not covered by the present study (Figure 2), in which ranges of mean annual rainfall (600–3,000 mm) and temperature (16 - ≤8 °C) are much wider (Agroconsultores, 1991; Agroconsultores, 1995; Agroconsultores, 2004; DGADR-SNIS, 2022).

The study area has distinct morpho-structural units and geology that result in diverse conditions influencing soil types. Geologically, the area is partially within the Hesperian (or Iberian) Massif, the core of the Iberian Peninsula (Central Iberian, Ossa-Morena, and South Portuguese Zones), comprising Precambrian and Paleozoic metamorphic and igneous formations (Julivert et al., 1974). It also occupies the Western and Algarve Meso-Cenozoic basins, and the Tagus-Sado Cenozoic basin, where varied sedimentary formations are present (Ramos and Ramos-Pereira, 2020). The primary morphological unit of the study area corresponds to the



Southern Portuguese Peneplain (Southern Meseta), a vast polygenic planation surface with varying altitudes (approximately between 200 and 400 m asl) that gradually descends from north to south and is interrupted by elevations of tectonic origin (Ferreira et al., 2005; Ramos and Ramos-Pereira, 2020). The polygenic planation is differently preserved depending on the type of rock, the faults that cross it, and the Quaternary incision of the river networks. In areas dominated by schists, the surface is heavily indented and lowered. A wide range of soil types has developed over varied igneous, metamorphic, and sedimentary rocks, and their characteristics are primarily related to the nature of the parent materials and the relief; to a lesser extent, they are related to the climate (Cardoso, 1965; Dachary, 1972; 1975; Cardoso, 1974; Monteiro, 2004; Monteiro et al., 2015; Guerreiro et al., 2025).

Legacy soil data

Legacy soil data is past information on soils available from various sources (Medeiros et al., 2024). In addition to the Classification of the Soils of Portugal (CSP), the legacy soil data and information used in the present study were twofold: (i) The 1:25,000 legacy soil map (DGADR-SNIS, 2022), based on the CSP, and associated reference soil profiles (RSP) used for the establishment of the respective categorical levels (SROA—Serviço de Reconhecimento e Ordenamento Agrário, 1973); and (ii) the legacy soil profile

collection (LPC) including 624 measured soil profiles, recorded from the 1960s to the present, and gathered from several studies and reports. Terms or names specific to the CSP and the 1:25,000 soil map are written in italics throughout the text.

The Portuguese soil classification (CSP)

The CSP is a hierarchical system with five categorical levels: orders, suborders, groups, subgroups, and families (Cardoso, 1974). A simplified classification key for the 10 orders, 19 suborders, 29 groups, and 60 subgroups is shown in [Supplementary Material 1](#). Orders are groups of soils based on horizons or characteristics whose presence or absence indicates profile differentiation or the nature of the dominant processes of formation. Suborders are groups of soils developed under similar soil-forming factors and processes, resulting in similar morphogenetic properties (Cardoso, 1974; Sousa et al., 2004). Groups are based on soil characteristics that indicate less important genetic processes or, in less evolved soils, climate conditions that are significant for pedogenetic evolution. Subgroups are subdivisions of groups, the majority of them defined by their central concept (typical) and class boundaries. A short explanation regarding CSP orders and suborders is provided below.

Incipient soils—Soils either without natural genetic horizons or with only the beginning of horizons, with C or (A)C profiles. They include *Lithosols* (effective depth ≤ 10 cm), *Regosols* (*Psammo-Regosols*, i.e., sandy soils developed on sands), *Alluvial soils* developing on recent alluvium (*Modern Alluvial soils*) and on old alluvium (*Old Alluvial soils*), and *Colluvial soils* (soils derived from colluvium).

Litholic soils—Soils with a low degree of evolution, with AC or ABC (cambic B; *sensu* Soil Survey Staff, 1960) horizons developed on non-calcareous materials. They comprise *Humic Litholic soils* and *Non-Humic Litholic soils*, according to the presence or absence of an Umbric epipedon (*sensu* Soil Survey Staff, 1960).

Calcareous soils—Soils with a low degree of evolution, with a profile type of AC and, to a lesser extent, ABC (cambic B; *sensu*, Soil Survey Staff, 1960) developed on calcareous rocks (consolidated and non-consolidated), with a variable content of carbonates throughout the profile. They are classified as *Brown Calcareous soils* and *Red Calcareous soils*.

Mollic soils—Soils with a profile type of AC or ABC (cambic B; *sensu* Soil Survey Staff, 1960), or ABaC (argillic B horizon, *sensu* Soil Survey Staff, 1960), showing a mollic epipedon. They only include one suborder (*Castanozems*) and may correspond to Mollisols (Soil Survey Staff, 1960).

Barros (Portuguese word applied to shrinking and swelling clay soils) – Soils that have all the characteristics of Vertisols, with a profile type of ABC (cambic B or argillic B, both *sensu* Soil Survey Staff, 1960), a high clay content ($\geq 30\%$), and shrinking and swelling properties due to alternating dry and wet conditions.

Argilluviated soils not strongly unsaturated—Soils that show an ABaC horizon sequence. The profile has a textural or argillic B horizon (*sensu* Soil Survey Staff, 1960) with a strong blocky structure and clay coatings on the ped surfaces, and base saturation of the B horizon is over 35% and increases or remains constant from the B

horizon to the C horizon. This order includes the sub-orders *Brown Mediterranean soils* and *Red-Yellow Mediterranean soils*.

Podzolized soils—Soils evolved with a profile of ABC, where the B horizon is defined as a spodic horizon (*sensu* Soil Survey Staff, 1960). They include *Hydromorphic Podzols* and *Non-Hydromorphic Podzols*, and may have or not continuous or discontinuous layers of “*ortstein*” or “*orterde*”, and are associated with the siliceous materials.

Halomorphic soils—Soils whose properties are determined by the presence of water-soluble salts and where exchangeable sodium is less than 15% of the total exchangeable Ca-Mg-K-Na. These soils generally occur on alluvium and are subdivided into *Saline soils with moderate salinity* or *with high salinity*, with salinity less than 0.2% or higher than 0.2%, respectively. A salt content of 0.2% corresponds approximately to an electrical conductivity of 4 dS m⁻¹.

Hydromorphic soils—Mineral soils characterized by temporary or permanent waterlogging due to groundwater or impeding layers, and developing redoximorphic features in the entire soil profile or in part of it. They are subdivided into *Hydromorphic soils without an eluvial horizon* and *Hydromorphic soils with an eluvial horizon*.

Hydromorphic organic soils—Soils showing a histic epipedon (*sensu* Soil Survey Staff, 1960), with a very high content of organic materials that have accumulated at the surface under conditions of permanent or nearly permanent water saturation.

The categorical family level corresponds to subdivisions of subgroups, which are primarily based on the specifications of the underlying lithological materials. Following the last update to the 1:25,000 soil map legend, the CSP includes 386 soil families (IHERA, 1999). The concept and categorical levels of CSP were developed before sufficient data and modern data processing tools became available, with too many soil families missing morphological and analytical data (IDRHa, SPCS, 2004).

1:25,000 soil mapping

In the study area, the main legacy soil information is the 1:25,000 soil map, which is based on conventional mapping approaches and on the CSP (Figure 1) and is accessible online as open-access vector data (DGADR-SNIS, 2022). It was developed by the Agrarian National Survey Centre (Ministry of Agriculture), and delineates countless complex soil map units composed of soil families, associations of soil families, soil phases, and rock outcrops. Soil phases specify subdivisions of any established categorical level based on variations in soil characteristics that are not significant for classification but are important for agricultural and forestry uses (e.g., *thin*, *thick*, *stony*, and *poorly drained soil phases*). Soil profiles were morphologically described and analyzed from the end of the 1950s to the end of the 1960s, primarily to establish CSP categorical levels. During fieldwork, surveyors used aerial photography to draft map units, which were then transferred to a topographic base map at a scale of 1:25,000. The map units were delineated following soil profile observations by surveyors, but no standards for the density and depth of observations were established. Thus, the allocation of soil units in the CSP system, which was primarily based on soil observations in the field and the nature of the underlying parent material, included too many subjective elements dependent on the knowledge, experience, and mental models of the surveyors or classifiers (Adhikari et al., 2014; Vacca et al., 2014;

Arrouays et al., 2020), who varied throughout the period of the 1:25,000 soil map elaboration, which posed great challenges regarding the correlation of soil units with international standards.

The CSP handbook only comprises a legacy dataset of 186 reference soil profiles (RSPs) that are non-georeferenced, and only 146 soil families are covered (SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1970; SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1973). Such a scarce RSP legacy was provided by the soil survey services, and soil families were reclassified according to the CSP (Cardoso, 1974; IHERA, 1999) as deemed necessary after re-examining the soil descriptions and the corresponding laboratory data. This set of RSPs was used for the assessment of the correspondence between the CSP's categorical levels and the WRB Reference Soil Groups (IUSS Working Group WRB, 2022). Because building correlations for the 386 soil families based on overly detailed and often ambiguous lithological designations is practically unfeasible, soil families were aggregated according to similarities in formation processes (igneous, metamorphic, or sedimentary rocks), silica (SiO₂) content, presence of carbonates, consolidation degree, sediment particle size, and transport or depositional agents of the respective lithological materials, as outlined by Guerreiro et al. (2024), Guerreiro et al. (2025). For example, soil families related to sandstones, such as those from Silves and Buçaco, along with stratified, brownish, reddish, and fine sandstones, were aggregated to originate a single soil family. Although some detail is lost when aggregating soil families, this process facilitates the conversion of the 1:25,000 soil map legend into the WRB.

Legacy soil profile collection

The objectives of the study were accomplished by identifying the national legacy soil resource data existing across different institutions and individuals (Ali et al., 2024; Bruyn and Prager, 2024), which are independent from the aforementioned 1:25,000 soil map. A substantial legacy soil profile collection (LPC) was acquired over decades from the last version of the current CSP (Cardoso, 1974) until 2024, through studies developed by national or regional authorities, academic institutions (e.g., theses and research projects), or farmers and private enterprises (e.g., soil and land evaluation). The collection was kept in several formats with limited accessibility. This helpful legacy soil data encompasses so far 624 georeferenced soil profiles, some of which are available in INIAV (2020), and are scattered across the study area (Figure 2), and correspond to a density of approximately one profile per 70 km². The main source of these profiles is the soil mapping conducted in the Alentejo region for irrigation purposes (Hidroprojecto, 1995; IDRH, 2003; DGADR, 2007), and studies on drivers of hydromorphic soil features developed over igneous or metamorphic mafic rocks (Fonseca, 2000; Monteiro, 2004; Monteiro et al., 2012), on characteristics and classification of soils formed on granites (Madeira and Furtado, 1983; Martins, 1992; Martins et al., 1995), on genesis and classification of soils developed on schists (Dachary, 1972; 1975; Ricardo et al., 1972; Pereira and Fitzpatrick, 1995; Ricardo et al., 1995; Ricardo et al., 1996), and on factors responsible for the occurrence of Podzols in Portugal (Monteiro et al., 2015). Other sources included the collection of soil monoliths at the School of Agriculture (University of Lisbon), the correlation of red soils (FAO,

1970), and the studies on soil characteristics in the Algarve region (Jahn and Stahr, 1988; Kopp et al., 1989).

Each soil profile was described, sampled by successive soil horizons, and subjected to laboratory analysis. As the legacy soil profile data had varying levels of completeness in terms of soil, field, environmental descriptions, and laboratory analyses, an expert-based quality assessment and standardization were required before the data could be compiled into a harmonized format. The compiled profile data points (Figure 3) were collated after harmonization and identification of Reference Soil Group (RSG) as outlined in the IUSS Working Group WRB (2022), for inclusion in a national data repository. The original soil profile records were projected into the standard WGS84 georeferencing system, using decimal degrees in the QGIS (3.44.0) environment (QGIS Development Team, 2025). To verify the accuracy of the soil profile locations, the WGS84 coordinate system was used to confirm that the points matched the site descriptions and geomorphological settings, and, at the very least, the boundaries of the original project area.

Correspondence between CSP and WRB RSGs

The scarcity of legacy laboratory data on the different soil properties of the CSP orders and suborders, along with the absence of some parameters, does not allow deriving taxonomic distances (Láng et al., 2013). Two procedures were then developed to evaluate the degree of correspondence between each CSP order and suborder and the WRB RSGs (IUSS Working Group WRB, 2022), as described below.

- i. The classification of 186 RSPs according to the CSP orders/suborders (used in the 1:25,000 soil map) was compared with that by the IUSS Working Group WRB (2022) system; when CSP suborders were specified by color, only orders were considered. That is, each reference soil profile (RSP) associated with the 1:25,000 soil map legend was classified using both the CSP and the WRB systems (Table 1).
- ii. The georeferenced legacy soil profile collection (LPC) was classified according to the IUSS Working Group WRB (2022) and used as a reference guide for the correspondence principles and further conversion of the 1:25,000 soil map legend. Soil profiles were then transformed into a point layer using their respective coordinates, and a buffer of 25 m was used to account for geo-referencing inaccuracies. Next, the geo-processing tool *intersect* was used to intersect the layer with the soil map units of the 1:25,000 soil map (DGADR-SNIS, 2022) to evaluate the correspondence rate between the WRB RSGs and the categorical levels of the CSP orders and suborders existing in the intersected 1:25,000 soil map units (Table 2).

The LPC was also framed within delineated landscape units to enable soil type prediction using key soil-forming factors, such as lithological groupings, relief classes, and climate (Bui and Moran, 2003; Vacca et al., 2014; Guerreiro et al., 2024; 2025). Climatic units were delineated using normalized temperature data from the most recent available period (1981–2010; IPMA, 2024). The data,

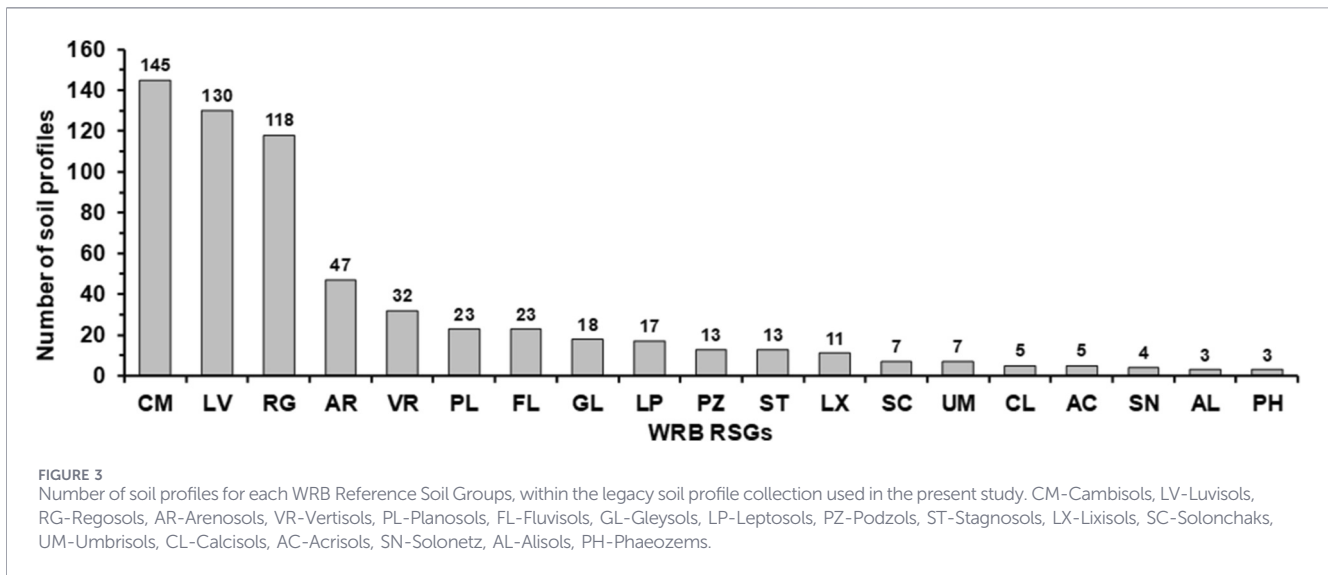


TABLE 1 Correspondence (%) between each Order/Suborder of the Classification of the Soils of Portugal and the WRB RSGs by using the reference soil profiles associated with the 1:25,000 soil mapping.

CSP Orders/Suborders	Nrp	WRB RSGs													
		LP	VT	SC	GL	PZ	PL	ST	UM	LV	CM	FL	AR	RG	
Incipient soils															
Lithosols	10	60	-	-	-	-	-	-	-	-	-	-	-	-	40
“Regosols”	2	-	-	-	-	-	-	-	-	-	-	-	100	-	-
Alluvial soils	13	-	-	-	-	-	-	-	-	-	-	69	8	23	-
Colluvial soils	3	-	-	-	-	-	-	-	-	-	-	-	-	-	100
Litholic soils															
Humic litholic soils	9	11	-	-	-	-	-	-	78	-	11	-	-	-	-
Non-humic litholic soils	14	7	-	-	-	-	-	-	7	-	21	-	-	-	65
Calcareous soils	23	9	-	-	-	-	-	-	-	-	35	-	-	-	56
“Barros” (vertisols)	12	-	83	-	-	-	-	-	-	-	17	-	-	-	-
Mollic soils															
“Castanozems”	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Argilluviated soils not strongly unsaturated	56	-	-	-	-	-	9	9	-	39	38	-	-	-	5
Podzolized soils															
Non-hydromorphic podzols	8	-	-	-	-	13	13	-	-	-	13	-	24	37	-
Hydromorphic podzols	2	-	-	-	-	50	-	-	-	-	-	-	50	-	-
Halomorphic soils															
Saline soils	9	-	-	44	34	-	-	-	-	-	-	22	-	-	-
Hydromorphic soils															
Hydromorphic soils without an eluvial horizon	13	-	-	-	39	-	15	31	-	-	-	-	-	-	15
Hydromorphic soils with an eluvial horizon	4	-	-	-	-	-	25	75	-	-	-	-	-	-	-
Hydromorphic organic soils	3	-	-	-	100	-	-	-	-	-	-	-	-	-	-

LP, Leptosols; VT, Vertisols; SC, Solonchaks; GL, Gleysols; PZ, Podzols; PL, Planosols; ST, Stagnosols; UM, Umbrisols; LV, Luvisols; CM, Cambisols; FL, Fluvisols; AR, Arenosols; RG, Regosols. Nrp, number of reference soil profiles. Values in bold indicate a degree of correspondence ≥50%.

TABLE 2 Proportion (%) of WRB RSGs (from the legacy soil profile collection) intersecting the 1:25,000-scale soil map corresponding to the different orders/suborders of the Classification of the Soils of Portugal (CSP).

CSP Orders/ Suborders	Np	WRB reference soil groups																		
		LP	VT	SC	GL	PZ	PL	ST	SN	PH	UM	CL	AC	LX	AL	LV	CM	FL	AR	RG
Incipient soils																				
Lithosols	29	24	-	-	-	-	*	-	-	-	-	-	*	7	-	*	38	-	-	21
“Regosols”	30	-	-	-	-	7	-	-	-	-	-	-	-	-	-	-	7	-	76	10
Alluvial soils	35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	66	9	19
Colluvial soils	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Litholic soils																				
Humic litholic soils	7	-	-	-	-	-	-	-	-	-	43	-	14	-	-	-	14	-	-	29
Non-humic litholic soils	145	*	-	-	-	-	*	*	-	-	-	-	-	-	*	14	19	-	14	43
Calcareous soils	34	*	*	-	-	-	-	-	-	-	-	14	-	-	-	9	49	-	-	23
“Barros” (vertisols)	31	-	78	-	-	-	-	-	-	-	-	-	-	-	-	6	16	-	-	-
Mollic soils																				
“Castanozems”	3	33	-	-	-	-	-	-	-	67	-	-	-	-	-	-	-	-	-	-
Argilluviated soils not strongly unsaturated	225	*	-	-	-	-	9	*	*	-	-	-	*	*	*	40	29	-	-	10
Podzolized soils																				
Non-hydromorphic podzols	44	-	-	-	-	23	5	-	-	-	-	-	-	-	-	-	11	-	25	36
Hydromorphic podzols	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Halomorphic soils																				
Saline soils	9	-	-	56	33	-	-	-	11	-	-	-	-	-	-	-	-	-	-	-
Hydromorphic soils																				
H. soils without an eluvial horizon	23	-	-	-	35	-	-	26	13	-	-	-	-	-	-	26	-	-	-	-
H. soils with an eluvial horizon	9	-	-	-	-	-	56	22	-	-	-	-	-	-	-	22	-	-	-	-
Hydromorphic organic soils	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

LP, Leptosols; VT, Vertisols; SC, Solonchaks; GL, Gleysols; PZ, Podzols; PL, Planosols; ST, Stagnosols; PH, Phaeozems; UM, Umbrisols; CL, Calcisols; AC, Acrisols; LX, Lisisols; AL, Alisols; LV, Luvisols; CM, Cambisols; FL, Fluvisols; AR, Arenosols; RG, Regosols. Np, number of legacy reference soil profiles. *Proportion less than 5%. Values in bold indicate a proportion ≥50%.

originally in multidimensional NetCDF (*.nc) raster format at 100-m resolution, were resampled to 1-km resolution. Classification was based on the mean annual temperature and the mean temperatures of the warmest and coldest months. Lithological groupings were established based on Engelen and Dijshoorn (2013), Gray et al.

(2016), and the IUSS Working Group WRB (2022), being separated primarily according to their geological origin (igneous, metamorphic, or sedimentary) and silica content; for sedimentary rocks, degree of consolidation, particle size, and the transport/depositional agent were also considered. The most updated and

harmonized geological map of mainland Portugal, at a 1:200,000 scale (LNEG, 2000), was used, and in sedimentary areas, the 1:25,000-scale soil map of Portugal (SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1973) was used as Supplementary Material. A relief unit map was digitally produced using the SRTM 1-arc sec Digital Terrain Model (DTM), which was resampled to a 25-m resolution and projected into the ETRS89-TM06 reference system. The relief classification followed the methodologies of Hammond, 1954, Hammond, 1964a, Hammond, 1964b and Morgan and Lesh (2005), with five relief units defined: Plains (p), Undulating (s), Strongly sloping (o), Steep (m), and Very steep (e). Next, the three layers were intersected to generate preliminary land units, considering a minimum mappable area of 30 ha at the chosen mapping scale (1:100,000).

Assignment of WRB qualifiers

Knowledge of soil characteristics is essential to enhancing the accuracy of digital soil mapping products and capturing spatial variations relevant to decision-making for the sustainable management of soil resources and land-use planning (Bruyn and Prager, 2024; Lagacherie, 2025). Therefore, during the legend conversion process, it is indispensable to identify and evaluate the occurrence and frequency of both principal (PQs) and supplementary (SQs) qualifiers associated with each WRB RSGs. As non-georeferenced and scarce RSPs do not provide pertinent morphological and analytical information regarding key diagnostic properties (e.g., abrupt textural differences, continuous rocks, lithic discontinuities, soil depths, and exchangeable aluminum), some PQs and SQs were inferred by framing each RSG (derived from the LPC) within delineated landscape units based on major soil-forming factors (Vacca et al., 2014; Guerreiro et al., 2025). Thus, soil profiles of the most representative RSGs were primarily grouped according to lithological groupings to identify relationships with key soil properties related to PQs and SQs (Gray et al., 2016). In addition, different CSP categorical levels were exploited to support the identification of PQs and SQs associated with correlated RSGs (Supplementary Material 1).

Results and discussion

Correspondence between CSP and WRB Reference Soil Groups

The majority of CSP categorical levels show a low correspondence degree with single WRB Reference Soil Groups (Table 1). The findings show that a one-to-one matching is not ascertained for any CSP orders, and the highest correspondence was found between the *Barros* and *Vertisols* RSGs (83%), as the characteristics established for the *Barros* RSG (Cardoso, 1974) are close to the key criteria of the *Vertisols* RSG (IUSS Working Group WRB, 2022). Within the CSP suborders, only *Colluvial* and *Humic Litholic* soils may show a straightforward correspondence with WRB RSGs: *Regosols* (100%) and *Umbrisols* (78%), respectively (Table 1). Other matches between the CSP and WRB RSGs may be established at the categorical group level. The group *Psammo-Regosols* (suborder *Regosols*) may correspond to *Arenosols*, as they are

primarily sandy because of their parent material, sand (Cardoso, 1974), while the group *Modern alluvial soils* (suborder *Alluvial soils*) closely fits the *Fluvisols*. The groups *Planosols* and *Planosolic soils* primarily correspond to the *Stagnosols* RSG, not *Planosols*, as they frequently lack an abrupt textural difference (SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1973). Available data for the group *Turf soils with sapric materials* (order *Hydromorphic organic soils*), occurring in limited alluvial areas, point out that their organic carbon content (SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1973) does not meet the diagnostic criteria for organic material (*Histosols*; IUSS Working Group WRB, 2022) and, therefore, may match the *Gleysols* RSG.

The majority of the above-mentioned correspondence trends are also clearly evidenced by sets of RSGs identified through the classification of legacy soil profile collections, which coincide with the soil map units assigned to different CSP orders or suborders (Table 2). In fact, the order “*Barros*” (78%) and the suborder *Regosols* (*Psammo-Regosols*, 76%) may correspond to a unique WRB RSGs to a high degree. It is evident that the map units of the majority of CSP orders and suborders comprise several RSGs, indicating a low correspondence degree with WRB RSGs (Tables 1, 2). These trends contrast with the high correlations achieved when converting mapping units from the Belgian soil map to the WRB (Dondeyne et al., 2014).

Notably, the map units corresponding to the suborder *Lithosols* (“soils derived from consolidated rocks, with an effective depth normally less than 10 cm”; Cardoso, 1974) comprise only 24% of *Leptosols*, with the remainder including *Cambisols*, *Regosols*, and other RSGs featuring an argic horizon. This low correspondence likely depends on surveyors’ application of the vague “effective depth” definition, which is therefore not comparable to the diagnostic property of continuous rock (IUSS Working Group WRB, 2022).

Although the suborder *Alluvial soils* only partially corresponds (66%) to the *Fluvisols* RSG (Table 2), we may emphasize that the group *Modern alluvial soils* (developing on recent alluvium) closely fits the RSG, while the group *Old alluvial soils* (developing on old alluvium, that is, river terraces) may correspond to *Regosols*, *Arenosols* and *Cambisols*.

Within the *Litholic soils*, the suborder *Humic Litholic soils* primarily correspond to *Umbrisols* (43%) and, to a lesser extent, to *Regosols* (29%), while the *Non-Humic* soils primarily correspond to *Regosols* (43%) followed by *Cambisols* (19%). The order *Calcareous soils* largely corresponds to *Cambisols* (47%) and only minimally to *Calcisols* (15%), as the majority of them do not exhibit a calcic horizon. Despite the small number of profiles, soil map units of “*Castanozems*” suggest that this suborder may correspond in high proportion to *Phaeozems* (67%).

Soil map units corresponding to *Argilluviated soils* only fit *Luvvisols* at a rate of 40% (Table 2), and include a wide range of RSGs (namely, *Cambisols*, *Regosols*, and *Planosols*). This trend may be associated with several factors: (i) the textural differentiation criteria used for the definition of the argillic horizon (Cardoso, 1974) are different from those used for the argic horizon (IUSS Working Group WRB, 2022); (ii) lithic discontinuities, as occurring in sediment parent materials, were not taken into consideration for qualifying the argillic horizon, as required by the IUSS Working Group WRB (2022) for the argic horizon; (iii) *Argilluviated soils* also

correspond to other RSGs with clay-enriched subsoils (Acrisols, Alisols, and Lixisols) (Table 2); and (iv) some *Argilluviated soils*, namely those associated with the subgroup *Para-Hydromorphic soils* may correlate with Planosols and Stagnosols (Tables 1, 2).

It is remarkable that 1:25,000 map units of *Podzolized soils* (DGADR-SNIS, 2022; Cardoso, 1974) comprise the Podzols RSG only at an extent of 23% (Table 2) and include other RSGs, such as Regosols (36%), Arenosols (25%), Cambisols (11%), and Planosols (5%). This trend may be associated with inconsistencies in the field observations by surveyors, and with the CSP scheme itself, as *Podzolized soils* “may have or not continuous or discontinuous layers of *ortstein* or *orterde*” [SIC] (Cardoso, 1965; 1974). That is, *Podzolized soils without ortstein* simply do not correspond to Podzols RSG (IUSS Working Group WRB, 2022), and may correspond to Arenosols (subgroup *Typical*), and Regosols and Cambisols (subgroup *Para-Litholic soils*, Supplementary Material 1). As no determinations of Al and Fe by oxalate (Al_{ox} , Fe_{ox}) were performed (SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1973), this resulted in criteria deficiencies for identifying diagnostic spodic B horizons (IUSS Working Group WRB, 2022).

The order *Halomorphic soils* occurs in alluvial areas. The group *Saline soils of high salinity* only partially fits the Solonchaks RSG (56%) because some of them may not meet the criteria for a salic horizon (IUSS Working Group WRB, 2022) and then may correspond to Gleysols and Solonetz RSGs, depending on the absence or presence of a natric horizon (IUSS Working Group WRB, 2022). Accordingly, the group *Saline soils of medium salinity* (sensu Cardoso, 1974) may comprise Gleysols or Fluvisols RGSs.

In the order *Hydromorphic soils* (Table 2), the suborder *with an eluvial horizon* (comprising the *Planosols* and *Planosolic soils* groups; Supplementary Material 1) corresponds to Planosols (56%), and Stagnosols (22%); it also corresponds to Luvisols (22%), which may exhibit stagnic properties and reducing conditions to a certain extent (Fonseca, 2000; Monteiro, 2004). Meanwhile, *Hydromorphic soils without an eluvial horizon* correspond to Gleysols RSG in alluvial landscapes, and to Stagnosols, Solonetz, and Luvisols in landscapes associated with intermediate and mafic rocks (Monteiro, 2004; Monteiro et al., 2012).

The low degree of correspondence between the CSP and WRB RSGs (Table 2) is related to (i) differences in the criteria used for the characterization of diagnostic horizons (e.g., argic, spodic, and salic horizons), (ii) ambiguous application of the effective depth definition of <10 cm; and (iii) the fact that the definitions or characteristics of the categorical levels of the CSP are not described or quantified with the level of detail required by the IUSS Working Group WRB (2022). This is dependent on the inconsistencies associated with the knowledge and experience of surveyors. Moreover, the absence of successive and systematic morphological and analytical standard characterization of soil profiles over different lithological materials, during the creation of the 1:25,000 soil map, hindered the identification of a wider range of relevant soil characteristics and soil types, and ultimately limited CSP updates (IDRHa, SPCS, 2004).

Based on the soil information used in the present study area and other legacy soil data (Tables 1, 2), it is likely that the majority of the WRB RSGs occur in mainland Portugal. Indeed, out of the 32 WRB RSGs, 13 (Leptosols, Vertisols, Solonchaks, Gleysols, Podzols,

Planosols, Stagnosols, Umbrisols, Luvisols, Cambisols, Fluvisols, Arenosols, and Regosols) are relevant in the area of the present study, while Anthrosols were mapped in the Northern and Central regions (Agroconsultores, 1995; Agroconsultores, 2004). The other eight RSGs (that is, Solonetz, Plinthosols, Nitisols, Phaeozems, Acrisols, Alisols, Lixisols, and Calcisols) occur to a limited extent or sporadically (Jahn and Stahr, 1988; Agroconsultores, 2004; Monteiro et al., 2012). Although *Organic soils* (*Hydromorphic*) are considered in the CSP (Supplementary Material 1), the occurrence of Histosols in mainland Portugal is doubtful, according to trends documented by Gómez-Miguel and Badía-Villas (2016) for mainland Spain. Although Technosols may occur, so far they have not been mapped.

This set of RSGs for the mainland Portugal highlights the wide variety of soils existing in the Mediterranean environment (Verheye and de la Rosa, 2005), with the region being probably more diverse in soils than other climatic regions due to the large variety of soil parent materials, landforms, and anthropic factors (e.g., deforestation and terrace building) and internal climate variations (Yaalon, 1997). Although Calcisols, Cambisols and Luvisols have been reported as the WRB RSGs occupying the largest areas in the Mediterranean region (Verheye and de la Rosa, 2005), the dominant RSGs in the present study area are Regosols, Cambisols, and Luvisols, as reported by Gómez-Miguel and Badía-Villas (2016) for the Mediterranean areas of Spain.

It is worth highlighting that Andosols are present throughout the Azores islands (Ricardo et al., 1977; Madeira, 1980) and, to a lesser extent, on Madeira Island (Madeira et al., 1994; Madeira et al., 2007). Also, Vertisols, Cambisols, Phaeozems, and Calcisols occur on the Madeira (Ricardo et al., 1992) and Porto Santo (Franco, 1994) islands, while Kastanozems and Nitisols were identified in the Porto Santo (Franco, 1994) and Santa Maria (Madeira et al., 2007) islands, respectively.

In summary, at least 24 WRB RSGs are likely present in Portugal, including 22 in the mainland.

Correspondence between CSP and WRB based on soil-forming factors

Lithological groupings

The degree of correspondence between the CSP categorical levels and the WRB RSGs based on lithological groupings was clearly improved (Table 3), aiding in the identification of dominant and codominant soils in respective landscape units and defining soil map units (IUSS Working Group WRB, 2022). For example, landscapes of granites and related rocks are largely Regosols (73%), with Cambisols present to a lesser extent (27%), consistent with 1:25,000 soil map units, in which *Non-Humic Litholic soils* are nearly exclusive (95%). It also aligns with the classification of soils developed on granites, within a wide range of rainfall (Martins, 1992; Martins et al., 1995). In soil map units related to *Humic Litholic soils*, Umbrisols may prevail (Tables 1, 2; Madeira and Furtado, 1983; Martins, 1992). In landscapes associated with diorites, quartz diorites, and related rocks, Luvisols are represented in a high proportion (77%), similar to *Argilluviated soils* (82%) in 1:25,000 soil map units. In landscapes of mafic rocks, the occurrence of Vertisols and

TABLE 3 Correspondence between the WRB RSGs and the CSP categorical levels according to different lithological groupings. Data in parentheses represent that proportion (%). Symbols for the WRB RSGs are the same as those in Table 2.

Lithological groupings	WRB RSGs ^a	CSP - Orders/suborders ^A
Igneous rocks		
Granites and related rocks	RG (73); CM (27)	<i>Litholic soils</i> (95), <i>Argilluviated soils</i> (5)
Diorites, quartz diorites, and related rocks	LV (77); CM (9); ST (7)	<i>Argilluviated soils</i> (82), <i>Litholic soils</i> (9), <i>Hydromorphic soils</i> (5)
Mafic rocks	VR (60); LV (30); CM (7)	“Barros” (60), <i>Argilluviated soils</i> (33), <i>Calcareous soils</i> (7)
Metamorphic rocks		
Gneisses and related rocks	RG (52); CM (40)	<i>Argilluviated soils</i> (63), <i>Non-Humic Litholic soils</i> (37)
Schists and related rocks	CM (34); LV (36); RG (13); LP (13)	<i>Argilluviated soils</i> (63), <i>Lithosols</i> (37)
Intermediate-mafic metamorphic rocks	LV (59); CM (22); RG (7); PL (6); SN (5)	<i>Argilluviated soils</i> (84), <i>Litholic soils</i> (10)
Marbles	CM (75); LV (25)	<i>Argilluviated soils</i> (100)
Sedimentary rocks		
Sands	AR (65); PZ (29); GL (6)	“Regosols” (59), <i>Podzolized soils</i> (29), <i>Argilluviated soils</i> (6), <i>Hydromorphic soils</i> (6)
Unconsolidated or poorly consolidated arenaceous materials	RG (63); AR (37)	<i>Litholic soils</i> (47), <i>Podzolized soils</i> (38), “Regosols” (15)
Arenites	RG (44); CM (22); AR (17); LP (11); LV (6)	<i>Podzolized soils</i> (39), <i>Litholic soils</i> (39), <i>Argilluviated soils</i> (11), <i>Regosols</i> (11)
Arenaceous materials on sandstones and/or clayey materials	PL (25); CM (25); RG (25); ST (13); AR (6)	<i>Podzolized soils</i> (31), <i>Litholic soils</i> (25), <i>Argilluviated soils</i> (22), “Regosols” (13), <i>Hydromorphic soils</i> (9)
Unconsolidated or poorly consolidated medium-textured materials	CM (25); LV (25); ST (25); PL (13); RG (12)	<i>Litholic soils</i> (75), <i>Argilluviated soils</i> (25)
Clayey materials	LV (36); PL (18); ST (18); VR (9); AC (9); CM (9)	<i>Argilluviated soils</i> (73), <i>Podzolized soils</i> (9), <i>Litholic soils</i> (9), <i>Hydromorphic soils</i> (9)
Gravelly sandy and/or clayey materials	CM (42); RG (29); PL (29)	<i>Argilluviated soils</i> (71); <i>Litholic soils</i> (14); <i>Podzolized soils</i> (14)
Compact limestones	CM (60); LV (40)	<i>Argilluviated soils</i> (60), <i>Calcareous soils</i> (40);
Non-compact limestones	CM (53); RG (33); CL (13)	<i>Calcareous soils</i> (93) <i>Argilluviated soils</i> (7)
Marls and related rocks	CM (54); VR (19); LV (19)	<i>Argilluviated soils</i> (54), <i>Calcareous soils</i> (27); “Barros” (19)

^aProportions less than 5% are not shown.

Luvissols, respectively at a rate of 60% and 30%, is similar to the occurrence of “Barros” and *Argilluviated soils* in soil mapping units, respectively 60% and 33% (Table 3). These trends suggest that, in soil mapping units associated with igneous rocks, CSP categorical levels are highly related to RSGs.

The degree of correspondence in soil mapping units associated with metamorphic rocks is lower than with igneous rocks. For instance, in landscapes associated with gneisses, *Regosols* (52%) and *Cambisols* (40%) are the dominant and codominant RSGs, similar to granite landscapes, while in 1:25,000 soil map units, *Argilluviated soils* are dominant (63%), and *Non-Humic Litholic soils* (37%) are codominant (Table 3). Such a low correspondence may be primarily related to differences in the criteria for defining the argillic (Cardoso, 1974) and argic horizons (IUSS Working Group WRB, 2022). These differences may also explain the patterns shown by soil map units related to marbles, where the proportion of *Argilluviated soils* is

much higher (100%) than that of *Luvissols* (25%; Table 3). The same is true for intermediate and mafic metamorphic rocks, where the proportions are 84% and 59%, respectively. Notably, soil map units in landscapes of schists and related rocks only encompass *Argilluviated soils* (63%) and *Lithosols* (37%) (Cardoso, 1974; DGADR-SNIS, 2022; Table 3); however, both *Luvissols* (36%; including *Lixisols*, *Acrisols*, and *Alisols*) and *Leptosols* (13%) are present to a lesser extent. Since *Cambisols* (34%) and *Regosols* (13%) also occur in these soils, we may conclude that there is a gap in the 1:25,000 soil map, because soils corresponding to *Litholic soils* (that is, *Leptosols*, *Regosols*, and *Cambisols*) are absent (DGADR-SNIS, 2022), contrasting with patterns on soil profile development variation in schist landscapes (Dachary, 1972; 1975; Ricardo et al., 1972; Pereira and FitzPatrick, 1995). In other words, both *Lithosols* and *Argilluviated soils* are overrepresented in map units on the 1:25,000 soil map.

There are big differences in the correspondence rate between CSP categorical levels and RSGs that occur in landscapes associated with sedimentary lithological groupings. A high correspondence rate was observed for sands, where the 1:25,000 soil map units included “*Regosols*” (sensu CSP, 59%) and *Podzolized soils* (29%), and Arenosols were dominant (65%) and Podzols were codominant (29%) soils, consistent with trends reported for temperate climates (Adhikari et al., 2014), and for mainland Portugal (Monteiro et al., 2015). Although *Podzolized soils* (31%–39%; Table 3) occur in soil map units of landscapes corresponding to unconsolidated or poorly consolidated arenaceous materials, arenites, or arenaceous materials on sandstones and/or clayey materials, Podzols are simply absent, corresponding primarily to Arenosols or Regosols, related to the subgroups *Typical* and *Para-Litholic soils of Podzolized soils without “ortstein”* (Cardoso, 1974; Supplementary Material 1). This trend aligns with Monteiro et al. (2015), who concluded that the area occupied by Podzols in mainland Portugal is much less than that reported in previous soil maps (Cardoso et al., 1973; ESDAC, 2004; DGADR-SNIS, 2022).

The occurrence of *Argilluviated soils* in soil map units associated with gravelly, sandy, and/or clayey materials (71%) or clayey materials (73%) denotes inconsistency, as Luvisols occur in a much lower proportion or are absent, because, in these materials, textural differentiation associated with lithic discontinuities does not allow for the development of an argic horizon (IUSS Working Group WRB (2022)). In contrast, the proportion of Planosols plus Stagnosols (29%–36%) is much higher than that of *Hydromorphic soils*, indicating that they may be primarily associated with the subgroup *Para-Hydromorphic of Argilluviated soils* (Supplementary Material 1).

Soil map units associated with non-compact limestones (Table 3) primarily encompass *Calcareous soils* (93%), and include Cambisols (53%), Regosols (33%), and Calcisols (13%). This relationship results from the fact that the CSP *Calcareous soils* develop on calcareous material (SROA–Serviço de Reconhecimento e Ordenamento Agrário, 1973; Cardoso, 1974), where the carbonates (primary carbonates) are mainly inherited from the parent material, and thus a calcic horizon occurs to a limited extent (IUSS Working Group WRB, 2022). Soil map units related to compact limestones and marls have *Argilluviated soils* occur at rates of 60% and 54%, respectively; however, Luvisols are present at lower rates (40% and 19%, respectively), while Cambisols are the dominant soil type (Table 3), which may be due to criteria differences regarding the argillic (Cardoso, 1974) and the argic (IUSS Working Group WRB, 2022) horizons.

Correspondences based on lithological groupings can better capture the occurrence and proportion of RSGs in soil map units, and are of great usefulness to improve the prediction of dominant and codominant soils and define soil map units (IUSS Working Group WRB, 2022). These results agree with the trends reported by Gray et al. (2011), Gray et al. (2014) regarding the distribution of RSGs at a global scale, and by Adhikari et al. (2014), Lamichhane et al. (2021) regarding a national distribution. Additionally, they align with the observation that the distribution of soil units in southern Portugal is primarily related to the nature of the respective parent material (Cardoso, 1974). However, this relationship is less evident in landscapes where relief (and, in some cases, climate) may exert a stronger influence than lithology.

Relief classes

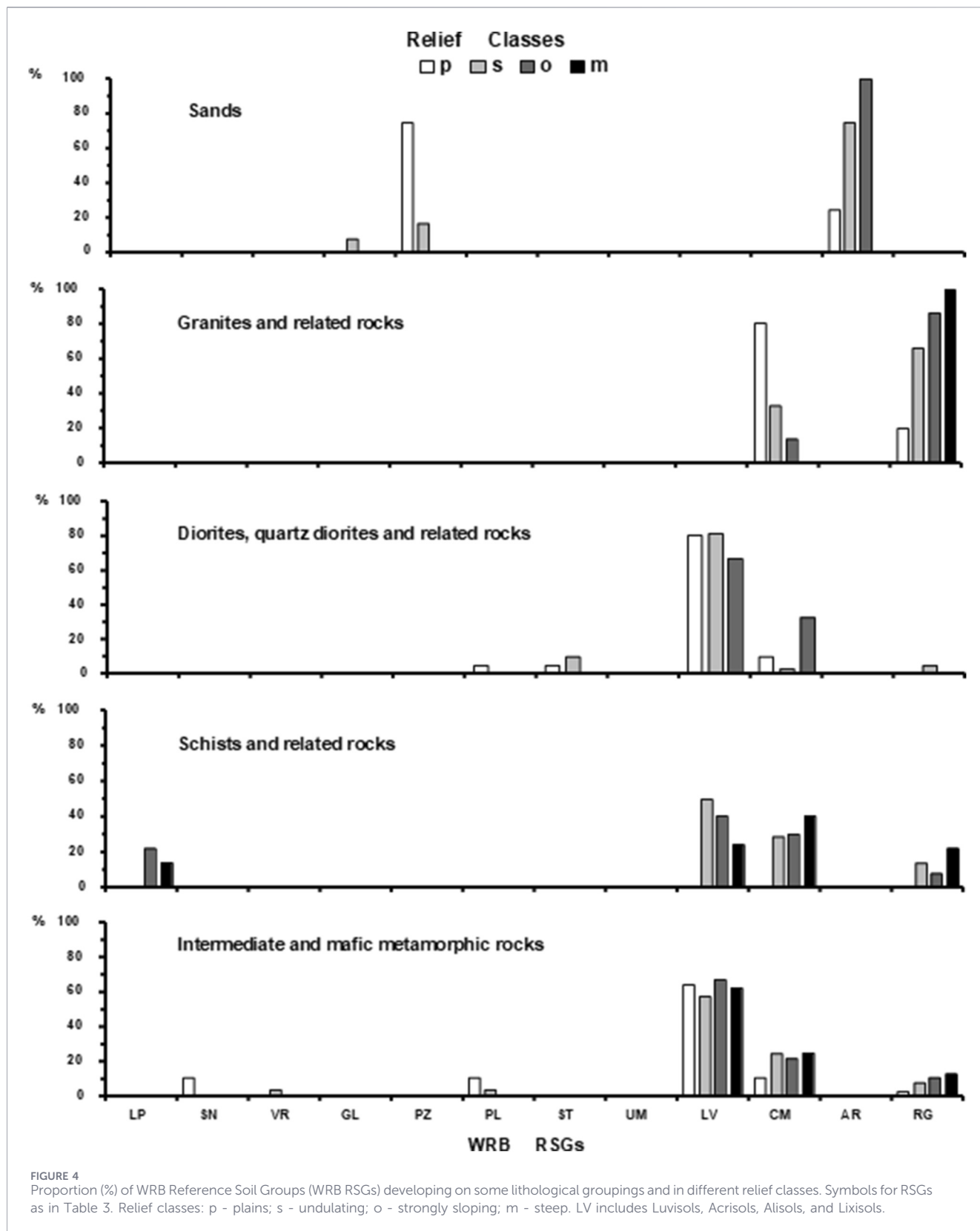
The wide variety of RSGs in schist landscapes, where the terrain surface is heavily indented and lowered (Ramos and Ramos-Pereira, 2020), indicates the need to look beyond lithological groupings to improve the accuracy of the proportion of RSGs in the landscape. This is because topography affects erosion, water runoff, and infiltration/percolation, along with soil profile development (Jenny, 1941; Heimsath et al., 1999; Buol et al., 2011; Zhao et al., 2025).

It is undeniable that relief classes (plains, sloping, strongly sloping, and steep) improve the conversion of map units from the 1:25,000 soil map to the WRB, strengthening the prediction of the proportion of RSGs that occur interchangeably in the landscape (Figure 4). For example, within sands, Podzols are largely dominant in plains, but sole Arenosols occur in strongly sloping areas, whereas in landscapes of granites and related rocks, Cambisols and Regosols are largely dominant and unique in plains and steep areas, respectively. A clear decrease in Luvisols (including Acrisols, Alisols, and Lixisols RSGs) is observed in schist landscapes, from undulating to steep areas, where Cambisols are most prevalent. However, variations in soil distribution patterns with relief classes are complex, owing to the occurrence of Regosols and Leptosols, which globally increase from strongly undulating to steep areas (Figure 4). Although the influence of relief on the proportion of RSGs is less pronounced in diorites, quartz diorites, and intermediate and metamorphic rock landscapes, the increment of Cambisols/Regosols in strongly sloping or steep areas, and the occurrence of Planosols, Stagnosols, and Solonetz only in plains or undulating landscapes, is notable. Future improvements in soil mapping accuracy could be achieved by incorporating additional environmental covariates and data sources. Additional covariates may include slope aspect, given its influence on soil thermal and moisture regimes (Weil and Brady, 2017), along with the Topographic Wetness Index (TWI), which captures spatial patterns of water accumulation (Beven and Kirkby, 1979; Lindsay, 2025).

These trends indicate clearly that the interaction between lithological parental material and topography may also support general conversion rules and guidelines to improve the distribution model of the majority of RSGs in landscapes, as reported in several studies (Bui and Moran, 2003; Adhikari et al., 2014; Gray et al., 2016; Dobos et al., 2019).

Climate

It should be emphasized, however, that the distribution pattern of RSGs in landscapes may also be influenced by climate classes, as in areas with higher rainfall and lower temperatures (i.e., at high altitudes and in mountainous areas), soils with high organic content (e.g. Umbrisols) may occur across several lithological groupings (Cardoso, 1974; Martins, 1992; Pereira and Fitzpatrick, 1995). In short, delineating land units based on soil-forming factors constitutes a useful tool to avoid or reduce correlation inconsistencies in the conversion of the legend of the 1:25,000 soil map to WRB RSGs. This enhances the accuracy of



the map units in the updated 1:100,000 soil map. Indeed, every landscape has its own combination of soil-forming factors that control soil-forming processes and, therefore, the soil type at any given location (Gómez-Miguel and Badía-Villas, 2016).

Given the complexity of landscapes and the limitations of legacy soil data (Hendriks et al., 2019), increasing the number and spatial distribution of soil profiles would improve soil mapping outcomes, as highlighted by Hounkpatin et al. (2018), Wadoux et al. (2020). It

TABLE 4 Proportion (%) of Principal Qualifiers (PQs) identified for WRB RSGs shown for different lithological groupings.

Lithological groupings	PQs*														
	le**	ap	sk	st	cc	ca	vr	cr	pe	eu	dy	ha	ab	et	gl
Regosols															
Granites	50 ^a -25 ^b	-	-	-	-	-	-	-	-	75	25	-	-	-	-
Gneisses	33-50	-	-	-	-	-	-	-	-	92	8	-	-	-	-
Schists	18-82	-	18	9	-	9	-	-	-	82	18	-	-	-	-
Unconsolidated or poorly consolidated arenaceous materials	5-0	-	-	5	-	-	-	-	-	89	11	-	-	-	-
Sandstones	38-25	-	-	-	-	-	-	-	-	63	37	-	-	-	-
Non-compact limestones	0-40	-	-	-	3	97	-	-	-	-	-	-	-	-	-
Cambisols															
Granites	50-0	-	-	-	-	-	-	-	-	67	33	-	-	-	-
Gneisses	78-11	-	-	-	-	-	-	-	-	78	22	-	-	-	-
Diorites	20-0	-	-	-	-	-	-	20	-	100	-	-	-	-	-
Schists	62-7	-	15	-	-	-	-	10	-	93	7	-	-	-	-
Non-compact limestones	36-0	-	-	-	10	90	-	13	-	-	-	-	-	-	-
Luvisols															
Diorites	7-0	56	-	33	-	-	9	5	-	-	-	23	-	-	-
Mafic rocks	22-0	44	-	33	-	-	33	11	-	-	-	22	-	-	-
Schists	31-19	33	4	-	-	-	-	48	-	-	-	7	-	-	-
Acrisols, alisols, lixisols															
Schists	53-0	38	13	-	-	-	-	38	-	-	-	-	-	-	-
Vertisols															
Mafic rocks	24-0	-	-	-	56	-	-	11	28	-	-	22	-	-	-
Arenosols															
Sands	-	-	-	-	-	3	-	-	-	87	13	-	-	-	-
Podzols															
Sands	-	-	-	-	-	-	-	-	-	-	-	-	80	20	20

*le, Leptic; ap, Abruptic; sk, Skeletic; st – Stagnic; cc, Calcic; ca, Calcaric; vr, Vertic; cr, Chromic; pe, Pellic; eu, Eutric; dy, Dystric; ha, Haplic; ab, Albic; et, Entic; gl, Gleyic.

**a–Endoleptic, b - Epileptic.

is essential to stimulate crowdsourced soil data and implement strategies by collecting more field data and expanding soil characterization and sampling (higher data density) to address uncertainty and/or poorly understood soil landscape relationships (Maynard et al., 2023) and spatial soil variability and accuracy in soil map units (Lagacherie, 2025).

Assignment of principal (PQs) and supplementary (SQs) qualifiers

The WRB allows for a more precise definition of soils through a second level, wherein one or more qualifiers are added to the RSG designation (IUSS Working Group WRB, 2022). Then, it is important to identify the most likely PQs associated with

correlated RSGs, as accurate, site-specific information on soil properties is critical to address the sustainable management of soil resources and many agronomic and silvicultural constraints (Terres et al., 2016; Maynard et al., 2023; Buenemann et al., 2023; Barrena-González et al., 2024; Demattè et al., 2025; Lagacherie, 2025).

Some soil properties can be inferred from several correlated RSGs (e.g., Leptosols, Gleysols, Vertisols, Arenosols, and Fluvisols), which occupy a small portion of the study area (Cardoso et al., 1973). However, the conversion process only allows for the acquisition of PQs from the CSP (and the 1:25,000 soil map) to a limited extent, because of the absence of relevant quantitative information on the majority of the key soil properties required by the WRB system (IUSS Working Group WRB, 2022). For example, the specifications provided by the CSP (Cardoso, 1974) on soil depth, the proportion

of coarse fragments, abrupt textural differences, the proportion of calcium carbonate, the differentiation of secondary calcium carbonate from calcaric-bearing material, and the exchangeable complex (with no determinations of exchangeable aluminum) are insufficient. Additionally, the criteria for soil color do not fully coincide with those of the WRB (IUSS Working Group WRB, 2022) and are primarily based on mere field observations by the soil surveyors. Therefore, soil qualifiers, such as Leptic (Endoleptic, Epileptic), Skeletic, Abruptic, Pellic, Chromic and Rhodic, Dystric and Eutric, cannot be assigned (or can only approximately be assigned) to different correlated RSGs.

Given the limitations in assigning WRB qualifiers, some PQs may be obtained tentatively from the legacy soil profile collection directly or by considering their dominance or proportion. Because these qualifiers are only applied to some RSGs, with their application related to their dominance within the set of legacy soil profiles organized according to different lithological groupings, as shown in Table 4. Overall, the Leptic qualifier (Endoleptic and Epileptic) strongly relates to soil parent material, and for similar parent material, its proportion decreases from the Regosols to Cambisols and from Cambisols to Luvisols; it is higher in soils developed on felsic igneous rocks and schists, and sandstones than on intermediate and mafic igneous rocks. Predicting the Leptic qualifier can be improved through interactions between lithological materials and relief classes (Gray and Murphy, 2002), an approach that may also enhance predictions of other qualifiers, such as Skeletic (in schist landscapes) and Stagnic (Luvisols).

In turn, the Calcaric and Calcic qualifiers are closely linked to lithology, as the former is primarily associated with soils (e.g., Regosols and Cambisols) developed on non-compact limestones, and the latter with soils (Vertisols) developed on mafic rocks. Similarly, the Vertic qualifier (Luvisols) is primarily related to mafic rocks.

The Chromic qualifier is not substantiated in the study's collection of soil profiles, as reported by Yaalon (1997) and Verheye and de la Rosa (2005) for Mediterranean region soils. This qualifier primarily occurs in soils that have an ABC profile, but the respective proportion is only significant (38%–48%) in soils with a clay-enriched subsoil (Luvisols, Acrisols, Alisols, and Lixisols) developed on schists (Table 4), suggesting a relationship between the qualifier and the nature of the soil parent material (Verheye and de la Rosa, 2005). Overall, the results also indicate that the Eutric qualifier is highly dominant in the study area, although small differences dependent on the soil parent material and on agricultural or silvicultural practices are expected (Table 4).

Supplementary Qualifiers may provide valuable insights into variations in texture and fertility status within the region. Texture classes and related qualifiers (Arenic, Loamic, Siltic, and Clayic) are important for soil water-related processes, organic carbon storage, and productivity (Schulze and Schutte, 2023) and are strongly associated with lithological materials (Table 5). In fact, the Clayic qualifier is primarily associated with clayey, fluvic materials, and mafic rocks, while the Arenic qualifier is associated with sands, the Siltic qualifier is associated with schists, and the Loamic qualifier is associated with other materials.

Specifications of SQs (Table 5) regarding the exchange complex (e.g., Magnesian or Sodic) may also reveal the lithological groupings

and, eventually, relief classes (Monteiro et al., 2012). The Magnesian qualifier occurs across the majority of the lithological groupings, namely intermediate and mafic metamorphic rocks (53%), unconsolidated or poorly consolidated medium-textured materials (63%), and clayey materials (64%). Specifically, the Sodic and Argisodic qualifiers account for 39% and 32%, respectively, of soils developed on diorites and metamorphic rocks (Table 5), and are primarily associated with Stagnosols and Planosols, as documented by Fonseca (2000), Monteiro (2004).

The relationships between lithology and key soil properties are essential for mapping soil properties, as stated by Gray et al. (2016). As with RSGs, more data are needed to improve their spatial prediction (Buenemann et al., 2023; Lagacherie, 2025).

To some extent, PQs of correlated RSGs can be obtained from the categorical levels of the CSP (Supplementary Material 1). For example, the Calcaric qualifier can be adopted for the RSGs associated with *Calcareous soils* (and *Barros* soils formed from calcareous materials), while the Eutric qualifier can be used for RSGs associated with *Modern alluvial soils* (Fluvisols) and *Kastanozems* (RSGs other than Phaeozems).

Other qualifiers can be inferred from the class boundaries of the typical subgroups of the CSP (Supplementary Material 1; Table 6). Subgroups such as *Para-Hydromorphic* may correspond to the Gleyic qualifier in RSGs influenced by groundwater and with deeper redoximorphic features, while those correlated with *Argilluviated soils* may correspond to the Stagnic qualifier (Monteiro, 2004; Monteiro et al., 2012). The subgroups *calcareous* (*Alluvial soils* and *Colluvial soils*) may correspond, as a proviso, to the Calcaric qualifier in correlated RSGs. The Calcic qualifier is adopted for correlated Vertisols that form over non-calcareous materials.

Soil phases in the 1:25,000 soil map legend (Cardoso, 1974) may also provide some insights into the occurrence and spatial distribution of some PQs. For example, the *thick soil phase* corresponds (100%) to the absence of the Leptic qualifier, but the *thin soil phase* coincides with the Leptic qualifier only at a proportion of 51% (33% Endoleptic and 18% Epileptic) (data not shown). Meanwhile, the *stony phase* only coincides with the Skeletic qualifier to a negligible extent (2%), while *poor-drained phases* only correspond to the Gleyic or Stagnic WRB qualifiers to a degree of 20%.

Some SQs can also be inferred from the CSP and the 1:25,000 map. For instance, *Humic Litholic soils* and *Non-Humic Litholic soils* (Supplementary Material 1; Cardoso, 1974) may correspond to Humic and Ochric SQs, respectively, which is consistent with the high prevalence of Ochric qualifiers (71%–99%) in soils formed from different lithological parent materials (Table 5). However, these trends should be considered alongside environmental variables (e.g., climate) along with land use and soil management.

Examples of converting soil units (Families; Cardoso, 1974) from the 1:25,000 soil map to the WRB (IUSS Working Group WRB, 2022) are shown in Supplementary Material 2.

The future of the CSP

Unquestionably, the current Classification of the Soils of Portugal (Cardoso, 1974; IHERA, 1999) does not accommodate

TABLE 5 Proportion (%) of Supplementary Qualifiers (SQs) occurring in soils developed on some lithological groupings (LGs).

LGs	SQs*										
	ar	lo	si	ce	oh	hu	mg	so	as	rp	ai
Granites	-	100	-	-	91	9	14	-	-	-	9
Diorites	-	95	-	5	95	5	27	27	11	-	2
Mafic rocks	-	17	3	50	90	10	23	10	-	-	3
Gneisses	8	83	-	-	96	4	13	4	-	-	4
Schists	-	17	30	37	71	29	35	5	-	1	1
Intermediate and mafic metamorphic rocks	-	79	-	12	99	1	53	26	6	-	-
Sandstones	6	67	-	-	100	-	22	-	-	17	11
Sands	100**	-	-	-	92	8	-	-	-	-	-
Alluvium	-	29	14	57	77	23	36	14	-	-	-
Unconsolidated or poorly consolidated arenaceous materials	13	47	-	-	97	3	19	-	-	19	-
Unconsolidated or poorly consolidated medium-textured materials	-	74	13	13	88	12	63	25	-	13	-
Clayey materials	-	9	9	82	91	9	64	18	-	9	9
Arenaceous materials on sandstones or clayey materials	28	50	-	16	97	3	44	22	-	56	-
Gravelly and sandy and/or clayey materials	-	57	14	29	86	14	43	-	-	43	-
Non-compact limestones	-	78	7	15	80	20	-	-	-	7	7

*ar, Arenic; lo, Loamic; si, Siltic; ce, Clayic; oh, Ochric; hu, Humic; mg, Magnesic; so, Sodic; as, Argisodic; rp, Raptic; ai, Aric.

**RSGs other than Arenosols.

the substantial advances in soil knowledge acquired in Portugal in the last decades (Pereira and FitzPatrick, 1995; IDRHa, SPCS, 2004; Sousa et al., 2004; Madeira et al., 2007; Monteiro et al., 2012; Monteiro et al., 2015), posing significant challenges for the updating and harmonizing of the existing soil maps in mainland Portugal (DGADR-SNIS, 2022). This limitation is partially due to the fact that the classification was developed considering the environmental setting of Southern Portugal, and therefore, it cannot be a true National Soil Classification. Further, the Classification of the Soils of Portugal still maintains, at the suborder categorical level, the vague term “Mediterranean soils”, which remains a source of confusion, mainly because of the variety of soils of different ages and origins that are grouped (FAO, 1970; Yaalon, 1997; Verheye and de la Rosa, 2005). The Classification of the Soils of Portugal has not been subjected to any modernization by introducing quantitative diagnostic criteria, linking the processes to diagnostics, or introducing new soil types and classification keys, unlike national classification systems (Kempen et al., 2009; Dondeyne et al., 2014; Michéli et al., 2019). It is therefore challenging to evaluate how it can be updated to cover soil diversity in the whole country, while ensuring simultaneously a high degree of correlation with the WRB (IUSS Working Group WRB, 2022).

Based on the status of the conventional 1:25,000 soil map, it was considered paramount decades ago to proceed to the revision and updating of the Classification of the Soils of Portugal (IDRHa, SPCS, 2004). At that time, its correspondence to the FAO (1998) was attempted by Sousa et al. (2004) using expert judgment, but it

was merely a proviso lacking precision, as the definitions of the categorical levels frequently do not include the level of description and quantification of characteristics required by the IUSS Working Group WRB (2022). As observed worldwide (Lagacherie, 2025), efforts to update the Classification of the Soils of Portugal and the 1:25,000 soil map were hindered by severe reductions in public financing for soil surveying, only allowing for the harmonization of existing soil maps (DGADR-SNIS, 2022). Given the current need to update and harmonize soil and land suitability maps, it is crucial to evaluate how the Classification of the Soils of Portugal can be modified to ensure the inclusion of large amounts of available soil legacy data and support harmonization with an international framework for the correlation of soils (IUSS Working Group WRB, 2022). Therefore, it is imperative to establish a national strategy that can garner broad consensus to be effective. Ultimately, the main point is to analyze the usefulness of updating the Classification of the Soils of Portugal to improve its relationship with the IUSS Working Group WRB (2022) and the accuracy of national soil mapping.

The maintenance of the current Classification of the Soils of Portugal is favoured by the fact that it was used in the soil mapping (at a 1:25,000 scale) of 54.4% of the mainland Portugal. However, in the soil map of the remaining 44,6% of the mainland (at a 1:100,000 scale; Agroconsultores, 1991; Agroconsultores, 1995; Agroconsultores, 2004), carried out with considerable analytical support, the terminology WRB was used, and no correlations were established with the Classification of the Soils of Portugal. Several options can be considered in this regard. First, the current

TABLE 6 Principal (PQs) and Supplementary (SQs) qualifiers applicable to correlated RSGs with some categorical levels of the Classification of the Soils of Portugal (CSP).

CSP		Correlated WRB RSGs	
Orders/Suborders/Groups	Subgroups	PQs	SQs
"Regosols" (sensu CSP)	<i>Para-hydromorphic</i>	Gleyic	-
Modern Alluvial soils	<i>Non-calcareous</i>	Eutric	-
	<i>Non-calcareous humic</i>	Eutric	Humic
	<i>Calcareous</i>	Calcaric	-
Colluvial soils	<i>Calcareous</i>	Calcaric	-
Humic Litholic soils	<i>Normals</i>	-	Humic
	<i>Para-Lithosols</i>	Leptic (Epileptic)	Humic
Non-Humic Litholic soils	<i>Normals</i>	-	Ochric
	<i>Para-Lithosols</i>	Leptic (Epileptic)	Ochric
	<i>Para-Calcareous soils</i>	Calcaric	Ochric
Calcareous soils	<i>Normals</i>	Calcaric	-
	<i>Para-"Barros"</i>	Vertic, Calcaric	-
	<i>Para-Lithosols</i>	Leptic (Epileptic), Calcaric	-
"Barros" (vertisols)	<i>Slightly decarbonated</i>	Calcic/Calcaric	-
	<i>Non-decarbonated</i>	Calcic/Calcaric	-
Argilluviated soils	<i>Para-"Barros"</i>	Vertic	-
	<i>Para-Hydromorphic</i>	Stagnic	-
	<i>With Plinthitic Materials</i>	Plinthic	-
Podzolized soils	<i>With Ortstein</i>	Ortsteinic	-
Halomorphic soils	<i>From alluvium</i>	Fluvic	-
Hydromorphic soils	<i>Para-Alluvial soils</i>	Fluvic, Eutric	-
	<i>Para-"Barros"</i>	Vertic	-
	<i>Para-Argilluviated soils</i>	Luvic	-
Hydromorphic organic soils	-	Fluvic, Eutric	Humic

classification could be maintained with pertinent alterations to incorporate new soil types identified in the mainland and autonomous regions. Second, a thorough revision could be undertaken, defining soil units at different taxonomic levels, in terms of descriptions and characteristics quantification, allowing an easy transposition to the WRB system. Those options are hindered, however, by the lack of unambiguous quantified criteria for numerous soil properties (e.g., diagnostic horizons, diagnostic properties, and diagnostic materials) based on laboratory and field data (IDRHa, SPCS, 2004), as revealed by the present study. Because of this, and the low degree of correspondence with the WRB (2022), we suggest identifying new soil units by using legacy soil data and new georeferenced field observations to obtain internationally correlated soil maps and overcome the obsolescence of the current Portuguese soil classification.

The most crucial approach is mapping new soil types and diagnostic categories based on stronger and more numerical criteria than the previous system, and analyzing their spatial patterns and relationships with the soil-forming factors while preserving the value of the national legacy soil information (Sousa et al., 2004; Dondeyne, et al., 2014; Madeira et al., 2015). Rather than seeing the present exercise as a conversion of legends, the reorganization of original soil types into higher-ranked classification categories, as determined by RSGs and qualifiers, provides new insights into the soil geography of mainland Portugal, as reported for other countries or regions (Adhikari et al., 2014; Dondeyne et al., 2014; Dobos et al., 2019). Because map users would need detailed information (Dondeyne et al., 2014), they can still refer to the information provided by the original 1:25,000 soil map, which implies converting the respective legend to the WRB system.

Conclusion and perspectives

The majority of the categorical levels in the Classification of the Soils of Portugal match the WRB RSGs to a lesser extent. The lowest correspondence (less than 50%) was found for the *Argilluviated soils not strongly unsaturated*, *Podzolized soils*, *Saline soils*, and *Hydromorphic soils without an eluvial horizon*. This correspondence is primarily due to differences in quantitative diagnostic criteria between those classification systems, the lack of well-defined morphogenetic and quantified diagnostic criteria and thresholds in the Classification of the Soils of Portugal, errors in the application of established quantitative criteria, and an insufficient set of reference soil profiles to reveal the range of soil units (and properties) in the area covered by this Classification. Legacy soil data are then indispensable for overcoming these limitations and updating and extending the Classification of the Soils of Portugal to cover the entire country, which could improve the correlation with the WRB system and the accuracy of future soil mapping.

Since fieldwork is not feasible due to budgetary constraints, the use of georeferenced legacy soil profile data, framed by soil-forming factors, is essential for implementing methodologies to convert the legend of the legacy 1:25,000 soil map and to validate both the soil classification and the updating of the national soil map. This approach is essential for the identification of spatial patterns and the prediction of soil units and properties in the landscape, thereby supporting the updated and harmonized soil information on which to base agricultural and environmental policies. However, the exclusive use of available legacy data has limitations due to its sparse and uneven distribution; therefore, future efforts must also prioritize the collection and integration of new soil data to ensure continuous soil map updating and a comprehensive soil information system.

The current methodology for converting the 1:25,000 soil map units to a WRB legend also has limitations associated with land-use changes, as some of the maps are based on data and field observations from sometimes more than 60 years ago, with the legacy soil profile collection gathered during the last 5 decades. Additionally, the expansion of irrigated areas, permanent crops (e.g., olive tree groves), forest plantations, and wildfires and encroachment may have affected the profile and characteristics of soils. Therefore, mapping land use temporal changes would be valuable for refining future soil mapping. The use of remote sensing data (including high-resolution data, such as LiDAR) could further enhance the characterization of soil properties (e.g., soil organic carbon, texture), capture changes in vegetation cover and anthropogenic landscape modifications (e.g., terracing), contributing to more accurate and dynamic soil mapping outputs.

Converting the legend of the current 1:25,000 soil map to a WRB legend at a scale of 1:100,000 could improve the spatial representation of soil units and soil properties. As map users need detailed spatial information on soil properties, the current legacy 1:25,000 soil map remains useful, provided that its legend is converted to the WRB by using conversion rules based on environmental soil-forming factors. These conversion efforts should also constitute an opportunity to update the

Classification of the Soils of Portugal and improve the accuracy of these maps.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/[Supplementary Material](#).

Author contributions

MM – Supervision, conceptualization, Investigation, writing and editing; SG – investigation, writing and editing; PA – investigation, writing and editing; VF – Investigation, writing and editing. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the protocol established between University of Lisbon - School of Agriculture (ISA) and the General Direction for Agriculture and Rural Development (DGADR) regarding the land suitability mapping, and by the University of Lisbon - School of Agriculture (ISA), through the “Professor Pedro Aguiar Pinto” Doctorate Incentive Award (SG). FCT - Fundação para a Ciência e Tecnologia, I.P. through project UID/04129/2025 (<https://doi.org/10.54499/UID/04129/2025>) of LEAF-Linking Landscape, Environment, Agriculture and Food.

Acknowledgements

The authors thank A. Azevedo Gomes, A. Afonso Martins (†), Carlos Alexandre, Fernando Raimundo, Fernando Monteiro (†), J. Casimiro Martins, Felícia Fonseca, João Duarte, Madalena Fonseca and Paulo Marques, for providing information and discussion to the morphological description and classification of the reference soil profiles. The enterprise “Florestas Sustentáveis”, João Coutinho, and Paulo Marques are also acknowledged for providing soil data, soil data analysis, and processing data, respectively.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontierspartnerships.org/articles/10.3389/sjss.2026.16368/full#supplementary-material>

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