Catena 264 (2026) 109746

Contents lists available at ScienceDirect

Catena

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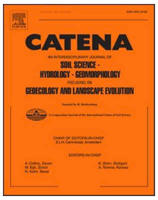

The influence of soil physico-chemical properties and land uses on organic carbon stocks in contrasting Mediterranean pedosystems

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ARTICLE INFO

Dataset link: Research Data unavailability explanation (Reference data)

Keywords:
Carbon cycle
Biodiversity hotspots
Factor analysis
Principal component analysis
Soil formation processes

ABSTRACT

Soil plays a pivotal role in the processes and behavior of the global carbon cycle, with soil organic carbon stocks (SOCs) representing the largest terrestrial carbon (C) pool. Mediterranean areas are among the world's biodiversity hotspots for conservation priorities. The island of Sardinia (southern Italy), due to the rare convergence of environmental and historical land use factors, is characterized by extremely peculiar soil conditions. This study investigated SOCs and their behavior in two contrasting Mediterranean pedosystems: Cambisols developed on granite (the most common pedosystem) *vs* Luvisols on limestone (one of the rarest), featuring different land covers with a gradient varying from agricultural (vineyard at different ages) to more natural areas (remnants of natural potential vegetation cover). Several soil physico-chemical features were assessed. An ANOVA was conducted to determine significant differences ($p < 0.05$) between and among investigated horizons and land uses. The variability and complex multiple relationships were analyzed by factor (FA) and principal component analysis (PCA). Results revealed that areas with natural or near-natural features exhibited significantly higher SOCs compared to more intensively managed and human-influenced land covers. Interestingly, the two investigated pedosystems, originating from diverse substrates and thus contributing to different soil formation processes, are characterized by significantly different SOC amounts and behaviors. Overall, soil features have a greater influence on SOCs than usually expected and previously reported. Consequently, this study suggests that SOC investigations, if not conducted in conjunction with a thorough soil analysis, may lead to inaccurate or misleading outcomes and subsequent conclusions.

1. Introduction

The Mediterranean Basin is one of the world's biodiversity hot-spot for conservation priorities (Myers et al., 2000). Today, only 4.7 % of the ancient primary vegetation (originally spanning 2,362,000 km^2) remains due to direct and indirect historical human activities (Cuttelod et al., 2009). Thus, it is now being considered an under–threat and the most susceptible European region; an issue exacerbated by the effects/impacts of climate change (Schröter et al., 2005) that are particularly exacerbated along the Mediterranean Basin (Giorgi, 2006; Cos et al., 2022).

Reducing the effects of climate change involves containing the atmospheric emission of greenhouse gases (GHGs), primarily carbon dioxide (CO_2). This goal can also be achieved through carbon (C) sequestration (Ramachandran Nair et al., 2010), *i.e.*, the process of transferring and storing atmospheric CO_2 in long-lasting C pools through natural processes (Lal, 2008).

Among the five primary C pools (oceans, lithosphere, pedosphere, atmosphere, and biosphere; Lal, 2008), the pedosphere represents the largest terrestrial C pool (Nave et al., 2019), holding approximately 1700 GtC, which is roughly twice the amount in the atmospheric (c.a. 875 GtC) and more than three times the total stored in the biotic (c.a. 450 GtC) (Friedlingstein et al., 2022) pools. Additionally, the carbon stored in the pedosphere plays a pivotal role in the global carbon cycle (Lal, 2004) and land management, thanks to its ability to perform multiple functions and provide benefits (Wiesmeier et al., 2019).

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https://doi.org/10.1016/j.catena.2025.109746
Received 27 June 2025; Received in revised form 28 November 2025; Accepted 14 December 2025

In contrast to C found in the other pools, the C featured in soils is usually much older and not inert, exhibiting a dynamic nature that influences its interactions with atmospheric CO_2 levels and, consequently, with climate change (Nave et al., 2019). Aside from its role in reducing atmospheric CO_2 concentration, soil C sequestration also contributes to enhancing soil organic carbon stocks (SOCs), thus improving soil quality and the overall ecosystem goods and services, such as (Lal et al., 2015): *i*) increasing water and nutrient retention; *ii*) reducing the risk of erosion and soil degradation; and, *iii*) promoting long-term food and nutrition security, as well as additional benefits such as enhanced soil structure, increased biological activity, improved resilience to drought and compaction, and support for terrestrial biodiversity. Multiple factors can impact SOC amounts and behavior, such as changes in soil/land use and management (Lal, 2004; Roder et al., 2023), as well as several soil physical and chemical features (Capra et al., 2018).

Over the past decade, there have been different studies aiming at investigating SOCs in various land covers across Sardinia (vineyard included), yielding significant findings. All of them focused on evaluating SOCs and soil quality under various land uses, analyzing a few specific soil parameters, and utilizing predictive models (Seddaiu et al., 2013; Francaviglia et al., 2014; Cappai et al., 2017; Francaviglia et al., 2017; Lozano García et al., 2020). Nonetheless, there is a lack of studies investigating the influence of soil physico-chemical parameters on SOCs while additionally considering the differences and related behaviors between highly contrasting pedosystems. Specifically, there is a critical knowledge gap regarding the extent to which intrinsic soil physico-chemical features or management-driven changes are the dominant controls on SOC stocks in contrasting soil types typical of Mediterranean pedoenvironments. This gap is particularly relevant for the region, given the mosaic of soils and the ongoing land use conversion from forest to intensive viticulture.

Accordingly, this study was specifically designed to address these open questions by pursuing the following objectives: *i*) quantitatively comparing SOC stocks and their vertical distribution in two contrasting Mediterranean pedosystems (Cambisols on granite *vs* Luvisols on limestone) under comparable land uses; *ii*) assessing the relative influence of soil physico-chemical properties and historical land use patterns (ranging from recently established to mature vineyards and natural forest remnants) on SOC retention; *iii*) disentangling the relative importance of inherent soil features *versus* current land use management as drivers of SOC quantity and behavior; *iv*) interpreting the complex relationships among multiple soil parameters and SOC dynamics (utilizing advanced multivariate statistical approaches) not as an end in itself, but to yield novel integrative insights into SOC stabilization mechanisms within each geopedological context.

2. Materials and method

2.1. Study areas

The two investigated pedosystems were in Monti (MON, hereafter; north−eastern Sardinia, Monti municipality, 40° 48′ 0″ N, 9° 20′ 0″ E) and Santa Maria La Palma (SMLP, hereafter; north-western Sardinia, Alghero municipality, 40° 39′ 39.56″ N, 8° 16′ 18.26″ E) locations (Fig. 1).

The island of Sardinia (central-western Italy) boasts one of the oldest histories of land use and related human-induced changes in Europe, dating back to the Nuragic culture (18th century to 238 BCE) (Balmuth, 1992). Its importance is also related to the presence of endemic plant species (Fois et al., 2022), representing (*i*) one of the last fragments of untouched holm oak (*Quercus ilex* L. subsp. Ilex; *Q. ilex*, hereafter) and cork oak (*Quercus suber* L., *Q. suber*, hereafter) forests (Bacchetta et al., 2009) (*ii*) one of the best-documented cases of ancient bio-cultural landscapes in the whole Mediterranean Basin (Malavasi et al., 2023). Forests and semi−natural areas are the dominant land use, covering 53 % of the territory, closely followed by agricultural areas (43 %) (Costantini and Dazzi, 2013). Wine production is a significant socio-economic reality (Benedetto et al., 2014). Vermentino is the second most important grape in the regional framework (28 % of the whole wine production), with its original production concentrated in the Gallura sub − region (north−eastern Sardinia), typically featured by granitic rocks, the most common Sardinian substrate (29 % of the whole Region; Aru et al., 1991). However, due to increasing market demand, it is now commonly produced in other Sardinian sub-regions, such as in the Nurra (northwestern Sardinia), where it is cultivated over a limestone substrate, representing less than 5 % of the region's total area (Aru et al., 1991).

Both areas are featured by a hot−summer Mediterranean climate according to the Köppen−Geiger classification (Köppen, 1936), with rainy, mild winters and hot and dry summers. In the MON site (300 m a.s.l.) the mean annual rainfall is 677 mm, while mean annual temperatures range from 9.6 °C (winter) to 20.4 °C (summer). In the SMLP site (34 m a.s.l.) the mean annual rainfall is 563 mm, with mean annual temperatures ranging 12.2 °C and 22.4 °C during the winter and summer period, respectively (Agenzia Regionale per la Protezione dell'Ambiente della Sardegna–ARPAS, 2020). The bioclimate is of the Mediterranean Pluviseasonal Oceanic type, being of the lower Mesomediterranean upper dry strong euoceanic isobioclimate at SMLP and the lower Mesomediterranean lower subhumid weak euoceanic isobioclimate at MON (Canu et al., 2015).

2.2. Selection of study sites and pedosystems

The selection of study sites and pedosystems was conducted using a multistep approach designed to capture the eco-pedological diversity of Sardinia while ensuring comparability and representativeness across land uses. We first conducted a comprehensive GIS-based overlay analysis in QGIS (QGIS Development Team, 2023), integrating regional land-use, vegetation, geological, morphological, and soil maps. All required information and datasets (Land Use Map of Sardinia, Geological and Soil Map, Vegetation Cover, *etc.*) were taken from the "Sardinia Geoportal" (RAS, 2025), *i.e.*, the official online portal providing centralized access to all Sardinia geographic data, such as maps, environmental datasets, and technical cartography. Thus, site identification was based on the following criteria: *i*) representing both the lithological and pedological variability of Sardinia, targeting two functionally contrasting reference soil systems typical of the Mediterranean, *i.e.*, Cambisols developed on granite, and Luvisols on limestone; *ii*) within each selected pedosystem, it was essential to identify paired areas supporting a sequence of comparable land uses; specifically, vineyards of the same grape cultivar (Vermentino), planted at three different time intervals (3, 15, and 30 years; V3, V15, V30), and remnant patches of the pre-existing forest (serving as proxies for potential natural vegetation, FOR); *iii*) candidate sites needed to be accessible and large enough to accommodate replicated sampling, while minimizing within-site geological and landscape variability.

The early GIS screening identified approximately fifteen candidates distributed across the whole of Sardinia territory. These sites were subsequently evaluated in the field to confirm that both the target soil types and land-use sequences were accurately represented. This approach ultimately led to the selection of only two possible pedosystems: a Cambisol-dominated landscape on granite in Monti (MON), and a Luvisol-dominated area on limestone in Santa Maria La Palma (SMLP). A representative picture of the two contrasting pedosystems is furnished in Fig. 2, showing a paradigmatic example of investigated soil profiles, allowing: *i*) direct comparison of the morphological differentiation between the two soils; *ii*) illustrating the uniqueness of the studied profiles, by visually linking pedogenetic features. This design enabled the investigation of SOC dynamics under rigorously controlled pedological and land-use contrasts, with relevance for Sardinian landscapes and Mediterranean-type ecosystems elsewhere.

A detailed soil survey was carried out on both pedosystems prior to

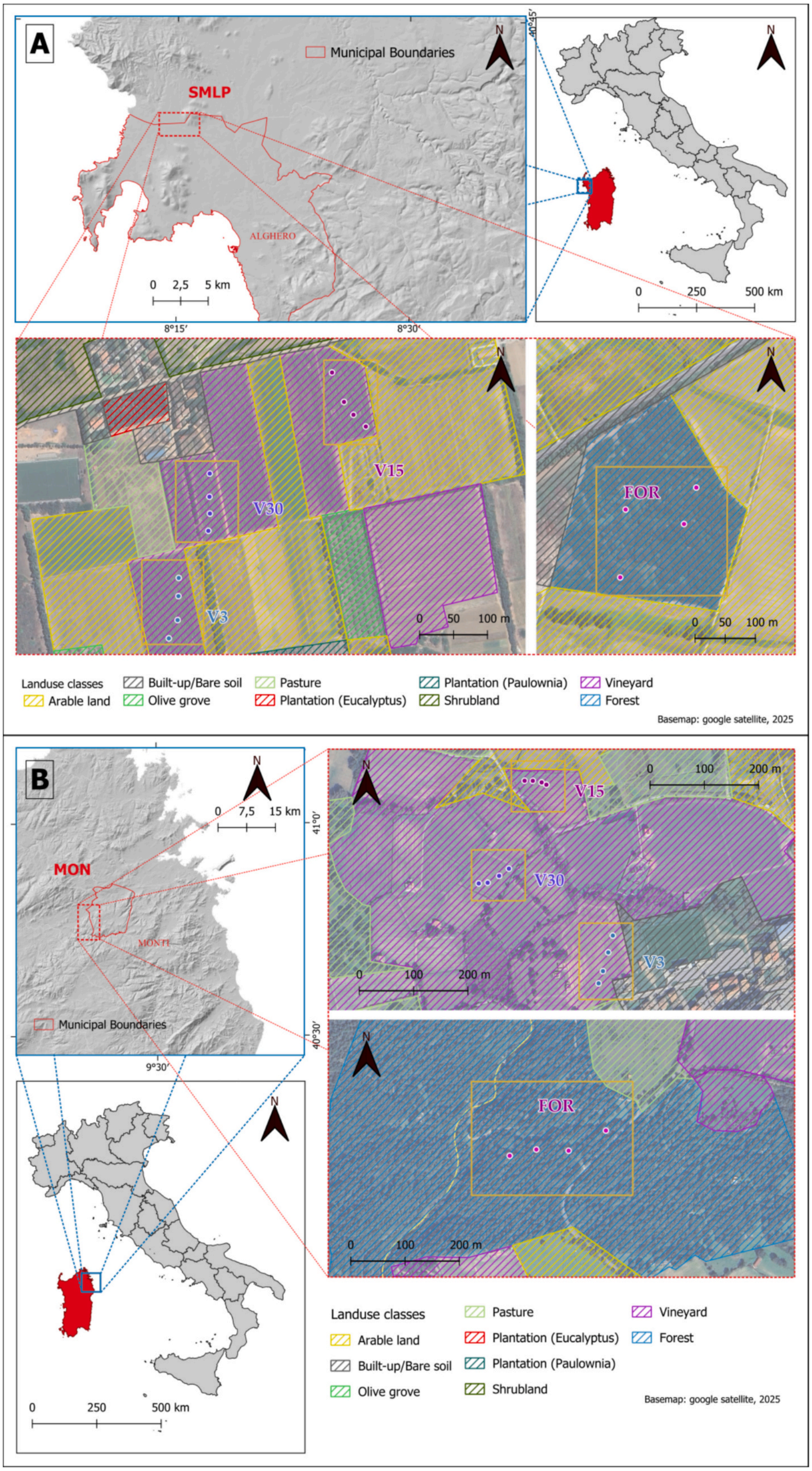

Fig. 1. Study areas and experimental design. MON: Monti; SMLP: Santa Maria La Palma; V3: Vermentino planted three years ago (at the time of the sampling activities, *i.e.*, 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; FOR−MON: cork oak (*Q. suber*) forest; FOR−SMLP: holm oak (*Q. ilex*) forest.

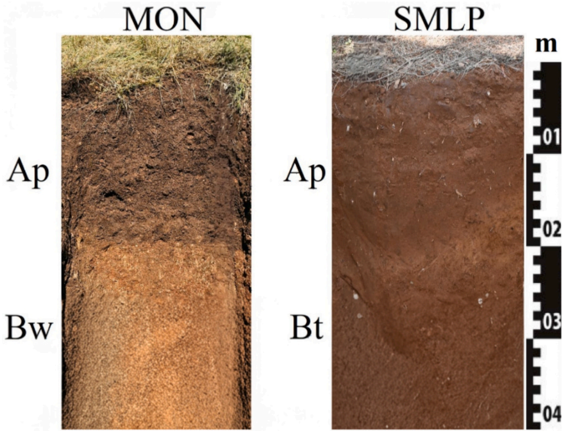

Fig. 2. Representative picture of the two contrasting pedosystems. MON: Monti (Dystric and Eutric Cambisols; IUSS Working Group WRB, 2022); SMLP: Santa Maria La Palma (Rhodic and Chromic Luvisols; IUSS Working Group WRB, 2022).

the initiation of sampling activities. The survey results provided crucial baseline information on soil horizon development, physical structure, and diagnostic properties (IUSS Working Group WRB, 2022), ensuring the representativeness of the selected profiles and guiding the subsequent sampling design. Overall, soil depth is rarely over 40/60 cm in both investigated pedosystems.

The MON site belongs to the most widespread Sardinian landscape units, *i.e.*, those characterized by intrusive rocks (granites, granodiorites, leucogranites) of the Paleozoic era, covering a surface area of approximately 29 % of the Sardinian Island (Aru et al., 1991). The pre-sampling pedological assessment, performed according to standard classification protocols (IUSS Working Group WRB, 2022), confirmed that the soils of this site are classified as Dystric and Eutric Cambisols (IUSS Working Group WRB, 2022). This pairing of soil and parent material (*i.e.*, Cambisols on granites) accounted alone for 17.5 % of the overall Sardinian surface, being mainly featured by sandy to sandy−loam texture, shallow soil depth, significant erosion risk, low or poor fertility (Aru et al., 1991). Regarding land use, they are, as typical for the entire Sardinian territory, closely related to the socio−cultural aspects. Monti is renowned for its widely cultivated Sardinian wine grape cultivar: the Vermentino (*vide supra*; Mercenaro et al., 2017). In Monti, as in the entire Gallura sub − region the agroforestry systems shaped the landscape, playing a vital socio−economic and cultural role. Sheep grazing shaded with *Q. suber* L. trees, accompanied by harvesting of non − timber forest products such as cork, is the most common land use (Bagella et al., 2016). This is the reason why only a few fragments of the original forest cover remain, especially in areas belonging to private owners and strategically located in morphological positions (such as the summit) thus allowing to avoid soil degradation processes affecting productive areas (usually located along the back− and foot−slope).

In SMLP soils are developed on limestones, dolomites, and dolomitic limestones of the Paleozoic and Mesozoic eras. They represent less than 5 % of Sardinia's total surface area (Aru et al., 1991). Soils were classified as Rhodic and Chromic Luvisols (IUSS Working Group WRB, 2022), constituting one of the rarest units (*i.e.*, Luvisols on limestone) in Sardinia, accounting for just 1.7 % of the territory. They are usually characterized by the presence of a clay to clay−loam soil texture, high rockiness and stoniness, shallow soil depth, and a strong risk of erosion. Although the classical Luvisol sequence includes a distinct eluvial (E) horizon above the argic (Bt) one, this was not morphologically evident in the studied SMLP profiles in the field (Fig. 2). However, according to the World Reference Base for Soil Resources criteria (IUSS Working Group WRB, 2022), the presence of a well-developed argic horizon is sufficient for Luvisol classification, even in the absence of a visible E horizon, provided that textural and chemical requirements are met. In carbonate soils of Mediterranean Sardinia, the absence of the E horizon is common due to past paleoclimatic conditions (Aru et al., 1991; Costantini and Dazzi, 2013). In fact, in Sardinian carbonate soils, the most common sequence is a surface A horizon (over a Bt), often rich in organic matter or subject to mixing due to pedogenic and biological activity. This surface horizon can encompass or obscure minor traces of eluviation, tending to mask or "destroy" the actual E. Thus, the Bt horizons are interpreted as largely relict features, formed during wetter paleoclimatic phases, and their presence remains the diagnostic criterion for Luvisols in these contexts (Aru et al., 1991; Costantini and Dazzi, 2013).

Even in these areas humans strongly shaped the original landscape with agriculture (such as vineyards), pasture, and tourism, representing among the most impacting human activities. The Vermentino grape was introduced in relatively recent times, if compared to MON site. The potential natural vegetation (PNV), once covering more than 75 % of the Nurra sub − region (north−western Sardinia), is mainly represented (in more inland areas, far from the sea influence) by *Q. ilex* L. forests (Bacchetta et al., 2009). Also in this case, the PNV still survives in small fragments, now protected by the Autonomous Region of Sardinia (RAS) for conservation purposes. Potential natural vegetation is the plant community that would become established if all sequences of secondary succession were completed without interference by humans under the present climatic and edaphic conditions, including those previously altered by human activities (Farris et al., 2010). Therefore, the PNV is a valuable reference for defining targets in restoration ecology or for forecasting and managing landscape evolution on a timescale of a few decades (Dostálek et al., 2007). It serves as a reference point for evaluating the effects of viticulture. By analyzing PNV, we can understand how vineyards impact the parameters investigated compared to the most natural land use.

2.3. Soil sampling

The sampling scheme was completely randomized (Fig. 1) with 4 replications for each investigated land use, thus: ***MON pedosystem***: a) MON—V3, *i.e.*, a vineyard planted 3 years ago (from the time of sampling activities); b) MON—V15, a vineyard planted 15 years ago; c) MON—V30, a vineyard planted 30 years ago; d) MON−FOR, a forest of cork oak representing the natural potential vegetation for the area; ***SMLP pedosystem***: a) SMLP−V3, a vineyard planted 3 years ago; b) SMPL−V15, a vineyard planted 15 years ago; c) SMPL−V30, a vineyard planted 30 years ago; d) SMLP−FOR, a forest of oak representing the natural potential vegetation for the area. All vineyards at both the MON (Monti) and SMLP (Santa Maria La Palma) sites are managed under conventional practices, including periodic irrigation and mechanical tillage. Tillage is typically performed with a tractor-mounted rotary plow (or disk harrow) to a depth of 20–30 cm. A pressure-compensated drip irrigation system is utilized throughout the growing season to maintain optimal soil moisture levels. All management practices are consistent across all vineyard age classes, with the obvious exception of changes made according to climate or plant annual needs and have been verified through direct communication with landowners and managers.

Soil pits (~60 cm deep) were excavated manually (Fig. 2), and samples were collected at two fixed depths: (i) 0–20 cm and (ii) 20–40 cm. Such depths were selected after a careful pedological investigation of the two analyzed areas. Indeed, for both MON and SMLP pedosystems we found a soil profile featured by an A_p (or A) − B($_t$ for SMPL and $_w$ for MON) followed by a lithic contact (R) or a C horizon at the depth from 40 till to 60 cm. Additionally, in all investigated cases the soil surface (A or A_p) and subsurface horizons (B_w or B_t) were included in the two fixed depths. This means that we were in front of one of those (rare) cases where the so−called sampling scheme at fixed depth (also called "soil control section" (SCS) approaches), corresponds to the pedogenetic horizon one (the "entire soil profile" (ESP) scheme) (Francaviglia et al., 2017), allowing us comparisons among the different soil land−uses.

Only for the aspect regarding the depth, the IPCC approach for SOCs investigation (IPCC, 2006) was not applicable in the investigated case, since it foresees sampling the first 0–30 cm, meaning mixing two samples with competently different physical−chemical and pedogenetic features, thus causing a misinterpretation of the obtained results (Roder et al., 2023).

Overall, 64 soil samples were investigated (4 land uses × 2 sites × 4 replicates × 2 soil depths) for the following analyses.

2.4. Soil analyses

During the field campaign, undisturbed samples from the A/Ap (0–20 cm) and Bt/Bw (20–40 cm) horizons were collected using the metal-cylinder method for bulk density determination (Soil Survey Staff, 2022).Soil physical−chemical analyses were conducted on soil air−-dried ⌀ < 2 mm according to Italian official procedures (Ministero per le Politiche Agricole e Forestali−MIPAF, 2000). Sand (2.0–0.2 mm), silt (0.02–0.002) and clay (< 0.002) fractions were separated by sedimentation procedure; samples were pre − treated with H_2O_2 and sodium hexameta−phosphate. Textural classes were thus identified according to USDA (Soil Survey Staff, 2022). Soil pH − H_2O was measured using a dynamic digital pH − meter in a soil:water suspension of 1:2.5. Soil electrical conductivity (EC; μS cm^{-1} 25 °C) was determined using a 1:5 soil:water suspension. Sieved samples were finely ground in a ball−mill grinder and used to determine soil organic carbon (SOC) and total N (g kg^{-1}) concentration by dry combustion using a high−efficiency CHN elemental analyzer (CHN 628; Leco, St. Joseph, Michigan, USA). Soil organic matter (SOM) was determined by using the Van Bemmelen coefficient (SOC × 1.724). Available P was extracted by the Olsen method, while total P was determined by spectrophotometry with the ascorbic acid method. Cation-exchange capacity (CEC) was measured by saturation with $BaCl_2$ at pH 8.2. Exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and micronutrients were determined by atomic absorption spectrophotometry following specific extraction procedures: Fe was extracted with HCl (HCl-extractable Fe), whereas Mn, Zn, and Cu were extracted with a mixture of HNO_3 and HCl (acid-extractable).

Soil organic carbon stocks (SOCs; t ha^{-1}) was determined as following (IPCC, 2006):

$$\mathrm{SOCs}\left(\mathrm{t\ ha^{-1}}\right) = \mathrm{HD} \times \mathrm{BD} \times (1 - \mathrm{CF}) \times \mathrm{SOC} \times 10 \tag{1}$$

where,

HD: thickness of the soil horizon (cm); BD: bulk density (g cm^{-3}); *CF*: volumetric fraction of coarse fragments (> 2 mm), expressed as a decimal; SOC: soil organic carbon content of the investigated horizon (%); 10: factor converting units to t ha^{-1}.

2.5. Statistical analyses

Univariate, bivariate, and multivariate statistics were carried out by using the software programs R (R Core Team, 2023), RStudio (Posit team, 2025), and Statistica 7.1 (StatSoft Inc. Development, 2006). The analysis of variance (ANOVA) was performed to detect statistically significant differences, by using the Tukey−HSD (honestly significant difference) post−hoc test at $p < 0.05$. All ANOVA assumptions, including normality (verified using Q-Q plots and the Shapiro–Wilk test), homogeneity (tested using Levene's test), and independence (achieved through randomized sampling), were fully met for all datasets. Where required, a Box–Cox transformation was applied to ensure normality. The multivariate statistics consisted of: *i*) a factor analysis (FA), which was employed for data interpretation and hypothesis testing, utilizing the procedure initially introduced by Reimann et al. (2002) and subsequently adapted by Capra et al. (2014) for soil physico−chemical datasets; *ii*) a principal component analysis (PCA), utilized for data compression and visualization, without presuming any causal relationships among the variables under investigation. Specifically, for the FA the following steps were followed: *i*) the complete dataset was assessed for normal distribution; *ii*) the raw datasets underwent Box–Cox transformation to approximate normality; *iii*) a Pearson correlation matrix (CM; *0.05, **0.01, ***0.001) was computed on the Box–Cox transformed data; and, *iv*) FA was performed based on the CM as described previously in point (*iii*). For enhancing the statistical robustness in the results interpretation, a varimax rotation was applied. The PCA was conducted using a robust approach (Filzmoser et al., 2009): *i*) dataset underwent an isometric logratio transformation (ilr); *ii*) as this transformation results in uninterpretable variables in terms of their original names, further steps were taken; *iii*) the data was subsequently back−transformed to the centered logratio (clr) transformation, enabling interpretation concerning the original variable names. Both PFA and PCA were performed on all sampled horizons, rather than restricting analysis to surface A horizons, because it offers greater statistical power and is the preferred approach in contemporary pedological studies (Filzmoser et al., 2009; Jolliffe and Cadima, 2016). This approach provides a complete assessment of multidimensional soil variability, capturing key vertical trends, land-use impacts, and pedogenic processes central to Mediterranean and stratified soil systems (Capra et al., 2014). When used in this way, it (i) maximizes representativeness, (ii) reveals the dominant variance factors and components, and (iii) allows empirical patterns to emerge naturally, thus (iv) avoiding bias or overfitting due to arbitrary horizon selection (Filzmoser et al., 2009; Capra et al., 2014; Jolliffe and Cadima, 2016). Principal factor analyses and PCA are broadly recommended for studies like those reported in the present paper, *i.e.*, investigating the interaction among soil formation, management, and SOCs across diverse pedoenvironments (Capra et al., 2018; Guo et al., 2018).

3. Results

3.1. Soil physical parameters

Table 1 shows the soil physical parameters within the surface (A or Ap horizon, 0–20 cm) and subsurface (Bw or Bt, 20–40 cm) soil horizons for the contrasting pedosystems (MON *vs* SMLP). In the MON pedosystem, featured by Cambisols developed on granite, the soil texture (USDA, 2017) is sandy−loam. Conversely, the SMLP, characterized by Luvisols on limestone, predominantly exhibited a clay-loam soil texture, with a higher clay content in the subsuface horizons.

Significant differences ($p < 0.05$) were observed between MON *vs* SMLP for all mineral fractions. The sand content was significantly higher in the MON pedosystem for both A and B horizons, across all land uses. Conversely, SMLP showed significantly higher silt and clay contents in both horizons, for all land covers. When comparing the different land covers, some significant differences ($p < 0.05$) were observed for sand and clay contents. At SMLP, the sand content in the B horizons is higher in vineyards than in FOR. In MON, the clay content in A horizons was significantly higher in V15 compared to V3 and V30. In SMLP, its content in B horizons was significantly higher in FOR compared to V15 and V30.

The BD was significantly higher in the A horizons of SMLP's vineyard areas compared to those of MON. The SMLP pedosystem, when assessing the differences between land covers, shows significant differences ($p <$ 0.05), with the FOR-land cover exhibiting the lowest BD values in both A and B horizons compared with vineyards.

3.2. Soil chemical parameters

Fig. 3 shows some of the soil chemical parameters investigated within the surface (A or A_p horizon, 0–20 cm) and subsurface (B_w or B_t, 20–40 cm) soil horizons, comparing the two contrasting Mediterranean pedosystems (MON *vs* SMLP). As expected, soils developed on granite (MON) are featured by an acidic pH (Fig. 3a), ranging from very strongly acidic (4.5) to neutral (6.8), with a mean value of 5.5 ± 0.2 (strongly

Table 1
Soil physical parameters for MON and SMLP pedosystems (mean ± SE).

Land cover	**Soil Horizon**	**Texture**	**Sand** (%)	**Silt** (%)	**Clay** (%)	**Bulk density** (g cm^{-3})
MON						
V3	A_p	SL	79 ± 3 Aa	11 ± 1 Ba	10 ± 2 Bb	1.0 ± 0.1 Ba
	B_w	SL	77 ± 3 Aa	12 ± 1 Ba	11 ± 2 Ba	1.3 ± 0.0 Aa
V15	A_p	SL	74 ± 2 Aa	12 ± 1 Ba	14 ± 1 Ba	1.1 ± 0.1 Ba
	B_w	SL	74 ± 2 Aa	12 ± 1 Ba	14 ± 2 Ba	1.4 ± 0.0 Aa
V30	A_p	SL	77 ± 2 Aa	15 ± 1 Ba	9 ± 1 Bb	1.2 ± 0.0 Ba
	B_w	SL	71 ± 2 Aa	16 ± 1 Ba	14 ± 1 Ba	1.4 ± 0.0 Aa
FOR	A	SL	76 ± 1 Aa	14 ± 1 Ba	10 ± 0 Bab	1.2 ± 0.1 Aa
	B_w	SL	75 ± 1 Aa	14 ± 1 Ba	11 ± 0 Ba	1.4 ± 0.0 Aa
Mean	A/A_p		76 ± 2	13 ± 1	11 ± 1	1.1 ± 0.1
	B_w		74 ± 2	14 ± 1	12 ± 1	1.4 ± 0.0
SMLP						
V3	A_p	CL	39 ± 4 Ba	30 ± 3 Aa	30 ± 2 Aa	1.4 ± 0.0 Aa
	B_t	CL	38 ± 5 Ba	31 ± 2 Aa	31 ± 3 Aab	1.4 ± 0.0 Aa
V15	A_p	CL	39 ± 1 Ba	32 ± 1 Aa	29 ± 1 Aa	1.4 ± 0.0 Aa
	B_t	CL	39 ± 1 Ba	32 ± 1 Aa	30 ± 2 Ab	1.4 ± 0.0 Aa
V30	A_p	CL	42 ± 2 Ba	30 ± 2 Aa	29 ± 1 Aa	1.3 ± 0.0 Aa
	B_t	CL	41 ± 2 Ba	29 ± 2 Aa	30 ± 1 Ab	1.4 ± 0.0 Aa
FOR	A	CL	42 ± 10 Ba	27 ± 4 Aa	31 ± 8 Aa	0.8 ± 0.2 Ab
	B_t	C	23 ± 4 Bb	29 ± 3 Aa	48 ± 7 Aa	1.0 ± 0.1 Bb
Mean	A/A_p		41 ± 4	30 ± 2	30 ± 3	1.2 ± 0.1
	B_t		35 ± 3	30 ± 2	34 ± 3	1.3 ± 0.0

MON: Monti; SMLP: Santa Maria La Palma; V3: Vermentino planted three years ago (at the time of the sampling activities, *i.e.*, 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; FOR−MON: cork oak (*Q. suber*) forest; FOR−SMLP: holm oak (*Q. ilex*) forest; C: clay; CL: clay loam; SL: sandy loam. A number followed by different capital letters showed significant differences ($p < 0.05$) among different pedosystems (MON *vs* SMLP) for the same land cover and soil horizon; different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem and soil horizon.

acidic) for the A and 5.7 ± 0.2 (acidic) for the B horizons. On the opposite, SMLP pedosystem, developed on limestone, shows a higher pH, ranging from slightly acidic (6.3) to slightly alkaline (7.6), with mean values of 6.6 ± 0.1 for A and 6.9 ± 0.2 (neutral) for B horizons. Due to these differences in parent material, when comparing MON (on granite) *vs* SMLP (on limestone), results revealed significant differences ($p < 0.05$) in both A and B horizon for nearly all land covers (V3 apart), where pH SMLP > MON. Among the different land covers, some significant differences ($p < 0.05$) were observed in the B horizon for the MON pedosystem, particularly highlighting the significant difference between the most acidic soil (5.3 ± 0.2) present in the FOR-land cover and the slightly acidic (6.3 ± 0.2) in V3.

Soil EC (Fig. 3b) was higher in SMLP than MON. On horizon A, when comparing the differences between the contrasting pedosystems, significant differences were observed in V3 and V30 land covers, with MON > SMLP in V3, while the opposite (SMLP > MON) for V30. On the B horizon, differences in V3 and FOR were observed, in which MON > SMLP in V3, while the contrary in FOR, with SMLP > MON.

Soil organic matter (SOM; Fig. 3c) was generally higher in SMLP than MON. Significant differences ($p < 0.05$) were observed in the V30 for both horizons and in FOR in the B horizon, with SMLP > MON. Regarding the different land covers within the pedosystems, the FOR presented significantly highest SOM contents on A horizons for both MON and SMLP. Additionally, in the B horizon, FOR land cover shows significantly higher SOM amounts compared to V30 for both MON and SMLP pedosystems.

Total N (Fig. 3d) showed means in SMLP exceeding twice the amount observed in MON, for both the A and B horizons. The comparison MON *vs* SMLP in both horizons for this parameter corresponded with the previous one for SOM.

Total P (Fig. 3e) in SMLP at the A horizon presented mean values 1.3 times higher than those in MON, while it was 1.4 times higher in the B horizon. When comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in V15 and FOR for both A and B horizons, with SMLP > MON. Conversely, the V3 A horizon showed a significantly higher concentration ($p < 0.05$) of MON compared to SMLP. At MON, when comparing the different land covers, it was observed that V30 showed a significantly higher ($p < 0.05$) total P concentration in the A horizon compared to V15 and FOR. Also, V30 and V3 were significantly higher ($p < 0.05$) than V15 in the B horizon. Similar outcomes were observed in SMLP, with V15 and V30 showing higher ($p < 0.05$) total P in the A than V3, while V30 showed higher total P than V3 in the B horizon.

Available P (Fig. 3f) among pedosystems, showed SMLP significantly ($p < 0.05$) higher values than MON in the V15 for both horizons. Conversely, MON was significantly higher than SMLP in the V30 A horizon and in the FOR-B horizon. When comparing the different land covers, the available P in V30 was significantly higher in the MON A horizon. At SMLP, the V30 was higher than V3 on the A horizon, and higher than V3 and FOR in the B one.

The C/N ratio (Fig. 3g) was similar for both pedosystems and horizons. When comparing MON *vs* SMLP, MON was significantly higher ($p < 0.05$) in the V30 surface and in the FOR subsurface horizon. Comparing the different land covers, at MON surface, the V30 was significantly higher ($p < 0.05$) than V15.

Exchangeable acidity (Fig. 3h) values were generally lower in SMLP, with the mean approximately 2.4 times lower than MON in the A horizon and about two times lower in the B horizon. In MON, H + Al showed significantly higher ($p < 0.05$) values than SMLP for V30 (both horizons) and in FOR (surface), as expected. However, the opposite was observed for V3 (both horizons), where SMLP > MON. Comparing the different land covers, some significant differences ($p < 0.05$) were observed in the B horizon at MON, with V15 showing higher H + Al than V3.

Exchangeable cations (Fig. 4) at MON were generally lower than at SMLP. Comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in some of the land covers for all exchangeable cations, with SMLP > MON, except for V3—B for Mg (which showed the opposite trend, with MON > SMLP). Some significant differences ($p < 0.05$) were observed when comparing the different land covers along the A horizon. At MON-A, the differences were observed only for exchangeable Mg and K, with V15 showing a higher concentration than V30 for Mg. In contrast, V30 showed the highest concentration for K. At SMLP-A, differences were observed for all exchangeable cations, with FOR showing the highest concentrations for almost all of them, except for Na, where V3 was higher than V30. Along B horizons, some significant differences ($p < 0.05$) were also observed. At MON—B, differences were observed only for K, with V30 higher than V15. At SMLP-B, the differences were observed for almost all exchangeable cations (except for Na), with FOR exhibiting the highest concentrations.

Legend as in Fig. 3.

Comparing CEC (Fig. 4e) in MON *vs* SMLP, significant differences ($p < 0.05$) were observed in the V3 and FOR land covers in both A and B horizons, with SMLP > MON. When comparing the different land covers

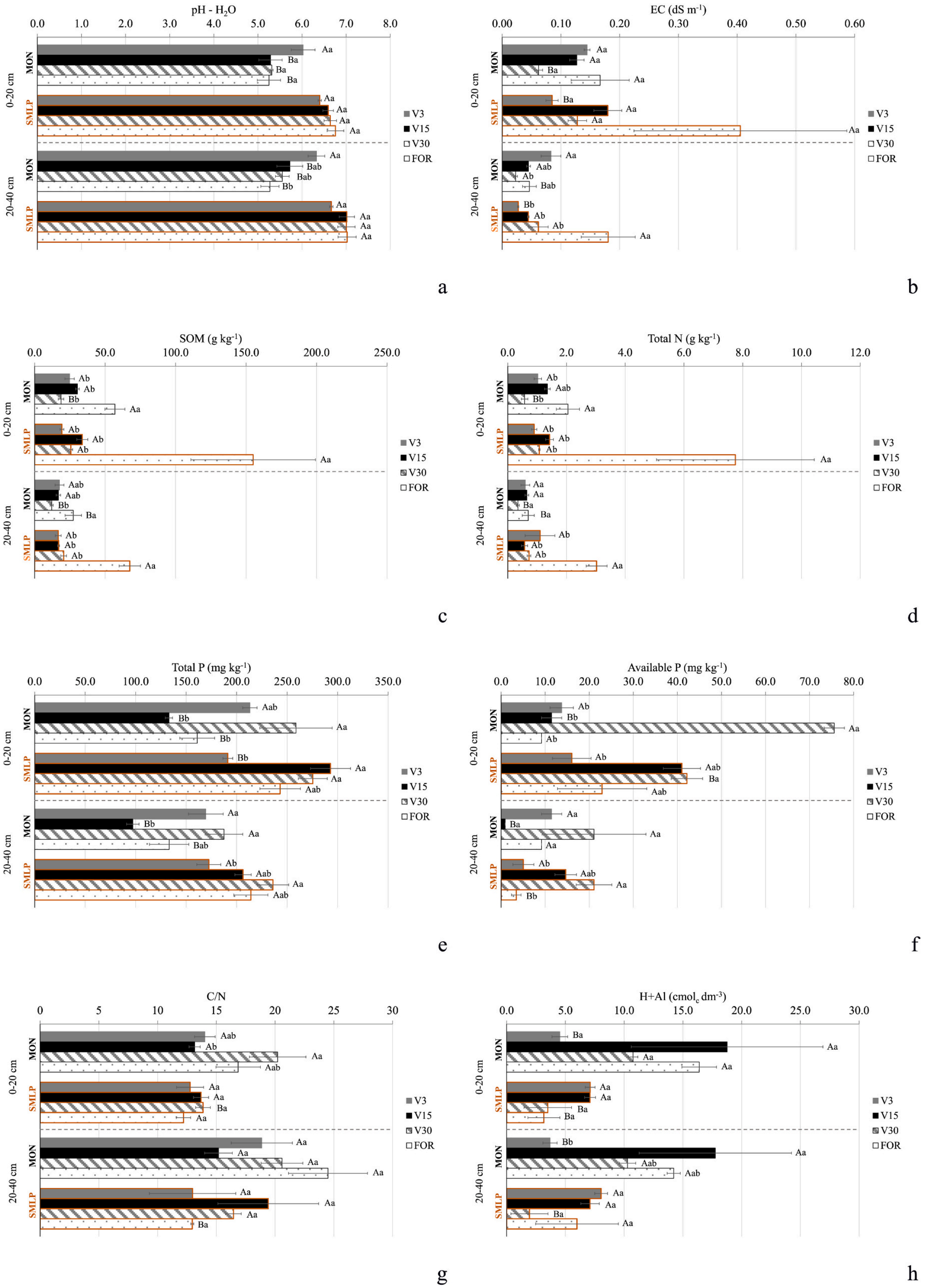

Fig. 3. Soil pH (a), electrical conductivity (b), soil organic matter (c), total N (d), total P (e), available P (f), C/N ratio (g), and H + AL (h) along A (0–20 cm) and B (20–40 cm) soil horizon and different pedosystems.

MON: Monti; SMLP: Santa Maria La Palma; V3: Vermentino planted three years ago, at the time of the sampling activities, *i.e.*, 2021; V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; FOR−MON: cork oak (*Q. suber* L.) forest; FOR−SMLP: holm oak (*Q. ilex* L.) forest. Different capital letters showed significant differences ($p < 0.05$) among different pedosystems within same land cover and soil horizon; different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem and soil horizon.

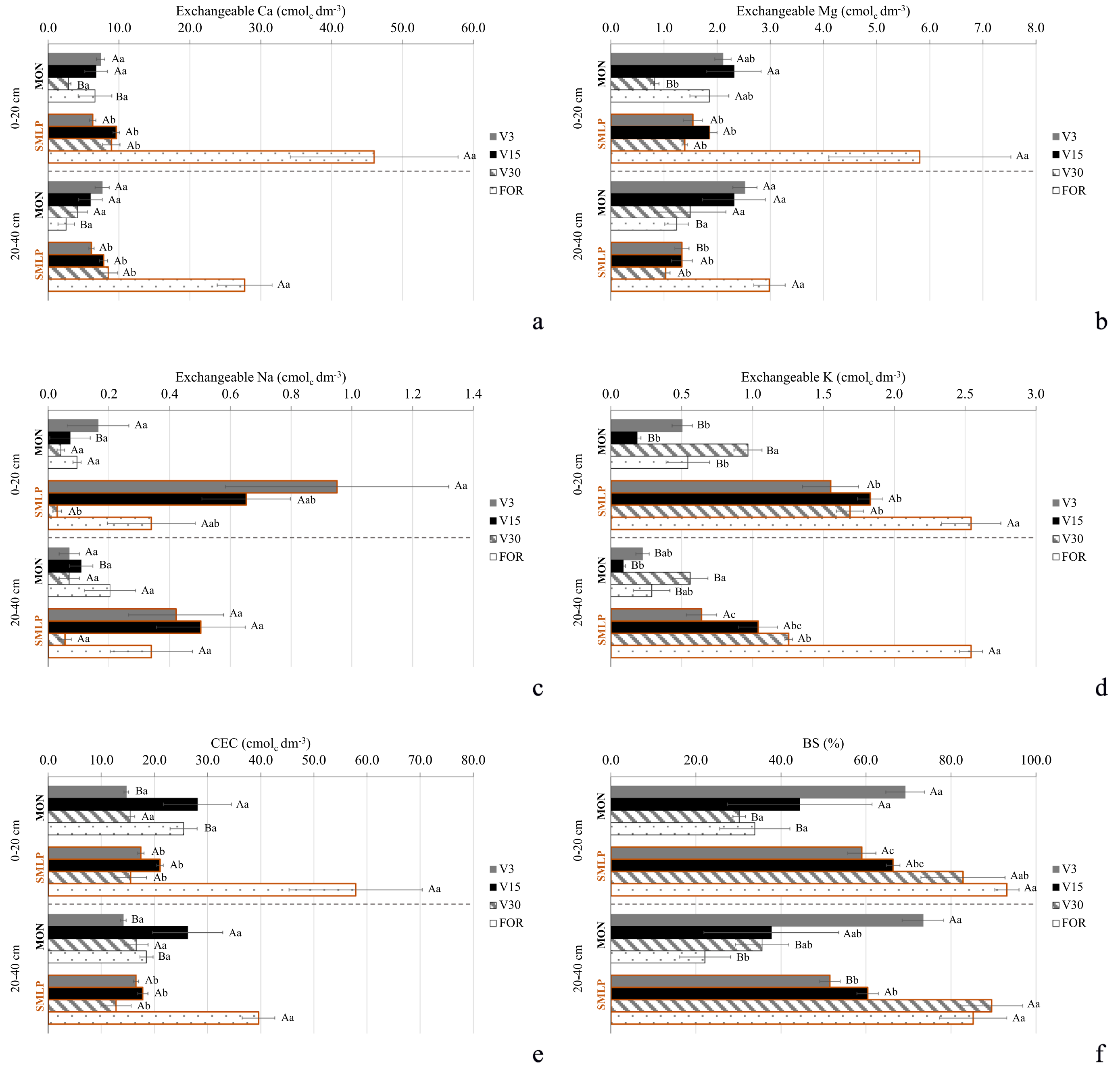

Fig. 4. Exchangeable cations (a-d), cation-exchange capacity (CEC) (e), and the base saturation (BS) (f) along surface (0–20 cm) and subsurface (20–40 cm) soil horizon and different pedosystems.

within pedosystems and soil horizons, significant differences ($p < 0.05$) were observed in SMLP, with FOR > V3 ≃ V15 ≃ V30 in both horizons.

Base saturation (Fig. 4f) in SMLP was 1.7 times higher than MON in both A and B horizons. Significant differences ($p < 0.05$) were observed in V30 and FOR for both horizons, with SMLP > MON; an inverse trend (MON > SMLP) was also observed for V3 in the B horizon. Among the different land covers, the differences were in the B horizon for MON and in both horizons for SMLP. In the case of subsurface-MON, V3 > FOR; while in the surface-SMLP, FOR > V15 ≃ V3, and in the subsurface-SMLP, V30 ≃ FOR > V3 ≃ V15.

Copper (Fig. 5a) showed similar mean values for both pedosystems and horizons. Significant differences ($p < 0.05$) were observed for V3 and V15 for both A and B horizons, and in the FOR-B horizon, where SMLP > MON. The opposite was observed in the V30—B horizon. When comparing the different land covers within the pedosystem and soil horizon, some significant differences ($p < 0.05$) were observed for both the A and B horizons at MON, and in the A horizon at SMLP. At MON, it was observed that V30 > V3 ≃ V15 ≃ FOR, while at SMLP, V15 > V3 ≃ V15 ≃ FOR.

Legend as in Fig. 3.

Comparing Fe (Fig. 5b) in MON *vs* SMLP for both A and B horizons, significant differences ($p < 0.05$) were observed for almost all land covers (except V30 in the B horizon), where SMLP > MON. When comparing the different land covers within the pedosystem and soil horizon, significant differences ($p < 0.05$) were observed only in the MON A horizon, where V3 > V15 ≃ V30 ≃ FOR.

Manganese (Fig. 5c) in MON and SMLP for both A and B horizons significantly differ ($p < 0.05$) for almost all land covers (except V30 in

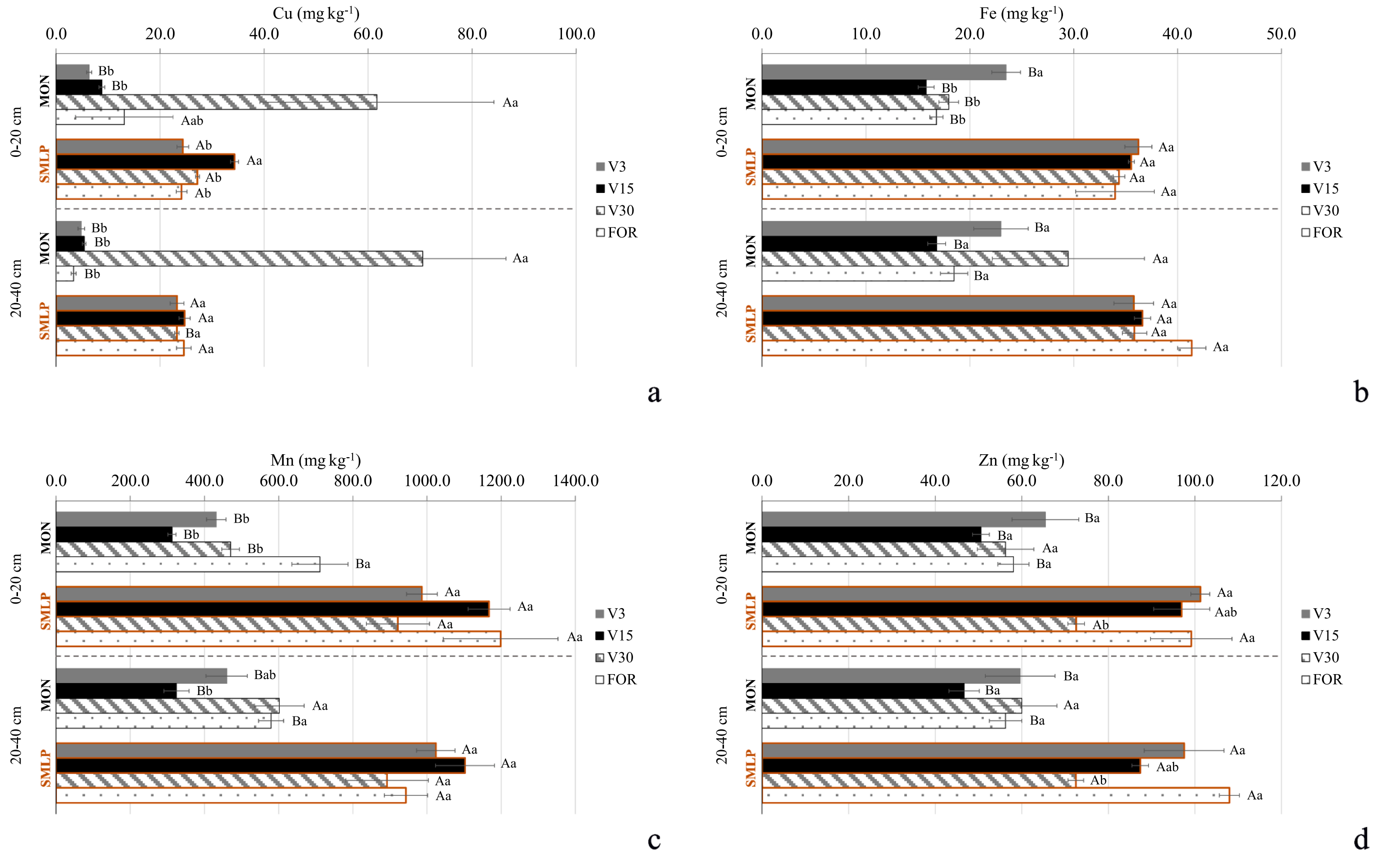

Fig. 5. Copper (a), Iron (b), Manganese (c), and Zinc (d) concentration along surface (0–20 cm) and subsurface (20–40 cm) soil horizon and different pedosystems.

the B horizon), with SMLP > MON. When comparing the different land covers within the pedosystem and soil horizon, significant differences ($p < 0.05$) were observed at MON in both soil horizons, with FOR > V3 ≃ V15 ≃ V30 in the A horizon and V30 ≃ FOR > V15 in the B horizon.

Zinc (Fig. 5d) differs significantly ($p < 0.05$) between MON and SMLP in both A and B horizons across almost all land covers (except for V30), where SMLP exceeds MON. Among the different land covers, significant differences ($p < 0.05$) were observed in SMLP for both horizons, where V3 ≃ FOR > V30.

3.3. *Soil organic carbon stocks*

Soil organic carbon stocks (SOCs; Fig. 6) ranged from 13.0 (V3, B horizon) to 89.5 t ha^{-1} (FOR, A horizon) at MON, showing a mean of 42.5 ± 3.4 t ha^{-1} and 30.2 ± 5.1 t ha^{-1} in the A and B horizons, respectively. The SMLP showed higher stocks compared to MON, presenting a broader range, varying from 19.8 (V3, B horizon) to 258.7 t ha^{-1} (FOR, A horizon). The means in the SMLP were approximately 1.6 times higher in the surface (67.0 ± 13.2 t ha^{-1}) and 1.3 times higher in the B horizon (40.6 ± 3.3 t ha^{-1}) than MON. As expected, SOCs showed

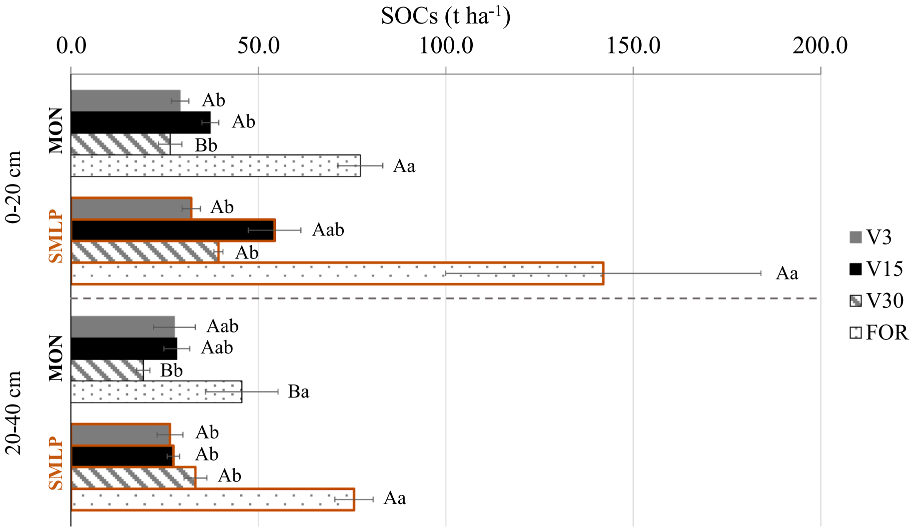

Fig. 6. Soil organic carbon stocks (SOCs) along surface (0–20 cm) and subsurface (20–40 cm) soil horizon and different pedosystems.

a similar pattern to SOM, with amounts as SMLP > MON. Among the different land covers, FOR displayed the highest stocks in the MON surface, and higher than V3 and V30 in the SMLP surface. Additionally, in the B horizons, FOR was higher than V30 in the MON, and it reached its highest value at SMLP.

Legend as in Fig. 3.

3.4. *Multivariate statistics*

3.4.1. *Principal factor analysis (PFA)*

Principal component analysis (Table 2) was performed for each of the pedosystems separately. For both, the eigenvalues, after matrix rotation, were greater than 1, demonstrating high model statistical reliability.

The PFA for MON and SMLP extracted a six- and five-component model, respectively. The MON-PFA accounts for 84 % of the overall variance, while SMLP accounts for 82 %. For the MON pedosystem, F1 (22 %) reveals a positive correlation among pH, EC, exchangeable cations (Ca and Mg), and BS, while these were inversely related to BD and C/N. In the SMLP pedosystem, F1 (36 %) extracted SOCs, total N, EC, all exchangeable cations, CEC, BS, and Mn, all of which were positively correlated, while negatively correlated with BD. Factor 2 in MON (19 %) inversely correlates Na with total and exchangeable P and K, and total Cu. In SMLP, F2 (19 %) extracted sand, C/N, and Mn as positively correlated, while a negative correlation was observed with clay, exchangeable K, Fe, and Zn. Factor 3 (F3) for MON (16 %) extracted SOCs, total N, EC, and Mn, all of which were positively correlated. In SMLP, F3 (11 %), the total and available P positively correlated with Cu. All the other extracted factors are of minor statistical importance.

3.4.2. *Principal component analysis (PCA)*

To better understand the behavior and identify the soil physicochemical parameters that exhibited greater importance in terms of the observed variability, as well as among the different investigated land covers, a PCA was performed for each pedosystem separately (Fig. 7a, b).

The MON−PCA revealed the first (PC1) and the second (PC2) components explaining 21 % and 19 % of the total variability, respectively (Fig. 7a), collectively accounting for 40 %. The SMLP−PCA (Fig. 7b) showed the first (PC1) and second components (PC2), explaining 35 % and 15 % of the variability, respectively, for a total of 50 %.

4. Discussion

4.1. *Soil physical parameters*

The sandy-loam texture in the MON pedosystem was expected, as the sand fraction usually strongly dominates soils developed on granite. Lozano García et al. (2020) argued that the physical features of Cambisols are significantly influenced by this substrate, characterized by intensive physico-chemical weathering, which leads to the dominance of sand particles in the soil mineral matrix. On the contrary, the higher clay content in Luvisols on SMLP underlines a difference in substrate development, being this last one developed on limestone and thus resulting in the presence of a clayey B subsurface horizon (Bt) through lisciviation processes (IUSS Working Group WRB, 2022), especially enhanced during different paleclimatic conditions; a fact featuring Luvisols on carbonate formation in Sardinia (Aru et al., 1991; Costantini and Dazzi, 2013).

A statistically significant difference was observed between MON and SMLP, indicating an influence of human activities, particularly in vineyards that were plowed to deep horizons, especially during the initial establishment period. In fact, in natural environments, the fine earth fraction aligns with natural soil horizontation, with sand and clay increasing in depth in Cambisols and Luvisols, respectively (Bryk, 2016). In vineyards, such a trend is significantly altered by soil preparation management activities typically conducted in these areas. Bulk density confirms such an idea. Indeed, in SMLP vineyards, the BD increased significantly in surface horizons (compared to MON) due to their clayey nature. The use of heavy machinery during the preparation period has a greater impact on this pedosystem, which features finer fractions. In MON, the dominance of the sand fraction significantly reduces the influence of heavy machinery use; the low clay content prevents subsequent problems associated with an increase in BD (Gong et al., 2003). This is also confirmed by the fact that in natural environments of the same pedosystem (FOR), BD presents considerably lower values, due to

Table 2
Factor loadings of a factor analysis ($n = 32$) for the MON and SMLP pedosystems; Extraction Method: principal factor analysis (PFA); Rotation Method: Varimax; bold loadings >0.4.

	Monti (MON)						Santa Maria La Palma (SMLP)				
	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5
pH	**0.761**	0.085	−0.232	−0.209	0.261	0.188	0.028	−0.116	−0.272	0.355	**−0.764**
EC	**0.461**	−0.068	**0.819**	−0.166	−0.106	0.012	**0.903**	0.247	0.222	0.033	0.152
Sand	−0.045	−0.088	0.022	**−0.982**	0.036	0.057	0.156	**0.911**	0.117	0.011	0.211
Silt	−0.261	−0.258	0.128	**0.860**	0.134	0.112	−0.381	−0.141	0.100	−0.226	**−0.765**
Clay	0.297	0.360	−0.145	**0.791**	−0.172	−0.185	0.018	**−0.921**	−0.176	0.099	0.147
BD	**−0.429**	0.319	−0.380	0.220	0.123	0.008	**−0.809**	0.196	0.118	−0.110	0.148
SOCs	−0.148	0.132	**0.908**	0.095	0.066	−0.151	**0.922**	0.040	0.117	0.106	0.148
Total N	0.218	0.002	**0.930**	0.017	−0.070	−0.253	**0.961**	0.139	0.015	0.038	0.158
C/N	**−0.564**	0.089	−0.261	0.021	**0.414**	0.311	−0.282	**0.402**	−0.241	0.146	−0.217
Total P	0.081	**−0.888**	0.056	−0.108	0.143	0.183	0.174	0.117	**0.824**	0.384	0.153
Available P	−0.256	**−0.806**	−0.162	−0.148	−0.123	0.122	0.044	0.337	**0.815**	0.177	0.306
Ca^{2+}	**0.895**	0.117	0.324	0.109	0.089	0.044	**0.983**	0.008	−0.027	0.147	0.004
Mg^{2+}	**0.840**	0.375	0.083	0.180	0.126	−0.059	**0.965**	0.093	0.052	−0.005	0.167
Na^{+}	−0.057	**0.445**	0.019	−0.164	**0.448**	0.080	0.116	0.053	0.124	**−0.728**	0.021
K^{+}	−0.111	**−0.854**	0.217	−0.119	0.153	0.125	**0.610**	**−0.550**	0.316	0.151	−0.011
CEC	0.062	0.197	0.249	0.069	−0.098	**−0.919**	**0.982**	−0.031	−0.056	−0.032	0.038
BS	**0.840**	0.052	0.020	−0.019	0.064	**0.509**	**0.457**	−0.136	0.241	**0.755**	−0.031
H + Al	−0.352	0.132	0.104	0.014	−0.152	**−0.900**	−0.240	−0.132	−0.245	**−0.727**	0.073
Cu	−0.160	**−0.773**	−0.214	0.370	0.154	−0.058	−0.108	−0.057	**0.913**	−0.202	−0.169
Fe	0.280	−0.046	−0.397	0.128	**0.749**	0.057	−0.264	**−0.869**	−0.102	−0.018	−0.219
Mn	−0.184	−0.188	**0.445**	0.128	**0.727**	0.057	**0.485**	**0.481**	0.255	−0.279	0.156
Zn	0.237	−0.145	−0.047	−0.111	**0.807**	0.121	0.241	**−0.642**	0.030	**−0.520**	−0.243
Prop. var. (%)	22	19	16	12	9	6	36	19	11	10	6
Cum. var. (%)	22	41	57	69	79	84	36	55	66	76	82
Eigenvalues	4.891	4.129	3.541	2.693	2.021	1.236	7.971	4.230	2.524	2.236	1.249

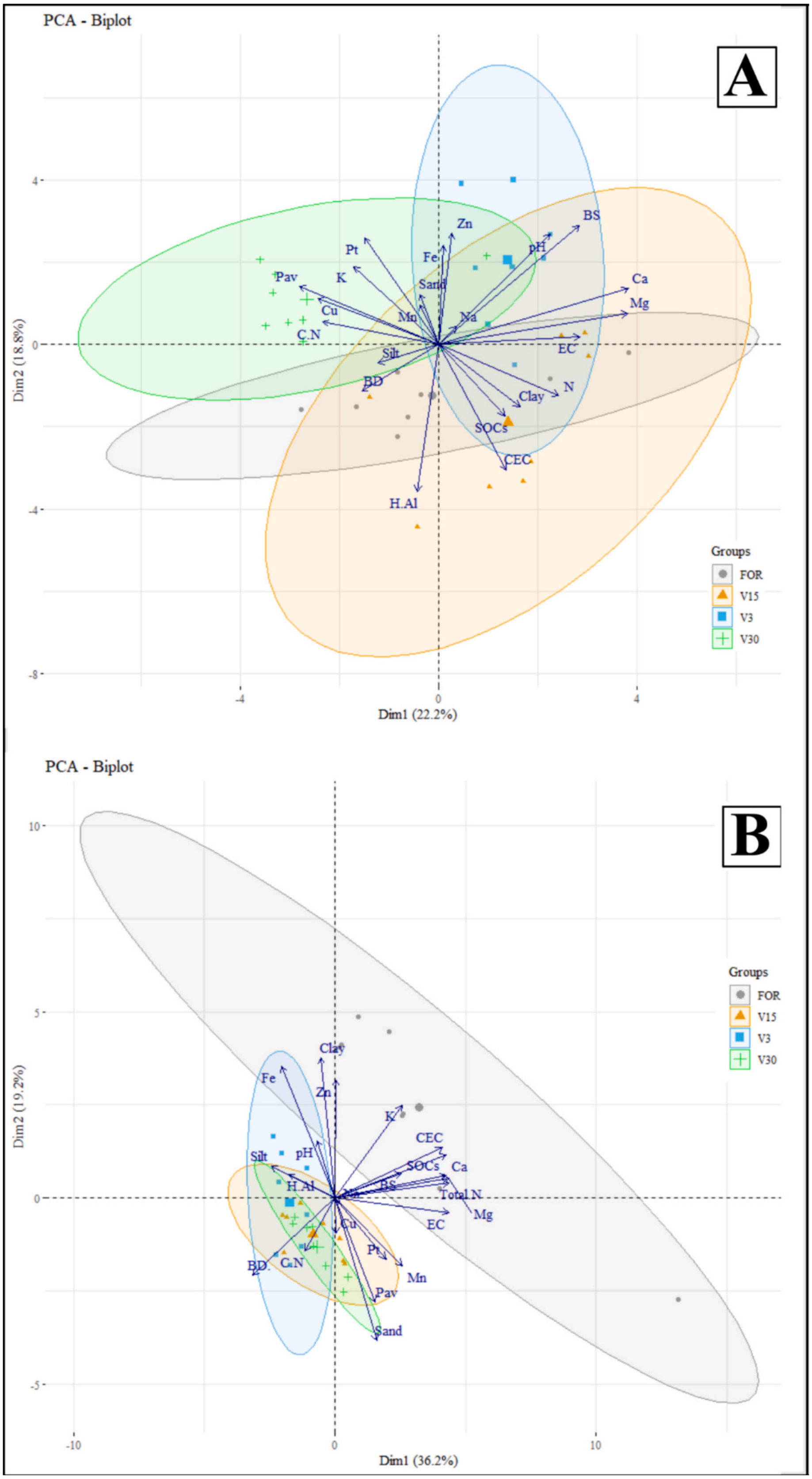

Fig. 7. Biplots of a principal component analysis for MON (a) and SMLP (b) site.

the absence of human disturbance and the resulting increase in soil organic carbon content.

4.2. Soil chemical parameters

Differences in pH between MON and SMLP (Fig. 3a) are due to the V3 relatively young soil, as the area was converted to a vineyard just 3 years before the field sampling activities. When an area is converted into a vineyard, soils are scraped by heavy machinery, which can lead to "*entisolization*" processes (Capra et al., 2012; Dazzi and Monteleone, 2007), a regression or temporary slowdown in soil evolutionary processes. This leads to leaching processes still not being strongly expressed, leaving higher levels of basic cations than in more developed FOR soils.

The higher EC (Fig. 3b) in both horizons of the V3 in MON can be attributed to several factors, primarily human influence on the soil, which lead to the leaching of soluble cations. When analyzing differences in land cover within the pedosystems, significant differences ($p < 0.05$) were observed for both MON and SMLP in the B horizon. At MON, the EC in the V3 land cover was significantly higher than in V30; this can be attributed to lower clay content (Table 1) and SOM amounts (Fig. 4c) in V30, which led to lower EC. Clay and SOM can serve as interfaces for the movement of substances between the solid and liquid phases of the soil, mainly through exchangeable cations, so, in general, the EC decreases as clay content decreases and *vice versa* (Corwin and Lesch, 2005). At SMLP, the FOR-land cover exhibited higher EC than other land uses, likely due to the higher SOM values (Fig. 3c) associated with this land cover, which contributed to its higher EC (Okoror and Amanze, 2024).

The higher SOM content (Fig. 3c) featuring SMLP can be attributed to several interacting factors. Carbonate-derived soils with finer texture (clay and clay-loam), promote greater SOM accumulation and stabilization than granitic soils (Wiesmeier et al., 2019; Brady and Weil, 2021) which are usually sandy and well-drained. Higher CEC characterizes soils developed on limestone, increasing moisture retention and formation of stable organo-mineral associations that physically protect OM from rapid mineralization (Wiesmeier et al., 2019). Expectations leaned towards higher concentrations in the FOR-land cover and lower concentrations in cultivated areas, due to OM inputs from vegetation within the FOR-land cover, contrasted with reduced OM and its rapid mineralization in cultivated areas (Costantini and Dazzi, 2013).

The FOR-land cover shows higher N content trends than agricultural areas for both investigated pedosystems (Fig. 3d). The findings of our study are consistent with previous research indicating that total N content tends to be higher in forest ecosystems than in vineyards in Mediterranean settings. This difference is ascribed to the continuous OM supply through litter deposition and root turnover in forests, along with the minimal disturbance characterizing these environments. In contrast, vineyard soils are regularly subjected to tillage, mechanization, and reduced organic returns from plant residues, all of which accelerate OM decomposition and mineralization, thereby reducing soil N stocks (Quéro et al., 2022). The transition from Mediterranean forest to vineyard results in marked declines in both SOM and total N, even decades after the land-use change (Quéro et al., 2022). Abad et al. (2021) underscored that forest soils consistently maintain greater total N levels than those under vine cultivation, a trend that is especially pronounced under conventional vineyard management.

The higher total P (Fig. 3e) in SMLP surface and subsurface horizons *vs* MON and in terms of land cover (V3, 15, 30 > > FOR) seem to be due respectively to: *i*) SMLP presents a general higher soil fertility, and *ii*) agricultural management practices affecting vineyards. These are also periodically fertilized with P-based fertilizers. Elevated P concentrations in agricultural areas, such as vineyards, are associated with the widespread use of P fertilizers/amendments, leading to P enrichment, particularly in older soils (Lu et al., 2023), such as V30.

Soils on granite exhibit lower P availability than those on limestone (Fig. 3f), especially for V15, due to fertilizer management in the area. While the SOM mineralization and decomposition are fundamental, ongoing processes that release plant-available P in all soils (Liu et al., 2014), the markedly higher total and available P concentrations observed in the vineyards, especially as a function of age, are primarily attributable to the repeated input of P-based fertilizers and amendments as part of conventional management (Lu et al., 2023). Such external additions exert a much powerful influence on P stocks in managed vineyard soils, eclipsing the contribution from endogenous cycling. Conversely, in the FOR areas, where fertilizer inputs are absent, the P pool is regulated by SOM turnover and natural biogeochemical processes. This distinction clarifies that, while both mechanisms operate simultaneously, the relative importance of management *vs* natural cycling determines the observed P levels in each land use.

Higher C/N values (Fig. 3g) observed in forest (FOR) soils reflect a predominance of carbon inputs over N, resulting in slower decomposition, N immobilization, and greater OC stabilization (Camponi et al., 2023), thus supporting the accumulation of stable SOC and enhanced fertility in undisturbed systems. On the contrary, vineyard soils consistently showed lower C/N ratios in both A and B horizons, suggesting rapid mineralization due to intensive management and reduced organic inputs (Quéro et al., 2022; Bonifacio et al., 2024). The spatial and vertical correspondence between sites with the highest C/N ratios and those with the highest SOC and total N, especially under forest, confirms the impact of land use and management on OM stabilization throughout the profile. These patterns indicate that anthropogenic disturbance promotes N depletion and carbon loss, effects that are not confined to surface horizons but are detectable at depth (Quéro et al., 2022; Camponi et al., 2023).

Exchangeable acidity displayed significant variation between the two pedosystems, with higher values recorded in MON, especially in the A horizon and for older vineyards (V30) and forest (FOR) soils (Fig. 3h). This highlights the combined influence of both parent material and land management, as the granitic substrate (MON) is inherently more acidic and has seen minimal corrective interventions, reinforcing the role of lithology in acid-base balance. Conversely, in SMLP, increased EA was observed in young vineyards (V3), likely due to the recent application of acidic fertilizers (Mokolobate and Haynes, 2002). Within MON, mid-aged vineyards (V15) exhibited the most pronounced acidification among the investigated land uses, with elevated $H^{+}+Al^{3+}$ concentrations and lower pH, thus facilitating Al mobility (Nair et al., 2019). These results show that both intrinsic soil properties and management history can modulate acid-base dynamics, with surface and subsurface differences reflecting the lasting impact of anthropogenic disturbance and local substrate. Thus, it becomes evident that both lithological factors and recent management have a direct and integrated effect on soil chemical fertility within Mediterranean vineyard and forest systems.

Soils developed on granitic substrates (MON) have consistently lower concentrations of exchangeable cations (Fig. 4) than those on limestone (SMLP), reflecting the lower nutrient base and CEC typical of Cambisols on granite *vs* Luvisols on limestone (Costantini and Dazzi, 2013; Yost and Hartemink, 2019). Within MON, fertilizer use in vineyards can modestly increase Mg and K levels, particularly at V15 and V30. These inputs, however, are insufficient to offset the nutrient constraints imposed by the parent material fully. In contrast, SMLP soils, especially under forest (FOR), display the highest cation concentrations, highlighting the role of undisturbed vegetation in sustaining nutrient stocks (Camponi et al., 2023). In SMLP vineyards, some cations (especially Na in young vineyards) are elevated due to management or irrigation practices. Still, overall nutrient reserves decline over time unless sustainable practices are implemented (Ferreira et al., 2020). Differences between natural and human-managed sites are most pronounced in the deeper B horizons, where long-term nutrient retention reflects the legacy of land cover. Collectively, these findings underscore the interplay among soil origin, land use, and management in controlling nutrient dynamics and fertility across Mediterranean vineyards and forests.

Observed differences in CEC (SMLP > > MON; Fig. 4e) reflect the influence of parent material and soil development processes, with SMLP soils characterized by higher clay and OM contents compared to the granite-derived MON soils. This aligns with the well-documented influence of colloidal fractions on increasing the soil exchange surface, thereby enhancing their potential to retain cations (Razzaghi et al., 2021). In SMLP, the higher CEC observed under undisturbed forest than across all vineyard stages highlights the importance of undisturbed vegetation in sustaining OM inputs and maintaining stable soil structure (Jiménez-Ballesta et al., 2023). The OM retention and persistence, along with clay minerals, improve chemical fertility, particularly under natural forest covers, in Mediterranean pedosystems (Camponi et al., 2023); in contrast, vineyards do not reach the fertility levels seen in forests. This difference reflects the combined effects of human-induced disturbances and lower OM returns (Bonifacio et al., 2024). All findings reinforce the notion that mineral and organic colloids have a key influence on soil chemical resilience, with significant practical implications for (*i*) ecosystem services and (*ii*) long-term soil productivity in Mediterranean regions (Wiesmeier et al., 2019).

The higher BS values (Fig. 4f) observed in SMLP compared to MON are a direct consequence of the calcareous nature and higher fertility associated with limestone-developed soils; a pattern furtherly influenced by land cover. Indeed, forest remnants sustain higher BS than vineyards, consistent with the greater OM inputs and reduced disturbance in natural vegetation. Differences among vineyard ages and between A and B horizons likely reflect site-specific management histories and the effect of vineyard establishment on nutrient cycling. Such trends highlight the pH's crucial role in regulating both the retention and availability of basic cations in Mediterranean pedosystems; therefore, both the parent material and land use must be taken into deep consideration from a sustainable soil fertility management perspective (Yost and Hartemink, 2019).

The distribution patterns of investigated PTE (Fig. 5), across the studied pedosystems highlight the strong interplay among substrate, OM, and anthropogenic influence. Clay-rich limestone soils supported higher contents of all four PTE, reflecting the strong affinity of transition metals for finer mineral and organic soil fractions (Kabata-Pendias and Szteke, 2015). In vineyards, especially the older ones, elevated Cu levels were revealed compared to natural land covers, a legacy of repeated application of Cu-based fertilizers and fungicides for disease control in viticulture (Brunetto et al., 2016). Iron was consistently higher in SMLP, aligning with greater clay content and the presence of Fe oxides typical of limestone-Luvisols (Pospíšilová et al., 2021). Manganese and Zn followed similar patterns, with concentrations positively related to both clay and OM pools, and residual or organic fractions playing an important role in their retention and bioavailability (Chen et al., 2021). Differences among land uses, especially the tendency for forests and older vineyards to accumulate more Mn and Zn, underscore the combined effects of long-term OM inputs and site-specific management. These findings reaffirm the sensitivity of trace elements to both natural soil-forming factors and agricultural interventions. Sustaining soil health in Mediterranean vineyards will require balancing crop protection needs with careful monitoring of trace metal buildup and its interactions with site-specific soil characteristics.

Overall, across the investigated sites, the evolution of key soil chemical parameters does not follow a strict progression with increasing vineyard age. The lack of proportionality is related to (*i*) the dynamic and site-specific nature of vineyard management and (*ii*) the inherent pedological variability featuring the Mediterranean landscapes. Despite the overall adoption of conventional cultivation practices, year-to-year differences in amendment and fertilizer regimes, and in management responses to climatic and overall environmental variability inevitably arise, thus requiring modulation of nutrient dynamics independently of simple aging effects (Ferreira et al., 2020; Bonifacio et al., 2024). Additionally, the contrasting influence of parent material and soil texture can further modulate the turnover, stabilization, and bioavailability of both organic and inorganic pools within each investigated pedosystem, often replacing potential chronological trends; a phenomenon underscoring the predominance of site history and management interventions in shaping soil chemical trajectories (Francaviglia et al., 2017; Lozano-García et al., 2020). The results presented here, grounded in empirical data and bolstered by direct farmer engagement, thus reaffirm that time since vineyard establishment should be interpreted in the context of a wider set of environmental and agronomic controls. Obtained findings, together with both direct information from farmers and literature, strengthen and contextualize the need for soil- and system-specific assessments in SOCs studies.

4.3. *Soil organic carbon stocks*

The distribution and magnitude of SOCs reported in our study decisively highlight the critical influence of both substrate and land use on carbon sequestration potential in Mediterranean pedosystems. The notably greater SOC stocks found in limestone-derived soils (SMLP), relative to their granitic counterparts (MON), reflect the inherent advantages of clay-rich matrices in OM stabilization through organo-mineral associations and improved aggregation, as previously demonstrated in Mediterranean and temperate environments (Willaarts et al., 2015; Wiesmeier et al., 2019). In the SMLP pedosystem, enhanced moisture retention, together with a higher CEC, finer-textured soils (offering greater protection), are all conditions conducive to longer OM residence times (Costantini and Dazzi, 2013; De Rosa et al., 2024).

Land cover emerged as a decisive factor in driving SOC dynamics, with remnant forest (FOR) patches consistently supporting the highest carbon stocks irrespective of substrate. This reflects the buffering effect of natural vegetation on OC pools, since forests supply long-term inputs of high-quality litter and root biomass, while highly limiting soil disturbance, thereby promoting the accumulation and persistence of SOM (Abad et al., 2021; Quéro et al., 2022). Such a protective effect is dramatically low, or absent, in intensively managed vineyards: here, both tillage and removal of crop residues accelerate OM mineralization and reduce the SOC accumulation (Lozano-García et al., 2020; Bonifacio et al., 2024).

A nuanced understanding emerges from the profile analyses, where SOC enrichment is much higher in the A surface horizons while distinctly decreased in the (B) subsurface one; a pattern shaped by both (*i*) the rhythm of OM inputs and (*ii*) the contrasting physico-chemical barriers to C stabilization. In fact, forest soils maintain higher SOC pools across all horizons, due to deeper root systems, reduced cultivation, and stronger organo-mineral interactions (Jobbágy and Jackson, 2000; Wiesmeier et al., 2019). On the contrary, vineyards, even those in favorable lithological settings, manifest SOC depletion with increasing soil depth, a signal of more pronounced anthropogenic disturbance and altered carbon cycling.

Overall, these findings highlight that SOC stocks in Mediterranean systems are closely tied to the soil pedogenic substrate and related physico-chemical features, vegetation cover, and intensity of land management. Considering the increasing urgency of climate adaptation and soil conservation in the Mediterranean Basin, preserving existing forest patches and restoring perennial or less-disturbed covers on vulnerable pedosystems appears vital for sustaining and enhancing soil carbon reservoirs. Targeted management aiming to (*i*) progressively reduce tillage intensity and (*ii*) protect belowground biomass to increase organic inputs is an imperative strategy to moderate SOC losses and maintain ecosystem services flows (Wiesmeier et al., 2019; Panagos et al., 2022).

4.4. *Multivariate statistics*

4.4.1. *Principal factor analysis (PFA)*

Factor 1 (22 %) confirms the key role played by the sandy, acidic nature of the investigated pedosystem, where a decrease in pH (due to leaching processes commonly associated with sandy soils) leads to a generalized decrease in soil fertility. In the SMLP pedosystem (F1: 36 %), the situation differs significantly, clearly demonstrating how the distinct nature of soils can play a fundamental role from various perspectives. In particular, this factor confirms the key role played by SOCs in improving general soil conditions. From this perspective, F1 strongly differentiates the two pedosystems by exhibiting completely different behaviors. In fact, in MON, F1 outlines "*the key role played by the sandy, acidic soil nature*" *vs*, for SMLP, "*the key role of SOCs in improving soil conditions*." Factor 2 in MON (19 %) mainly reflects the interaction between exchangeable base cations and P forms on soil exchange and/or adsorption sites. Indeed, in acidic, strongly leached Cambisols, high mobility and competition among exchangeable cations (notably Na^+, K^+, Ca^{2+}, and Mg^{2+}) can significantly alter P dynamics. Cations can (*i*) compete with P for adsorption sites or (*ii*) promote P leaching, thereby reducing the amount of plant-available phosphorus. The observed negative correlation between Na and P forms in this factor underlines how ion exchange processes, coupled with ongoing leaching, intensify P depletion in these soils. This pattern is well documented in the literature for acidic, weathered soils subject to intense cation leaching (Guera and da Fonseca, 2022). Thus, such a factor can be referred to as "*exchangeable cation–P competition*." In SMLP, F2 (19 %) is directly associated with the soil's textural class, *i.e.*, clay-loam, characterized by a high presence of clay minerals. Thus, as the mineral colloidal fraction increases, an increase in exchangeable cations is expected. Conversely, this is obviously negatively correlated with sand. Such a factor can be interpreted as "*the importance of the mineral colloidal fraction (clay) in cation exchangeable processes*." It is interesting to note that the second factor for both pedosystems clearly underlines the influence of soil physical features (texture); for MON, it was related to its sandy nature, while for SMLP, clay prevailed, as expected, in differentiating the two pedosystems. Even if such an outcome could be "obvious" in terms of soil classification (we already know that "sandy" Cambisols characterize the MON site, while "clayey" Luvisols the SMLP one), it is interesting to stress that: *i*) the PFA clearly separates the two pedosystems also in terms of variability, and that *ii*) their intrinsic genetic and physico-chemical nature has a significant influence on the entire system variability, thus *iii*) physico-chemical characteristics clearly differentiate the MON *vs* SMLP pedosystems. Factor 3 (F3) for MON (16 %) indicates the well-known relationship between SOCs and total N (Brady and Weil, 2021), the former being the primary soil source of the latter. The increase in Mn is explained by considering that such an element is strongly influenced by OC content, both in terms of source and in its affinity for organic colloidal fractions (Kabata-Pendias and Pendias Kabata Pendias and Pendias, 2001; Kabata-Pendias and Szteke, 2015). The positive relationship between SOCs and EC is because as soil OC increases, cations and anions increase accordingly, thus an increase in EC is observed (Corwin and Lesch, 2005). In SMLP, F3 (11 %) reveals a human-induced geochemical correlation, with total and available P positively correlated with Cu. This strong relationship is best explained by typical vineyard management practices in Mediterranean regions, where both P fertilizers and Cu-based fungicides are commonly and frequently applied. As a result, P and Cu tend to accumulate concurrently in the soil, and their observed correlation is more a consequence of these simultaneous but distinct inputs rather than Cu impurities in fertilizers. In fact, the routine application of Cu-based fungicides for disease management represents the dominant pathway for Cu buildup in vineyard soils (Kabata-Pendias and Pendias Kabata Pendias and Pendias, 2001; Kabata-Pendias and Szteke, 2015). Therefore, the statistics likely reflect the combined legacy of fertilization and plant protection practices, underscoring the complexity of the anthropogenic signal in cultivated soils. Thus, comparing F3 in MON *vs* SMLP, we can name the former as "*the role of SOCs in influencing some soil fertility-related parameters*," while the latter as "*the influence of human activities on the investigated pedosystem*." Notably, the SOCs' role in the MON pedosystem was highlighted just in F3, thus assuming a significantly less important role within the explained variability for the pedosystem itself, and when compared with SMLP. All the other extracted factors merely show chemical and geochemical processes of minor impact inside the investigated pedosystems.

In general, the PFA unveiled several noteworthy findings. Both pedosystems exhibited a great influence of their parent material on physico-chemical parameters, with a notable decrease in magnitude in the factor loadings, particularly in F1, when comparing SMLP to MON. In SMLP, F1 and F2 accounted for more than 50 % of the variance, whereas in MON, it required three factors (F1, F2, and F3) to achieve the same level of variance. The prominence of SOCs was much more evident in SMLP (extracted at F1 with a factor loading of 0.922) compared to MON (extracted at F3 with a factor loading of 0.908), highlighting the importance of the SMLP pedosystem in terms of SOC and soil fertility.

4.4.2. Principal component analysis (PCA)

The MON−PCA (PC1: 21 %; PC2: 19 %; cumulative variability: 40 %; Fig. 7a) revealed that the areas investigated are entirely different in terms of variability, primarily due to differences in land cover, clearly varying from agricultural (V3, V15, and V30) to more natural areas (FOR). Specifically, the analysis demonstrated that vineyards are strongly influenced by soil fertility, with the following observed trends: *i*) V3 is mainly influenced by pH and base saturation (BS); *ii*) V15 is somewhat closer to V3, with the additional influence of some exchangeable cations (Ca and Mg) and EC; *iii*) V30 is mainly influenced by microelements (such as Fe and Zn), total and available P, exchangeable K, and sand content. These findings in the vineyards may be attributed to the influence of time on soil development. In fact, in V3, *i.e.*, the younger vineyard, it was observed that pH and base saturation play a pivotal role, as is typical in the early stage of soil development. As time passed, this influence, although still present, became less significant, and in V15, an increasing influence of exchangeable cations was observed, typically in more developed, yet still young, soils (Capra et al., 2018). It must be underlined that even if the age of the soil cannot be referred to from the time the vineyard began, such activities can "*entisolize*" the soil, *i.e.*, are responsible for the soil's regressive processes (Dazzi and Monteleone, 2007). Indeed, it was observed that in V30, *i.e.*, the oldest investigated vineyard, parameters such as microelements (Cu, Fe, Mn, and Zn), total and available P, and exchangeable K significantly increase their influence as typically observed in more developed, or less younger, soils (Kabata-Pendias and Pendias Kabata Pendias and Pendias, 2001; Kabata-Pendias and Szteke, 2015). Conversely, in more natural areas (FOR), a greater influence of SOCs and N was observed.

The SMLP−PCA (PC1: 35 %; PC2: 15 %; cumulative variance: 50 %; Fig. 7b) revealed, as observed for MON pedosystem, a clearly different pattern in land use distribution along the biplot. Thus, investigated land uses are influenced to varying degrees according to specific soil parameters; obviously, as expected, some parameters can simultaneously influence different land uses, thus not being exclusive to a single system. Summarizing: vineyards (V3, V15, and V30) showed an evident influence from bulk density. This can be explained by considering that all these systems are periodically strongly influenced by mechanical plowing activities conducted with heavy machinery. In the investigated pedosystem, where soils are clayey in texture, such human activities bring an increase in BD, thus influencing the entire pedosystem. This is confirmed by the fact that the other investigated land use (FOR) is more influenced by other soil-related fertility parameters (SOCs, BS, P, N, CEC, exchangeable cations, several micronutrients).

Overall, the PCA for MON pedosystem showed that a "time – related" component mainly influences vineyards. At the same time, in most natural environments, SOCs and related parameters (such as N and CEC) play the most important role. For the SMLP pedosystem, a greater influence of human activities on soil behavior was observed. However, differences in the substrate and subsequent soil formation processes seem to play a significant role. Indeed: *i*) MON pedosystem being mainly featured by a sandy texture seems to be less prone to being influenced by human activities, especially if related to the use of heavy machinery; *ii*) in the SMLP pedosystem, the clay texture brings an opposite behavior showing less resilience. This outcome confirmed previous results, demonstrating that Mediterranean soils developed on limestone are typically more fragile and at-risk pedosystems (Capra et al., 2018).

5. Conclusions

This study provides new insights into how both soil genesis and management distinctly shape soil organic carbon stocks (SOCs) and related properties across contrasting Mediterranean pedosystems. By pursuing a comparative approach across granite-derived Cambisols and limestone-derived Luvisols, and their respective gradients from vineyard to remnant forest, important outcomes emerge: (*i*) SOCs are consistently higher under natural (or minimally disturbed) vegetation, regardless of soil substrate, and decrease with depth. Natural forest remnants act as pivotal carbon reservoirs, while vineyards (particularly older ones) show significantly lower carbon stocks, highlighting the impact of land cover conversion and persistence; (*ii*) soil features, such as texture and parent material, strongly influence SOCs. Additionally, human management-driven changes, such as tillage and fertilization, can either mitigate or amplify these differences. Overall, the clear divergence between sandy Cambisols and clay-rich Luvisols underscores the need for site-adapted practices; (*iii*) the multivariate analysis demonstrates that the primary influence on SOCs varies according to underlying substrate and management history. In granite-derived pedosystems, substrate-related limitations (such as low CEC) prevail; in limestone-derived ones, both natural fertility and human influence interact to modify SOCs dynamics and fertility; (*iv*) from a management perspective, these findings argue for land management strategies that explicitly recognize the heterogeneity of Mediterranean soils. For climate change mitigation, carbon accounting, and ecosystem service frameworks, policies must move beyond a "one-size-fits-all" approach and integrate pedological knowledge in both vineyard restoration and forest conservation. The paper demonstrates that we need to link pedological processes to practical implications to fully understand SOCs' behaviors and dynamics, even in the view of a transferable framework for other Mediterranean and at-risk landscapes. Future research should focus on targeted, long-term monitoring and site-tailored experimentation to safeguard SOCs functions and resilience amid ongoing land-use change.

CRediT authorship contribution statement

Antonio Ganga: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ludmila Ribeiro Roder:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amaral Guerrini:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Rafael Barroca da Silva:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Emmanuele Farris:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Alfredo Maccioni:** Writing – original draft, Investigation, Formal analysis, Data curation. **Gian Franco Capra:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Funding

This work has been developed within the framework of the project e.INS- Ecosystem of Innovation for Next Generation Sardinia (cod. ECS 00000038) funded by the Italian Ministry for Research and Education (MUR) under the National Recovery and Resilience Plan (NRRP) - MISSION 4 COMPONENT 2, "From research to business" INVESTMENT 1.5, "Creation and strengthening of Ecosystems of innovation" and construction of "Territorial R&D Leaders", CUP J83C21000320007.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Maria Chiara Ruggiu, Angelo Manca, Nicoletta Melis, Marco Marrosu (AGRIS), Roberto Mattu, Gian Franca Bonamici, Elisa Marras, Ilaria Incollu, Mara Mameli, Mario Deroma, and Linda Canu for their active support during the project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.109746.

Data availability

Research Data unavailability explanation (Reference data) (Please note the attached file)

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