UNIVERSITY OF SASSARI

DEPARTMENT OF ARCHITECTURE, DESIGN AND URBAN PLANNING
PHD COURSE IN ARCHITECTURE AND ENVIRONMENT
XXXVI CYCLE

DOCTORAL THESIS

Comparing soil organic carbon stocks in contrasting Mediterranean pedosystems:

How physical-chemical properties and land uses influence its behavior

SUPERVISOR
Prof. Gian Franco Capra

CANDIDATE
Ludmila Ribeiro Roder

CO-SUPERVISOR
Prof. Iraê Amaral Guerrini

ACADEMIC YEAR 2022/2023

Comparing soil organic carbon stocks in contrasting Mediterranean pedosystems

How physical-chemical properties and land uses influence its behavior

Ludmila Ribeiro Roder

Department of Architecture, Design and Urban Planning
University of Sassari
Sassari, Italy

ABSTRACT

Soils play a pivotal role in the global carbon cycle processes and behavior, with soil organic carbon stocks (SOCs) representing the largest terrestrial carbon (C) pool. Soil C sequestration enhanced soil quality and the overall ecosystem goods and services, together with socio-economic benefits. The Mediterranean areas are one of the world's biodiversity hotspots for conservation priorities. The Sardinia Island (south Italy) hosts peculiar eco- and pedosystems thanks to its peculiar climatic, geological, geomorphological, and ancient land use history featured for one of the oldest civilizations (Nuragic, 6,000 BC). All factors are brought together in extremely peculiar soil conditions. This study aimed to investigate SOCs and related behavior in two contrasting Mediterranean pedosystems in Sardinia (Cambisols developed on granite *vs* Luvisols on limestone), featuring different land covers, by comparing: *i)* surface *vs* deep soil horizons (A *vs* B); *ii)* different land covers inside and between the two investigated pedosystems. Several properties were assessed, including vegetation (vascular plants), litter (C, N, C/N, litter carbon stocks, P, Ca, Mg, Na, K, Cu, Fe, Mn, and Zn), and soil physical- (sand, silt, and clay contents, bulk density) chemical features (pH, electrical conductivity, soil organic matter, total N, total P, available P, C/N, exchangeable H+Al, exchangeable cations, cation-exchange capacity, base saturation, Cu, Fe, Mn, and Zn), wherever feasible. Statistical analyses were performed to determine: *i*) significant differences ($p < 0.05$) between and among investigated horizons and land uses; *ii*) bivariate correlation between investigated parameters (Pearson's Correlation Matrix (CM)); variability and complex multiple relationships among investigated parameters through factor analysis (FA), while a principal component analysis (PCA) was conducted to identify the soil physical-chemical parameters having greater importance in terms of observed variability within (a) the investigated pedosystem, as well as (b) among the different land covers. Results revealed that areas with natural or close-to-natural features exhibited significantly higher SOCs amounts compared to more intense and human-influenced land covers. Furthermore, the differences in substrate and following soil formation processes between the two investigated pedosystems led to different SOCs behaviors, demonstrating a strong relation between SOCs and intrinsic soil features. This emphasizes the greater importance of soil nature in influencing SOCs, greater compared to that shown by land cover variations. Consequently, this study blatantly demonstrates that SOCs investigations, if

not carried out through an in-depth soil investigation, may lead to inaccurate, or even wrong, outcomes and following considerations.

Keywords: Soil organic carbon, Mediterranean pedosystems, Vegetation, Litter, Soil.

Dedicated to my beloved family and supervisors

CONTENTS

1 INTRODUCTION 1
2 MATERIAL AND METHODS 5
2.1 STUDY AREA 5
2.2 FIELD SAMPLING ACTIVITIES 8
2.2.1 MONTI SITE 9
2.2.2 SANTA MARIA LA PALMA SITE 11
2.3 VEGETATION INVESTIGATION 13
2.4 LITTER SAMPLING AND ANALYSES 14
2.5 SOIL SAMPLING AND ANALYSES 15
2.6 STATISTICAL ANALYSES 16
3 RESULTS AND DISCUSSION 17
3.1 MONTI PEDOSYSTEM 18
3.1.1 VEGETATION INVESTIGATION 18
3.1.2 LITTER FEATURES 23
3.1.3 SOIL FEATURES 25
3.1.4 MULTIVARIATE STATISTICS 34
3.2 SANTA MARIA LA PALMA PEDOSYSTEM 42
3.2.1 VEGETATION INVESTIGATION 42
3.2.2 LITTER FEATURES 50
3.2.3 SOIL FEATURES 52
3.2.4 MULTIVARIATE STATISTICS 60
3.3 MONTI *VS* SANTA MARIA LA PALMA PEDOSYSTEM 68
3.3.1 VEGETATION INVESTIGATION 68
3.3.2 LITTER FEATURES 75
3.3.3 SOIL FEATURES 77
3.3.4 MULTIVARIATE STATISTICS 90
4 CONCLUSION 94
ACKNOWLEDGEMENT 96
REFERENCES 99

1 INTRODUCTION

The Mediterranean Basin is one of the world's biodiversity hotspots for conservation priorities, originally spanning 2,362,000 km² of primary vegetation (Myers et al., 2000). However, only a scant 4.7% of its original extent remained (Myers et al., 2000) due to direct and indirect human activities throughout history, resulting in an under-threat (Cuttelod et al., 2009) and the most susceptible European region to the effects of climate change (Schröter et al., 2005).

Climate change is dramatically impacting human and natural systems (Intergovernmental Panel On Climate Change (IPCC), 2023), and the ongoing changes are purportedly linked to greenhouse gases (GHGs, hereafter) emissions caused mainly by human activities involving land-use change, soil cultivation, deforestation, biomass and fossil fuels burning, wetland drainage (Lal, 2008). Among the most critical GHGs is the carbon dioxide (CO_2). By comparing its concentration in 2021 *vs* the pre-industrial era, it surged to 414.7 ppm, with a net increase of 50%; the growth over the past decade (2011-2020) amounted to 5.1 ± 0.02 gigatons of carbon per year (GtC yr^{-1}) (Friedlingstein et al., 2022).

When is referred to reducing the effects of climate change, especially global warming (a term referring to the evaluation of an increase in the mean temperature observed on the Earth's surface when compared to the pre-industrial period; IPCC, 2022), it implies reducing atmospheric concentrations of GHGs, mainly carbon dioxide (CO_2), and these reductions can also be achieved through carbon (C) sequestration (Ramachandran Nair et al., 2010). Carbon sequestration is the process that involves transferring and safely storing atmospheric CO_2 in long-lasting C pools induced by natural or anthropogenic processes (Lal, 2008).

On a worldwide scale, there exist five primary C pools: Hydrosphere, Lithosphere, Pedosphere, Atmosphere, and Biosphere (Lal, 2008). The Pedosphere (soil pool) represents the largest terrestrial C pool (Nave et al., 2019), holding approximately 1700 GtC, which is roughly twice the amount in the atmospheric (about 875 GtC) pool and more than three times the total stored in the biotic (about 450 GtC) (Friedlingstein et al., 2022). Thanks to its capacity to perform multiple functions (Wiesmeier et al., 2019), it plays a pivotal role in the global carbon cycle (Lal, 2004) and land management.

In contrast to C found in the other pools, the C present in soils: *i)* typically boasts much older; *ii)* is not inert (due to the inputs and outputs); and *iii)* exhibits a dynamic nature, influencing 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 (SOC) concentration, restoring soil quality and the overall ecosystem goods and services, such as increasing availability of water and nutrients, reducing the risk of erosion, and promoting long-term food and nutrition security to society, together with others several benefits (Lal et al., 2015). Multiple factors can impact the SOC concentration and sequestration, including soil physical-chemical features (such as pH, base saturation, exchangeable cations, CEC, and bulk density), soil use and management (Lal, 2004; Roder et al., 2023; Yost and Hartemink, 2019). Furthermore, it is significantly influenced by the vegetation cover (Oertel et al., 2016).

Like the soil, litter, i.e., the soil surface organic horizon (O), is also a vital carbon source. Plant litter constitutes the soil's primary source of organic carbon (Xu et al., 2022). It performs a crucial role in maintaining the balance of the site, mainly through recycling the essential bases to the plants, safeguarding against water erosion, and facilitating the percolation of water into deeper soil horizons (Costantini and Dazzi, 2013). This organic material is subject to decomposition, partially forming the soil organic matter (SOM), playing an essential function in C sequestration from the atmosphere (Xu et al., 2022).

In Europe, the Mediterranean region is spread over the southern part of the continent, surrounded by the Mediterranean Sea, extending through 12 countries and accounting for 11% of European territory (Ferreira et al., 2022). The main islands in the Basin are Sardinia and Sicily (Italy) (Costantini and Dazzi, 2013). Sardinia covers over 24,000 km² (Aru et al., 1991), and its importance is mainly related to hosting an abundant population of endemic plant and animal species, also representing one of the last fragments of untouched evergreen oak (*Quercus ilex* L.) forests and dense Mediterranean maquis in Europe (Migheli et al., 2009).

Sardinia boasts the oldest history of land use in Italy, dating back to the *Nuragic* civilization around 6,000 years ago, resulting in soils that have undergone significant changes from their original pedogenesis (Costantini and Dazzi, 2013). Concerning land cover in the Sardinia region, forests and semi-natural areas are the dominant land use, covering 53% of the territory; following closely are agricultural areas, which make up 43% of the land, with a notable presence of pastures and forage systems (Costantini and Dazzi, 2013).

Owing to its location at the heart of the western Mediterranean Basin, and including its unique/distinctive geologic and climatic attributes (high temperature during summer and extended drought periods; Costantini and Dazzi, 2013), Sardinia is acknowledged as particularly vulnerable to the effects of climate change, and even a slight increase in temperature could trigger a range of environmental challenges in this area (Caloiero and Guagliardi, 2021). The primary impacts of climate change in Sardinia are linked to a warmer climate, resulting in reduced precipitation, mainly during winter, higher mean annual temperatures, and increased instances of hazards (such as droughts and floods), all of which have significant effects on water resources and vegetation dynamics (Caloiero and Guagliardi, 2021; Sirigu and Montaldo, 2022). As Sardinia is a coastal area, the impacts are also linked to the tourism demand and, consequently, to economics since it represents a source of income and employment (Köberl et al., 2016). In addition, also the Mediterranean pedoenvironments face adverse effects, including mainly the increased risk of land degradation (attributed to higher SOM degradation caused by the elevation of the mean annual temperature) and erosive processes (driven by heavy rainfall) (Cerdà et al., 2010).

Over the past decade, there have been extensive studies (Cappai et al., 2017; Francaviglia et al., 2014, 2017; Lozano-García et al., 2020; Seddaiu et al., 2013) into the investigation of SOC stocks (SOCs) in various land covers across Sardinia, yielding significant findings. Many of these studies have focused on evaluating SOCs and soil quality under different land uses, analyzing specific physical-chemical parameters, such as soil particle size, bulk density, SOC, and N concentration. Nonetheless, there remains a conspicuous dearth of studies dedicated to investigating the multifaceted relationships and correlations between SOCs, vegetation, litter, and other soil physical-chemical parameters in such an important environment as Sardinia. Moreover, the comparison between two significant pedosystems (*vide infra*), such as Cambisols on granite and Luvisols on limestone, has yet to be explored from this standpoint.

Sardinia's landscape is predominantly characterized by units dominated by intrusive rocks, particularly granites, which cover around 29% of the region's total area, making them the most prevalent geomorphological feature. In contrast, landscape units on limestone constitute only 5%, making them one of the rarest units inside the region. More specifically, considering the soils within these conditions, Sardinia's territory comprises approximately 17.5% of Cambisols units on granite and just 1.7% of Luvisols units on limestone (Aru et al., 1990, 1991). These soils are distinct from each other and hold significant representativeness in

the context of Sardinia, with Cambisols on granites being one of the most widespread and Luvisols on limestone is one of the rarer soils.

In this context, the present research aimed to investigate SOCs and behavior by comparing two contrasting Mediterranean pedosystems (Cambisols developed on granite *vs* Luvisols developed on limestone) – i.e., a complex array of soils usually sharing similar genetic and physical-chemical features – featured by different land covers. Soil features were assessed along surface A (usually ranging from 0-20 cm) and deep B horizons (typically found between 20-40 cm soil deep). Additionally, where feasible, the soil litter and vegetation features were assessed too. Consequently, more specifically, it was aimed to investigate SOCs and behavior in contrasting Mediterranean pedosystems by comparing: *i)* surface *vs* deep soil horizons (A *vs* B); *ii)* different land covers/uses inside and between the two investigated pedosystems. The multiple aims are due to the complexity of the investigated systems, featured by a long history of socio-economic and environmental human influence mixed with still highly natural, even if fragmented, environments. Results can help clarify SOCs' behavior and dynamics in such complex environments.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The study was conducted in the Sardinia region, the second-largest island (in terms of area) in the Mediterranean Sea (southwest Italy). Investigated areas are located in northern (Monti municipality, MON hereafter, 40° 48′ 0″ N, 9° 20′ 0″ E) and north-western (Santa Maria La Palma, SMLP, 40° 39′ 39.56″ N, 8° 16′ 18.26″ E) Sardinia (Fig. 1).

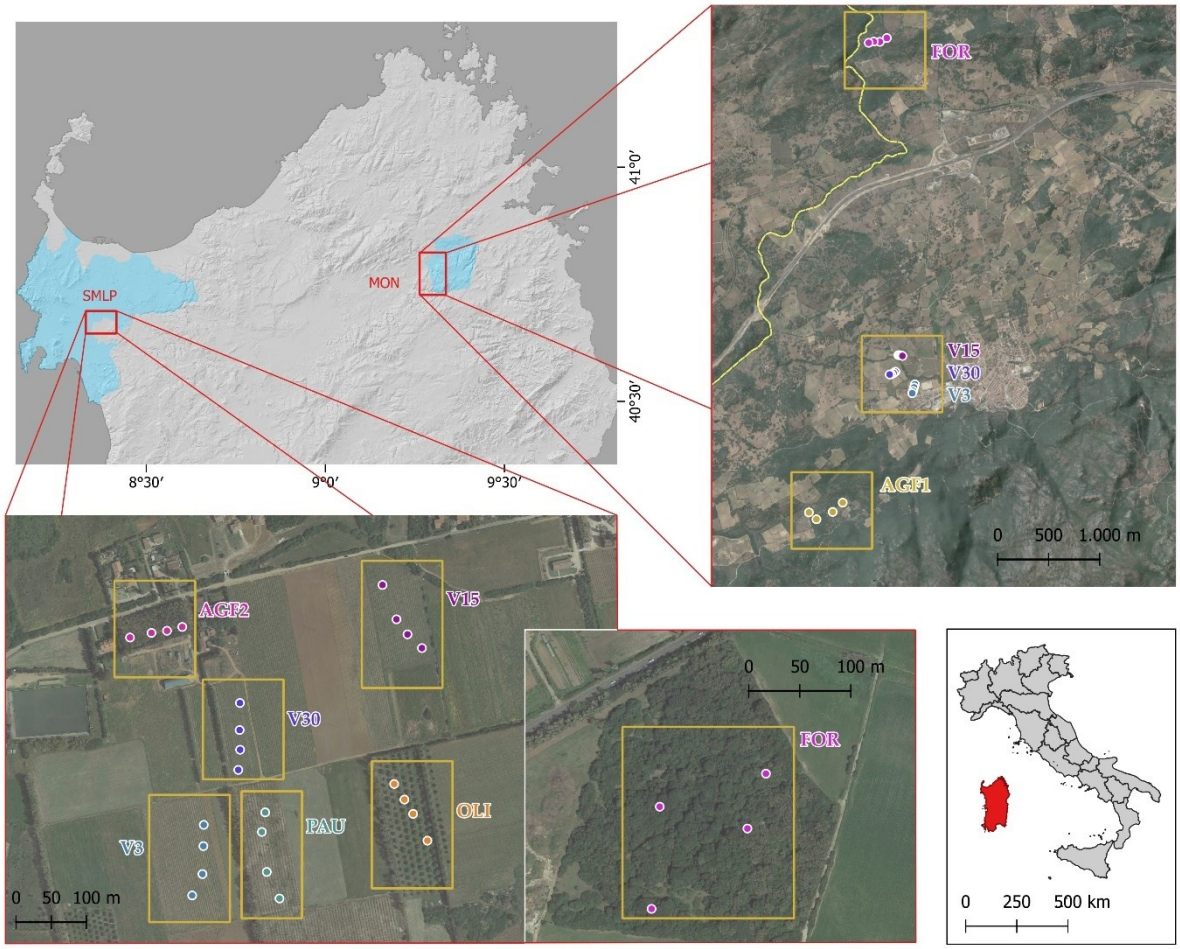


Fig. 1. Study areas and experimental design. MON: Monti; SMLP: Santa Maria La Palma; V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.; FOR-MON: cork oak forest; FOR-SMLP: holm oak (*Quercus ilex* L.) forest; OLI: olive groves; PAU: *Paulownia sp.* plantation.

Investigated areas are characterized by a hot-summer Mediterranean climate according to the Köppen-Geiger classification (Köppen, 1936), with rainy, mild winters and hot and dry summers (Caloiero and Guagliardi, 2021). The Monti site (300 m a.s.l.) experiences higher precipitation levels, with an average annual rainfall of 677 mm (Table 1). The mean annual temperatures range from a minimum of 9.6ºC to a maximum of 20.4ºC, with the lowest temperature (3.1ºC) reached in February and the highest (31.7ºC) in July. The Santa Maria La Palma (34 m a.s.l.) site is characterized by drier conditions, with an average annual rainfall of c.a. 563 mm, which also contributes to higher mean annual minimum and maximum temperatures, which are 12.2ºC and 22.4ºC, respectively; the lowest temperature (5.3ºC) recorded in January, while the highest (32.0ºC) in August (ARPAS, 2020).

Table 1

Features of the sites.

Site	Monti (MON)	Santa Maria La Palma (SMLP)
Elevation (a.s.l.)	300	34
Mean annual rainfall (mm $year^{-1}$)	677	563
Maximum rainfall (mm $month^{-1}$) and period (month)	107 in December	109 in November
Minimum rainfall (mm $month^{-1}$) and period (month)	6 in July	5 in July
Mean annual maximum temperature (ºC)	20.4	22.4
Mean annual minimum temperature (ºC)	9.6	12.2
Maximum temperature (ºC) and period (month)	31.7 in July	32.0 in August
Minimum temperature (ºC) and period (month)	3.1 in February	5.3 in January
Drought period	July	July and August

Both sites exhibit distinct geological, morphological, land use, historical, and socio-cultural characteristics that set them apart. The geology of Sardinia is predominantly composed of magmatic rocks, which have their origins in the Caledonian-Hercynian orogenetic cycles, and owing to geological and climatic conditions, the region exhibits a range of distinct features, with soils influenced by a variety of parent materials (Costantini and Dazzi, 2013).

The Monti site, for instance, belongs to the most spread Sardinia landscape units (in terms of geomorphological features), i.e., landscapes on intrusive rocks (such as granites, granodiorites, leucogranites) of the Paleozoic era, which encompasses approximately 29% of the Sardinia's surface (Aru et al., 1990, 1991). Soil survey, conducted before the sampling activities (*vide supra*), reveals soils belongs to Dystric and Eutric Cambisols (IUSS Working Group WRB, 2022). This pairing of soil and parent material (i.e., Cambisols on granites) is included among the most common units in Sardinia, accounting alone for 17.5% of the surface, featuring substantial rockiness and stoniness, shallow soil depth, significant erosion risk, low or poor fertility (Aru et al., 1990, 1991). Regarding land use, closely related to socio-cultural aspects, Monti is renowned for its widely cultivated Sardinian grape cultivar, Vermentino. Vermentino is an up-and-coming white wine grape, ranking as the fifth most popular in terms of sales volume in Italy; notably, Sardinian Vermentino has received the prestigious controlled and guaranteed denomination of origin (DOCG) status (Mercenaro et al., 2017), the highest recognition for native wine production. In Monti, there is a presence of a social winery of Vermentino. In addition to Vermentino cultivation, great importance is given to agroforestry systems in this municipality, in particular, the grazing land by sheep shaded with *Quercus suber* L. (cork oak) trees, accompanied by harvesting of non-timber forest products such as cork. Cork finds its primary uses in wine bottle production and as insulation material (Vogiatzakis et al., 2005), representing an important local socio-economic income.

In contrast, the Santa Maria La Palma site is situated within the landscape unit on limestones, dolomites, and dolomitic limestones of the Paleozoic and Mesozoic eras, which cover only 5% of Sardinia's total surface area (Aru et al., 1990, 1991). Soils were classified as Rhodic and Chromic Luvisols (IUSS Working Group WRB, 2022), included among one of the rarest units (i.e., Luvisols on limestone) in Sardinia, accounting for just 1.7% of the territory. Luvisols on limestone, also known as "Terra Rossa" or red Mediterranean soil (Costantini and Dazzi, 2013), are also marked by high rockiness and stoniness, shallow soil depth, a strong risk of erosion, and with current use the *Quercus ilex* L. coppicing (Aru et al., 1990, 1991). Santa Maria La Palma, also as Monti, hosts important socio-economic activities that drive the different land uses, such as vineyard cultivation and the presence of social winery, sheep and goats grazing, olives groves, commercial plantation of wood species (*Paulownia* sp.), in addition to the *Q. ilex* coppicing.

2.2 FIELD SAMPLING ACTIVITIES

Sites selection followed a step-by-step methodology, as following reported: *i)* a first analysis was conducted through a GIS analysis to individuate two contrasting pedosystems by using the Sardinia Soil Map (ORSS, 2023; Aru et al., 1990); *ii)* subsequently, on-site field recognition was conducted on several areas by finally selecting MON and SMLP (*vide supra*); *iii)* the two chosen sites were carefully investigated as successively outlined.

A first field soil survey, together with the collection of already realized soil analysis and soil maps, was conducted and compared to characterize and, finally, classify (IUSS Working Group WRB, 2022) and map soils in the selected areas. By this, two contrasting pedosystems were finally identified: *i)* Monti (MON) – Cambisols (CM, hereafter) on granite; *ii)* Santa Maria La Palma (SMLP) – Luvisols (LV, hereafter) on limestone. Both pedosystems exhibit features that are of significant environmental, cultural, and socio-economic importance at the local, regional, and national scale (*vide supra*).

Climatic conditions, geological and geomorphological features, natural vegetation, and land covers were all carefully investigated and, where necessary (as in the case of land covers/uses), mapped, since it is well-known that all these factors have a significant influence on SOCs (*vide supra*).

Different land covers were investigated, considering both commonalities and differences between the two selected sites. In particular, commonalities were represented by the presence of: *i)* three vineyard areas featured by the same grape cultivar (Vermentino, V), cultivated along the same period, i.e., 3 (V3), 15 (V15) and 30 (V30) years ago (at the time of the sampling activities, i.e., 2021); *ii)* the so-called potential natural vegetation (PNV), represented, in both sites, by oak (*Quercus* genus; *Quercus suber* L. for MON and *Quercus ilex* L. for SMLP (located in the "Bonassai" station) forests, i.e., the typical forest formation featuring Sardinian most natural areas. Differences were investigated in terms of: *i)* for the MON site by additionally investigating the most important (from both socio-economic and cultural viewpoint) and widespread Sardinia silvopastoral agroforestry system, i.e., a scattered cork oak trees (where a considering distance from each other characterizes every single tree; the total tree cover usually ranges from 7-250 trees ha^{-1}; Moreno et al., 2018) featured by intensive sheep grazing under the canopy and between trees; *ii)* for the SMLP site by also investigating other typical land uses featuring (for both cultural and socio-economic reasons) the limestone areas of Sardinia (such as olive groves, *Eucalyptus camaldulensis* Dehn.

plantations, *Paulownia* sp. plantations). All the previously reported sites are briefly summarized in Table 2.

Table 2

Site/pedosystem main features in terms of land cover (CORINE Land Cover; CLC2018).

Site/ pedosystem	Land cover		Label
Monti (MON)/ Cambisols (CM)	Agricultural	Permanent crop: Vineyard (Vermentino) planted 3 years ago	V3
	Agricultural	Permanent crop: Vineyard (Vermentino) planted 15 years ago	V15
	Agricultural	Permanent crop: Vineyard (Vermentino) planted 30 years ago	V30
	Agricultural	Agroforestry: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees, accompanied by harvesting of non-timber forest products such as cork.	AGF1
	Forest	Forest: natural cork oak (*Quercus suber* L.)	FOR
Santa Maria La Palma (SMLP)/ Luvisols (LV)	Agricultural	Permanent crop: Vineyard (Vermentino) planted 3 years ago	V3
	Agricultural	Permanent crop: Vineyard (Vermentino) planted 15 years ago	V15
	Agricultural	Permanent crop: Vineyard (Vermentino) planted 30 years ago	V30
	Agricultural	Permanent crop: Olive groves	OLI
	Agricultural	Agroforestry: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn. trees	AGF2
	Forest	Forest: *Paulownia* sp. plantation	PAU
	Forest	Forest: holm oak (*Quercus ilex*)	FOR

2.2.1 MONTI SITE

In the Monti site (Cambisols over granite, CM), the following land covers/uses were investigated: 1) vineyard (*Vitis vinifera* L. with Vermentino grape cultivar planted 3 (V3; Fig. 2a), 15 (V15; Fig. 2b) and 30 (V30; Fig. 2c) years before the time of the sampling activities (2021), cultivated with tillage to a depth of 20-30 cm, supplemented with mineral fertilization; irrigation, herbicides and pesticides together with weed removal from inter-row spaces, through

mechanical equipment, are common agricultural practices during the year; 2) the agro-forestry system, consisting of grazing land (annually fertilized by the owners) by sheep shaded with *Quercus suber* L. (cork oak) trees; the cork is periodically harvested for wine bottle stoppers and other commercial uses (such as the cores of cricket balls) (AGF1; Fig. 2d); and 3) the forest land covers, here represented by a highly natural cork oak forest (FOR; Fig. 2e).



a



b



c



d



e

Fig. 2. Investigated land covers in the MON pedosystem: a, b, and c) vineyard with Vermentino grape cultivar planted three (V3) (a), fifteen (V15) (b) and thirty (V30) (c) years before the sampling activities (2021); d) AGF1: grazing land by sheep shaded with *Quercus suber* L. (cork oak) trees (the so-called "*pascolo arborato*", in Italian); and e) FOR: natural cork oak forest.

2.2.2 SANTA MARIA LA PALMA SITE

In the Santa Maria La Palma site (Luvisols on limestone, LV), the following land covers/uses were investigated: 1) vineyard (*Vitis vinifera* L.) with the same features reported for the MON site (*vide supra*) (Figs. 3a-c), with tillage employed to a depth of 20-30 cm, mineral fertilization, irrigation, and without weed cleaning between rows; 2) olive groves (OLI; Fig. 3d) with no specific agronomic management as typical for Sardinian olive cultivation; 3) *Eucalyptus calmadulensis* Dehn. plantation grazed by goats under the canopy (AGF2; Fig. 3e); 4) a commercial plantation of *Paulownia* sp. (whose wood is widely used for its intrinsic sound-absorbing and thermal, electrical, and hygroscopic insulation properties, as well as cabinet-making, etc.) (PAU; Fig. 3f) planted c.a. 15 years before sampling activities (2021); and, 5) a holm oak (*Quercus ilex* L.) forest (FOR; Fig. 3g) located in the "Bonassai" station; it represents the last fragment of the original potential natural vegetation featuring the area before the massive reclamation conducted during the fascist period aiming at increasing agricultural areas.



a



b



c



d



e



f



g

Fig. 3. Investigated land covers in the SMLP pedosystem: a, b, and c) vineyard with Vermentino grape cultivar planted three (V3) (a), fifteen (V15) (b), and thirty (V30) (c) years before the sampling activities (2021); d) olive plantation (OLI); e) *Eucalyptus calmadulensis* Dehn. plantation in association with goat's pasture (AGF2); f) *Paulownia* sp. commercial plantation (PAU); g) holm oak (*Quercus ilex* L.) forest (FOR).

2.3 VEGETATION INVESTIGATION

To gain a deeper understanding of the ecological behavior in the different land covers and pedosystems, a phytosociological survey of vascular plants was carried out, when feasible, to account for the diverse array of plant forms encountered. This survey included a floristic inventory conducted in four field replicates, each consisting of 4 m² plots (2 x 2 m) between April and July 2021. Each species was assessed and assigned a value using the conventional alphanumeric scale of Braun-Blanquet (1928) and modified by Pignatti (1976), which reflects its coverage across the entire surveyed area. Subsequently, this scale was converted into a numerical scale according to Van der Maarel (1979) (Table 3).

Table 3

Conventional alphanumeric scale of Braun-Blanquet (1928), as modified by Pignatti (1976) and transformed (as numerical scale) by Van der Maarel (1979).

Braun-Blanquet scale		Van der Maarel scale
r =	rare individuals	1
+ =	cover < 1%	2
1 =	cover 1 – 20%	3
2 =	cover 20 – 40%	5
3 =	cover 40 – 60%	7
4 =	cover 60 – 80%	8
5 =	cover 80 – 100%	9

Within the MON pedosystem, the vegetation investigation focused exclusively on AGF1 and FOR land covers. This arose from the impractical investigation of vineyards (V3, V15, and V30) during the sampling activities, due to land use winery-advised vineyard management practices, which involve the complete removal of vegetation in the inter-rows.

2.4 LITTER SAMPLING AND ANALYSES

Litter was sampled by randomly placing a 50- by 50-cm wooden frame (as a reference area), when feasible. The litter was dried in an oven at 65ºC and weighed on a precision laboratory scale (0.01 g) to measure the total dry mass and, subsequently, milled. It was used for the C and N analyses by dry combustion using a CHN elemental analyzer (CHN 628; Leco, St. Joseph, Michigan, USA) and for the total concentration of several macro- and micronutrients (P, Ca, Mg, Na, K, Cu, Fe, Mn, and Zn) by acid digestion followed by spectrometry (AAnalyst 200, Atomic Absorption Spectrometer; PerkinElmer instruments). The litter C stocks (LCs) were then calculated by multiplying the C by the litter mass.

Litter features in the MON pedosystem were exclusively determined for the agroforestry (AGF1) and forest (FOR) land covers. Indeed, land use management practices carried out in the vineyards (*vide supra*), foresee the complete litter removal.

2.5 SOIL SAMPLING AND ANALYSES

In each sampling site (Table 2), surface (A horizon, 0-20 cm depth) and deep soil (B, 20-40 cm depth) horizons (disturbed and undisturbed) were collected in four different plots to have four field replicates for each land cover, totalizing eight soil samples (4 samples x 2 depths). The undisturbed samples were gathered by the core sampling method and were used to determine the bulk density (BD; g cm^{-3}), calculated by dividing the dry weight of soil by the volume.

The decision to investigate the two horizons was based on their shallow soil depth (Aru et al., 1990, 1991), a characteristic that is particularly pronounced in the Luvisols on limestone. Therefore, this choice was made to ensure the presence of both horizons in both pedosystems.

Several soil physical-chemical analyses were conducted on soil air-dried < 2 mm according to the official methods for soil analysis from the Italian Republic (MIPAF, 1999). For particles, wet-sieved soil was used, undergoing pre-treatment with hydrogen peroxide (to remove organic matter and cementing substances), followed by a sedimentation procedure. Soil texture was classified according to the USDA (Soil Survey Staff, 2011) as clay (< 0.002 mm), silt (< 0.05 mm), and sand (< 2 mm).

Soil reaction (pH-H_2O) was measured using a dynamic digital pH meter with soil: water suspension as 1:2.5 H_2O. Soil electrical conductivity (EC; µS cm^{-1} 25 °C) was determined using a 1:5 soil: water suspension. The testing for the secondary carbonates was conducted, but they were not present in the samples.

Subsamples were finely ground in a ball-mill grinder and used to determine soil organic carbon (SOC; g kg^{-1}) 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; g kg^{-1}) was determined by multiplying SOC by the Van Bemmelen coefficient, 1.724 (Nelson and Sommers, 1983). Soil organic carbon stock (SOCs; t ha^{-1}) was set on by multiplying carbon concentration by bulk density (BD; g cm^{-3}) and soil depth (cm), SOCs = SOC × BD × depth.

Available phosphorus (as P_2O_5; mg kg^{-1}) was extracted by the Olsen method. Total P was determined by spectrometry with the ascorbic acid method. Cation-exchange capacity (CEC; $cmol_c$ dm^{-3}) via $BaCl_2$-triethanolamine method at pH 8.2. Soluble cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}; $cmol_c$ dm^{-3}) by atomic absorption spectrometer. Iron (Fe; mg kg^{-1}) was

measured through the HCl acid solubilization method, and the content was determined by atomic absorption spectrometer. Manganese (Mn; mg kg^{-1}), zinc (Zn; mg kg^{-1}), and copper (Cu; mg kg^{-1}) were measured through the HNO_3 and HCl acid solubilization method, and the content was determined by atomic absorption spectrometer.

2.6 STATISTICAL ANALYSES

Statistics (univariate and multivariate) were carried out by using the software programs R (R Core Team, 2023), RStudio (RStudio Team, 2023), and Statistica 7.1 (StatSoft Inc Development, 2006). The analysis of variance (ANOVA) was performed to gauge statistical differences ($p < 0.05$) within the investigated vegetation, litter, and soil physical-chemical parameters and sites. Also, a comparison was conducted using the Tukey-HSD (honestly significant difference) test at $p < 0.05$. 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 physical-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, 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 (although it will not be detailed in the text); and, *iv*) FA was performed based on the CM as described previously in point (*iii*); *v*) varimax rotation was applied to enhance the statistical robustness and aid in the interpretation of the results. The principal component analysis (PCA) was conducted using the robust approach proposed by 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.

3 RESULTS AND DISCUSSION

This chapter is structured into three specific sub-chapters, as following reported and explained:

i) Monti (MON) pedosystem: in this part, all investigated soil depths/horizons (A and B) as well as land covers will be considered. Thus, (a) the three vineyards featured the same grape cultivar (Vermentino) but cultivated along 3 (V3), 15 (V15) and 30 (V30) years before the time of the sampling activities (2021), (b) the agroforestry system (AGF1), and (c) the natural potential vegetation, i.e., the cork oak forest (FOR);

ii) Santa Maria La Palma (SMLP) pedosystem: as for MON pedosystem (*vide point (i))*, all investigated soil depths/horizons and land covers have been considered. Consequently, reported results are for (a) vineyards of three different ages (*vide supra*), (b) olive groves (OLI), (c) agroforestry under *E. camaldulensis* cover (AGF2), (d) *Paulownia* sp. plantation (PAU), and (e) the natural potential vegetation, i.e., the holm-oak forest (FOR);

iii) Comparison between the investigated Mediterranean pedosystems, i.e., Monti (MON) *vs* Santa Maria La Palma (SMLP): in this case, only comparable land uses were taken into account. This was done to compare differences among pedosystems. Thus, it compared the three vineyards (V3, V15, and V30) and the natural potential vegetation (FOR).

The ratio for presenting results in this way is based on the idea of showing and comparing obtained outcomes starting from a more general view to more specific soil-related aspects. As a matter of fact, points (*i*) and (*ii*) will report results without comparing differences in terms of the investigated pedosystem. However, in these parts, several important aspects will be reported and explained before comparing (in the (*iii*) part) the two contrasting pedosystem. It represents a step-by-step approach that will facilitate the understanding of all complexes and articulated obtained results.

3.1 MONTI PEDOSYSTEM

3.1.1 VEGETATION INVESTIGATION

The vascular plants' investigation documented a list of 19 families, 44 genera and 48 vascular plants species (Table 4). Broadly, the biodiversity was characterized by Asteraceae (10 sp., 21%), Poaceae (8 sp., 17%), Apiaceae (4 sp., 8%), Rosaceae (4 sp., 8%), and Fabaceae (3 sp., 6%), constituting 60% of the total species (Fig. 4a).

Table 4

Floristic list of the vascular plants at MON pedosystem.

Family	Species	AGF1	FOR
Amaryllidaceae	*Allium roseum* L. subsp. *roseum*		×
Apiaceae	*Daucus carota* L.	×	×
	Eryngium tricuspidatum L.		×
	Oenanthe pimpinelloides L.	×	
	Smyrnium olusatrum L.		×
Asparagaceae	*Asparagus officinalis* L. subsp. *officinalis*	×	×
	Ruscus aculeatus L.		×
Asphodelaceae	*Asphodelus ramosus* L. subsp. *ramosus*	×	×
Asteraceae	*Achillea ligustica* All.		×
	Carlina corymbosa L.	×	×
	Carlina gummifera (L.) Less.	×	×
	Galactites tomentosus Moench	×	
	Glebionis coronaria (L.) Spach		×
	Leontodon tuberosus L.	×	×
	Pilosella ziziana (Tausch) F.W. Schultz & Sch. Bip.	×	
	Pulicaria odora (L.) Rchb.	×	×
	Taraxacum sect. Taraxacum	×	×
	Urospermum dalechampii (L.) Scop. ex F.W.Schmidt	×	×
Caryophyllaceae	*Petrorhagia prolifera* (L.) P.W. Ball & Heywood	×	

Family	Species	AGF1	FOR
Cistaceae	*Cistus creticus* subsp. *eriocephalus* (Viv.) Greuter & Burdet	×	
	Cistus monspeliensis L.	×	×
Fabaceae	*Cytisus villosus* Pourr.	×	×
	Trifolium angustifolium L. subsp. *angustifolium*	×	
	Trifolium campestre Schreb.	×	
Fagaceae	*Quercus ilex* L.	×	×
	Quercus suber L.	×	×
Geraniaceae	*Geranium dissectum* L.		×
Juncaceae	*Luzula forsteri* (Sm.) DC.		×
Oleaceae	*Fraxinus ornus* L. subsp. *ornus*		×
	Phillyrea angustifolia L.		×
Plantaginaceae	*Plantago lanceolata* L.	×	×
Poaceae	*Anthoxanthum aristatum* Boiss.	×	×
	Avena barbata Pott ex Link	×	×
	Brachypodium sylvaticum (Huds.) P.Beauv. subsp. *sylvaticum*	×	×
	Cynosurus polybracteatus Poir.	×	
	Dactylis glomerata L. subsp. *hispanica* (Roth) Nyman	×	×
	Festuca ligustica (All.) Bertol.	×	×
	Lagurus ovatus L.	×	
	Macrobriza maxima (L.) Tzvelev	×	×
Ranunculaceae	*Nigella damascena* L.	×	
Rosaceae	*Poterium sanguisorba* L.	×	×
	Pyrus spinosa Forssk.	×	×
	Rosa sempervirens L.	×	
	Rubus ulmifolius Schott	×	
Rubiaceae	*Galium palustre* subsp. *elongatum* (C. Presl) Arcang.		×
	Rubia peregrina L.		×
Smilacaceae	*Smilax aspera* L.	×	
Thymelaeaceae	*Daphne gnidium* L.	×	

Where: AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest.

Assessing the distribution of life-forms (Fig. 4b), herbaceous perennials (Hemicrytophytes – H) exhibited a notable predominance at 40%, succeeded by annual plants (Therophytes – T) at 25%, woody forms (Phanaerophytes – P at 12% and nano-Phanaerophytes – Np at 10%), and non-wood perennials (Geophytes – G) at 8%. Regarding dominant chorotypes (Fig. 4c), Steno-Mediterranean emerged at 44%, followed by Euro-Mediterranean at 27%, and Eurasian at 15%, accounting for 86% of the total.

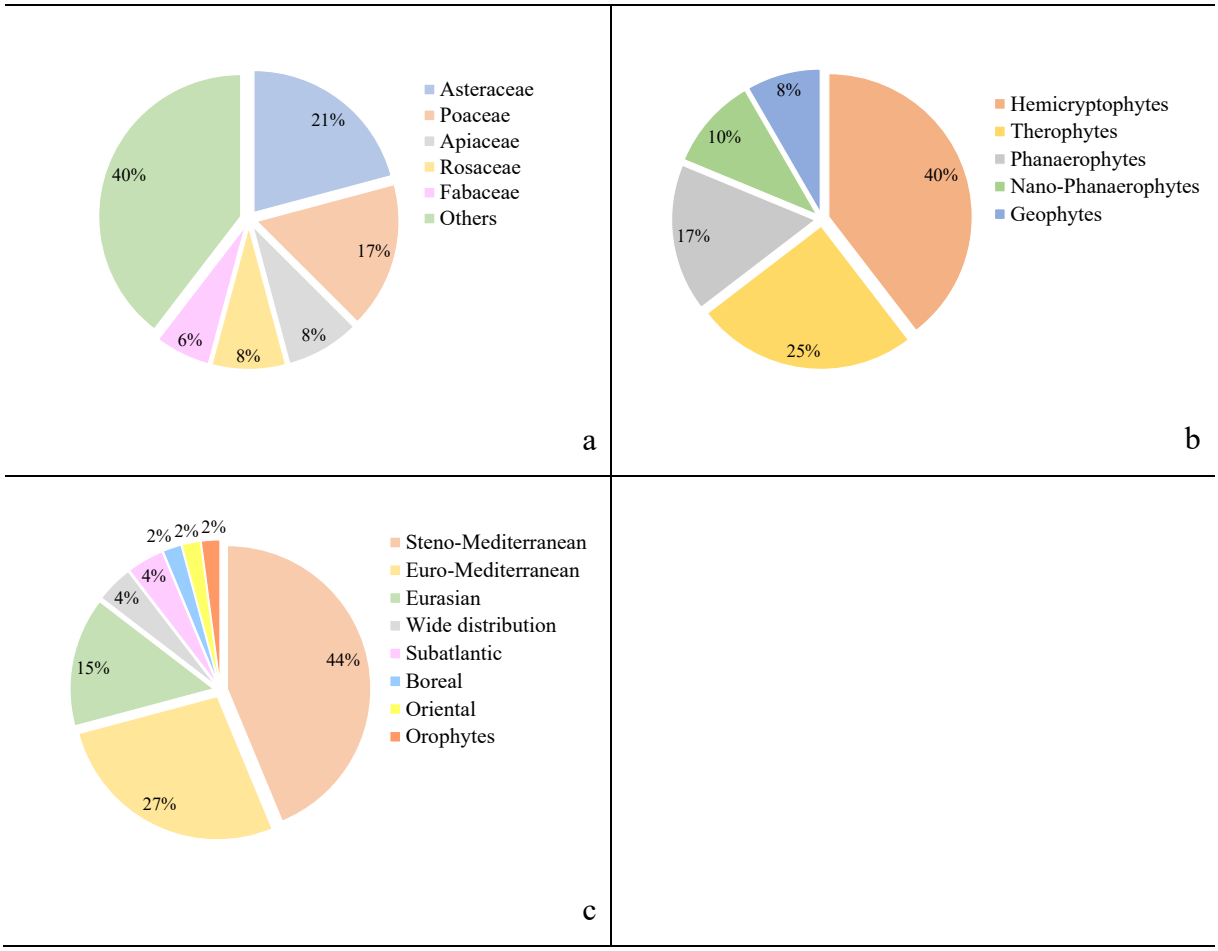


Fig. 4. Vascular plants abundance of MON pedosystem in terms of: a) families, b) life-form, and c) chorotypes.

When assessing the differences among the different land covers, vascular plants richness (range: 7 (FOR) to 23 (AGF1), mean: 18 ± 2; Fig. 5a) and Shannon-Weaver Diversity Index (H': range: 1.7 (FOR) to 2.9 (AGF1), mean: 2.6 ± 0.2; Fig. 5b) did not show significant differences ($p < 0.05$).

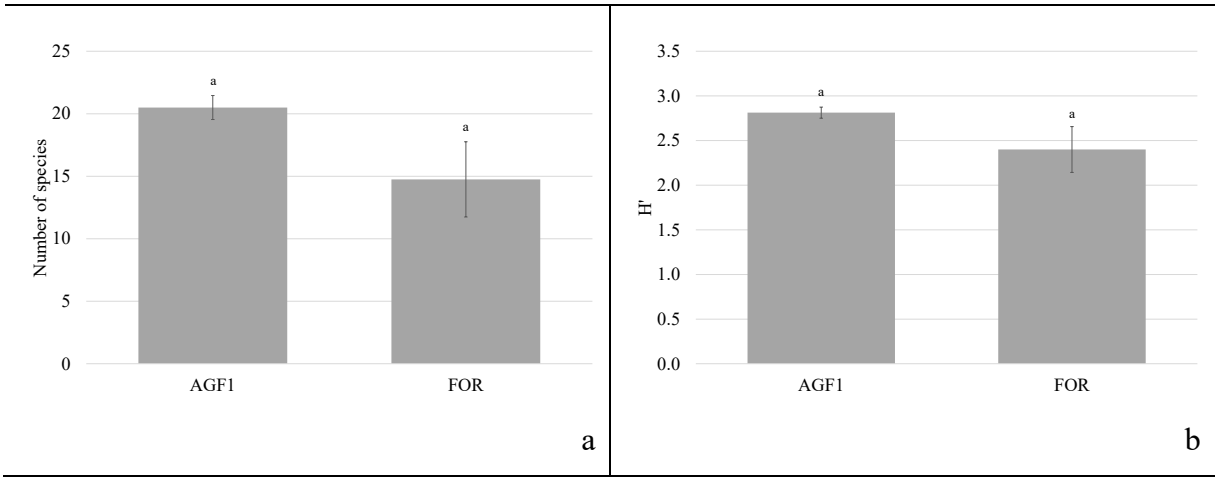


Fig. 5. Vascular plants richness (a) and Shannon-Weaver Diversity Index (b) along different land cover for MON pedosystem. AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest. Different lowercase letters showed significant differences ($p < 0.05$) among land covers.

Concerning the life-form (Fig. 6a), there were no significant differences ($p < 0.05$) observed among different land covers for Phanaerophytes (P: range 9 (AGF1) to 71% (FOR), mean: 25 ± 8%), nano-Phanaerophytes (Np: range 0 (AGF1 and FOR) to 14% (AGF1), mean: 6 ± 2%), Hemicrytophytes (H: range 29 (FOR) to 48% (AGF1), mean: 42 ± 3%), Geophytes (G: range 0 (FOR) to 15% (FOR), mean: 7 ± 2%), and Therophytes (T: range 0 (FOR) to 32% (AGF1 and FOR), mean: 19 ± 5%).

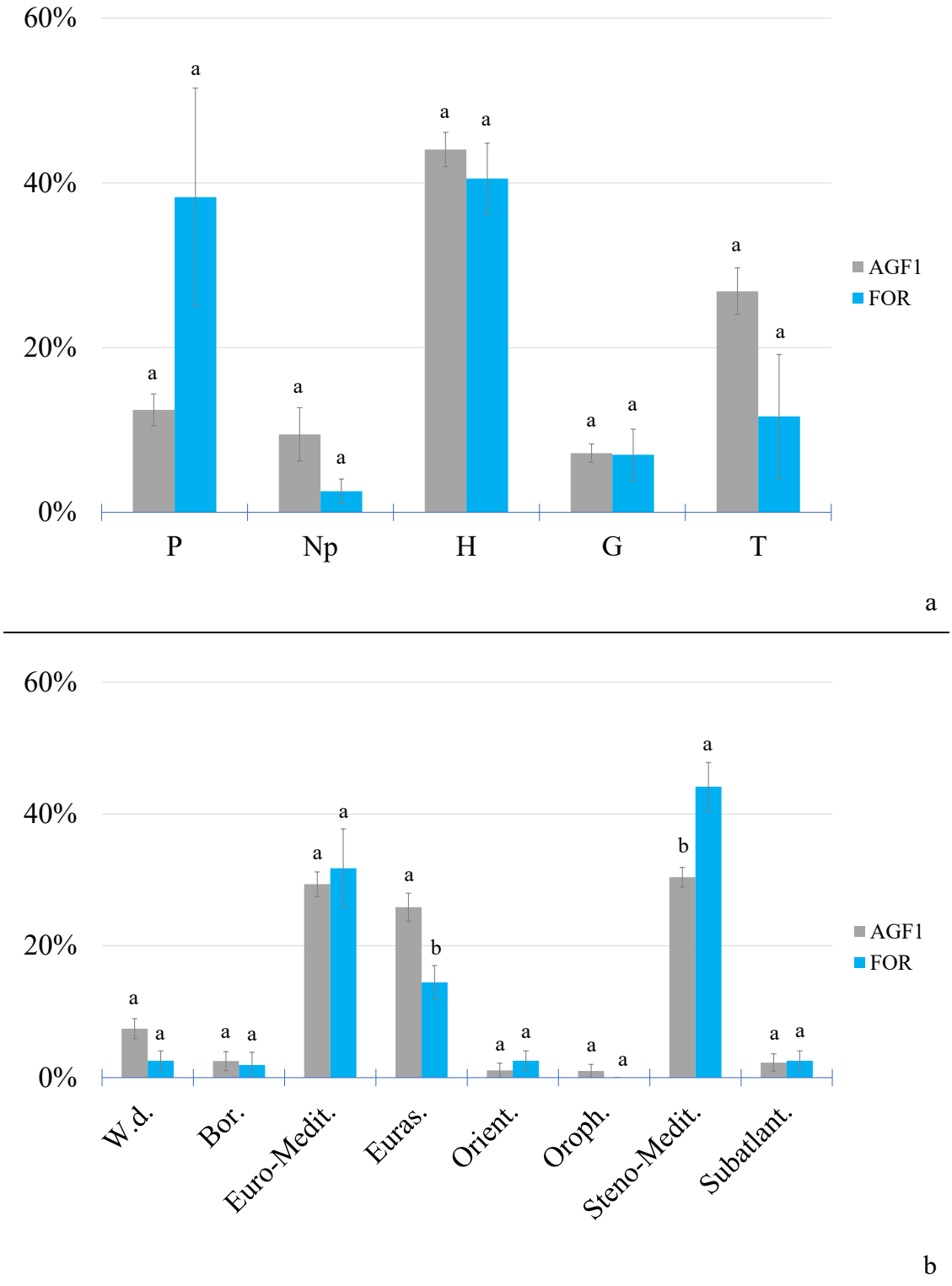


Fig. 6. Vascular plants life-form (a) and chorotype (b) along different land covers for MON pedosystem. AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest. Life-form: P: Phanaerophytes; Np: nano-Phanaerophytes; H: Hemicryptophytes; G: Geophytes; T: Therophytes. Chorotype: W.d.: wide distribution; Bor.: Boreal; Euro-Medit.: Euro-Mediterranean; Euras.: Eurasian; Orient.: Oriental; Oroph.: Orophyte; Steno-Medit.: Steno-Mediterranean; Subatlant.: Subatlantic. Different lowercase letters showed significant differences ($p < 0.05$) among land covers.

For the chorotype (Fig. 6b), some significant differences ($p < 0.05$) were observed. The Eurasian (range: 8 (FOR) to 32% (AGF1), mean: 20 ± 2%) exhibited a higher presence in the AGF1 land cover, while the Steno-Mediterranean (range: 26 (AGF1) to 53% (FOR), mean: 37 ± 3%) showed a higher presence in the FOR. Conversely, the other chorotypes, including Wide distribution (range: 0 (FOR) to 11 % (AGF1), mean: 5 ± 2%), Boreal (range: 0 (AGF1 and FOR) to 8% (FOR), mean: 2 ± 2%), Euro-Mediterranean (range: 16 (FOR) to 43% (FOR), mean: 31 ± 4%), Oriental (range: 0 (AGF1 and FOR) to 5% (FOR), mean: 2 ± 1%), Orophyte (range: 0 (AGF1 and FOR) to 4% (AGF1), mean: 1 ± 1%), and Subatlantic (range: 0 (AGF1 and FOR) to 5% (AGF1 and FOR), mean: 2 ± 1%), did not exhibit significant differences.

Overall, the investigation on vegetation shows that the plant community composition, structure, and diversity among the land covers featuring the MON pedosystem (i.e., agroforestry and forest) are similar. Despite agroforestry being subject to human activities (such as agronomic practices and sheep grazing), these influences do not seem to have a significant impact on the investigated plant features when compared to the less disturbed and more natural land cover represented by the cork oak forest.

3.1.2 LITTER FEATURES

Litter features of the MON pedosystem are presented in table 5. Notably, among the different studied features, sodium (Na: range: 0.28 (FOR) to 0.70 g kg^{-1} (AGF1), mean: 0.52 ± 0.06 g kg^{-1}) was the only feature that exhibited significant differences ($p < 0.05$), with a higher concentration in the AGF1 compared to FOR. No significant differences ($p < 0.05$) were observed for the others (C: range: 28.5 (FOR) to 56.8% (AGF1), mean: 47.3 ± 4.4%; N: range: 1.0 (AGF and FOR) to 1.5% (AGF and FOR), mean: 1.3 ± 0.1%; C/N ratio: range: 26 (FOR) to 55 (AGF1), mean: 38 ± 4; litter carbon stocks (LCs): range: 0.8 (AGF1) to 6.2 t ha^{-1} (FOR), mean: 3.0 ± 1.0 t ha^{-1}; P: range: 0.00 (AGF1) to 0.03 g kg^{-1} (FOR), mean: 0.01 ± 0.00 g kg^{-1}; Ca: range: 1.68 (FOR) to 10.98 g kg^{-1} (FOR), mean: 7.37 ± 1.36 g kg^{-1}; Mg: range: 1.26 (FOR) to 2.16 g kg^{-1} (FOR), mean: 1.69 ± 0.15 g kg^{-1}; K: range: 1.44 (AGF1) to 3.66 g kg^{-1} (AGF1), mean: 2.55 ± 0.38 g kg^{-1}; Cu: range: 6.00 (FOR) to 27.00 mg kg^{-1} (AGF1), mean: 11.96 ± 3.85 mg kg^{-1}; Fe: range: 360 (FOR) to 8700 mg kg^{-1} (FOR), mean: 2099 ± 1023 mg kg^{-1}; Mn: range

576 (AGF1) to 1665 mg kg^{-1} (AGF1), mean: 992 ± 212 mg kg^{-1}; and Zn: range 17.70 (FOR) to 37.80 mg kg^{-1} (FOR), mean: 25.94 ± 3.24 mg kg^{-1}).

Table 5

Chemical parameters of the litter at the MON pedosystem.

	AGF1	FOR
C (%)	52.8 ± 1.5 a	41.9 ± 7.3 a
N (%)	1.3 ± 0.1 a	1.2 ± 0.1 a
C/N	43 ± 5 a	33 ± 3 a
LCs (t ha^{-1})	2.4 ± 1.1 a	3.7 ± 0.9 a
P (g kg^{-1})	0.01 ± 0.00 a	0.01 ± 0.00 a
Ca (g kg^{-1})	7.15 ± 0.67 a	7.59 ± 2.04 a
Mg (g kg^{-1})	1.83 ± 0.10 a	1.54 ± 0.21 a
Na (g kg^{-1})	0.62 ± 0.05 a	0.41 ± 0.07 b
K (g kg^{-1})	2.59 ± 0.49 a	2.50 ± 0.26 a
Cu (mg kg^{-1})	14.09 ± 4.36 a	9.82 ± 3.33 a
Fe (mg kg^{-1})	1349 ± 87 a	2849 ± 1960 a
Mn (mg kg^{-1})	893 ± 260 a	1090 ± 163 a
Zn (mg kg^{-1})	25.49 ± 2.30 a	26.39 ± 4.18 a

Where: AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest. A number followed by different lowercase letters showed significant differences ($p < 0.05$) between different land covers.

Generally, there is variability in litter nutrient concentrations depending on the species (Krishna and Mohan, 2017). In the two investigated land covers, the species composition and dominance are alike (*vide supra*), with a notable presence of the *Q. suber* trees, and this similarity also reflected in the litter features, with no great significant differences observed among them.

3.1.3 SOIL FEATURES

Soil physical parameters

Based on the USDA particle-size classification (USDA, 2017), the soil texture class in the MON pedosystem was mainly sandy loam (Table 6). This was expected since the sand fraction usually strongly dominates Cambisols developed on granite. Lozano-García et al. (2020) argued that the physical features of Cambisols are significantly influenced by the granite substrate, being this rock characterized by intensive physical-chemical weathering, leading to the dominance of sand particles in the soil mineral matrix. The MON pedosystem showed a high sand content in all studied land covers, ranging from 66.7% (V30, A horizon) to 87.0% (V3, B horizon), with a mean of 77.4 ± 1.6% in the surface (A horizon; 0-20 cm) and 74.9 ± 1.9% in deep (B; 20-40 cm) horizon; significant differences ($p < 0.05$) were observed between the surface *vs* deep horizons at V30 land cover, along with some significant differences ($p < 0.05$) among the different land covers, in which AGF1 was significantly higher than V15 in the investigated surface horizon. In particular, the differences at V30 are likely attributed to land use practices and management of agricultural areas, such as the application of synthetic fertilizers, which affect soil properties by stimulating the growth of aboveground and belowground biomass, which, in turn, leads to increased SOM (Fig. 7c), contributing to improved soil structure and a reduction in the BD (Singh and Sapkota, 2022). For silt (range: 7.3 (V3, A horizon) to 17.6% (V30, A horizon), mean surface: 12.6 ± 1.0%, mean deep: 13.2 ± 0.9%), no significant differences ($p < 0.05$) were observed either between surface and deep horizons or among different land covers. Regarding the clay content (range: 5.6 (AGF1, A horizon) to 16.4% (V15, B horizon), mean surface: 10.0 ± 0.8%, mean deep: 11.9 ± 1.1%) showed significant differences ($p < 0.05$) between surface *vs* deep horizons at V30 (due to land use practices and management; *vide supra*) and at FOR.

The bulk density (BD: range: 0.9 (V3 and FOR, A horizon) to 1.5 g cm^{-3} (V3, V15, and FOR, B horizon), mean surface: 1.1 ± 0.1 g cm^{-3}, mean deep: 1.4 ± 0.0 g cm^{-3}) showed significantly ($p < 0.05$) an increase with increasing depth for most land covers (except for AGF1). Deeper horizons tend to have higher BD because they are typically characterized by a lower presence of SOM (Fig. 7c), decrease in porosity, experience less disturbance, and exhibit greater preservation of the parent material structure (Sequeira et al., 2014); thus, there is an inverse correlation between BD and SOM (Keller and Håkansson, 2010).

Table 6

Soil physical parameters at MON pedosystem; mean ± standard error (SE).

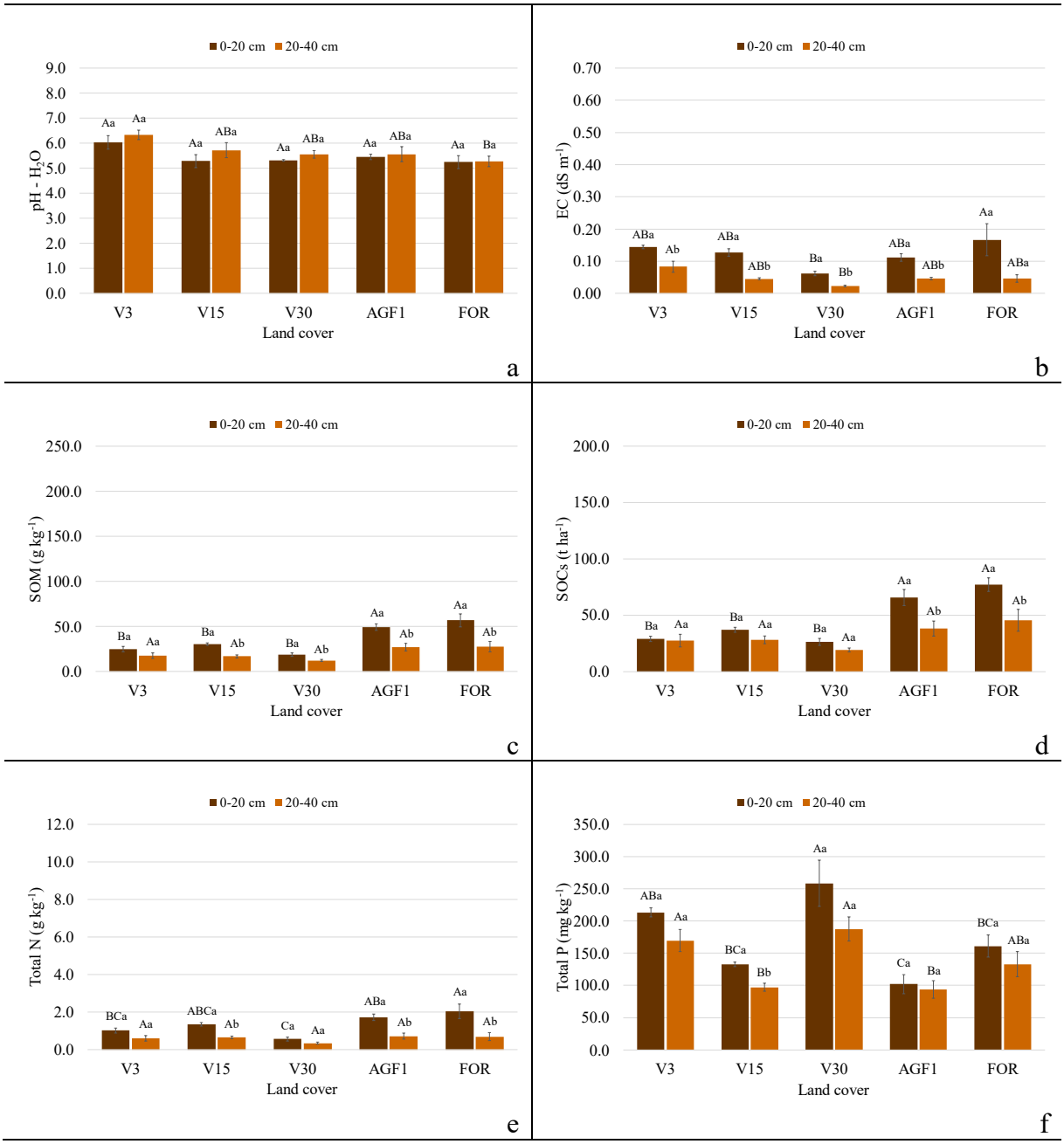
Land cover	Soil Horizon	Texture class	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})
V3	A	SL	78.6 ± 2.9 ABa	11.4 ± 1.4 Aa	10.0 ± 1.5 ABa	1.0 ± 0.1 Ab
	B	SL	77.2 ± 2.8 Aa	12.3 ± 1.4 Aa	10.5 ± 1.5 Aa	1.3 ± 0.0 ABa
V15	A	SL	73.8 ± 1.6 Ba	12.4 ± 0.8 Aa	13.8 ± 0.8 Aa	1.1 ± 0.1 Ab
	B	SL	74.0 ± 2.4 Aa	12.0 ± 0.9 Aa	14.0 ± 1.5 Aa	1.4 ± 0.0 Aa
V30	A	SL	76.8 ± 1.7 ABa	14.6 ± 1.2 Aa	8.6 ± 0.5 Bb	1.2 ± 0.0 Ab
	B	SL	70.7 ± 1.7 Ab	15.8 ± 0.9 Aa	13.5 ± 1.0 Aa	1.4 ± 0.0 ABa
AGF1	A	LS	82.1 ± 1.2 Aa	10.4 ± 0.7 Aa	7.5 ± 1.0 Ba	1.1 ± 0.0 Aa
	B	SL	78.3 ± 1.9 Aa	11.8 ± 0.8 Aa	9.9 ± 1.2 Aa	1.2 ± 0.1 Ba
FOR	A	SL	75.6 ± 0.7 ABa	14.4 ± 0.7 Aa	10.0 ± 0.4 ABb	1.2 ± 0.1 Ab
	B	SL	74.6 ± 0.5 Aa	14.0 ± 0.7 Aa	11.4 ± 0.2 Aa	1.4 ± 0.0 Aa
Mean	A		77.4 ± 1.6	12.6 ± 1.0	10.0 ± 0.8	1.1 ± 0.1
	B		74.9 ± 1.9	13.2 ± 0.9	11.9 ± 1.1	1.4 ± 0.0

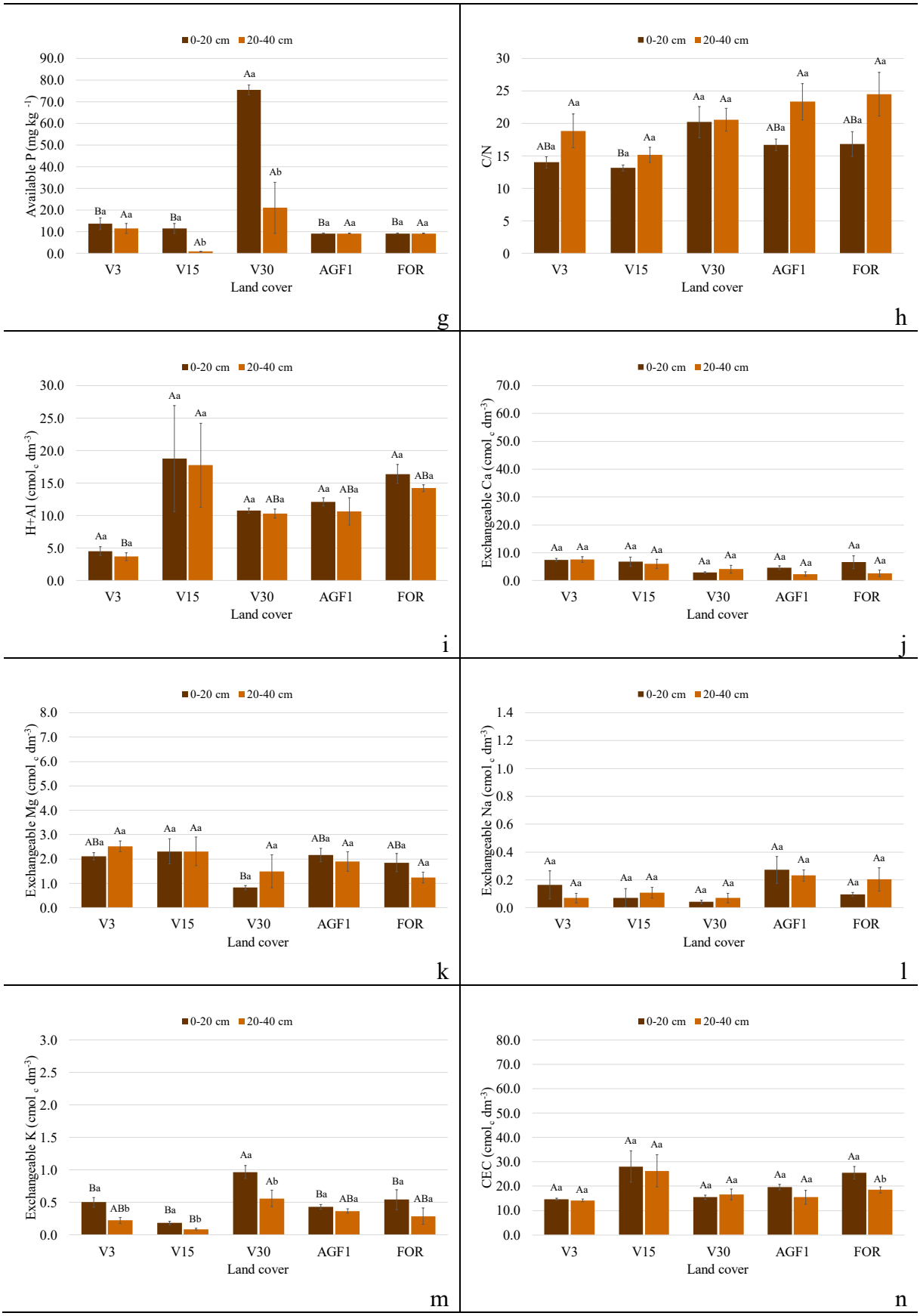
Where: V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest; LS: loamy sand; SL: sandy loam. A number followed by different capital letters showed significant differences ($p < 0.05$) among land covers within the same investigated soil horizon; different lowercase letters showed significant differences ($p < 0.05$) between surface and deep horizon within the same land cover.

Soil chemical parameters

Fig. 7 shows the soil chemical parameters between the surface (A horizon; 0-20 cm) and deep (B; 20-40 cm) horizon under different land cover. The MON-pedosystem is developed on granitic rocks (*vide supra*) and, consequently, exhibited an acidic pH (Fig. 7a), that ranged from very strongly acidic (4.5 at V15, A horizon) to neutral (6.8 at V3, B horizon), with a mean of 5.5 ± 0.2 for the surface horizon and 5.7 ± 0.2 for the deep one; no significant differences ($p < 0.05$) were observed between surface and deep horizons. However, among the different land covers, some significant differences ($p < 0.05$) were observed in the deep horizon, 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. Such a difference between these two different land covers seems to be related to the fact that the V3 is a relatively young soil since the area started to be used as a vineyard just three years before the field sampling activities (2021). Indeed, it must be underlined that when an area is converted into vineyard, soils are scrapped by heavy machinery with the risk of being affected by

"entisolization" processes (Dazzi and Monteleone, 2007), i.e., a regression or temporary slowdown in soil evolutionary processes (Capra et al., 2012). Sometimes, this can bring to the formation of anthropogenic soils, if most or the entire soil profile is affected; however, in this case, just the surface A horizon and, partially, the deep B one were affected. Thus, even though a human-induced regression process was partially observed, this was not enough to create anthropogenic soils with a relative taxonomic shift. However, this brings to the fact that leaching processes are still not strongly expressed, leaving higher amounts of basic cations compared to more developed FOR's soils, where leaching activities are more enhanced.




0-20 cm
20-40 cm
Available P (mg kg-1)
C/N
H+Al (cmolc dm-3)
Exchangeable Ca (cmolc dm-3)
Exchangeable Mg (cmolc dm-3)
Exchangeable Na (cmolc dm-3)
Exchangeable K (cmolc dm-3)
CEC (cmolc dm-3)
V3
V15
V30
AGF1
FOR
Land cover
g
h
i
j
k
l
m
n

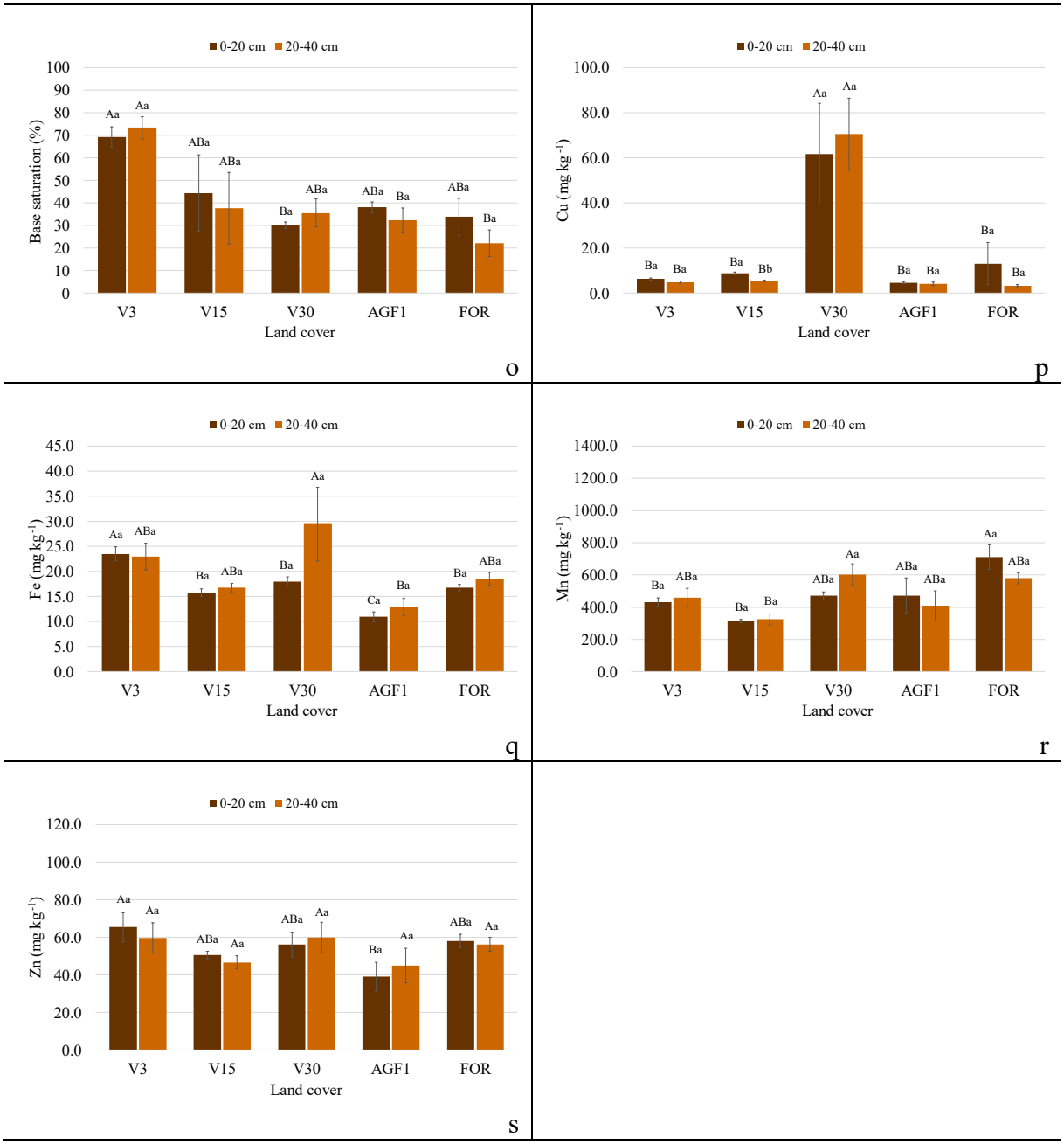


Fig. 7. Soil chemical parameters along surface (0-20 cm, darker color) and deep (20-40 cm, lighter color) soil horizons and different land cover for the Monti (MON) pedosystem. V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest. Different capital letters showed significant differences ($p < 0.05$) among land covers within the same investigated soil horizon, while different lowercase letters showed significant differences ($p < 0.05$) between surface (A horizon; 0-20 cm) and deep (B; 20-40 cm) horizon within the same land cover.

Soil electrical conductivity (EC: range: 0.02 (V30, B horizon) to 0.26 dS m^{-1} (FOR, A horizon), mean surface: 0.12 ± 0.02 dS m^{-1}, mean deep: 0.05 ± 0.01 dS m^{-1}; Fig. 7b) showed significant higher EC in the surface *vs* deep horizon, in almost all land covers (except at FOR). It was an expected result since the surface horizons are influenced by a substantial organic matter accumulation (Costantini and Dazzi, 2013), in which the exchange surface within, along with the decomposition, releases soluble ions into the soil surface solution, which can accumulate in the upper horizons, ultimately resulting in higher EC (Corwin and Lesch, 2005). When comparing the different land uses, the EC at the V30 land cover was significantly ($p < 0.05$) lower than that at FOR in the surface horizon, as well as lower than V3 for the deep horizon. This observation is likely attributed to V30 presenting the lower clay content (Table 6) and one of the lowest SOM amounts (Fig. 7c) in surface horizons compared to other land uses. Clay content and SOM 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).

Soil organic matter (SOM: range 9.1 (V3, B horizon) to 75.6 g kg^{-1} (FOR, A horizon), mean surface: 36.1 ± 3.5 g kg^{-1}, mean deep: 20.6 ± 3.1 g kg^{-1}; Fig. 7c) exhibited surface concentration significantly ($p < 0.05$) higher for nearly all land covers (except for V3). This outcome was expected, as SOM comprises various plant residues derived from litter inputs that tend to accumulate in surface horizons (Dazzi, 2021). When comparing different land covers, both FOR and AGF1 land covers presented significantly ($p < 0.05$) higher surface SOM compared to the others. In Mediterranean soils, there is a prevailing trend of decreasing organic matter in cultivated areas, primarily attributed to: *i)* reduced OM inputs; and, *ii)* its rapid mineralization (Costantini and Dazzi, 2013). As expected, when assessing the soil organic carbon stocks (SOCs: range 13.0 (V3, B horizon) to 89.5 t ha^{-1} (FOR, A horizon), mean surface: 47.2 ± 4.2 t ha^{-1}; mean deep: 31.8 ± 5.4 t ha^{-1}; Fig. 7d), similar outcomes were observed to the SOM one. Surface horizons exhibited significantly higher stocks than deep ones, particularly in more natural areas (AGF1 and FOR). Furthermore, when comparing different land covers, for both FOR and AGF1, significantly higher surface stocks than other covers were observed.

Total nitrogen (Total N: range 0.2 (V3, B horizon) to 3.1 g kg^{-1} (FOR, A horizon), mean surface: 1.3 ± 0.2 g kg^{-1}, mean deep: 0.6 ± 0.1 g kg^{-1}; Fig. 7e) showed surface with significantly higher ($p < 0.05$) concentration than the deep one for almost all land covers (V3 and V30, apart). Such an observation is related to the fact that the total N is strictly correlated to the OM amounts being SOM (Fig. 7c) its main source (Brady and Weil, 2010). This is

precisely why, among the different land covers, in this case too, the FOR displayed significantly the highest ($p < 0.05$) total N concentration in the surface horizon compared to others.

Total phosphorus (Total P: range 60.0 (AGF1, B horizon) to 360.0 mg kg^{-1} (V30, A horizon), mean surface: 173.6 ± 15.7 mg kg^{-1}, mean deep: 136.2 ± 15.1 mg kg^{-1}; Fig. 7f) presented significant differences ($p < 0.05$) between surface *vs* deep horizon only in the V15. The V30 land cover exhibited significantly higher ($p < 0.05$) total P concentrations in the surface horizon compared to AGF1 and higher concentrations in the deep horizon compared to AGF1 and V15. These findings may be related to the extensive use of P fertilizers in agricultural areas (such as vineyards in this case), resulting in P enrichment (Filipelli, 2008).

Available P (range: 0.9 (V15 and V30, B horizon) to 82.5 mg kg^{-1} (V30, A horizon), mean surface: 23.8 ± 1.4 mg kg^{-1}, mean deep: 10.4 ± 2.8 mg kg^{-1}; Fig. 7g) exhibited surface horizon significantly higher ($p < 0.05$) than the deep one in the agricultural land covers (V15 and V30). The V30 showed the highest ($p < 0.05$) available P compared to all the other land covers in the surface horizon. Since soil available P primarily originates from the breakdown of organic P in the soil through processes such as mineralization or SOM decomposition (Liu et al., 2014), observed results seem to be attributed to these processes.

The carbon-to-nitrogen ratio (C/N: range: 12 (V15, A horizon) to 35 (FOR, B horizon), mean surface: 16 ± 1, mean deep: 20 ± 2; Fig. 7h) did not showed significant differences ($p < 0.05$) between surface *vs* deep horizon. In the surface horizon, some significant differences ($p < 0.05$) were observed among the different land covers, in which the V30 was significantly higher ($p < 0.05$) than V15. As the C/N ratio represents the relationship between the SOC and the total N concentration (Costantini and Dazzi, 2013), this finding is intricately linked to the observed SOM (Fig. 8C) and the lower total N concentration (Fig. 7e) in the V30 land cover. These parameters resulted in a higher C/N in the V30, implying also a slower litter decomposition ratio compared to the others (Costantini and Dazzi, 2013).

Exchangeable acidity (H+Al: range: 2.0 (V3, B horizon) to 34.9 $cmol_c$ dm^{-3} (V15, A horizon), mean surface: 12.5 ± 2.3 $cmol_c$ dm^{-3}, mean deep: 11.3 ± 2.1 $cmol_c$ dm^{-3}; Fig. 7i) did not presented significant differences ($p < 0.05$) between surface *vs* deep horizon, nor among the different land covers in the surface horizon. In the deep horizon, the V15 was significantly higher ($p < 0.05$) than the V3. This higher value in V15 can be attributed to the relatively lower pH in this land cover compared to the V3, even if the difference in pH between these two was not significant ($p < 0.05$). Nevertheless, the trend of decreasing soil pH has a noticeable influence on increasing the exchangeable Al, and given that Al typically coexists with hydroxyl groups, its solubility is directly linked to the concentrations of H^+ ions (Nair et al., 2019).

Exchangeable cations (Ca^{2+}: range 0.4 (FOR, B horizon) to 11.9 $cmol_c\ dm^{-3}$ (FOR, A horizon), means of 5.7 ± 1.1 $cmol_c\ dm^{-3}$ for surface horizon and 4.5 ± 1.2 $cmol_c\ dm^{-3}$ for deep one; Mg^{2+}: 0.6 (V30, A horizon; V15, V30 and FOR, B horizon) to 3.5 $cmol_c\ dm^{-3}$ (V30, B horizon), means of 1.9 ± 0.3 $cmol_c\ dm^{-3}$ for surface and 1.9 ± 0.4 $cmol_c\ dm^{-3}$ for deep; Na^{+}: 0.0 (V3, V15, V30, and AGF1, A horizon; V3 and V30, B horizon) to 0.5 $cmol_c\ dm^{-3}$ (AGF1, A horizon), means of 0.1 ± 0.1 $cmol_c\ dm^{-3}$ for surface and 0.1 ± 0.0 $cmol_c\ dm^{-3}$ for deep; K^{+}: 0.1 (V15, A horizon; V3, V15, and FOR, B horizon) to 1.2 $cmol_c\ dm^{-3}$ (V30, A horizon), means of 0.5 ± 0.1 $cmol_c\ dm^{-3}$ for surface and 0.3 ± 0.1 $cmol_c\ dm^{-3}$ for deep; Figs. 7j-m) did not show significant differences ($p < 0.05$) between surface *vs* deep horizon, except the K, which showed significantly higher concentrations on the surface in the agricultural land covers (V3, V15, and V30). When comparing the different land covers along the surface horizon, some significant differences ($p < 0.05$) were observed only for the exchangeable Mg and K, in which the V15 was higher than V30 for the Mg, and the V30 showed the highest concentration for the K. In the deep horizon, some significant differences ($p < 0.05$) were observed just for K, in which the V30 showed the highest ($p < 0.05$) concentration. The higher values in the surface horizon observed in the agricultural areas (vineyards), in comparison to other land covers, may be attributed to land management practices involving the application of fertilizers and/or organic amendments aimed at enhancing soil fertility (Chowdhury et al., 2021). Consequently, these practices lead to higher concentrations of exchangeable cations, especially in the upper horizon, particularly in areas under long-term implementation (i.e., V15 and V30).

Cation exchange capacity (CEC: range: 9.0 (AGF1, B horizon) to 40.0 $cmol_c\ dm^{-3}$ (V15, A horizon), mean surface: 20.7 ± 2.3 $cmol_c\ dm^{-3}$, mean deep: 18.2 ± 2.7 $cmol_c\ dm^{-3}$; Fig. 7n) presented significant differences ($p < 0.05$) between surface and deep horizons in the FOR land cover, with the surface horizon showing the highest CEC. However, when comparing the different land covers in both the surface and deep horizon, no significant differences ($p < 0.05$) were observed. The observed values in the FOR land cover can be ascribed to soil parameters such as pH, SOM, and clay content, which generally have a significant influence on the CEC (Manrique et al., 1991).

For base saturation (BS: range 9 (V15, A horizon; FOR, B horizon) to 87% (V3, B horizon), mean surface: 43 ± 7%, mean deep: 40 ± 8%; Fig. 7o), no significant differences ($p < 0.05$) were observed between surface and deep horizons. When comparing the different land covers, the V3 was significantly higher ($p < 0.05$) than V30 on the surface and higher than AGF1 and FOR on the deep horizon. The observed results are associated with soil pH, wherein

elevated pH values coincide with higher concentrations of some or all exchangeable cations, and consequently BS (Yost & Hartemink, 2019).

Copper (Cu: range: 2.3 (FOR, B horizon) to 99.0 mg kg^{-1} (V30, A horizon), mean surface: 18.9 ± 6.7 mg kg^{-1}, mean deep: 17.7 ± 3.6 mg kg^{-1}; Fig. 7p) showed significant differences ($p < 0.05$) between the surface and deep horizon in the V15, with higher values observed in the surface horizon. Copper typically exhibits low mobility in soil and displays relatively minor variations in its overall content within soil profiles, resulting in the accumulation in the upper horizon (Kabata-Pendias and Pendias, 2001). Comparing the different land covers along both horizons, the V30 land cover was significantly higher ($p < 0.05$) for both surface and deep. The heightened presence of Cu in the V30 is likely attributable to agricultural practices by anthropogenic sources of this element. Agricultural areas such as vineyards have faced fungal diseases, leading to a consistent application of copper-based fungicides as a protective measure for the plants; this practice has resulted in the accumulation of the element (Brunetto et al., 2016; Pietrzak and McPhail, 2004).

Iron (Fe: range: 8.3 (AGF1, B horizon) to 51.3 mg kg^{-1} (V30, B horizon), mean surface: 17.0 ± 0.9 mg kg^{-1}, mean deep: 20.1 ± 2.8 mg kg^{-1}; Fig. 7q) did not presented significant differences ($p < 0.05$) between surface and deep horizons. Regarding different land covers, some significant differences were observed for both horizons. On the surface, the V3 presented significantly ($p < 0.05$) the highest content, while for the deep horizon, the V30 significantly ($p < 0.05$) differed from AGF1. The Fe content in soils is related to the parent material and is a consequence of soil processes (Kabata-Pendias and Pendias, 2001).

For manganese (Mn: range: 165.0 (AGF1, B horizon) to 880.6 mg kg^{-1} (FOR, A horizon), mean surface: 479.7 ± 49.4 mg kg^{-1}, mean deep: 475.0 ± 56.8 mg kg^{-1}; Fig. 7r), no significant differences were observed between the surface *vs* deep horizon. On the surface, the FOR land cover was significantly higher ($p < 0.05$) than V3 and V15. In the deep horizon, the V30 presented significantly higher ($p < 0.05$) content than V15. Even if the variations of Mn content are generally associated with clay content, it is frequently noted that SOM's can also influence it (Kabata-Pendias and Pendias, 2001). For this reason, the higher Mn observed in FOR land cover seems to be related to the higher SOM (Fig. 7c).

Zinc (Zn: range: 22.3 (AGF1, A horizon) to 82.5 mg kg^{-1} (V30, B horizon), mean surface: 53.9 ± 5.5 mg kg^{-1}, mean deep: 53.5 ± 6.5 mg kg^{-1}; Fig. 7s) did not present significant differences ($p < 0.05$) between the surface and deep horizon, nor among different land covers in the deep horizon. Among different land covers on the surface, V3 was significantly higher ($p < 0.05$) than AGF1. Higher Zn concentrations in agricultural areas, such as vineyards, are

often attributed to the intensive application of agrochemicals and soil amendments (Sonoda et al., 2019), as for Cu.

3.1.4 MULTIVARIATE STATISTICS

Principal Factor Analysis (PFA)

The PFA was conducted to obtain a more comprehensive understanding of the observed outcomes and related relationships. In particular, two PFAs have been implemented by taking into account the investigated parameters in: *i*) surface A and deep B horizons; and, *ii)* vegetation, litter, and only soil surface A horizon. The ratio was to firstly (in (*i*)) consider the whole of soil physical-chemical parameters along both investigated soil horizons and land uses. In this way, the whole complexity and variability of interactions and relationships can be considered. While in (*ii*), by only considering the surface horizon, vegetation and litter, meaning realizing a more in-depth investigation among the more involved soil horizons (A and litter, i.e., a mix of Oi, Oe, and Oa, horizons) in terms of interaction with vegetation (Capra et al., 2018), where feasible. In the MON pedosystem, the vineyards did not present vegetation and litter during sampling activities (*vide supra*), thus, the PFA of point (*ii*) in MON considered only the AGF1 and FOR land covers.

PFA – Surface and deep soil horizons

The PFA extracted a three-component model (Table 7), with all factors showing eigenvalues greater than 1, thus demonstrating the high statistical reliability of the implemented model. These three factors explained 55% of the total variation. The first one (F1) accounted for 21% of the variance, revealing a positive correlation between C/N and H+Al, along with a negative correlation with pH, EC, exchangeable cations (Ca and Mg), and BS. This factor highlighted a consistent pattern observed in acidic soils (such as those in MON pedosystem), where a decrease in soil pH corresponds to lower EC, reduced concentrations of exchangeable cations (e.g., Ca and Mg), and consequently, lower BS. Additionally, the factor emphasized that as soil pH decreases, there is an increase in exchangeable acidity (H+Al) (Nair et al., 2019). This factor can thus be interpreted as *"the role of soil pH in influencing exchangeable cations*

behavior." The second factor (F2, 19% of variance), extracted exchangeable Mg and Na as positive concordant, while they are negatively related to total and available P, exchangeable K, and Cu. This shows an exchangeable base competition for exchange sites. As a matter of fact, the equilibria between the exchangeable cations in the soil colloidal fractions and in the soil water are influenced by multiple aspects such as those related to soil leaching and plant nutrition (as shown by the negative correlation of Mg and Na *vs* P forms). In acidic, strongly leached pedosystems (as in MON) this competition has a great influence on P behavior too, by bringing to its depletion. Such a factor can be called "*the influence of cation competition for exchangeable sites in influencing P behavior*." The third factor (F3, 16% of total variance), extracted EC, SOCs, total N, and Mn as all positively concordant, while inversely correlated with BD and Fe. This factor indicates the well-known relationship between SOCs and total N (Brady and Weil, 2010), being the first the main soil source of the second. The increase in Mn is explained by taking into account 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, 2001). 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 & Lesch, 2005). The negative correlation between EC and Fe is usually observed, in acidic soil conditions (as for Cambisols on granite); indeed, Fe-compounds formation are negatively related to EC values (Kabata-Pendias and Pendias, 2001), Finally, the negative correlation between SOCs and BD, show the ability of SOM in reducing BD (Keller & Håkansson, 2010). Overall, this factor can be interpreted as *"the role of SOCs in influencing some soil fertility-related parameters and improving BD."*

Summarizing, for the MON pedosystem, when all land uses and horizons are taken into account, the PFA mainly reveals the importance of the sandy, acidic nature of the soil matrix in mainly influencing observed variability. The SOCs had a "relative" (even if not negligible) role, being extracted as the third and last factor.

Table 7

Factor loadings of a factor analysis (n = 40) for the MON pedosystem considering surface and deep soil horizons; Extraction Method: principal factor analysis (PFA); Rotation Method: Varimax; bold loadings > 0.4.

	Monti (MON)		
	F1	F2	F3
pH	**-0.762**	0.126	-0.231
EC	**-0.444**	-0.114	**0.811**
Sand	0.053	0.040	0.078
Silt	0.227	-0.297	0.061
Clay	-0.273	0.184	-0.175
BD	0.320	0.273	**-0.431**
SOCs	0.191	0.248	**0.887**
Total N	-0.122	0.075	**0.947**
C/N	**0.488**	0.191	-0.354
Total P	-0.149	**-0.864**	0.024
Available P	0.218	**-0.834**	-0.139
Ca^{2+}	**-0.871**	0.046	0.328
Mg^{2+}	**-0.769**	**0.417**	0.166
Na^{+}	0.083	**0.542**	0.081
K^{+}	0.151	**-0.788**	0.257
CEC	0.025	0.172	0.250
BS	**-0.907**	-0.001	0.034
H+Al	**0.441**	0.126	0.091
Cu	0.196	**-0.716**	-0.158
Fe	-0.298	-0.113	**-0.405**
Mn	0.165	-0.133	**0.409**
Zn	-0.244	-0.218	-0.113
Proportional variance (%)	21	19	15
Cumulative variance (%)	21	40	55
Eigenvalues	4.645	4.128	3.436

PFA – Vegetation, litter, and surface soil horizon

The PFA extracted mainly a three-component model (Table 8), collectively explaining 77% of the total variation. The first factor (F1), accounting for 34% of the total variance, showed a positive correlation among the Shannon-Weaver Index and several soil chemical parameters (pH, EC, SOCs, N, total P, exchangeable cations (Ca, Mg, and K), CEC, BS, and Mn). Conversely, they are all inversely related to litter parameters (C, N, and C/N) and C/N ratio. This factor shows that in the investigated pedosystem, SOCs play an important role in increasing biodiversity. As a matter of fact, as SOCs increased the Shannon-Weaver index increased too; as expected, with increasing of all the other SOM-influenced parameters (*vide supra* and *infra*). Consequently, this factor can be interpreted as "*the positive influence of SOCs in increasing biodiversity.*" Factor 2 (30% of the total variance), extracted all vegetation parameters, Mg and Na in the litter, pH, sand, Na, and BS in the soil as all correlated; conversely, all these parameters were negatively associated with P in the litter, silt, clay, total P, CEC, H+Al and some micronutrients (Mn, Fe, and Zn) into the soil. This factor shows a complex and articulated series of multiple comparisons involving vegetation, litter, and soil. Firstly, it confirms that vegetation indexes are strongly influenced by soil parameters with particular emphasis on BS. These relationships are better expressed in sandy-leached soils, as showed by the positive correlation with sand and the negative with CEC and micronutrients. Thus, this factor can be called "*the influence of soil-sandy nature in influencing vegetation biodiversity and richness*." The third factor (F3) explained 13% of the variance, revealing positive correlations between litter parameters (N, K, Cu, and Zn), while negatively with litter C/N, soil clay, and soil Na. This seems to show that during litter humification processes (the process mainly affecting litter in the investigated environments, compared to mineralization), high C/N ratio, basic cations (N and K) as well as some micronutrients (in this case especially Cu and Zn) are released into the mineral soil environment. During such a process, the clay fraction (note the negative correlation with it) favored humification since these minerals can retain large N amount. For all these reasons, such a factor can be named "*the role of humification processes in soil litter*."

Finally, it is interesting to note that when only surface A horizon, together with vegetation and litter, are considered, PFA immediately reveals the most important role played by SOCs if compared to the previous PFA (Table 7). As a matter of fact, even if the sandy acidic soil nature still plays a pivotal role, it was extracted as II factor (it was the first in the

previous elaboration, see Table 7). Thus, by excluding deep horizon (Bw) and considering also litter and vegetation parameters, the SOCs assume the most important role.

Table 8

Factor loadings of a factor analysis (n = 8) for the MON pedosystem considering vegetation, litter, and surface soil horizon; Extraction Method: principal factor analysis (PFA); Rotation Method: Varimax; bold loadings > 0.4.

	F1	F2	F3
Richness (V_S)	0.375	**-0.847**	0.159
Number of different families (V_F)	0.399	**-0.709**	0.137
Shannon-Weaver Index (V_H')	**0.426**	**-0.783**	0.327
L_C	**-0.890**	-0.185	-0.218
L_N	**-0.552**	0.154	**0.479**
L_LCs	0.189	0.014	0.196
L_C/N	**-0.584**	-0.376	**-0.605**
L_P	-0.233	**0.441**	0.116
L_Ca	-0.313	0.252	-0.224
L_Mg	-0.005	**-0.704**	0.090
L_Na	-0.360	**-0.490**	0.223
L_K	0.094	-0.002	**0.947**
L_Cu	-0.102	-0.182	**0.802**
L_Fe	0.330	-0.016	0.154
L_Mn	-0.161	0.124	0.082
L_Zn	0.320	-0.145	**0.688**
S_pH	**0.671**	**-0.664**	-0.069
S_EC	**0.937**	0.106	0.120
S_Sand	-0.268	**-0.861**	0.387
S_Silt	0.152	**0.884**	-0.120
S_Clay	0.347	**0.615**	**-0.628**
S_BD	-0.350	0.125	-0.279
S_SOCs	**0.701**	0.041	-0.216
S_N	**0.981**	0.079	-0.097

S_C/N	**-0.546**	-0.064	0.021
S_Pt	**0.672**	**0.718**	0.027
S_Ca	**0.979**	0.019	-0.007
S_Mg	**0.628**	-0.315	-0.154
S_Na	-0.224	**-0.807**	**-0.427**
S_K	**0.765**	0.010	0.304
S_CEC	**0.839**	**0.404**	0.055
S_BS	**0.772**	**-0.427**	-0.094
S_H+Al	0.059	**0.707**	0.124
S_Cu	0.340	0.041	0.167
S_Fe	0.111	**0.972**	-0.034
S_Mn	**0.673**	**0.655**	0.190
S_Zn	0.245	**0.870**	0.222
Proportional variance (%)	34	30	13
Cumulative variance (%)	34	64	77
Eigenvalues	12.551	11.085	4.869

Where: Green part (V_) = vascular plant parameters, gray part (L_) = litter parameters, and orange part (S_) = soil parameters (A horizon, 0-20 cm depth).

Principal Component Analysis (PCA)

The PCA was performed to identify the soil physical-chemical parameters that exhibited greater importance related to the pedosystem's observed variability as well as among the different investigated land covers. Essential variables were identified using the biplots, i.e., the most common and reliable graphic representation for PCA analysis. The first (PC1) and the second (PC2) components explained 21% and 19% of the total variability, respectively (Fig. 8), collectively accounting for 40%. The PCA revealed that the investigated areas are completely different in terms of variability, primarily due to differences in land cover, clearly varying from agricultural (V3, V15, and V30) to more natural areas (AGF1 and 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, base saturation (BS), and clay content; *ii)* V15 is rather closer to V3, with the additional influence of some exchangeable cations (Ca and Mg) and electrical conductivity (EC); *iii)* V30 is mainly influenced by microelements (Cu, Fe, Mn, and Zn), total and available P, exchangeable K, silt content. These findings in the vineyards

may be attributed to the influence of time on the soil development. As a matter of fact, in V3, i.e., the younger vineyard, it was observed that pH and base saturation play a pivotal role as typical in the early stage of soil development. As time went by, such an influence, even if still present, became less important, and in V15 it was observed an increasing influence of exchangeable cations as typically observed in more developed, but still young, soils. It must be underlined that even if the age of the soil cannot be referred from the time of vineyard began, such kind of 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, exchangeable K greatly increase their influence as typically observed in more developed, or less younger, soils (Kabata-Pendias and Pendias, 2001). Conversely, in more natural areas a greater influence of SOCs and N, with the trend AGF1 > FOR, was observed. This observation can be attributed to the similarity in vegetation composition between AGF1 and FOR land covers in the MON pedosystem, with the main difference lying in land use for sheep grazing. The AGF1 land cover, exposed N/NE, is featured by lower temperatures, water stagnation, higher fertility, and thicker vegetation, resulting in elevated soil fertility and SOCs compared to the FOR. Additionally, such a system is strongly influenced by sheep grazing, by returning feces and urine to the soil, being responsible for an important additional contribution in soil organic matter and N increase (Barsotti et al., 2013).

Overall, the PCA for MON pedosystem showed that vineyards are mainly influenced by a "time-related" component, while in most natural environments SOCs and related parameters (such as N and CEC) play the most important role.

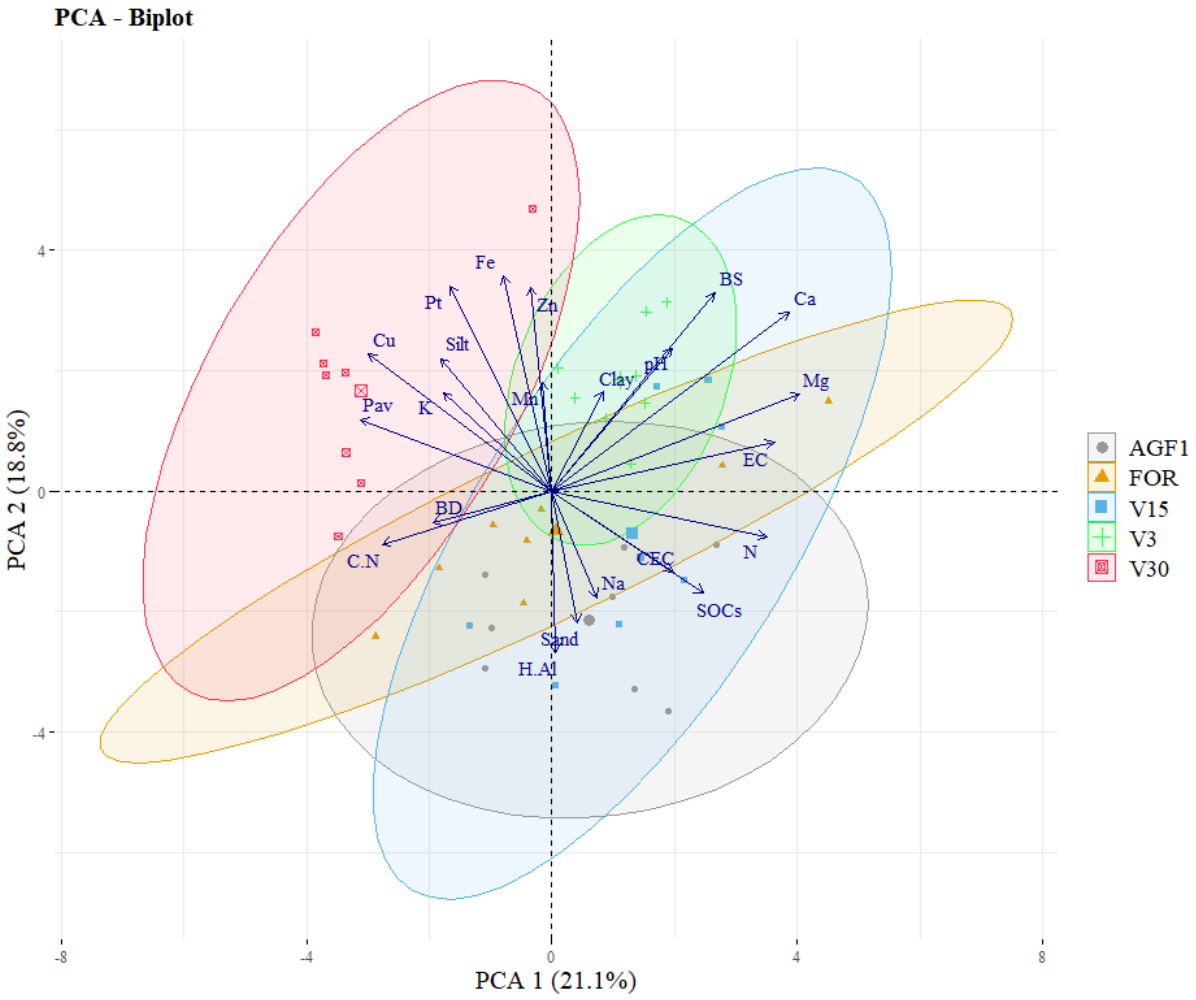


Fig. 8. Principal component analysis related to soil physical-chemical parameters from Monti pedosystem. V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; AGF1: grazing land by sheep shaded with cork oak (*Quercus suber* L.) trees; FOR: cork oak forest. BD: bulk density; EC: electrical conductivity; N: total nitrogen; Pt: total phosphorus; Pav: available phosphorus; C.N: carbon-to-nitrogen ratio; H.Al: exchange acidity; Ca: exchangeable calcium; Mg: exchangeable magnesium; Na: exchangeable sodium; K: exchangeable potassium; CEC: cation exchange capacity; BS: base saturation; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc.

3.2 SANTA MARIA LA PALMA PEDOSYSTEM

3.2.1 VEGETATION INVESTIGATION

The complete list of vascular plants in the SMLP pedosystem (Table 9) included 34 families, 79 genera, and 89 species. The overall biodiversity was represented by Poaceae (20 sp., accounting for 22%), Asteraceae (14 sp., 16%), Fabaceae (12 sp., 14%), Rosaceae (4 sp., 5%), and Geraniaceae (3 sp., 3%), accounting for 60% (Fig. 9a).

Table 9

Floristic list of the vascular plants in the SMLP pedosystem.

Family	Species	V3	V15	V30	OLI	AGF2	PAU	FOR
Amaranthaceae	*Atriplex patula* L.	×		×				
Anacardiaceae	*Pistacia lentiscus* L.					×		×
Apiaceae	*Anethum foeniculum* L.				×			
	Daucus carota L.				×	×	×	
Araceae	*Arisarum vulgare* O.Targ.Tozz. subsp. *vulgare*					×		×
Arecaceae	*Chamaerops humilis* L. subsp. *humilis*							×
Asparagaceae	*Asparagus officinalis* L. subsp. *officinalis*		×		×	×		×
Asphodelaceae	*Asphodelus ramosus* L. subsp. *ramosus*							×
Asteraceae	*Andryala integrifolia* L.	×	×	×	×			
	Calendula arvensis (Vaill.) L.			×				
	Cichorium intybus L.				×			
	Crepis bellidifolia Loisel.		×					
	Crepis vesicaria L.			×	×	×		
	Dittrichia viscosa (L.) Greuter subsp. *viscosa*				×		×	
	Erigeron canadensis L.	×	×				×	
	Hedypnois rhagadioloides (L.) F.W. Schmidt				×			
	Helminthotheca echioides (L.) Holub		×	×	×	×	×	

Family	Species	V3	V15	V30	OLI	AGF2	PAU	FOR
	Reichardia picroides (L.) Roth		×	×	×			
	Senecio vulgaris L.		×	×				
	Sonchus asper (L.) Hill	×	×	×	×	×	×	
	Symphyotrichum squamatum (Spreng.) G.L. Nesom	×				×	×	
	Urospermum dalechampii (L.) Scop. ex F.W.Schmidt				×			
Caryophyllaceae	*Polycarpon tetraphyllum* (L.) L. subsp. *alsinifolium* (Biv.) Ball	×						
Convolvulaceae	*Convolvulus arvensis* L.	×	×	×		×	×	
Cyperaceae	*Carex distachya* Desf.							×
Dioscoreaceae	*Dioscorea communis* (L.) Caddick & Wilkin							×
Ericaceae	*Arbutus unedo* L.							×
Fabaceae	*Lathyrus latifolius* L.							×
	Lathyrus ochrus (L.) DC.					×		
	Lotus ornithopodioides L.	×	×	×	×	×		
	Lotus parviflorus Desf.	×	×	×	×			
	Medicago polymorpha L.	×	×	×	×	×		
	Scorpiurus muricatus L.					×		
	Trifolium arvense L.				×			
	Trifolium campestre Schreb.	×	×	×	×	×	×	
	Trifolium glomeratum L.	×			×			
	Vicia sativa L.	×		×	×	×	×	
Fagaceae	*Quercus ilex* L.					×		×
	Quercus suber L.							×
Gentianaceae	*Schenkia spicata* (L.) G. Mans.	×	×	×	×	×		
Geraniaceae	*Erodium malacoides* (L.) L'Hér. subsp. *malacoides*	×		×	×			
	Geranium dissectum L.		×	×	×		×	
	Geranium purpureum Vill.					×		
Hypericaceae	*Hypericum perforatum* L.				×		×	
Lamiaceae	*Ajuga iva* (L.) Schreb.					×		
	Stachys arvensis (L.) L.		×			×		
Malvaceae	*Malva sylvestris* L.		×	×				

Family	Species	V3	V15	V30	OLI	AGF2	PAU	FOR
Myrtaceae	*Eucalyptus camaldulensis* Dehnh.					×	×	
	subsp. *camaldulensis*							
	Myrtus communis L.							×
Oleaceae	*Olea europaea* L.				×	×		×
Orobanchaceae	*Bellardia viscosa* (L.) Fisch. & C.A. Mey.				×			
Oxalidaceae	*Oxalis corniculata* L.	×						
Papaveraceae	*Fumaria officinalis* L.			×				
Plantaginaceae	*Plantago lanceolata* L.		×	×	×		×	
	Veronica arvensis L.	×	×		×			
Poaceae	*Anisantha tectorum* (L.) Nevski	×	×	×	×	×	×	
	Avena barbata Pott ex Link	×	×	×	×		×	
	Brachypodium distachyon (L.) P. Beauv.		×	×		×	×	
	Brachypodium retusum (Pers.) P. Beauv.							×
	Bromus hordeaceus L.	×	×	×	×		×	
	Catapodium rigidum (L.) C.E. Hubb. subsp. *rigidum*	×		×	×	×		
	Dactylis glomerata L. subsp. *hispanica* (Roth) Nyman					×		
	Dasypyrum villosum (L.) P. Candargy						×	
	Festuca myuros L. subsp. *myuros*	×	×	×	×			
	Hordeum murinum L. subsp. *leporinum* (Link)	×	×	×	×		×	
	Arcang.							
	Lolium multiflorum Lam.	×	×					
	Lolium temulentum L.	×					×	
	Macrobriza maxima (L.) Tzvelev				×		×	
	Oloptum miliaceum (L.) Röser & H.R. Hamasha					×		×
	Parapholis cylindrica (Willd.) Romero Zarco	×		×	×		×	
	Poa annua L.	×	×	×				
	Poa infirma Kunth			×				
	Polypogon viridis (Gouan) Breistr. subsp. *viridis*	×						
	Rostraria cristata (L.) Tzvelev	×	×		×			
	Triticum vagans (Jord. & Fourr.) Greuter				×			
Polygonaceae	*Polygonum aviculare* L. subsp. *aviculare*	×	×					

Family	Species	V3	V15	V30	OLI	AGF2	PAU	FOR
	Rumex crispus L.	×		×			×	
Primulaceae	*Lysimachia arvensis* (L.) U. Manns & Anderb.	×	×	×	×	×		
Ranunculaceae	*Clematis cirrhosa* L.							×
	Ranunculus muricatus L.	×		×	×			
Rhamnaceae	*Rhamnus alaternus* L. subsp. *alaternus*							×
Rosaceae	*Crataegus monogyna* Jacq.							×
	Poterium sanguisorba L.				×			
	Rosa sempervirens L.							×
	Rubus ulmifolius Schott							×
Rubiaceae	*Rubia peregrina* L.					×		×
	Theligonum cynocrambe L.					×		
Santalaceae	*Osyris alba* L.							×
Smilacaceae	*Smilax aspera* L.							×

Where: 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; OLI: olive groves; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.*;* PAU: *Paulownia sp*. plantation; FOR: holm oak (*Quercus ilex* L.) forest.

In general, the life-form (Fig. 9b) analysis revealed a clear dominance of annual plants (Therophytes – T) at 55% of the total, followed by herbaceous perennials (Hemicrytophytes – H) at 20%, woody plants (Phanaerophytes - P) at 12%, non-wood perennials (Geophytes – G) at 6%, and a limited diversity of woody forms (nano-Phanaerophytes – Np at 6% and Chamaephytes – Ch at 1%). In terms of the chorological spectrum (Fig. 9c), the Steno-Mediterranean chorotype was the predominant at 32%, followed by Euro-Mediterranean at 26%, Eurasian at 15%, and wide distribution at 12%, collectively representing 85% of the total.

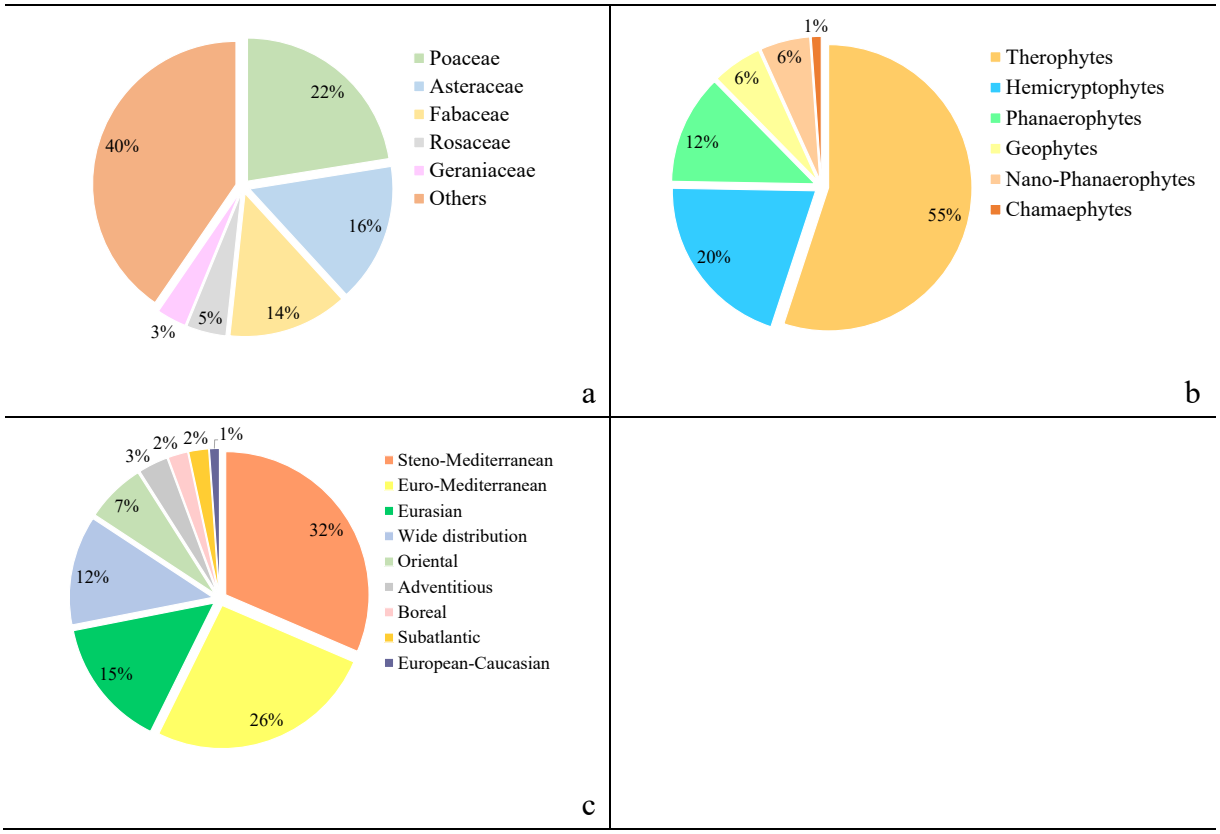


Fig. 9. Vascular plants abundance of the SMLP pedosystem in terms of: a) families, b) life-form, and c) chorotypes.

The results from ANOVA indicate some significant influence of land cover on vascular plants richness (Fig. 10a) and Shannon-Weaver Index (Fig. 10b). The highest species richness (range: 10 (FOR) to 25 (OLI), mean: 18 ± 1; Fig. 10a) was significantly observed ($p < 0.05$) in OLI, whereas FOR displayed the lowest, while Shannon-Weaver Diversity Index (H': range: 2.2 (FOR) to 3.0 (OLI), mean: 2.7 ± 0.1; Fig. 10b) was significantly higher ($p < 0.05$) in the V30 and OLI compared to AGF2, PAU, and FOR.

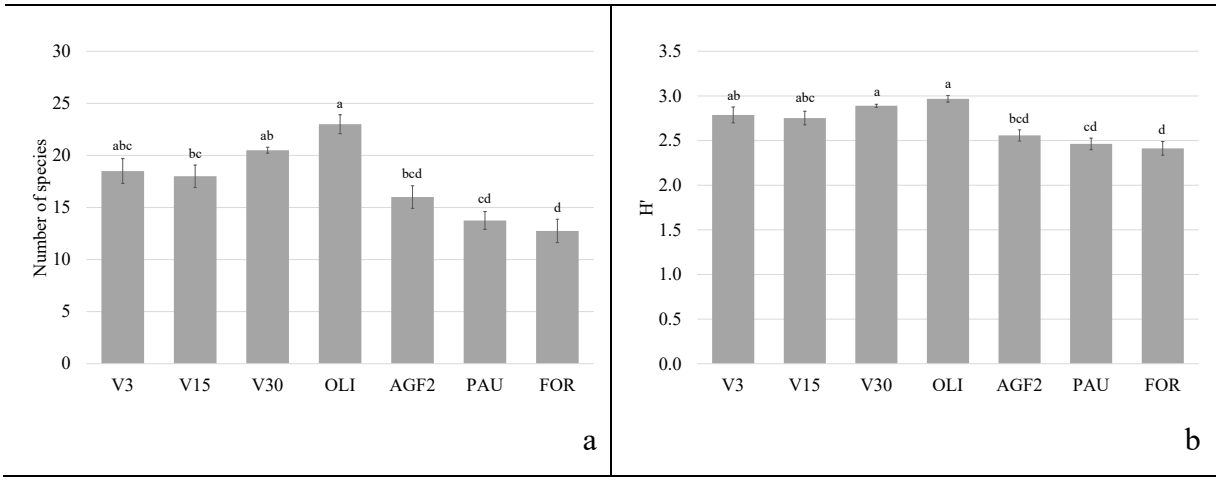
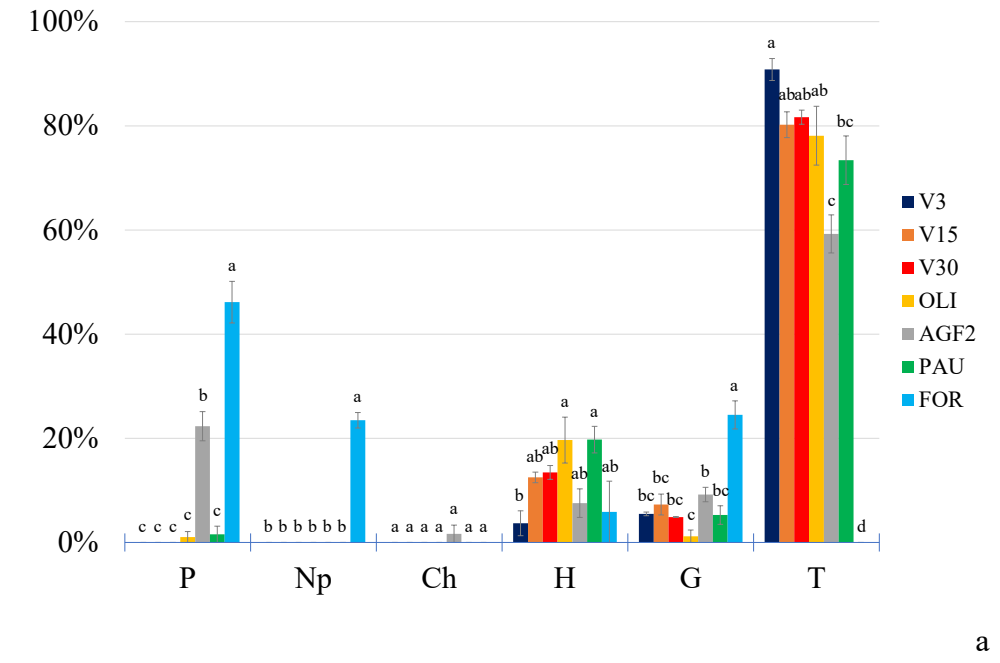
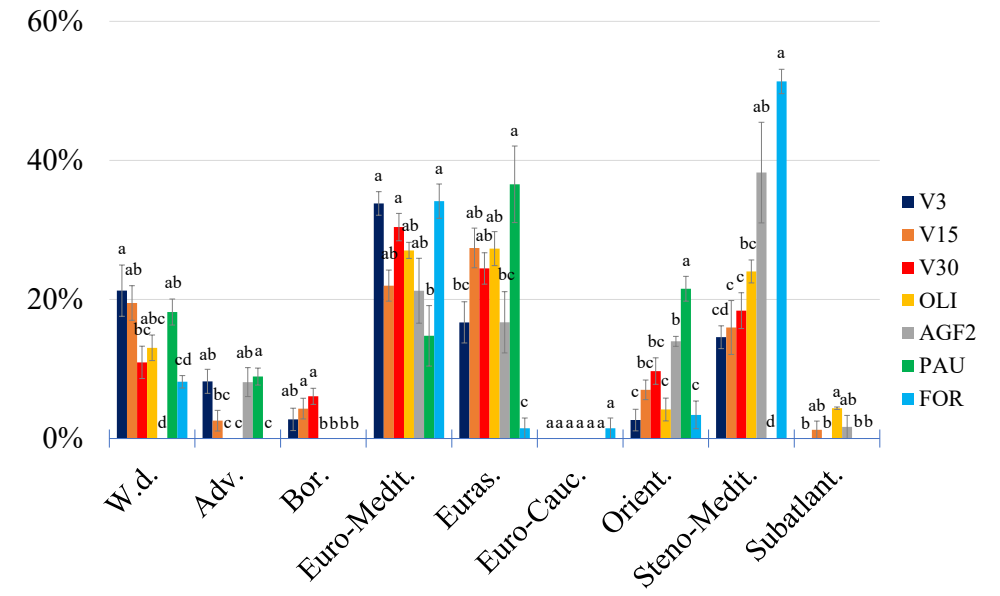


Fig. 10. Vascular plants richness (a) and Shannon-Weaver Index (b) along different land cover for SMLP pedosystem. V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; OLI: olive groves; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.; PAU: *Paulownia sp.* plantation; FOR: holm oak (*Quercus ilex* L.) forest. Different lowercase letters showed significant differences ($p < 0.05$) among land covers.

Concerning the life-form (Fig. 11a), results indicated that Phanaerophytes (P: range: 0 (V3, V15, V30, OLI, and PAU) to 54% (FOR), mean: 10 ± 1%) and nano-Phanaerophytes (Np: range: 0 (V3, V15, V30, OLI, AGF2, and PAU) to 27% (FOR), mean: 3 ± 0%) were significantly highest ($p < 0.05$) in the FOR land cover, as expected. Chamaephytes (Ch: range: 0 (all) to 7% (AGF2), mean: 0 ± 0%) did not showed significant differences ($p < 0.05$) among the different land covers. Hemicrytophytes (H: range: 0 (V3, AGF2, and FOR) to 29% (OLI), mean: 12 ± 3%) were higher in the PAU and OLI compared to V3. Geophytes (G: range: 0 (OLI and PAU) to 30% (FOR), mean: 8 ± 1%) were most prevalent ($p < 0.05$) in FOR land cover, while being lowest in OLI. Therophytes (T: range: 0 (FOR) to 94% (V3), mean: 66 ± 3%) were most abundant in V3 and less in FOR.



a



b

Fig. 11. Vascular plants life-form (a) and chorotype (b) along different land cover for SMLP pedosystem. 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; OLI: olive groves; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.; PAU: *Paulownia* sp. plantation; FOR: holm oak (*Quercus ilex* L.) forest. Life-forms: P: Phanaerophytes; Np: nano-Phanaerophytes; Ch: Chamaephytes; H: Hemicryptophytes; G: Geophytes; T: Therophytes. Chorotypes: W.d.: Wide distribution; Adv.: Adventitious; Bor.: Boreal; Euro-Medit.: Euro-Mediterranean; Euras.: Eurasian; Euro-Cauc.: European-Caucasian; Orient.: Oriental; Steno-Medit.: Steno-Mediterranean; Subatlant.: Subatlantic. Different lowercase letters showed significant differences ($p < 0.05$) among land covers.

The chorotypes (Fig. 11b) exhibit diverse trends among the different land covers. The wide distribution (W.d.: range 0 (AGF2) to 30% (V3), mean: 13 ± 2%) chorotype was significantly higher ($p < 0.05$) in V3 compared to V30, AGF2, and FOR. Adventitious (Adv.: range: 0 (V15, V30, OLI, and FOR) to 14% (AGF2), mean: 4 ± 1%) was significantly higher in PAU than V15, V30, OLI, and FOR. Boreal (Bor.: range: 0 (V3, V15, OLI, AGF2, PAU, and FOR) to 10% (V30), mean: 2 ± 1%) showed V15 and V30 higher than the others (V3 apart). Euro-Mediterranean (Euro-Medit.: range: 6 (PAU) to 40% (FOR), mean: 26 ± 3%) revealed V3, V30, and FOR with higher presence than PAU. Eurasian (Euras.: range: 0 (FOR) to 50% (PAU), mean: 22 ± 3%) was significantly higher in PAU compared to V3, AGF2, and FOR. European-Caucasian (Euro-Cauc.: range: 0 (all) to 6% (FOR), mean: 0 ± 0%) showed no significant differences among the different land covers. Oriental (Orient.: range: 0 (V3, OLI, and FOR) to 25% (PAU), mean: 9 ± 2%) showed the highest presence in the PAU land cover. Steno-Mediterranean (Steno-Medit.: range: 0 (PAU) to 56% (AGF2), mean: 23 ± 3%) was significantly higher in FOR compared to the others (AGF2 apart). Subatlantic (Subatlant.: range: 0 (V3, V15, V30, AGF2, PAU, FOR) to 7% (AGF2), mean: 1 ± 0%) was significantly higher in OLI than V3, V30, PAU, and FOR.

Summarizing, results suggest that the investigated land covers are influenced by human activities, particularly in agricultural areas, including permanent crops such as olive groves and vineyards. These are featured by higher plant richness and diversity compared to more natural and, consequently, less-human-influenced areas, including agroforestry, *Paulownia* sp. plantation, and holm-oak forest. The composition of the vascular plants also varied, with a predominance of wood forms (Phanerophytes and Nano-Phanerophytes) and non-wood perennials (Geophytes) observed in the most natural and less-human influenced land cover (forest), while a predominance of annual plants (Terophytes) in the more-human influenced land cover (vineyards) was observed. Regarding the chorotype, it was observed a predominance of species from Mediterranean areas (Steno-Mediterranean and Euro-Mediterranean) in more natural land covers, such as forests.

3.2.2 LITTER FEATURES

Table 10 shows the litter features of the SMLP pedosystem. Some significant differences ($p < 0.05$) were observed among the different land covers for most of the investigated parameters.

Carbon (C: range: 40.7 (OLI) to 54.4% (OLI), mean: 50.5 ± 1.4%) concentration did not show significant differences among different land covers. Nitrogen (N: range: 0.8 (PAU) to 1.8% (FOR), mean: 1.2 ± 0.1%) showed a clear significant ($p < 0.05$) difference between the FOR and the other land covers (OLI apart). In forest ecosystems, litter serves as the primary pathway for delivering nutrients to the soil, and considerable amounts of C and N are bound in the dead tissues of stems and branches (Staaf and Berg, 1981). Consequently, due to the previously observed outcomes, the natural areas (FOR) showed the highest litter carbon stocks (LCs: range: 0.0 (OLI) to 8.4 t ha^{-1} (FOR), mean: 2.9 ± 0.5 t ha^{-1}) also, while agricultural areas (V3, V15, V30, and OLI) and silvicultural (PAU) the lowest. The litter amounts varied following litter production rates and decomposition, thus impacting litter dynamics (Facelli and Pickett, 1991).

The C/N ratio (range: 24 (OLI) to 65 (PAU), mean: 45 ± 3) was significantly higher ($p < 0.05$) in PAU than in FOR. The C/N ratio is also used in determining litter quality; generally, a lower C/N ratio indicate higher litter quality, corresponding to a higher litter decomposition rate (Berg and McClaugherty, 2008). This suggests that the FOR is prone to experiencing a greater rate of litter decomposition compared to other land covers.

Phosphorus (P: range 0.00 (FOR) to 0.03 g kg^{-1} (V30), mean: 0.02 ± 0.00 g kg^{-1}) was significantly higher ($p < 0.05$) in the V30 than AGF2 and FOR, which showed the lowest contents. It is considered a regulating nutrient (Krishna & Mohan, 2017), presenting an increasing trend during the decomposition process as a result of carbon loss (Berg and McClaugherty, 2008).

Calcium concentration (Ca: range 1.02 (PAU) to 24.01 g kg^{-1} (AGF), mean: 7.88 ± 1.20 g kg^{-1}) was higher in the AGF2 than the other land covers (FOR apart). This result could be related to the interaction between soil and litter, wherein an increased soil N concentration led to a decreased soil pH, thus leaching available Ca, resulting in a lower concentration of this nutrient in the plant litter (Perakis et al., 2013). Magnesium (Mg: range 0.96 (V3 and PAU) to 2.46 g kg^{-1} (FOR), mean: 1.42 ± 0.17 g kg^{-1}) and sodium (Na: range 0.34 (PAU) to 0.69 g kg^{-1} (FOR), mean: 0.49 ± 0.04 g kg^{-1}) did not show significant differences. Potassium (K: range:

1.67 (FOR) to 6.06 g kg^{-1} (OLI), mean: 3.59 ± 0.32 g kg^{-1}) showed the highest contents in the agricultural areas (V15, V30, and OLI) differing from AGF2, which showed the lowest. Other nutrients, such as Ca, Mg, and K, generally exhibit weaker retention in the litter (Berg and McClaugherty, 2008).

Among the microelements (Cu: range: 5.10 (PAU) to 34.50 mg kg^{-1} (V15), mean: 12.01 ± 2.20 mg kg^{-1}; Fe: range: 359 (OLI) to 10920 mg kg^{-1} (OLI), mean: 2845 ± 1120 mg kg^{-1}; Mn: range: 48 (V30) to 1008 mg kg^{-1} (FOR), mean: 238 ± 63 mg kg^{-1}; and Zn: range: 16.80 (FOR) to 58.20 mg kg^{-1} (V30), mean: 31.89 ± 3.89 mg kg^{-1}), just the Mn showed significant differences ($p < 0.05$). It suggested that the holm oak litter retains higher Mn than V3, V30 and PAU.

Table 10

Chemical parameters of the litter at the SMLP pedosystem.

SMLP	V3	V15	V30	OLI	AGF2	PAU	FOR	Mean
C (%)	51.3 ± 0.7 a	49.8 ± 2.3 a	51.9 ± 0.7 a	49.0 ± 3.1 a	48.3 ± 1.3 a	50.9 ± 1.1 a	52.1 ± 0.7 a	50.5 ± 1.4
N (%)	1.1 ± 0.1 bc	1.1 ± 0.0 bc	1.1 ± 0.1 bc	1.3 ± 0.1 ab	1.1 ± 0.0 bc	1.0 ± 0.1 c	1.5 ± 0.1 a	1.2 ± 0.1
C/N	47 ± 3 ab	46 ± 4 ab	47 ± 3 ab	39 ± 6 ab	45 ± 2 ab	54 ± 4 a	35 ± 2 b	45 ± 3
LCs (t ha^{-1})	2.3 ± 0.3 c	1.2 ± 0.3 c	2.0 ± 0.5 c	0.9 ± 0.8 c	4.7 ± 0.8 b	1.4 ± 0.3 c	7.7 ± 0.3 a	2.9 ± 0.5
P (g kg^{-1})	0.02 ± 0.00 abc	0.02 ± 0.00 ab	0.02 ± 0.00 a	0.02 ± 0.00 ab	0.01 ± 0.00 bc	0.02 ± 0.00 ab	0.01 ± 0.00 c	0.02 ± 0.00
Ca (g kg^{-1})	3.76 ± 0.27 c	4.05 ± 0.31 c	4.65 ± 0.25 c	8.66 ± 3.39 bc	19.42 ± 2.30 a	1.78 ± 0.30 c	12.81 ± 1.61 ab	7.88 ± 1.20
Mg (g kg^{-1})	1.14 ± 0.10 a	1.44 ± 0.19 a	1.37 ± 0.08 a	1.67 ± 0.36 a	1.45 ± 0.17 a	1.11 ± 0.09 a	1.77 ± 0.23 a	1.42 ± 0.17
Na (g kg^{-1})	0.45 ± 0.02 a	0.52 ± 0.07 a	0.49 ± 0.03 a	0.48 ± 0.04 a	0.55 ± 0.04 a	0.38 ± 0.02 a	0.55 ± 0.06 a	0.49 ± 0.04
K (g kg^{-1})	3.97 ± 0.30 ab	4.47 ± 0.29 a	4.49 ± 0.10 a	4.52 ± 0.58 a	2.11 ± 0.20 c	3.15 ± 0.46 abc	2.41 ± 0.27 bc	3.59 ± 0.32
Cu (mg kg^{-1})	12.00 ± 1.44 a	18.74 ± 5.31 a	11.63 ± 1.36 a	11.37 ± 2.87 a	12.74 ± 1.73 a	8.84 ± 1.28 a	8.77 ± 1.45 a	12.01 ± 2.20
Fe (mg kg^{-1})	2100 ± 607 a	3239 ± 1892 a	1350 ± 511 a	3959 ± 2379 a	4721 ± 973 a	2474 ± 961 a	2069 ± 517 a	2845 ± 1120
Mn (mg kg^{-1})	156 ± 18 b	208 ± 86 ab	86 ± 23 b	206 ± 80 ab	340 ± 45 ab	117 ± 33 b	555 ± 156 a	238 ± 63
Zn (mg kg^{-1})	35.46 ± 3.27 a	36.58 ± 3.03 a	37.28 ± 7.11 a	31.56 ± 5.48 a	29.52 ± 2.72 a	28.26 ± 2.20 a	24.58 ± 3.38 a	31.89 ± 3.89

Where: 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; OLI: olive groves; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.*;* PAU: *Paulownia sp*. plantation; FOR-SMLP: holm oak (*Quercus ilex* L.) forest. A number followed by different lowercase letters showed significant differences ($p < 0.05$) between different land covers.

3.2.3 SOIL FEATURES

Soil physical parameters

In the SMLP pedosystem, the prevailing textural class (USDA particle-size; USDA, 2017) was clay loam (Table 11). The investigated Luvisols on limestone are featured by a wide range of clay content, varying from 15.8% (FOR, A horizon) to 59.7% (FOR, B horizon), with a mean of 28.0 ± 2.4% in the surface and 32.5 ± 2.3% in deep horizon. The sand content ranged from 16.1% (FOR, B horizon) to 64.3% (FOR, A horizon), averaging 42.4 ± 3.2% on the surface and 37.9 ± 2.1% on the deep horizon. Notably, significant differences ($p < 0.05$) were observed for clay and sand content between surface and deep horizons in the AGF2 land cover in an inverse relation (i.e., higher sand and lower clay content in the surface, and the reverse was true in the deep horizon). This was expected, since investigated Luvisols developed on limestone are featured by a clayey B deep horizon (argic, Bt). For silt content (range: 15.2% (FOR, A horizon) to 39.2% (FOR, B horizon), mean surface: 29.6 ± 1.9%, mean deep: 29.6 ± 1.7%), no significant differences ($p < 0.05$) were observed between the surface and deep horizon nor among different land covers.

The bulk density (BD: range: 0.4 g cm^{-3} (FOR, A horizon) to 1.6 g cm^{-3} (OLI, B horizon), mean surface: 1.3 ± 0.1 g cm^{-3}, mean deep: 1.3 ± 0.0 g cm^{-3}) did not show significant differences ($p < 0.05$) between the surface and deep horizons; however, some significant differences were observed among land cover for both surface and deep horizons. The lowest BD was observed in the FOR-land cover for both horizons; this is due to the combination of factors associated with the forest ecosystem, such as the higher presence of SOM (Fig. 12c), the lower human disturbance when compared to agricultural areas, and the physical presence of a more enhanced and developed and root networks.

Table 11

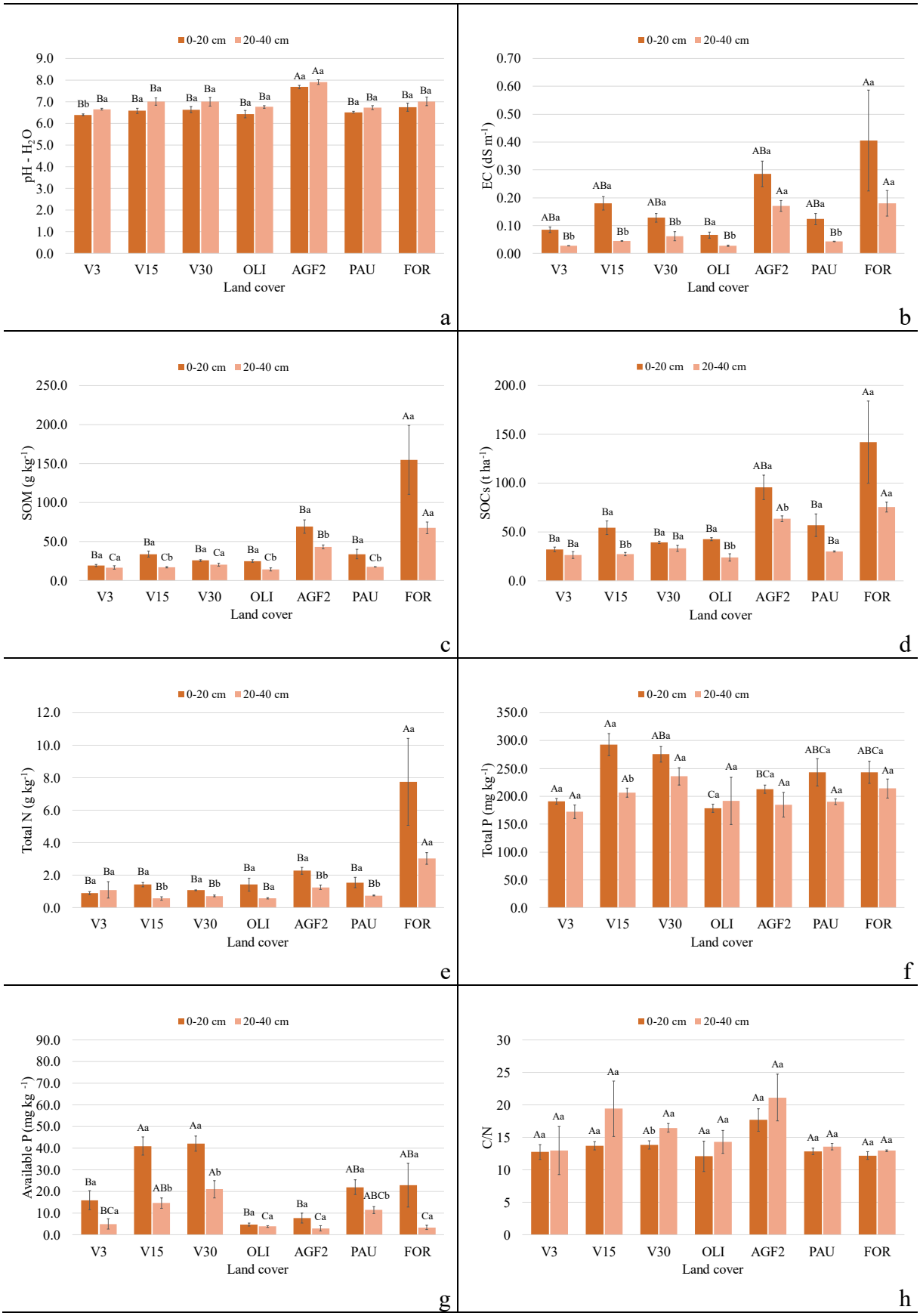
Soil physical parameters for SMLP pedosystem; mean ± standard error (SE).

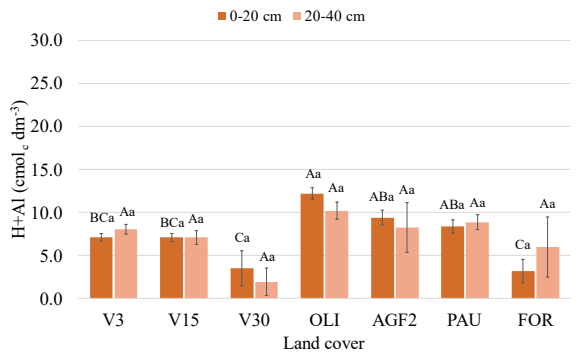
Land cover	Soil Horizon	Texture class	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})
V3	A	CL	39.2 ± 3.8 Aa	30.4 ± 2.5 Aa	30.4 ± 2.1 Aa	1.4 ± 0.0 Aa
	B	CL	38.3 ± 4.7 Aa	30.9 ± 2.3 Aa	30.8 ± 2.6 Ba	1.4 ± 0.0 ABa
V15	A	CL	39.1 ± 0.7 Aa	31.7 ± 0.9 Aa	29.2 ± 1.3 Aa	1.4 ± 0.0 Aa
	B	CL	38.9 ± 0.8 Aa	31.6 ± 0.9 Aa	29.5 ± 1.7 Ba	1.4 ± 0.0 ABa
V30	A	CL	41.6 ± 2.2 Aa	29.5 ± 1.9 Aa	28.9 ± 0.8 Aa	1.3 ± 0.0 Aa
	B	CL	40.7 ± 1.9 Aa	29.2 ± 1.6 Aa	30.1 ± 0.7 Ba	1.4 ± 0.0 ABa
OLI	A	L	44.2 ± 1.9 Aa	29.8 ± 0.8 Aa	26.0 ± 1.4 Aa	1.5 ± 0.0 Aa
	B	CL	42.5 ± 2.1 Aa	29.5 ± 0.7 Aa	28.0 ± 1.8 Ba	1.4 ± 0.0 ABa
AGF2	A	L	49.4 ± 2.6 Aa	28.4 ± 2.4 Aa	22.2 ± 2.5 Ab	1.2 ± 0.0 Aa
	B	CL	41.2 ± 0.7 Ab	27.3 ± 1.6 Aa	31.5 ± 1.0 Ba	1.3 ± 0.0 Ba
PAU	A	CL	41.6 ± 0.6 Aa	30.1 ± 1.0 Aa	28.3 ± 1.0 Aa	1.4 ± 0.0 Aa
	B	CL	40.6 ± 0.6 Aa	29.4 ± 1.3 Aa	30.0 ± 1.3 Ba	1.5 ± 0.0 Aa
FOR	A	CL	42.1 ± 10.3 Aa	26.9 ± 4.0 Aa	31.0 ± 7.5 Aa	0.8 ± 0.2 Ba
	B	C	23.1 ± 4.0 Ba	29.4 ± 3.4 Aa	47.5 ± 7.4 Aa	1.0 ± 0.1 Ca
Mean	A		42.4 ± 3.2	29.6 ± 1.9	28.0 ± 2.4	1.3 ± 0.1
	B		37.9 ± 2.1	29.6 ± 1.7	32.5 ± 2.3	1.3 ± 0.0

Where: 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; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.*;* PAU: *Paulownia sp*. plantation; FOR: holm oak (*Quercus ilex* L.) forest; OLI: olive groves; C: clay; CL: clay loam; L: loam. A number followed by different capital letters showed significant differences ($p < 0.05$) among land covers within the same investigated soil horizon; different lowercase letters showed significant differences ($p < 0.05$) between surface and deep horizon within the same land cover.

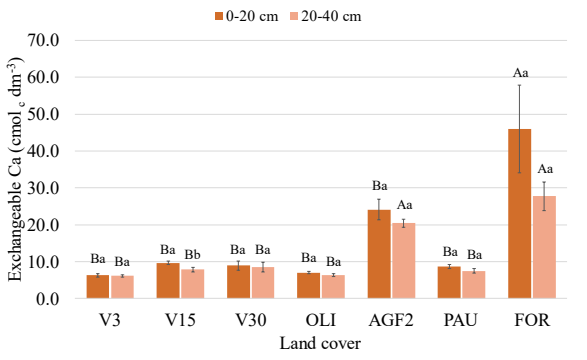
Soil chemical parameters

For the SMLP-pedosystem, which presents soils developed over limestone, pH (Fig. 12a) is more alkaline, ranging from slightly acidic (6.2 at OLI, A horizon) to moderately alkaline (8.1 at AGF2, B horizon), with mean values of 6.7 ± 0.1 for surface and 7.0 ± 0.1 for deep horizons; significant differences were observed between surface *vs* deep horizon at V3. The pH values in surface soil typically exhibit lower values because of the SOM richness found in this horizon and the influence of its decomposition results in the generation of organic acids, which in turn decreases the pH in surface horizons (Hong et al., 2019). Among different land covers, some significant differences ($p < 0.05$) were observed for both surface and deep horizons, in which AGF2 land cover significantly differed from others, presenting the highest pH values for both horizons; this observation can be attributed to the influence of the parent material (limestone).

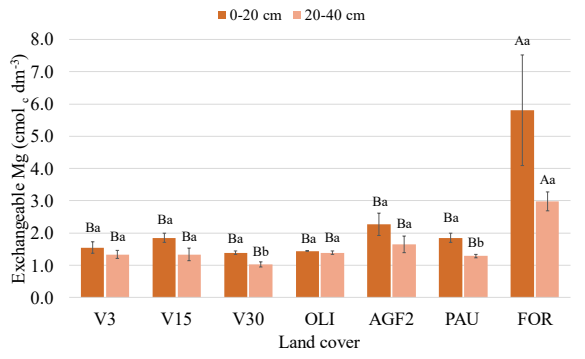

0-20 cm
20-40 cm
pH - H2O
EC (dS m-1)
SOM (g kg-1)
SOCs (t ha-1)
Total N (g kg-1)
Total P (mg kg-1)
Available P (mg kg -1)
C/N
V3
V15
V30
OLI
AGF2
PAU
FOR
Land cover
a
b
c
d
e
f
g
h


0-20 cm
20-40 cm
H+Al (cmol$_c$ dm^{-3})
30.0
25.0
20.0
15.0
10.0
5.0
0.0
BCa Aa
BCa Aa
Ca Aa
Aa Aa
ABa Aa
ABa Aa
Ca Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

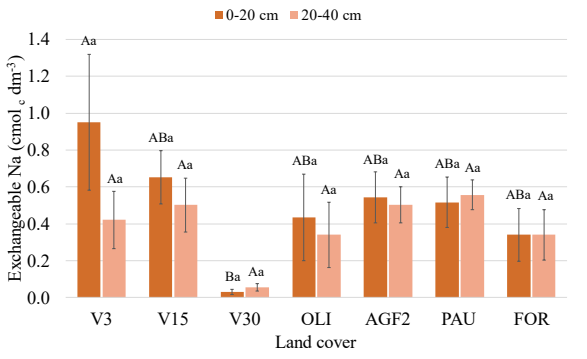
i


0-20 cm
20-40 cm
Exchangeable Ca (cmol$_c$ dm^{-3})
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Ba Ba
Ba Bb
Ba Ba
Ba Ba
Ba Aa
Ba Ba
Aa Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

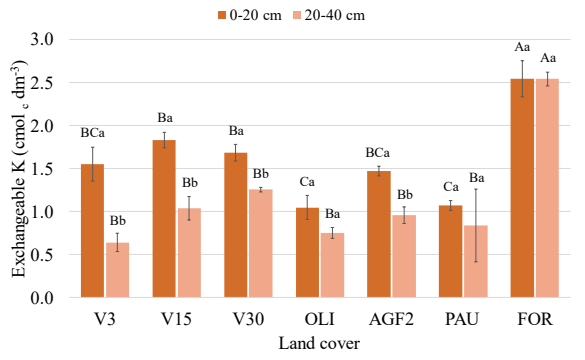
j


0-20 cm
20-40 cm
Exchangeable Mg (cmol$_c$ dm^{-3})
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Ba Ba
Ba Ba
Ba Bb
Ba Ba
Ba Ba
Ba Bb
Aa Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

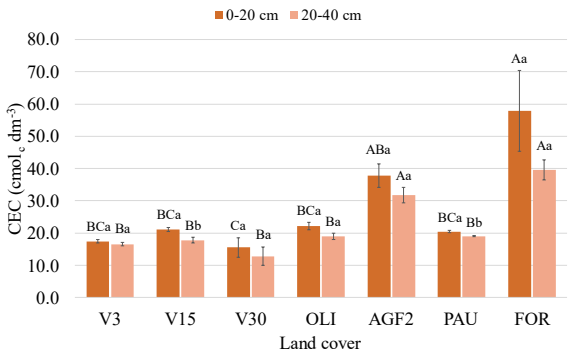
k


0-20 cm
20-40 cm
Exchangeable Na (cmol$_c$ dm^{-3})
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Aa Aa
ABa Aa
Ba Aa
ABa Aa
ABa Aa
ABa Aa
ABa Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

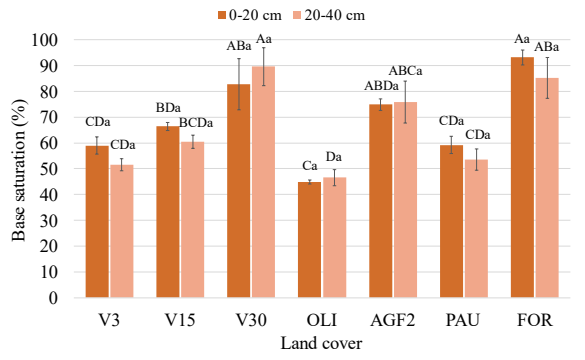
l


0-20 cm
20-40 cm
Exchangeable K (cmol$_c$ dm^{-3})
3.0
2.5
2.0
1.5
1.0
0.5
0.0
BCa Bb
Ba Bb
Ba Bb
Ca Ba
BCa Bb
Ca Ba
Aa Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

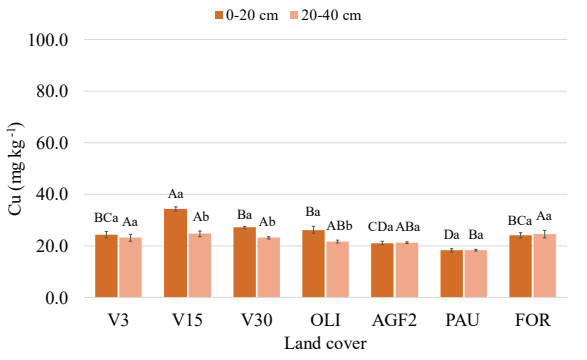
m


0-20 cm
20-40 cm
CEC (cmol$_c$ dm^{-3})
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
BCa Ba
BCa Bb
Ca Ba
BCa Ba
ABa Aa
BCa Bb
Aa Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

n


0-20 cm
20-40 cm
Base saturation (%)
100
90
80
70
60
50
40
30
20
10
0
CDa CDa
BDa BCDa
ABa Aa
Ca Da
ABDa ABCa
CDa CDa
Aa ABa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

o


0-20 cm
20-40 cm
Cu (mg kg^{-1})
100.0
80.0
60.0
40.0
20.0
0.0
BCa Aa
Aa Ab
Ba Ab
Ba ABb
CDa ABa
Da Ba
BCa Aa
V3 V15 V30 OLI AGF2 PAU FOR
Land cover

p

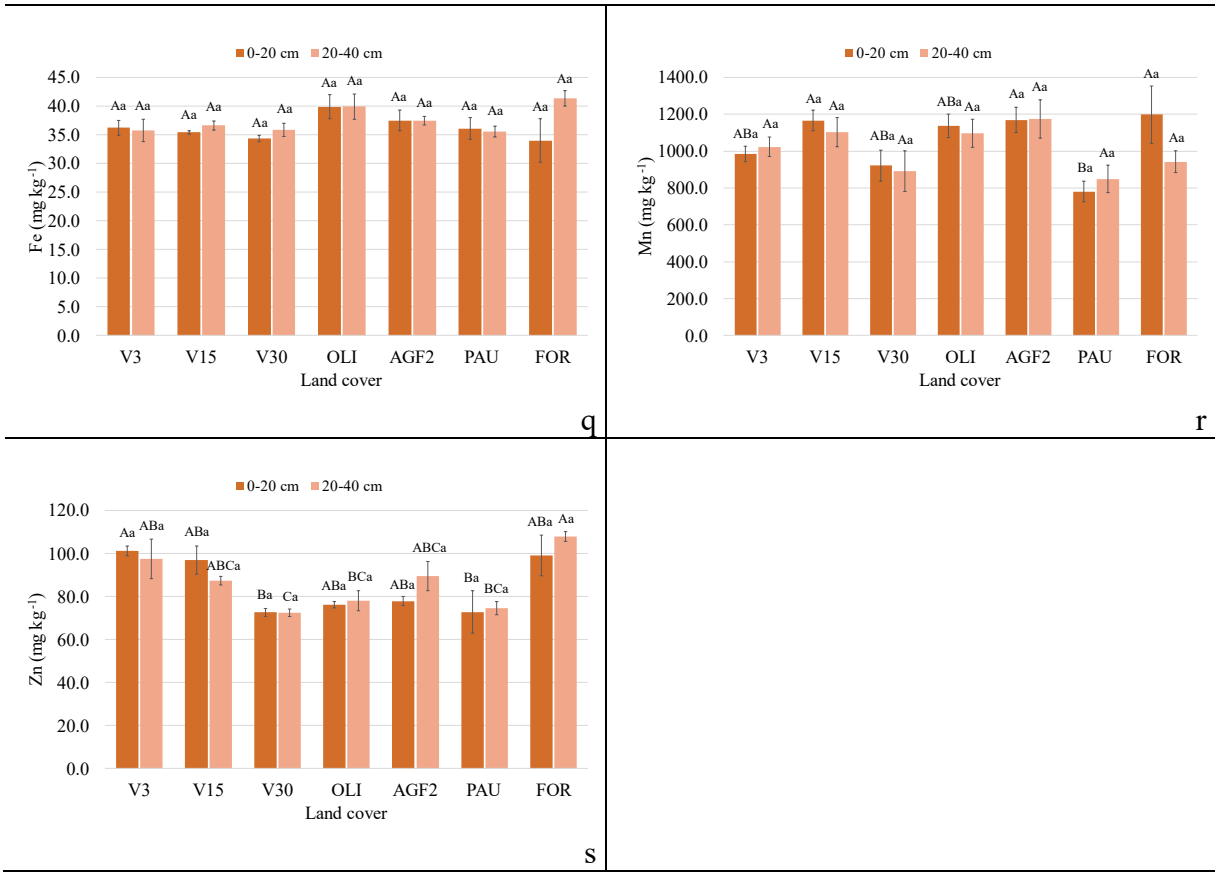


Fig. 12. Soil chemical parameters along the surface (0-20 cm, darker color) and deep (20-40 cm, lighter color) soil horizons and different land cover for the Santa Maria La Palma (SMLP) pedosystem. V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; OLI: olive groves; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.; PAU: *Paulownia sp*. plantation; FOR: holm oak (*Quercus ilex* L.) forest. Different capital letters showed significant differences ($p < 0.05$) among land covers within the same investigated soil horizon, while different lowercase letters showed significant differences ($p < 0.05$) between surface (A horizon; 0-20 cm) and deep (B; 20-40 cm) horizon within the same land cover.

Since the pedosystem presents a clay rich-soil, soil electrical conductivity (EC: range: 0.02 dS m^{-1} (OLI, B horizon) to 0.95 dS m^{-1} (FOR, A horizon), mean surface: 0.18 ± 0.04 dS m^{-1}, mean deep: 0.08 ± 0.01 dS m^{-1}; Fig. 12b) was higher. Significant differences ($p <$ 0.05) were observed for almost all land cover between surface *vs* deep horizon (except for FOR) and this is attributed for the same reason as observed in the MON pedosystem (i.e., the organic matter richness and the decomposition influence) and because of the higher clay contents. When comparing the different land uses, some significant differences ($p < 0.05$) were observed for surface and deep horizons, in which FOR land cover significantly differed from OLI on the surface, and from vineyards (V3, V15, and V30), OLI and PAU land cover in the deep horizon.

This observation seems to be related to the higher SOM values found in both horizons in FOR land cover compared to the others (Fig. 12c), leading to higher EC values.

Soil organic matter (SOM: range 9.7 (OLI, B horizon) to 283.1 g kg^{-1} (FOR, A horizon), mean surface: 51.7 ± 9.6 g kg^{-1}, mean deep: 28.1 ± 2.4 g kg^{-1}; Fig. 12c) presented most of the land covers (except V3, V30, and FOR) significantly ($p < 0.05$) higher concentrations on the surface horizon. The FOR land cover significantly ($p < 0.05$) presented the highest surface and deep SOM concentration compared to the other land covers, mostly due to the vegetation OM inputs (*vide supra*; Costantini and Dazzi, 2013). Similarly, when assessing the soil organic carbon stocks (SOCs: range 15.5 (OLI, B horizon) to 258.7 t ha^{-1} (FOR, A horizon), mean surface: 66.1 ± 11.2 t ha^{-1}, mean deep: 40.0 ± 2.9 t ha^{-1}; Fig. 12d), surface horizon showed higher stocks for some of the land covers (V15, OLI, and AGF2). Moreover, when comparing the different land covers, FOR showed significantly higher stocks than the others (AGF2 apart) in both surface and deep horizons.

For total nitrogen (Total N: range: 0.3 (V15, B horizon) to 15.6 g kg^{-1} (FOR, A horizon), mean surface: 2.3 ± 0.6 g kg^{-1}, mean deep: 1.1 ± 0.2 g kg^{-1}; Fig. 12e), the surface horizon exhibited significantly ($p < 0.05$) higher total N concentrations *vs* deep horizon for almost all land covers, with the exceptions being observed for V3, OLI, and FOR. Among all land covers in SMLP, the FOR was significantly ($p < 0.05$) higher in both horizons than the others. As previously argued (for MON-pedosystem, *vide supra*), these observations are related to the SOM concentrations, which are consequently reflected in the total N concentrations.

Total phosphorus (Total P: range: 133.7 (OLI, B horizon) to 330.0 mg kg^{-1} (V15, A horizon), mean surface: 233.9 ± 14.1 mg kg^{-1}, mean deep: 199.4 ± 17.3 mg kg^{-1}; Fig. 12f) sowed significant differences ($p < 0.05$) between surface *vs* deep horizons only in the V15 land cover, which exhibited higher concentrations on the surface. Among the different land covers, the V3 and V15 were significantly higher ($p < 0.05$) on the surface compared to the other covers, possibly attributed to the use of P fertilizers (*vide supra*).

The values for available P (range: 0.9 (V3 and AGF2, B horizon) to 51.3 mg kg^{-1} (V30, A horizon), mean surface: 22.4 ± 4.1 mg kg^{-1}, mean deep: 8.9 ± 1.9 mg kg^{-1}; Fig. 12g) presented significant differences ($p < 0.05$) between surface *vs* deep horizon mainly in the agricultural areas (V15 and V30) and in the PAU. The agricultural land covers V15 and V30 show significantly higher contents ($p < 0.05$) than V3, OLI, and AGF2 in the surface horizon; while for the deep horizon, the V30 was significantly higher ($p < 0.05$) than V3, OLI, AGF2, and FOR. All of these findings may be associated with previously mentioned processes

(mineralization and decomposition of SOM) as well, and also due to the P fertilizers and consequently, P enrichment.

For the carbon-to-nitrogen ratio (C/N: range 5 (V3, B horizon; OLI, A horizon) to 32 (V15 and AGF2, B horizon), mean surface: 14 ± 1, mean deep: 16 ± 2; Fig. 12h), between surface *vs* deep horizon, significant differences ($p < 0.05$) were observed in the V30, in which the ratio in the deep horizon was significantly higher than the surface, thus being related to the SOM and the lowest total N in the deep horizon. Among land covers in both horizons, no significant differences were observed.

Exchangeable acidity (H+Al: range 0.0 (V30, A and B horizons; FOR, A and B horizons; AGF2, B horizon) to 16.1 $cmol_c\ dm^{-3}$ (FOR, B horizon), mean surface: 7.3 ± 0.9 $cmol_c\ dm^{-3}$, mean deep: 7.2 ± 1.6 $cmol_c\ dm^{-3}$; Fig. 12i) did not show significant differences ($p < 0.05$) between the surface *vs* deep horizons and neither in the deep horizon among the different land covers. In the surface horizon, the OLI land cover was significantly higher ($p < 0.05$) than V30 and FOR, mainly attributed to its lower pH when compared to the other two, even though these pH differences did not show statistical significance ($p < 0.05$). This result aligns with the observation found in the MON pedosystem (*vide supra*), linking decreasing pH to increasing H+Al.

Exchangeable cations (Ca^{2+}: range 5.4 (V3, A and B horizon; OLI, B horizon) to 81.5 $cmol_c\ dm^{-3}$ (FOR, A horizon), mean surface: 15.8 ± 2.5 $cmol_c\ dm^{-3}$, mean deep: 12.1 ± 1.2 $cmol_c\ dm^{-3}$; Mg^{2+}: 0.8 (V30, B horizon) to 10.9 $cmol_c\ dm^{-3}$ (FOR, A horizon), mean surface: 2.3 ± 0.4 $cmol_c\ dm^{-3}$, mean deep: 1.6 ± 0.2 $cmol_c\ dm^{-3}$; Na^{+}: 0.0 (V30, A and B horizon) to 2.0 $cmol_c\ dm^{-3}$ (V3, A horizon), mean surface: 0.5 ± 0.2 $cmol_c\ dm^{-3}$, mean deep: 0.4 ± 0.1 $cmol_c\ dm^{-3}$ in the deep; K^{+}: 0.4 (V3 and PAU, B horizon) to 3.1 $cmol_c\ dm^{-3}$ (FOR, A horizon), mean surface: 1.6 ± 0.1 $cmol_c\ dm^{-3}$, mean deep: 1.1 ± 0.1 $cmol_c\ dm^{-3}$; Figs. 12j-m) showed some significant differences ($p < 0.05$). Between surface *vs* deep horizon, significantly higher values ($p < 0.05$) in the surface were observed for Ca (Fig. 12j) in the V15, for Mg (Fig. 12k) in the V30 and PAU, and for K (Fig. 12m) in almost all land covers (except OLI, PAU, and FOR). The observed higher concentrations could be associated with the influence of fertilizers and/or organic amendments (*vide supra*), associated with OM inputs from the vegetation cover. When comparing different land covers within the surface and deep horizons, some significant differences ($p < 0.05$) were observed for all exchangeable cations. The FOR land cover consistently showed the highest values for Ca, Mg and K in both surface and deep horizon. Additionally, for Na, the V3 was higher than V30 on the surface horizon. The higher values of the exchangeable cations for the FOR land cover in this pedosystem, particularly appear to be

related to various factors, including the pH, clay content, weathering of the parent material (the limestone, which influences the availability of Ca^{2+}, since the Ca input main results from this process or applications of Ca sources), and the addition of OM through vegetation inputs (Manrique et al., 1991; Wood et al., 2005).

Cation exchange capacity (CEC: range 9.4 (V30, B horizon) to 95.3 $cmol_c\ dm^{-3}$ (FOR, A horizon), mean surface: 27.5 ± 3.1 $cmol_c\ dm^{-3}$, mean deep: 22.4 ± 1.6 $cmol_c\ dm^{-3}$; Fig. 12n) presented significant differences ($p < 0.05$) between surface and deep horizon in the V15 and PAU land covers. For surface horizons, some significant differences ($p < 0.05$) were observed among different land covers, with FOR differing significantly from the others, except with AGF2. In the deep horizon, FOR and AGF2 were significantly ($p < 0.05$) higher. All these observations are related to the aforementioned soil parameters, which play a significant role in influencing CEC values.

Base saturation (BS: range: 39 (OLI, B horizon) to 100% (V30 and FOR, A horizon; V30, FOR and AGF2, B horizon), mean surface: 69 ± 3%, mean deep: 66 ± 5%; Fig. 12o) showed some significant differences for both surface and deep horizons. On the surface, the FOR was significantly higher ($p < 0.05$) from almost all land covers, except with V30 and AGF2. On the deep horizon, the V30 was significantly higher ($p < 0.05$) from almost all of them, except with AGF2 and FOR. As for MON, the results are linked to soil pH (*vide supra*).

Copper (Cu: range: 17.3 (PAU, A horizon) to 36.0 mg kg^{-1} (V15, A horizon), mean surface: 25.1 ± 0.9 mg kg^{-1}, mean deep: 22.5 ± 0.8 mg kg^{-1}; Fig. 12p) showed significant differences ($p < 0.05$) between the surface and deep horizon for some land cover, such as V15, V30, and OLI. When comparing the surface horizon among the different land covers, the V15 showed the highest concentration. The results for SMLP are associated with the utilization of fungicides for protecting the vineyards, as previously discussed in the case of MON (*vide supra*).

Iron (Fe: range: 23.3 (FOR, A horizon) to 45.9 mg kg^{-1} (OLI, B horizon), mean surface: 36.2 ± 1.7 mg kg^{-1}, mean deep: 37.5 ± 1.3 mg kg^{-1}; Fig. 12q) did not showed significant differences between surface and deep horizons, nor among different land covers in both horizons.

Manganese (Mn: range: 605.9 (V30, B horizon) to 1611.9 mg kg^{-1} (FOR, A horizon), mean surface: 1051.6 ± 75.2 mg kg^{-1}, mean deep: 1011.9 ± 79.3 mg kg^{-1}; Fig. 12r) did not present significant differences ($p < 0.05$) between surface and deep horizon. On the surface, some significant differences ($p < 0.05$) were observed, in which V15, AGF2, and FOR

showed higher Mn than PAU. As observed for the MON pedosystem, the results could be related to SOM contents instead of clay (*vide supra*).

For zinc (Zn: range: 45.0 (PAU, A horizon) to 120.0 mg kg^{-1} (FOR, A horizon; V3, B horizon), mean surface: 85.3 ± 4.8 mg kg^{-1}, mean deep: 86.8 ± 4.2 mg kg^{-1}; Fig. 12s) no significant differences ($p < 0.05$) were observed in the surface *vs* deep horizon. Some significant differences ($p < 0.05$) were observed for both surface and deep horizons when comparing different land covers, in which the V3 was significantly higher than V30 and PAU on the surface, and in the deep, the FOR land cover was significantly higher than V30, OLI, and PAU. The observed surface results in the vineyard might be related to agrochemicals and/or soil amendments, as observed for the MON pedosystem (*vide supra*).

3.2.4 MULTIVARIATE STATISTICS

Principal Factor Analysis (PFA)

PFA – Surface and deep soil horizons

The PFA performed by considering both surface (A) and deep (Bt) soil horizons extracted a five-component model of highly significant importance (eigenvalues > 1) (Table 12). Overall, the cumulative variance reached 77%, thus showing a high model reliability. Factor 1 (F1), accounting alone for 35% of the total variance, extracted SOCs, total N, EC, exchangeable cations (Ca, Mg, and K), CEC, BS, and Mn as all positively correlated, while negatively with silt and BD. This suggests that SOCs highly influenced the SMLP pedosystem variability (high factor loadings: > 0.9), reflecting its importance and influence on most of the investigated soil parameters. As a matter of fact, this factor highlighted that SOCs strongly influenced the whole fertility in terms of total N, Mn, exchangeable cations, CEC, and BS; thus, when soil organic carbon stocks increase all these pivotal parameters will tremendously be improved accordingly. Indeed, and as expected, an increase in SOCs determines a decrease in BD, showing a further positive influence on soil, i.e., a net porosity improvement. This factor can be interpreted as *"the importance of SOCs in improving soil physical-chemical features of the entire SMLP pedosystem with particular emphasis for fertility."* Factor 2 (F2) explained 15% of the variance and revealed sand content as negatively correlated with clay, exchangeable K, Fe, and Zn. This factor is directly associated with the soil's textural class, i.e., clay-loam,

featured by a high presence of clay minerals. Thus, as 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 cations exchangeable processes."* Factor 3 (F3), representing 12% of the variance, withdraws total P, available P, and BS as positively concordant, while negatively with Na and H+Al. In particular, it shows that at increasing P into the soil environment an increase in overall soil fertility was expected (BS increased) while, conversely (and obviously), acidic cations decreased. Thus, it can be named "*the influence of colloidal fractions into the soil matrix.*" Factor 4 (F4) and 5 (F5) shows a lower overall variance if compared with the other extracted factors, i.e., 9% and 6%, respectively. F4 extracted pH and C/N as positively correlated, while negatively with available P; as soil C decomposition processes proceeds acidic cations (such as H^+) are released into the soil environment thus increasing soil pH while decreasing P availability (Kabata-Pendias and Pendias, 2001). F5 revealed a positive correlation between microelements (Cu, Mn, and Zn), a correlation of geochemical reasons since these elements are strictly related to each other (Kabata-Pendias and Pendias, 2001). Consequently, F4 and 5 can be named "*the role of pH in SOC decomposition processes*" and the "*geochemical relation among selected microelements*", respectively.

Overall, the PFA extracted by taking into account all investigated land uses and both horizons (A and B), clearly showed the pivotal importance of SOCs in the SMLP pedosystem. It was extracted as the first factor, positively influencing several physical-chemical parameters and determining a general soil improvement in terms of fertility and physical features (improved soil porosity).

Table 12

Factor loadings of a factor analysis (n = 56) for the SMLP pedosystem considering surface and deep soil horizons; Extraction Method: principal factor analysis (PFA); Rotation Method: Varimax; bold loadings > 0.4.

	Santa Maria La Palma (SMLP)				
	F1	F2	F3	F4	F5
pH	0.147	-0.055	0.018	**0.860**	-0.074
EC	**0.903**	0.264	0.167	0.011	0.138
Sand	0.184	**0.932**	-0.075	0.076	-0.001
Silt	**-0.459**	-0.255	-0.079	0.062	0.316
Clay	0.028	**-0.887**	0.121	-0.113	-0.155
BD	**-0.766**	0.290	-0.130	-0.222	-0.128
SOCs	**0.905**	0.086	0.172	0.011	-0.006
Total N	**0.945**	0.100	0.103	-0.183	0.015
C/N	-0.137	0.213	0.113	**0.768**	-0.027
Total P	0.156	0.195	**0.675**	-0.301	0.274
Available P	0.072	0.318	**0.653**	**-0.472**	0.344
Ca^{2+}	**0.971**	-0.029	0.129	0.143	-0.000
Mg^{2+}	**0.949**	0.068	0.075	-0.192	0.060
Na^{+}	0.128	0.090	**-0.509**	-0.166	0.264
K^{+}	**0.530**	**-0.464**	0.366	-0.113	0.341
CEC	**0.974**	-0.020	-0.095	0.069	0.011
BS	**0.463**	-0.179	**0.732**	0.279	0.064
H+Al	-0.189	0.067	**-0.812**	-0.122	-0.065
Cu	-0.074	-0.108	0.264	-0.228	**0.855**
Fe	-0.240	**-0.611**	-0.336	0.130	0.069
Mn	**0.421**	0.398	-0.182	0.235	**0.515**
Zn	0.207	**-0.645**	-0.043	0.041	**0.447**
Proportional variance (%)	35	15	12	9	6
Cumulative variance (%)	35	50	62	71	77
Eigenvalues	7.600	3.342	2.740	1.980	1.362

PFA – Vegetation, litter, and surface soil horizon

The PFA extracted a three-factor model elucidating 60% of the overall data variation (Table 13). In particular, F1, representing an impressive 32% of the variance (meaning that only one factor explained more than 50% of the overall observed variability), revealed a positive correlation among some soil physical-chemical parameters (such as EC, sand, SOCs, N, exchangeable cation (Ca, Mg, and K), CEC, BS, and Mn) as well as selected litter parameters (such as LCs, Ca, and Mn); on the opposite, they are all negatively related with silt and BD, some plant (richness (S) and Shannon-Weaver Index (H')) and litter (P, K, and Zn) parameters. This factor shows that at increasing SOCs, several soil physical-chemical parameters improved accordingly. Indeed, it was observed an improvement in macro- (N) and micro-(Mn) nutrients, exchangeable cation (Ca, Mg, and K), CEC, and BS, thus an overall soil fertility enhancement. Additionally, an increase in SOCs brings to a decrease in BD (note the negative correlation between the two parameters), thus improving general physical edaphic conditions such as porosity and aeration, meaning a better environment for the plant's root system. Obviously, an increase in carbon stocked in the litter was observed too; an aspect showing that the whole soil-litter system has been generally improved. The inverse correlation with P, K, and Zn in litter "simply" shows that at increasing SOCs some elements are (a) lost by leaching or mineralization processes or (b) immobilized by humification, depending on chemical reactions (where the increase/decrease in concentration of some elements can completely change the *equilibrium* of the whole system) that are out of the scope of the present research. From this point of view, a future step of the research should be focused on explaining the whole complexity of these mechanisms too. Very interesting, the F1 shows an inverse correlation with S (richness) and H' (Shannon-Weaver Index), thus it could be apparently stated that at improving soil general conditions these plant parameters are featured by worst performances, i.e., less biodiversity and richness. However, this is the wrong way to read obtained outcomes. Indeed, when plant richness and related indexes increase, they are not always an index of ecosystem improvement. For instance, in a strongly human-affected environment, these two vegetation parameters can increase because the number of species increases, since humans can create fragmentation, meaning a plethora of different micro-environments and, consequently, extremely distinct edaphic conditions, where different species can find the best growing conditions. As a matter of fact, in the previously reported case, even if the environment is strongly affected by human activities, these two parameters, if read alone without an overall complex view of the entire involved ecosystems and related processes, are telling us that

biodiversity increases. As explained by Coppola et al. (2010), a PFA must be read by taking into account all the complex relationships among investigated parameters by also considering field observation and previously reported outcomes. A PFA is not a closed box but requires a "general overview" approach that can be complex, and also requires experience. So, coming back to the obtained results the inverse correlation between a general soil improvement *vs* S and H' shows us that we are moving towards a stabilization in vegetation cover condition, which we call (at least for forest cover) "natural potential vegetation" (NPV). In Mediterranean ecosystems, the NPV is very often (as in our investigated area) featured by very few dominant species, such as in holm oak forests. These are the reasons why at increasing SOCs and general soil conditions enhancement, it was observed an inverse correlation with these specific plant parameters. Consequently, we can name this factor as "*the role of SOCs in improving soil features under a soil-vegetation equilibrium condition*." Factor 2 (F2, 16% of the variance) extracted litter parameters only, by revealing a positive correlation between Mg, Cu, Fe, and Mn, while they are negatively correlated with C and C/N. Also in this case, this factor shows that at increasing C and, consequently, C/N, mineralization processes prevail, thus releasing (together with COx, NOx, etc. into the atmosphere) some elements into the soil environments. This factor can thus be interpreted as "*the role of mineralization processes in selected micronutrient behavior*." Factor 3 (F3, 12% of the variance) is similar to F3 previously extracted in the PFA elaborated considering all land uses and horizons (*vide supra;* Table 12); so, it was named "*the influence of colloidal fractions into the soil matrix.*"

Overall, as already observed in the PFA elaborated considering all land uses and soil horizons (Table 12), also in this case the pivotal role of SOCs clearly arises. Consequently, it is clear that for this specific pedosystem SOCs strongly influence (a) most soil features (improving them and general edaphic conditions), (b) the soil-litter, as well as (c) the soil-vegetation relationships.

Table 13

Factor loadings of a factor analysis (n = 28) for the SMLP pedosystem considering vegetation, litter, and surface soil horizon; Extraction Method: principal factor analysis (PFA); Rotation Method: Varimax; bold loadings > 0.4.

	F1	F2	F3
Richness (V_S)	**-0.718**	0.050	-0.160
Number of different families (V_F)	0.021	-0.150	-0.048
Shannon-Weaver Index (V_H')	**-0.759**	-0.014	-0.074
L_C	0.129	**-0.959**	0.111
L_N	0.224	0.302	-0.109
L_LCs	**0.640**	-0.098	-0.051
L_C/N	-0.181	**-0.551**	0.073
L_P	**-0.633**	0.138	**0.483**
L_Ca	**0.447**	0.125	-0.260
L_Mg	0.073	**0.581**	-0.038
L_Na	0.296	0.255	0.236
L_K	**-0.701**	0.311	0.174
L_Cu	-0.207	**0.776**	0.231
L_Fe	-0.053	**0.954**	-0.158
L_Mn	**0.446**	**0.425**	-0.111
L_Zn	**-0.546**	0.332	0.282
S_pH	0.161	0.079	-0.144
S_EC	**0.865**	-0.003	0.295
S_Sand	**0.410**	0.141	0.038
S_Silt	**-0.619**	-0.088	-0.223
S_Clay	-0.143	-0.133	0.094
S_BD	**-0.561**	0.079	-0.106
S_SOCs	**0.898**	-0.012	0.164
S_N	**0.874**	-0.042	0.183
S_C/N	-0.055	-0.117	0.006
S_Pt	0.128	0.009	**0.866**
S_Pav	0.070	-0.081	**0.886**
S_Ca	**0.891**	-0.045	0.141

S_Mg	**0.903**	-0.082	0.202
S_Na	0.140	0.025	-0.264
S_K	**0.401**	-0.123	0.375
S_CEC	**0.896**	-0.009	0.007
S_BS	**0.473**	-0.095	**0.560**
S_H+Al	-0.308	0.218	**-0.727**
S_Cu	-0.239	0.100	0.337
S_Fe	-0.398	-0.056	**-0.623**
S_Mn	**0.535**	0.317	0.064
S_Zn	0.056	0.198	0.070
Proportional variance (%)	32	16	12
Cumulative variance (%)	32	48	60
Eigenvalues	12.087	5.988	4.404

Where: Green part (V_) = vascular plant parameters, gray part (L_) = litter parameters, and orange part (S_) = soil parameters (A horizon, 0-20 cm depth).

Principal Component Analysis (PCA)

The first (PC1) and the second component (PC2) explained 35% and 15% of the variability, respectively (Fig. 13), thus meaning an impressive 50% of the total variability. Also, as observed for the MON pedosystem, PCA revealed a clearly different pattern in land use distribution along the biplot. Thus, investigated land uses are influenced in different magnitudes according to the specific soil parameters; obviously, as expected, some parameters can contemporaneously influence different land uses, thus being not exclusive to one single system. Summarizing: V3, V15, V30, OLI and PAU showed a clear influence from bulk density. This can be explained by taking into account that all these systems are periodically (V3, V15, V30, and OLI) or have been (PAU) strongly influenced by mechanical plowing activities conducted with heavy machinery. In the investigated pedosystem, where soils are clayey in texture, such kind of human activities bring an increase in BD, thus influencing the entire pedosystem. This is confirmed by the fact that all the other investigated land uses are more influenced by other soil parameters such as Mn in AGF2, and, as expected, soil-related fertility parameters (SOCs, BS, P, N, CEC, exchangeable cations, BS, several micronutrients) in FOR.

Overall, PCA for the SMLP pedosystem showed the great influence of human activities in influencing soil behavior. These findings suggest that the SMLP pedosystem

experiences greater influences from human activities if compared to the MON pedosystem. Differences in the substrate and following soil formation processes seem to play a pivotal 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 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 usually more fragile and under-risk pedosystems (Capra et al., 2018; Torrent, 2005).

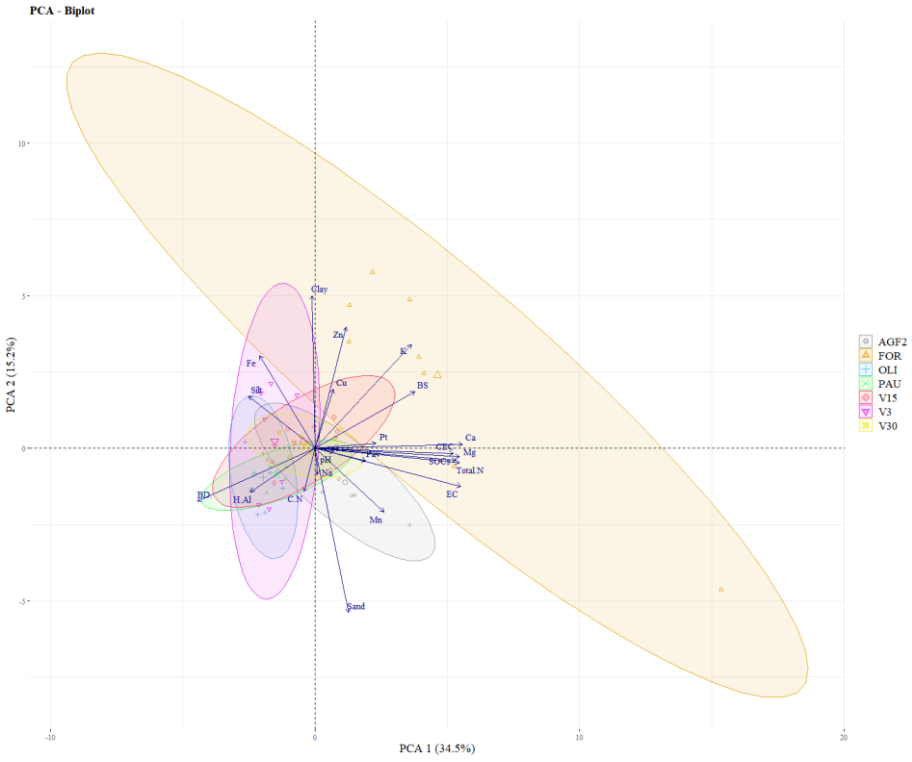


Fig. 13. Principal component analysis related to soil physical-chemical parameters from Santa Maria La Palma pedosystem. V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; AGF2: grazing land by goat shaded with *Eucalyptus camaldulensis* Dehn.*;* PAU: *Paulownia sp*. plantation; FOR: holm oak (*Quercus ilex* L.) forest; OLI: olive groves. BD: bulk density; EC: electrical conductivity; N: total nitrogen; Pt: total phosphorus; Pav: available phosphorus; C.N: carbon-to-nitrogen ratio; H.Al: exchange acidity; Ca: exchangeable calcium; Mg: exchangeable magnesium; Na: exchangeable sodium; K: exchangeable potassium; CEC: cation exchange capacity; BS: base saturation; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc.

3.3 MONTI *VS* SANTA MARIA LA PALMA PEDOSYSTEM

3.3.1 VEGETATION INVESTIGATION

The investigation documented a list comprising 35 families, 85 genera, and 95 vascular plant species (Table 14) within the commonly investigated land covers. It is noteworthy that the land use management in the vineyards in the MON pedosystem differs from that in SMLP, resulting in the absence of vegetation during the sampling activities. Consequently, data regarding vineyards in MON are not available (*vide supra*). Among the observed families, the most abundant were Poaceae (21 sp., 22%), Asteraceae (18 sp., 19%), Fabaceae (10 sp., 11%), Rosaceae (5 sp., 5%), constituting 57% of the total species (Fig. 14a).

Table 14

Floristic list of the vascular plants in the contrasting pedosystems.

Family	Species	MON	SMLP			
		FOR	V3	V15	V30	FOR
Amaranthaceae	*Atriplex patula* L.		×		×	
Amaryllidaceae	*Allium roseum* L. subsp. *roseum*	×				
Anacardiaceae	*Pistacia lentiscus* L.					×
Apiaceae	*Daucus carota* L.	×				
	Eryngium tricuspidatum L.	×				
	Smyrnium olusatrum L.	×				
Araceae	*Arisarum vulgare* O.Targ.Tozz. subsp. *vulgare*					×
	Chamaerops humilis L. subsp. *humilis*					×
Asparagaceae	*Asparagus officinalis* L. subsp. *officinalis*	×		×		×
	Ruscus aculeatus L.	×				
Asphodelaceae	*Asphodelus ramosus* L. subsp. *ramosus*	×				×
Asteraceae	*Achillea ligustica* All.	×				
	Andryala integrifolia L.		×	×	×	
	Calendula arvensis (Vaill.) L.				×	

Family	Species	MON	SMLP			
		FOR	V3	V15	V30	FOR
	Carlina corymbosa L.	×				
	Carlina gummifera (L.) Less.	×				
	Crepis bellidifolia Loisel.			×		
	Crepis vesicaria L.				×	
	Erigeron canadensis L.		×	×		
	Glebionis coronaria (L.) Spach	×				
	Helminthotheca echioides (L.) Holub			×	×	
	Leontodon tuberosus L.	×				
	Pulicaria odora (L.) Rchb.	×				
	Reichardia picroides (L.) Roth			×	×	
	Senecio vulgaris L.			×	×	
	Sonchus asper (L.) Hill		×	×	×	
	Symphyotrichum squamatum (Spreng.) G.L. Nesom		×			
	Taraxacum sect. Taraxacum	×				
	Urospermum dalechampii (L.) Scop. ex F.W. Schmidt	×				
Caryophyllaceae	*Polycarpon tetraphyllum* (L.) L. subsp. *alsinifolium* (Biv.) Ball		×			
Cistaceae	*Cistus monspeliensis* L.	×				
Convolvulaceae	*Convolvulus arvensis* L.		×	×	×	
Cyperaceae	*Carex distachya* Desf.					×
Dioscoreaceae	*Dioscorea communis* (L.) Caddick & Wilkin					×
Ericaceae	*Arbutus unedo* L.					×
Fabaceae	*Cytisus villosus* Pourr.	×				
	Lathyrus latifolius L.					×
	Lotus ornithopodioides L.		×	×	×	
	Lotus parviflorus Desf.		×	×	×	
	Medicago polymorpha L.		×	×	×	
	Scorpiurus muricatus L.					
	Trifolium campestre Schreb.		×	×	×	
	Trifolium glomeratum L.		×			
	Vicia sativa L.		×		×	

Family	Species	MON	SMLP			
		FOR	V3	V15	V30	FOR
Fagaceae	*Quercus ilex* L.	×				×
	Quercus suber L.	×				×
Gentianaceae	*Schenkia spicata* (L.) G. Mans.		×	×	×	
Geraniaceae	*Erodium malacoides* (L.) L'Hér. subsp. *malacoides*		×		×	
	Geranium dissectum L.	×		×	×	
Juncaceae	*Luzula forsteri* (Sm.) DC.	×				
Lamiaceae	*Stachys arvensis* (L.) L.			×		
Malvaceae	*Malva sylvestris* L.			×	×	
Myrtaceae	*Myrtus communis* L.					×
Oleaceae	*Fraxinus ornus* L. subsp. *ornus*	×				
	Olea europaea L.					×
	Phillyrea angustifolia L.	×				
Oxalidaceae	*Oxalis corniculata* L.		×			
Papaveraceae	*Fumaria officinalis* L.				×	
Plantaginaceae	*Plantago lanceolata* L.	×		×	×	
	Veronica arvensis L.		×	×		
Poaceae	*Anisantha tectorum* (L.) Nevski		×	×	×	
	Anthoxanthum aristatum Boiss.	×				
	Avena barbata Pott ex Link	×	×	×	×	
	Brachypodium distachyon (L.) P. Beauv.			×	×	
	Brachypodium retusum (Pers.) P. Beauv.					×
	Brachypodium sylvaticum (Huds.) P.Beauv. subsp. *sylvaticum*	×				
	Bromus hordeaceus L.		×	×	×	
	Catapodium rigidum (L.) C.E. Hubb. subsp. *rigidum*		×		×	
	Dactylis glomerata L. subsp. *hispanica* (Roth) Nyman	×				
	Festuca ligustica (All.) Bertol.	×				
	Festuca myuros L. subsp. *myuros*		×	×	×	
	Hordeum murinum L. subsp. *leporinum* (Link) Arcang.		×	×	×	
	Lolium multiflorum Lam.		×	×		
	Lolium temulentum L.		×			

Family	Species	MON	SMLP			
		FOR	V3	V15	V30	FOR
	Macrobriza maxima (L.) Tzvelev	×				
	Oloptum miliaceum (L.) Röser & H.R. Hamasha					×
	Parapholis cylindrica (Willd.) Romero Zarco		×		×	
	Poa annua L.		×	×	×	
	Poa infirma Kunth				×	
	Polypogon viridis (Gouan) Breistr. subsp. *viridis*		×			
	Rostraria cristata (L.) Tzvelev		×	×		
Polygonaceae	*Polygonum aviculare* L. subsp. *aviculare*		×	×		
	Rumex crispus L.		×		×	
Primulaceae	*Lysimachia arvensis* (L.) U. Manns & Anderb.		×	×	×	
Ranunculaceae	*Clematis cirrhosa* L.					×
	Ranunculus muricatus L.		×		×	
Rhamnaceae	*Rhamnus alaternus* L. subsp. *alaternus*					×
Rosaceae	*Crataegus monogyna* Jacq.					×
	Poterium sanguisorba L.	×				
	Pyrus spinosa Forssk.	×				
	Rosa sempervirens L.					×
	Rubus ulmifolius Schott					×
Rubiaceae	*Galium palustre* subsp. *elongatum* (C. Presl) Arcang.	×				
	Rubia peregrina L.	×				×
Santalaceae	*Osyris alba* L.					×
Smilacaceae	*Smilax aspera* L.					×

Where: 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 (*Quercus suber* L.) forest; FOR-SMLP: holm oak (*Quercus ilex* L.).

The life-form (Fig. 14b) analysis showed a distinct dominance of annual plants (Terophytes – T) at 45%, followed by herbaceous perennials (Hemicrytophytes – H) at 26%, woody plants (Phanaerophytes - P) at 15%, non-wood perennials (Geophytes – G) at 8%, and a limited diversity of woody forms (nano-Phanaerophytes – Np) at 6%. Regarding the chorological spectrum (Fig. 14c), the Steno-Mediterranean chorotype emerged as the predominant at 36%, followed by Euro-Mediterranean at 26%, Eurasian at 14%, and wide distribution at 11%, together accounting for 87% of the total.

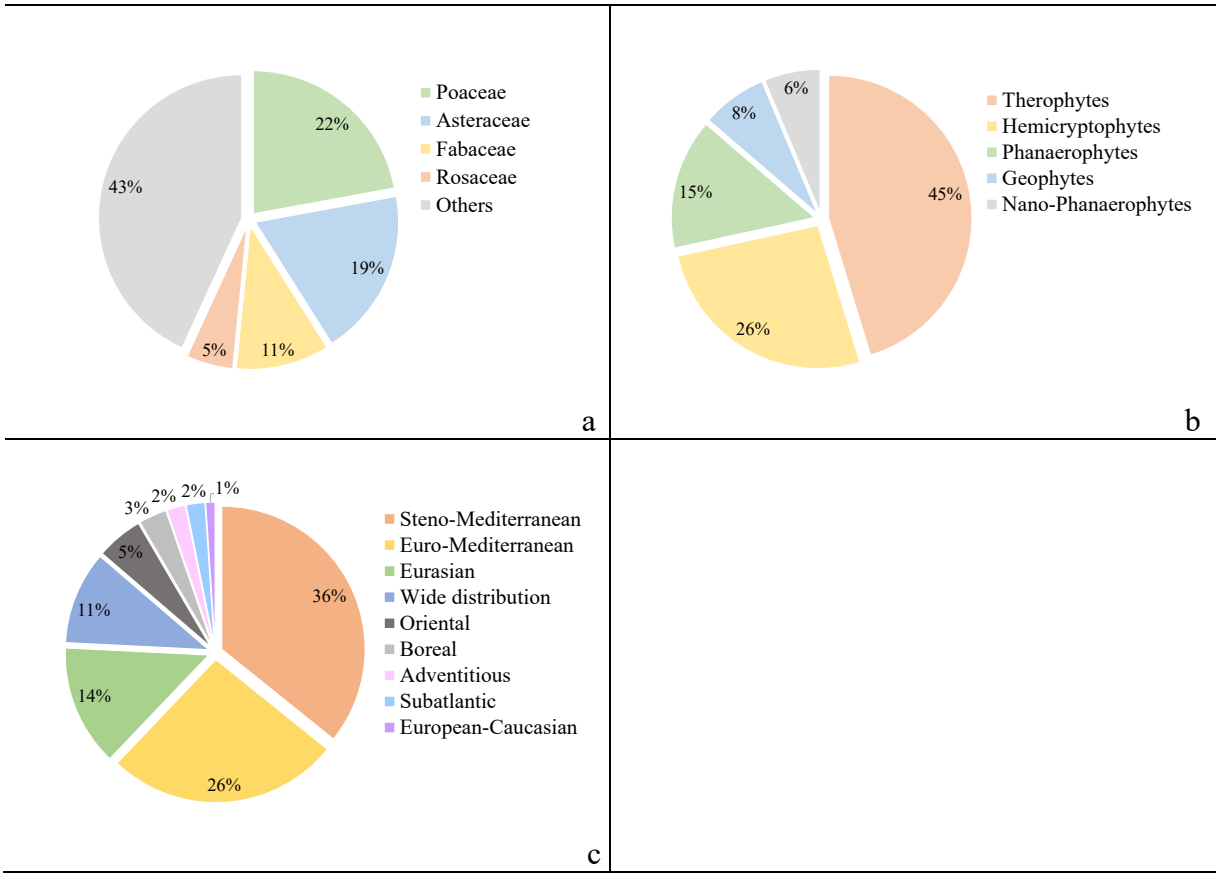


Fig. 14. Vascular plants abundance of the contrasting pedosystems together in terms of: a) families, b) life-form, and c) chorotypes.

Comparing the differences between the contrasting pedosystems (MON *vs* SMLP), the ANOVA focused solely on FOR land cover, owing to the absence of vascular plants in MON vineyards (thus, unavailable data). Consequently, the analysis for the different land covers was exclusively carried out for SMLP as well. Vascular plants richness (Fig. 15a) and Shannon-Weaver's Diversity Index (H'; Fig. 15b) in the FOR land cover between MON *vs*

SMLP did not exhibit significant differences ($p < 0.05$). In the comparison of different land covers within SMLP, FOR was significantly ($p < 0.05$) less rich and less diverse.

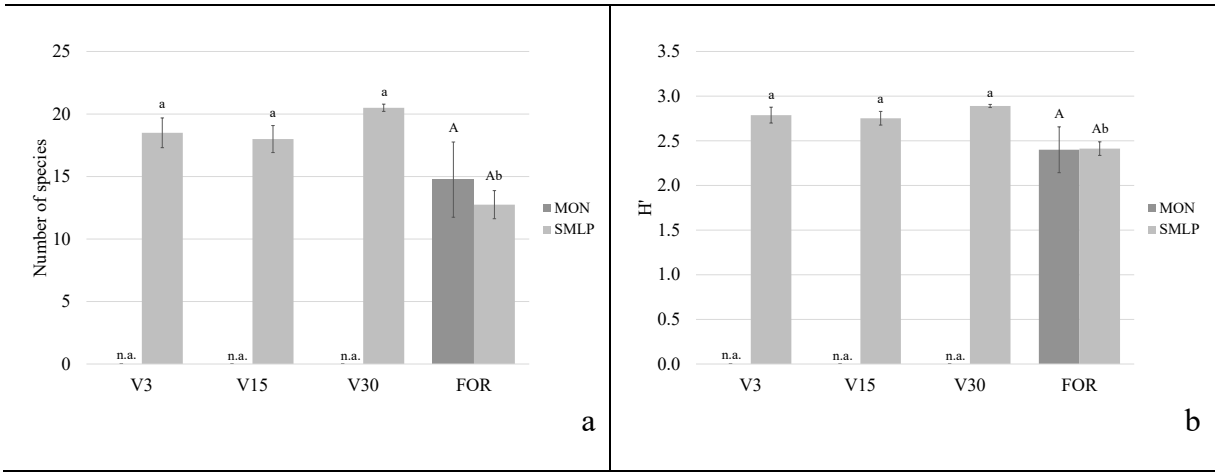


Fig. 15. Vascular plants richness (a) and Shannon-Weaver's Diversity Index (b) along different land cover for MON *vs* SMLP pedosystem. V3: Vermentino planted three years ago (at the time of the sampling activities, i.e., 2021); V15: Vermentino planted fifteen years ago; V30: Vermentino planted thirty years ago; FOR-MON: cork oak (*Quercus suber* L.) forest; FOR-SMLP: holm oak (*Quercus ilex* L.) forest. Different capital letters showed significant differences ($p < 0.05$) among different pedosystems (MON *vs* SMLP) for the same land cover, while different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem. n.a.: data not available.

Concerning the life-form (Table 15) among the contrasting pedosystems, results indicated some significant differences ($p < 0.05$) between MON *vs* SMLP for the FOR land cover. The woody form (nano-Phanaerophytes – Np) was significantly higher in the SMLP (range: 20 to 27%) than MON (range: 0 to 5%). Also, non-wood perennials (Geophytes – G) showed SMLP (range: 18 to 30%) > MON (range: 0 to 15%). On the contrary, herbaceous perennials (Hemicrytophytes – H) were significantly higher in MON (range: 29 to 47%) than SMLP (range: 0 to 24%). When comparing the different land covers in the SMLP, the FOR land cover showed significantly ($p < 0.05$) higher presence of wood forms (Phanerophytes and Nano-Phanerophytes) and non-wood perennials (Geophytes) compared to the agricultural areas (vineyards). On the contrary, for the annual plants (Terophytes), the vineyard cultivated over 30 years (V30) exhibits the highest ($p < 0.05$) presence.

Table 15

Vascular plants life-form and chorotype comparing contrasting pedosystems (Monti *vs* Santa Maria La Palma): mean ± standard error (SE).

	MON				SMLP			
	V3	V15	V30	FOR	V3	V15	V30	FOR
Life-form								
Phanaerophytes	n.a.	n.a	n.a.	38 ± 13 A	0 ± 0 b	0 ± 0 b	0 ± 0 b	46 ± 4 Aa
Nano-Phanaerophytes	n.a.	n.a.	n.a.	3 ± 1 B	0 ± 0 b	0 ± 0 b	0 ± 0 b	23 ± 1 Aa
Hemicryptophytes	n.a.	n.a.	n.a.	41 ± 4 A	4 ± 2 a	12 ± 1 a	13 ± 1 a	6 ± 6 Ba
Geophytes	n.a.	n.a.	n.a.	7 ± 3 B	5 ± 0 b	7 ± 2 b	5 ± 0 b	24 ± 3 Aa
Therophytes	n.a.	n.a.	n.a.	12 ± 8 A	91 ± 2 a	80 ± 2 b	82 ± 1 b	0 ± 0 Ac
Chorotype								
Wide distribution	n.a.	n.a.	n.a.	3 ± 1 B	21 ± 4 a	19 ± 2 a	11 ± 2 ab	8 ± 1 Ab
Adventitious	n.a.	n.a.	n.a.	0 ± 0	8 ± 2 a	3 ± 1 b	0 ± 0 b	0 ± 0 b
Boreal	n.a.	n.a.	n.a.	2 ± 2 A	3 ± 2 ab	4 ± 1 ab	6 ± 1 a	0 ± 0 Ab
Euro-Mediterranean	n.a.	n.a.	n.a.	32 ± 6 A	34 ± 2 a	22 ± 2 b	30 ± 2 ab	34 ± 2 Aa
Eurasian	n.a.	n.a.	n.a.	14 ± 3 A	17 ± 3 b	27 ± 3 a	24 ± 2 ab	1 ± 1 Bc
European-Caucasian	n.a.	n.a.	n.a.	0 ± 0 A	0 ± 0 a	0 ± 0 a	0 ± 0 a	1 ± 1 Aa
Oriental	n.a.	n.a.	n.a.	3 ± 1 A	3 ± 2 a	7 ± 1 a	10 ± 2 a	3 ± 2 Aa
Steno-Mediterranean	n.a.	n.a.	n.a.	44 ± 4 A	15 ± 2 b	16 ± 4 b	18 ± 3 b	51 ± 2 Aa
Subatlantic	n.a.	n.a.	n.a.	3 ± 1 A	0 ± 0 a	1 ± 1 a	0 ± 0 a	0 ± 0 Aa

Where: 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 (*Quercus suber* L.) forest; FOR-SMLP: holm oak (*Quercus ilex* L.) forest. 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 same investigated feature, while different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem and same investigated feature. N.a.: not available.

For the chorotypes (Table 15), it was observed significant differences ($p < 0.05$) between MON *vs* SMLP only for the Wide distribution, in which SMLP (range: 6 to 10%) > MON (range: 0 to 5%), and Eurasian, which showed MON (range: 8 to 20%) > SMLP (range: 0 to 6%). When comparing different land covers for the SMLP, the chorotypes exhibit different trends. The wide distribution (range: 5 (V30) to 30% (V3), mean: 15 ± 2%) chorotype was significantly higher ($p < 0.05$) in V3 and V15 compared to FOR. Adventitious (range: 0 (V15, V30, and FOR) to 13% (V3), mean: 3 ± 1%) was significantly highest in V3. Boreal (range: 0 (V3, V15, and FOR) to 10% (V30), mean: 3 ± 1%) showed V30 higher than FOR. Euro-Mediterranean (range: 17 (V15) to 40% (FOR), mean: 30 ± 2%) revealed V3 and FOR with higher presence than V15. Eurasian (range: 0 (FOR) to 33% (V15), mean: 18 ± 2%) was significantly higher in V15 compared to V3 and FOR. Steno-Mediterranean (range: 10 (V15)

to 55% (FOR), mean: 25 ± 2%) was significantly highest in FOR. European-Caucasian (range: 0 (all) to 6% (FOR), mean: 0 ± 0%), Oriental (range: 0 (V3 and FOR) to 14% (V30), mean: 6 ± 2%), and Subatlantic (range: 0 (all) to 5% (V15), mean: 0 ± 0%) did not show significant differences.

In summary, observed findings suggest that, when comparing contrasting pedosystems, there were no significant differences in the richness and diversity of the forest communities. However, there were significant differences ($p < 0.05$) in the variety of life-forms, with the holm-oak forest (FOR-SMLP) exhibiting a higher prevalence of wood forms (Nano-Phanerophytes) and non-wood perennials (Geophytes), while the cork-oak forest (FOR-MON) showed a greater presence of herbaceous perennials (Hemicrytophytes). The extraction of cork induces local disturbances (Díaz-Villa et al., 2003), and this human impact may be related to the increased prevalence of this life-form. Additionally, significant differences ($p < 0.05$) were observed in terms of chorotypes, with the holm-oak forest (FOR-SMLP) featuring a higher presence of the wide distribution chorotype, while the cork-oak (FOR-MON) demonstrates a greater prevalence of the Eurasian chorotype.

3.3.2 LITTER FEATURES

When comparing the contrasting Mediterranean pedosystems under the common land covers (Table 16), litter data from the vineyards in the MON pedosystem was not available (*vide supra*). Consequently, the comparison between MON and SMLP was exclusively carried out for the FOR land cover. Results revealed significant differences ($p < 0.05$) just for the litter carbon stocks, where SMLP (range: 7.2 to 8.4 t ha^{-1}; mean: 7.7 ± 0.3) > MON (range: 2.3 to 6.2 t ha^{-1}; mean: 3.7 ± 0.9). This finding could be attributed to the holm-oak forest tree cover, with its ability to higher litter production. The other parameters did not show significant differences between the investigated pedosystems.

When comparing the different land covers for the SMLP pedosystem, the results were similar to the previous one (please note Section 3.2.2), showing significantly ($p < 0.05$) higher N concentration, LCs, Ca, and Mn in the FOR land cover.

Table 16

Chemical parameters of the litter comparing MON *vs* SMLP pedosystems.

MON	V3	V15	V30	FOR	Mean
C (%)	n.a.	n.a	n.a.	41.9 ± 7.3 A	-
N (%)	n.a.	n.a.	n.a.	1.2 ± 0.1 A	-
C/N	n.a.	n.a.	n.a.	33 ± 3 A	-
LCs (t ha^{-1})	n.a.	n.a.	n.a.	3.7 ± 0.9 B	-
P (g kg^{-1})	n.a.	n.a.	n.a.	0.01 ± 0.00 A	-
Ca (g kg^{-1})	n.a.	n.a.	n.a.	7.59 ± 2.04 A	-
Mg (g kg^{-1})	n.a.	n.a.	n.a.	1.54 ± 0.21 A	-
Na (g kg^{-1})	n.a.	n.a.	n.a.	0.41 ± 0.07 A	-
K (g kg^{-1})	n.a.	n.a.	n.a.	2.50 ± 0.26 A	-
Cu (mg kg^{-1})	n.a.	n.a.	n.a.	9.82 ± 3.33 A	-
Fe (mg kg^{-1})	n.a.	n.a.	n.a.	2849 ± 1960 A	-
Mn (mg kg^{-1})	n.a.	n.a.	n.a.	1090 ± 163 A	-
Zn (mg kg^{-1})	n.a.	n.a.	n.a.	26.39 ± 4.18 A	-
SMLP					
C (%)	51.3 ± 0.7 a	49.8 ± 2.3 a	51.9 ± 0.7 a	52.1 ± 0.67 Aa	51.3 ± 1.1
N (%)	1.1 ± 0.1 b	1.1 ± 0.0 b	1.1 ± 0.1 b	1.5 ± 0.1 Aa	1.2 ± 0.1
C/N	47 ± 3 a	46 ± 4 a	47 ± 3 a	35 ± 2 Aa	44 ± 3
LCs (t ha^{-1})	2.3 ± 0.3 b	1.2 ± 0.3 b	2.0 ± 0.5 b	7.7 ± 0.3 Aa	2.9 ± 0.5
P (g kg^{-1})	0.02 ± 0.00 b	0.02 ± 0.00 b	0.02 ± 0.00 a	0.01 ± 0.00 Ac	0.02 ± 0.00
Ca (g kg^{-1})	3.76 ± 0.27 b	4.05 ± 0.31 b	4.65 ± 0.25 b	12.81 ± 1.61 Aa	6.32 ± 0.61
Mg (g kg^{-1})	1.14 ± 0.10 a	1.44 ± 0.19 a	1.37 ± 0.08 a	1.77 ± 0.23 Aa	1.42 ± 0.17
Na (g kg^{-1})	0.45 ± 0.02 a	0.52 ± 0.07 a	0.49 ± 0.03 a	0.55 ± 0.06 Aa	0.50 ± 0.05
K (g kg^{-1})	3.97 ± 0.30 a	4.47 ± 0.29 a	4.49 ± 0.10 a	2.41 ± 0.27 Ab	3.83 ± 0.24
Cu (mg kg^{-1})	12.00 ± 1.44 a	18.74 ± 5.31 a	11.63 ± 1.36 a	8.77 ± 1.45 Aa	12.78 ± 2.39
Fe (mg kg^{-1})	2100 ± 607 a	3239 ± 1892 a	1350 ± 511 a	2069 ± 517 Aa	2189 ± 882
Mn (mg kg^{-1})	156 ± 18 b	208 ± 86 ab	86 ± 23 b	555 ± 156 Aa	251 ± 71
Zn (mg kg^{-1})	35.46 ± 3.27 a	36.58 ± 3.03 a	37.28 ± 7.11 a	24.58 ± 3.38 Aa	33.47 ± 4.20

Where: 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 (*Quercus suber* L.) forest; FOR-SMLP: holm oak (*Quercus ilex* L.) forest. A number followed by different capital letters showed significant differences ($p < 0.05$) among different pedosystems within the same land cover; different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem. N.a.: not available.

3.3.3 SOIL FEATURES

Soil physical parameters

Table 17 shows the soil physical parameters within the surface (A horizon, 0-20 cm) and deep (B, 20-40 cm) soil horizons for the contrasting pedosystems (MON *vs* SMLP) across common land covers (V3, V15, V30, and FOR). In the MON pedosystem, where Cambisols have developed on granite parent material, the soil texture (USDA, 2017) is sandy loam. This sandy loam is a result of the substantial influence of the granite substrate on physical-chemical weathering processes, leading to the prevalence of sand particles in the soil mineral matrix (Lozano-García et al., 2020). Conversely, the SMLP, with Luvisols on limestone, predominantly showed a clay loam soil texture (USDA, 2017), with higher clay content in the deep horizon than at the surface. This difference arose from pedogenetic processes, particularly clay migration, resulting in the development of an argic deep horizon (IUSS Working Group WRB, 2022).

Table 17

Soil physical parameters for MON and SMLP pedosystems; mean ± standard error (SE).

Land cover	Soil Horizon	Texture class	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})
MON						
V3	A	SL	78.6 ± 2.9 Aa	11.4 ± 1.4 Ba	10.0 ± 1.5 Bb	1.0 ± 0.1 Ba
	B	SL	77.2 ± 2.8 Aa	12.3 ± 1.4 Ba	10.5 ± 1.5 Ba	1.3 ± 0.0 Aa
V15	A	SL	73.8 ± 1.6 Aa	12.4 ± 0.8 Ba	13.8 ± 0.8 Ba	1.1 ± 0.1 Ba
	B	SL	74.0 ± 2.4 Aa	12.0 ± 0.9 Ba	14.0 ± 1.5 Ba	1.4 ± 0.0 Aa
V30	A	SL	76.8 ± 1.7 Aa	14.6 ± 1.2 Ba	8.6 ± 0.5 Bb	1.2 ± 0.0 Ba
	B	SL	70.7 ± 1.7 Aa	15.8 ± 0.9 Ba	13.5 ± 1.0 Ba	1.4 ± 0.0 Aa
FOR	A	SL	75.6 ± 0.7 Aa	14.4 ± 0.7 Ba	10.0 ± 0.4 Bab	1.2 ± 0.1 Aa
	B	SL	74.6 ± 0.5 Aa	14.0 ± 0.7 Ba	11.4 ± 0.2 Ba	1.4 ± 0.0 Aa
Mean	A		76.2 ± 1.7	13.2 ± 1.0	10.6 ± 0.8	1.1 ± 0.1
	B		74.1 ± 1.9	13.6 ± 1.0	12.3 ± 1.1	1.4 ± 0.0
SMLP						
V3	A	CL	39.2 ± 3.8 Ba	30.4 ± 2.5 Aa	30.4 ± 2.1 Aa	1.4 ± 0.0 Aa
	B	CL	38.3 ± 4.7 Ba	30.9 ± 2.3 Aa	30.8 ± 2.6 Aab	1.4 ± 0.0 Aa
V15	A	CL	39.1 ± 0.7 Ba	31.7 ± 0.9 Aa	29.2 ± 1.3 Aa	1.4 ± 0.0 Aa
	B	CL	38.9 ± 0.8 Ba	31.6 ± 0.9 Aa	29.5 ± 1.7 Ab	1.4 ± 0.0 Aa
V30	A	CL	41.6 ± 2.2 Ba	29.5 ± 1.9 Aa	28.9 ± 0.8 Aa	1.3 ± 0.0 Aa
	B	CL	40.7 ± 1.9 Ba	29.2 ± 1.6 Aa	30.1 ± 0.7 Ab	1.4 ± 0.0 Aa
FOR	A	CL	42.1 ± 10.3 Ba	26.9 ± 4.0 Aa	31.0 ± 7.5 Aa	0.8 ± 0.2 Ab
	B	C	23.1 ± 4.0 Bb	29.4 ± 3.4 Aa	47.5 ± 7.4 Aa	1.0 ± 0.1 Bb
Mean	A		40.5 ± 4.3	29.6 ± 2.3	29.9 ± 2.9	1.2 ± 0.1
	B		35.3 ± 2.9	30.3 ± 2.1	34.4 ± 3.1	1.3 ± 0.0

Where: 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 forest; FOR-SMLP: holm oak (*Quercus ilex* L.) 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, while different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem and soil horizon.

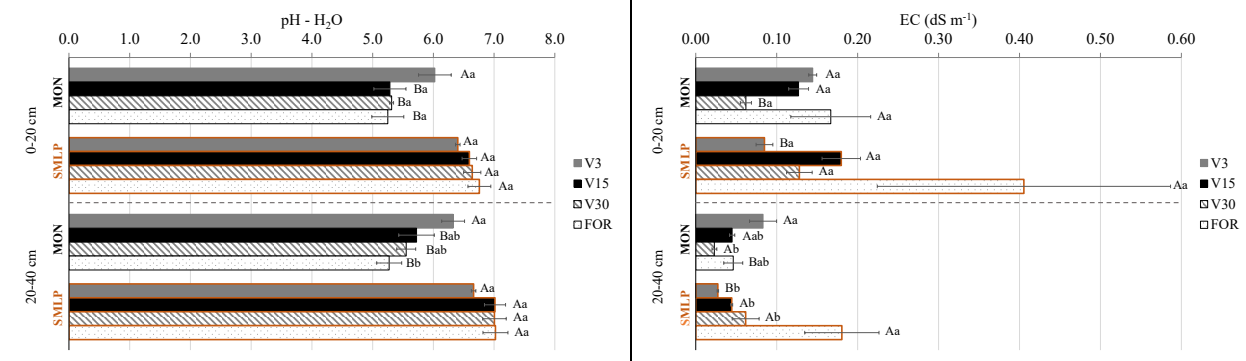
Due to the previous explanation, significant differences ($p < 0.05$) were observed between MON *vs* SMLP regarding sand, clay, and silt contents. The sand content was significantly higher in the MON for both surface and deep horizon (range from 66.7% (V30, B horizon) to 87.0% (V3, B horizon), with means of 76.2 ± 1.7% and 74.1 ± 1.9% for surface and deep horizons, respectively) compared to SMLP (range from 16.1% (FOR, B horizon) to 64.3% (FOR, A horizon), with means of 40.5 ± 4.3% in the surface and 35.3 ± 2.9% in the deep) for all land covers, as expected. On the other hand, silt and clay contents were significantly higher

in the SMLP for both horizons (silt: range from 15.2% (FOR, A horizon) to 39.2% (FOR, B horizon), with means of 29.6 ± 2.3% in the surface and 30.3 ± 2.1% in the deep; clay: range from 15.8% (FOR, A horizon) to 59.7% (FOR, B horizon), means of 29.9 ± 2.9% in the surface and 34.4 ± 3.1% in the deep) than MON (silt: range from 7.3% (V3, A horizon) to 17.6% (V30, A horizon), means of 13.2 ± 1.0% in the surface and 13.6 ± 1.0% in the deep; clay: range from 5.8% (V3, A horizon) to 16.4% (V15, B horizon), means of 10.6 ± 0.8% in the surface and 12.3 ± 1.1% in the deep horizon) for all land covers. Some significant differences ($p < 0.05$) were observed for sand and clay contents when comparing the different land covers. For the sand content, at SMLP, the agricultural areas (vineyards) were higher than FOR in the deep horizon. For the clay content, the V15 was significantly higher than V3 and V30 in the surface in the MON, while FOR was significantly higher than V15 and V30 in the deep horizon in the SMLP. The results could be related to the human influence in the agricultural areas (management practices, such as soil preparation), leading to differences in the deeper horizons.

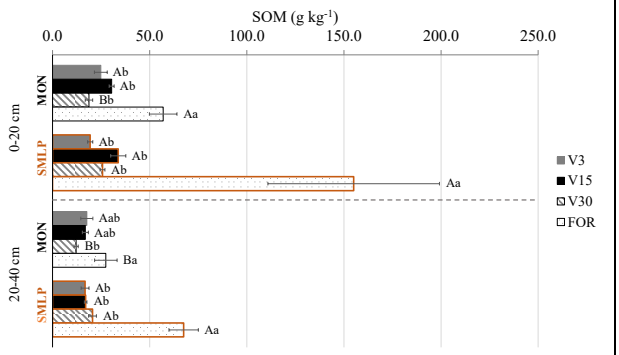
The bulk density (Table 17) in the SMLP pedosystem (range: 0.4 g cm^{-3} (FOR, A horizon) to 1.5 g cm^{-3} (V3 and V15, A horizon; V15, B horizon), with means of 1.2 ± 0.1 g cm^{-3} for the surface and 1.3 ± 0.0 g cm^{-3} for the deep horizon) was significantly higher than MON (range: 0.9 g cm^{-3} (V3 and FOR, A horizon) and 1.5 g cm^{-3} (V3, V15, and FOR, B horizon), with means of 1.1 ± 0.1 g cm^{-3} in the surface horizon and 1.4 ± 0.0 g cm^{-3} in the deep one) for almost all land covers (FOR apart) in the surface horizon. When comparing the different land covers, significant differences ($p < 0.05$) were observed in the SMLP pedosystem, with FOR land cover showing the lowest BD in both surface and deep horizons. The lower BD in FOR could be related to different factors, such as the higher SOM and less human influence compared to agricultural areas.

Soil chemical parameters

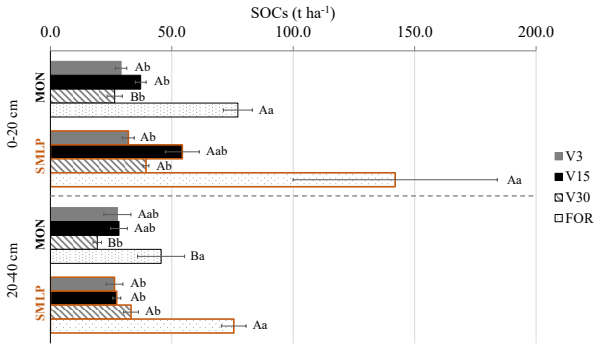
Fig. 16 shows the soil chemical parameters within the surface (A horizon, 0-20 cm) and deep (B, 20-40 cm) soil horizons, comparing two contrasting Mediterranean pedosystems (Monti-MON *vs* Santa Maria La Palma-SMLP) across common land covers (V3, V15, V30, and FOR). At MON, soils are developed on granitic rocks (*vide supra*) and, for this reason, display an acidic pH (Fig. 16a), ranging from very strongly acidic (4.5 at V15, A horizon) to neutral (6.8 at V3, B horizon), with mean values of 5.5 ± 0.2 for the surface horizon and 5.7 ± 0.2 for the deep. On the other hand, the SMLP, developed over limestone, exhibits a more alkaline/neutral pH, ranging from slightly acidic (6.3 at V15 and FOR, A horizon) to slightly alkaline (7.6 at V30 and FOR, B horizon), with mean values of 6.6 ± 0.1 for surface and 6.9 ± 0.2 for deep horizons. Due to these intrinsic differences related to the parent material, when comparing MON (on granite) *vs* SMLP (on limestone), results revealed significant differences ($p < 0.05$) in both surface and deep horizon for nearly all land covers (V3 apart), where SMLP > MON. Among the different land covers, some significant differences ($p < 0.05$) were observed in the deep horizon for the MON pedosystem, in which the FOR land cover displayed the most acid soil (5.3 ± 0.2), while V3 showed slightly acidic (6.3 ± 0.2). As discussed in the preceding subchapter, this difference between the two land covers seems to be linked to the youthfulness of V3 soil, which has been utilized as a vineyard for only three years before the field sampling activities (2021), characterizing soil undergoing a human-induced "entisolization" processes (Dazzi and Monteleone, 2007). These processes influence leaching, which is not still strongly expressed, leading to higher amounts of basic cations compared to the more developed FOR soils, where leaching activities are more enhanced.



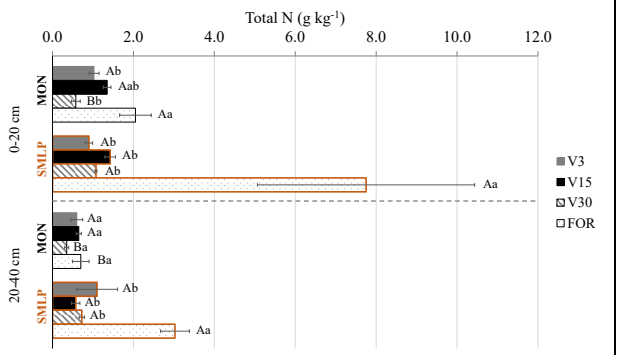
a b


SOM (g kg-1)
0.0
50.0
100.0
150.0
200.0
250.0
0-20 cm
20-40 cm
MON
SMLP
Ab
Aa
Aab
Bb
Ba
V3
V15
V30
FOR

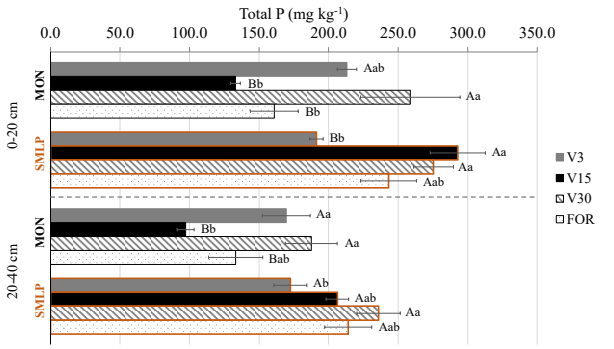
c


SOCs (t ha-1)
0.0
50.0
100.0
150.0
200.0
0-20 cm
20-40 cm
MON
SMLP
Ab
Aa
Aab
Bb
Ba
V3
V15
V30
FOR

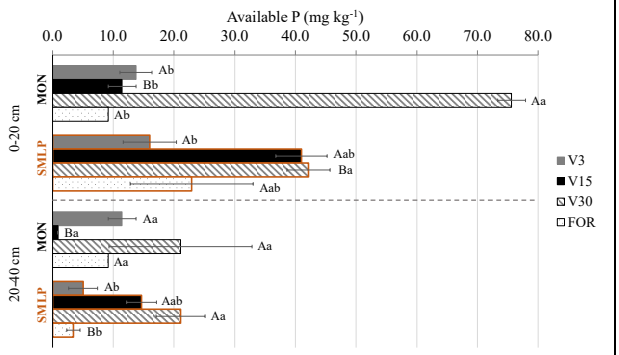
d


Total N (g kg-1)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
0-20 cm
20-40 cm
MON
SMLP
Ab
Aa
Aab
Bb
Ba
V3
V15
V30
FOR

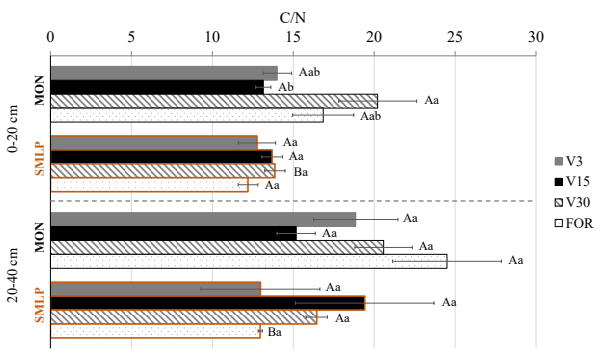
e


Total P (mg kg-1)
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
0-20 cm
20-40 cm
MON
SMLP
Ab
Aa
Aab
Bb
Bab
V3
V15
V30
FOR

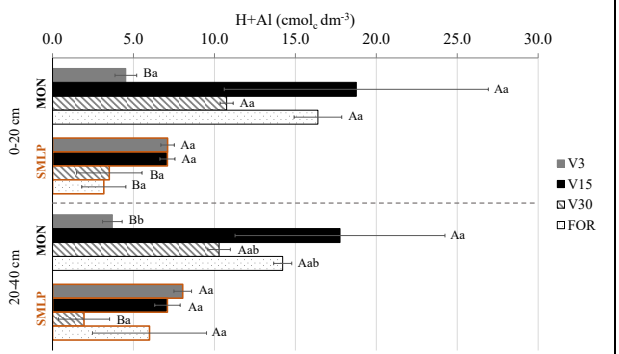
f


Available P (mg kg-1)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
0-20 cm
20-40 cm
MON
SMLP
Ab
Aa
Aab
Bb
Ba
V3
V15
V30
FOR

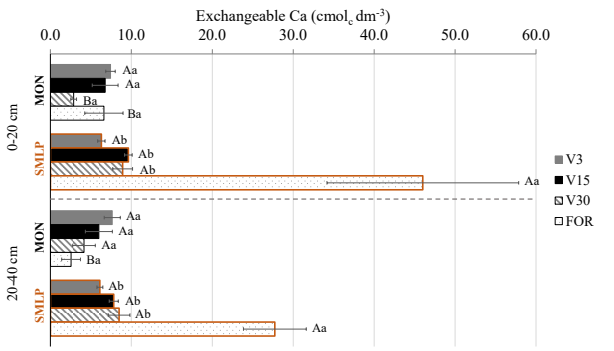
g


C/N
0
5
10
15
20
25
30
0-20 cm
20-40 cm
MON
SMLP
Ab
Aa
Aab
Ba
V3
V15
V30
FOR

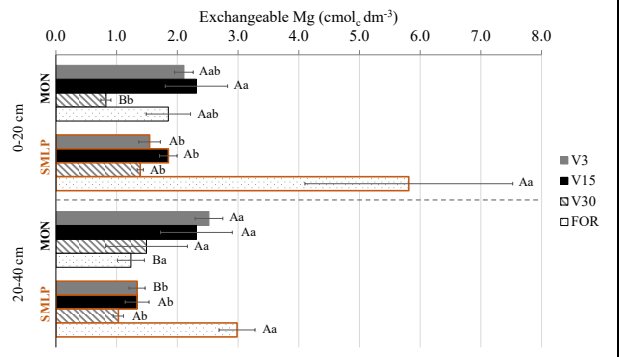
h


H+Al (cmolc dm-3)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
0-20 cm
20-40 cm
MON
SMLP
Ba
Aa
Bb
Aab
V3
V15
V30
FOR

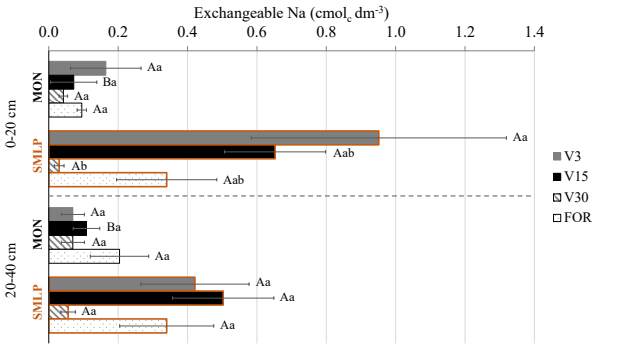
i


Exchangeable Ca (cmolc dm-3)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
0-20 cm
20-40 cm
MON
SMLP
Aa
Ba
Ab
V3
V15
V30
FOR

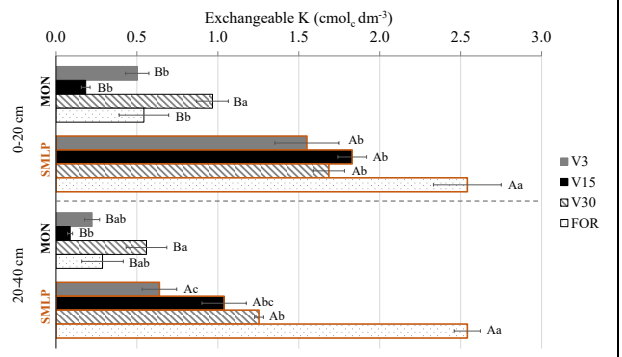
j


Exchangeable Mg (cmol$_c$ dm^{-3})
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0
0-20 cm
20-40 cm
MON
SMLP
Aab Aa Bb Aab
Ab Ab Ab Aa
Aa Aa Aa Ba
Bb Ab Ab Aa
V3
V15
V30
FOR

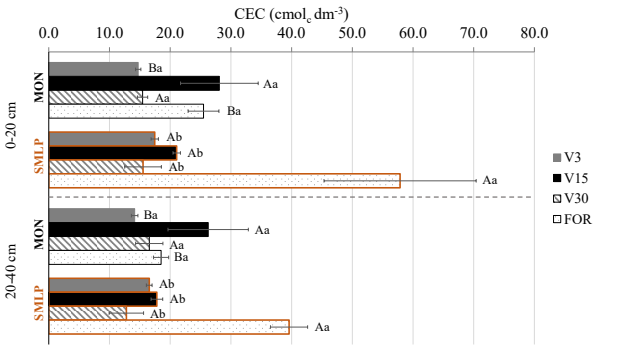
k


Exchangeable Na (cmol$_c$ dm^{-3})
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
0-20 cm
20-40 cm
MON
SMLP
Aa Ba Aa Aa
Aa Aab Ab Aab
Aa Ba Aa Aa
Aa Aa Aa Aa
V3
V15
V30
FOR

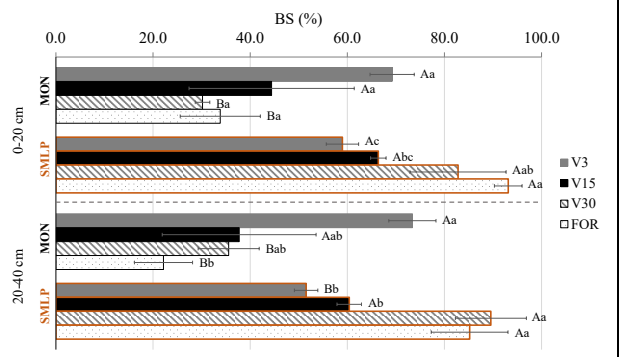
l


Exchangeable K (cmol$_c$ dm^{-3})
0.0 0.5 1.0 1.5 2.0 2.5 3.0
0-20 cm
20-40 cm
MON
SMLP
Bb Bb Ba Bb
Ab Ab Ab Aa
Bab Bb Ba Bab
Ac Abc Ab Aa
V3
V15
V30
FOR

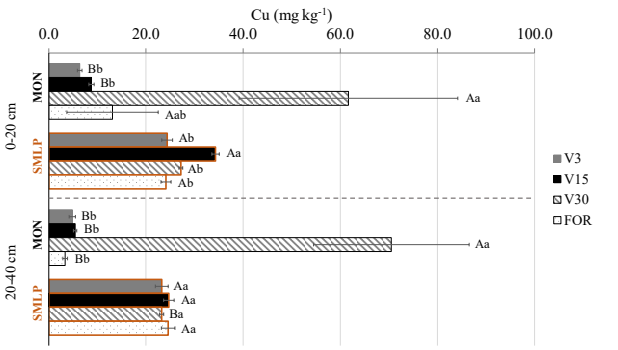
m


CEC (cmol$_c$ dm^{-3})
0.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0
0-20 cm
20-40 cm
MON
SMLP
Ba Aa Aa Ba
Ab Ab Ab Aa
Ba Aa Aa Ba
Ab Ab Ab Aa
V3
V15
V30
FOR

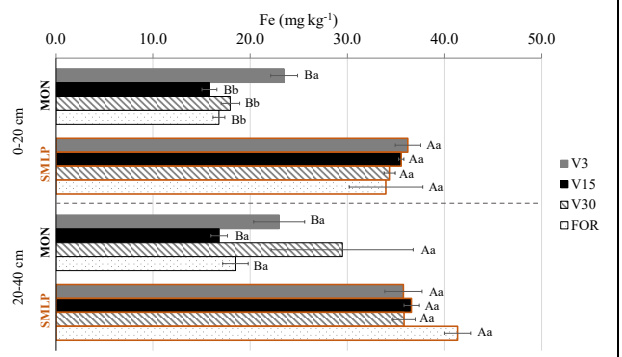
n


BS (%)
0.0 20.0 40.0 60.0 80.0 100.0
0-20 cm
20-40 cm
MON
SMLP
Aa Aa Ba Ba
Ac Abc Aab Aa
Aa Aab Bab Bb
Bb Ab Aa Aa
V3
V15
V30
FOR

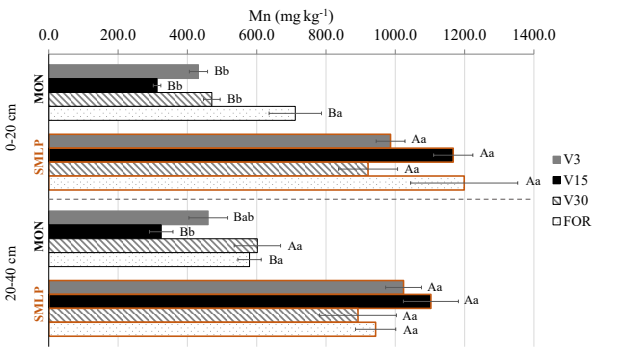
o


Cu (mg kg^{-1})
0.0 20.0 40.0 60.0 80.0 100.0
0-20 cm
20-40 cm
MON
SMLP
Bb Bb Aa Aab
Ab Aa Ab Ab
Bb Bb Aa Bb
Aa Aa Ba Aa
V3
V15
V30
FOR

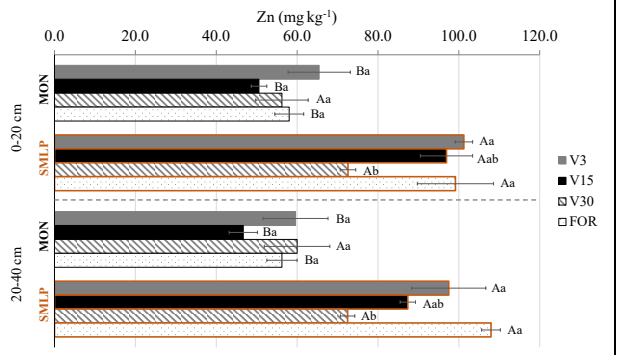
p


Fe (mg kg^{-1})
0.0 10.0 20.0 30.0 40.0 50.0
0-20 cm
20-40 cm
MON
SMLP
Ba Bb Bb Bb
Aa Aa Aa Aa
Ba Ba Aa Ba
Aa Aa Aa Aa
V3
V15
V30
FOR

q


Mn (mg kg^{-1})
0.0 200.0 400.0 600.0 800.0 1000.0 1200.0 1400.0
0-20 cm
20-40 cm
MON
SMLP
Bb Bb Bb Ba
Aa Aa Aa Aa
Bab Bb Aa Ba
Aa Aa Aa Aa
V3
V15
V30
FOR

r



S

Fig. 16. Soil chemical parameters along surface (0-20 cm) and deep (20-40 cm) soil horizon and different pedosystems (Monti (MON) and Santa Maria La Palma (SMLP)) for the common land covers: 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 forest; FOR-SMLP: holm oak (*Quercus ilex* L.) forest. Different capital letters showed significant differences ($p < 0.05$) among different pedosystems within same land cover and soil horizon, while different lowercase letters showed significant differences ($p < 0.05$) between different land covers within the same pedosystem and soil horizon.

Soil electrical conductivity (EC; Fig. 16b) at MON ranged from 0.02 dS m^{-1} (V30, B horizon) to 0.26 dS m^{-1} (FOR, A horizon), with means of 0.13 ± 0.02 dS m^{-1} in the surface and 0.05 ± 0.01 dS m^{-1} in the deep horizon. At SMLP, EC exhibited higher values, ranging from 0.03 dS m^{-1} (V3, B horizon) to 0.95 dS m^{-1} (FOR, A horizon), with means of 0.20 ± 0.06 dS m^{-1} in the surface horizon and 0.08 ± 0.02 dS m^{-1} in the deep one. When comparing MON *vs* SMLP in both surface and deep horizons, significant differences ($p < 0.05$) were observed in certain land covers. On the surface, differences were observed in V3 and V30, with MON > SMLP in V3, while the opposite was observed for V30, where SMLP > MON. On the deep horizon, it was observed differences in V3 and FOR, in which MON > SMLP in V3, while the contrary in FOR, with SMLP > MON. The unexpected higher EC in V3 at MON pedosystem (even though we are expecting lower EC due to its granite parent material) can be attributed to several factors, primarily human influence on the soil, resulting in the leaching of soluble cations as discussed earlier (*vide supra*). When comparing the different land covers, some significant differences ($p < 0.05$) were observed for both pedosystems in the deep horizon. At MON, the EC in the V3 land cover was significantly ($p < 0.05$) higher than V30, possibly due to the lower clay content and SOM amounts in the V30, leading to decreased EC (*vide supra*). At SMLP, the FOR land cover exhibited higher EC than other land uses, likely linked to the higher SOM (Fig. 16c) values in this land cover, contributing to elevated EC values.

Soil organic matter (SOM; Fig. 16c) showed concentrations ranging from 9.1 (V3, B horizon) to 75.6 g kg^{-1} (FOR, A horizon) at MON, with mean values of 32.7 ± 3.4 g kg^{-1} in the surface and of 18.5 ± 2.9 g kg^{-1} in the deep horizon. At SMLP, SOM generally showed higher concentrations, ranging from 13.5 g kg^{-1} (V3, B horizon) to 283.1 g kg^{-1} (FOR, A horizon), with means of 58.5 ± 12.7 g kg^{-1} in the surface horizon and 30.5 ± 3.1 g kg^{-1} in the deep one. When comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in the V30 for both horizons and in FOR in the deep horizon, with SMLP > MON. These results could be related to higher soil fertility in SMLP compared to MON, resulting in higher SOM contents. When comparing different land covers, the FOR presented significantly the highest ($p < 0.05$) SOM on the surface for both pedosystems. Additionally, in the deep horizon, FOR was significantly higher than V30 at MON and the highest at SMLP. Expectations leaned towards higher concentrations in the FOR land cover and lower in cultivated areas, primarily attributed to the OM inputs originating from vegetation within the FOR land cover, contrasted with the reduced OM and its rapid mineralization in the cultivated areas (Costantini and Dazzi, 2013).

Soil organic carbon stocks (SOCs; Fig. 16d) ranged from 13.0 (V3, B horizon) to 89.5 t ha^{-1} (FOR, A horizon) at MON, showing a mean in the surface horizon of 42.5 ± 3.4 t ha^{-1} and of 30.2 ± 5.1 t ha^{-1} in the deep one. The SMLP generally 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 deep horizon (40.6 ± 3.3 t ha^{-1}) than MON. As expected, SOCs showed a similar pattern of SOM, with amounts as SMLP > MON. Among the different land covers, the FOR displayed the highest stocks in MON-surface and higher than V3 and V30 in the SMLP-surface. Also, in the deep horizons, FOR was higher than V30 in the MON, and the highest at SMLP. The high SOCs recorded in the forests' land covers could be due to the less human influence, leading to higher litter accumulation and consequently, higher amounts of SOM (*vide supra*).

Total nitrogen (Total N; Fig. 16e) exhibited concentrations ranging from 0.2 (V3, B horizon) to 3.1 g kg^{-1} (FOR, A horizon) at MON, featuring mean values of 1.3 ± 0.2 g kg^{-1} in the surface and 0.6 ± 0.1 g kg^{-1} in the deep horizon. In comparison, SMLP exhibited a broader range, from 0.3 (V15, B horizon) to 15.6 g kg^{-1} (FOR, A horizon), with means exceeding 2 times higher for both surface (2.8 ± 0.7 g kg^{-1}) and deep horizon (1.4 ± 0.3 g kg^{-1}) than MON. Given the strict correlation between total N and OM (*vide supra*) (Brady and Weil, 2010), the comparison MON *vs* SMLP in both horizons for this parameter corresponded with the previous

one (SOM), i.e., V30 showed significantly higher ($p < 0.05$) concentrations in SMLP for both horizons, as well as in FOR in the deep horizon. Also, due to this correlation between total N, OM, and its primary source (SOM), when comparing the different land covers, the FOR land cover was significantly higher ($p < 0.05$) than agricultural areas (V15 apart) in the surface horizon at MON pedosystem. Additionally, it held the highest ($p < 0.05$) concentrations among all land covers for both horizons at SMLP.

Total phosphorus (Total P; Fig. 16f) ranged from 82.5 (V15, B horizon) to 360.0 mg kg^{-1} (V30, A horizon) at MON, with a mean of 191.5 ± 15.9 mg kg^{-1} and 146.8 ± 15.3 mg kg^{-1} in surface and deep horizon, respectively. At SMLP, values ranged from 150.0 (V3, B horizon) to 330.0 mg kg^{-1} (V15, A horizon), with means 1.3 times higher in the surface (250.7 ± 14.8 mg kg^{-1}) and 1.4 times higher in the deep horizon (207.2 ± 13.1 mg kg^{-1}) compared to MON. When comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in V15 and FOR for both surface and deep horizons, with SMLP > MON. Conversely, the V3 surface horizon showed significantly higher ($p < 0.05$) concentration in the MON instead of SMLP. These findings could be attributed to the fact that the SMLP presents an intrinsically higher soil fertility and due to agricultural management (in the case of the V3 in MON, with the use of fertilizers/amendments, leading to higher P content). 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 surface horizon compared to V15 and FOR. Also, V30 and V3 were significantly higher ($p < 0.05$) than V15 in the deep one. Similar outcomes were observed in SMLP, with V15 and V30 showing significantly higher ($p < 0.05$) total P than V3 in the surface, while showing V30 significantly higher than V3 in the deep horizon. Elevated P concentrations in agricultural areas, like vineyards, could be associated with the widespread use of P fertilizers/amendments, leading to an enrichment of P (Filipelli, 2008) (*vide supra*), particularly in those with advanced ages, such as V30.

Available P (Fig. 16g) at MON ranged from 0.9 (V15 and V30, B horizon) to 82.5 mg kg^{-1} (V30, A horizon), with means of 27.5 ± 1.8 mg kg^{-1} in the surface and 10.7 ± 3.5 mg kg^{-1} in the deep horizon. At SMLP, the concentrations ranged from 0.9 (V3, B horizon) to 51.3 mg kg^{-1} (V30, A horizon), with means of 30.5 ± 5.6 mg kg^{-1} in the surface and 11.1 ± 2.5 mg kg^{-1} in the deep horizon. When comparing MON *vs* SMLP, SMLP showed significantly ($p < 0.05$) higher available P than MON in the V15 for both horizons. On the other hand, MON was significantly higher than SMLP in the V30 surface and in the FOR deep horizon. Generally, soils on granite show a higher P availability than those on limestone (Camponi et al., 2023). However, in the current study, the opposite was observed for the V15, possibly attributed to the

management of the area with fertilizers and/or amendments. When comparing the different land covers, the V30 was significantly higher than the other land covers at MON surface; while at SMLP, it was significantly higher than V3 on the surface, and than V3 and FOR in the deep horizon. The primary origin of soil P is derived from the transformation of soil organic P, driven by processes such as SOM mineralization and decomposition (Liu et al., 2014), and the observed results are thus likely influenced by them.

The carbon-to-nitrogen ratio (C/N; Fig. 16h) at MON exhibited a range from 12 (V15, A horizon) to 35 (FOR, B horizon), with means of 16 ± 1 in the surface and 20 ± 2 in the deep horizon. The ratio at SMLP was similar, ranging from 5 (V3, B horizon) to 32 (V15, B horizon), with mean values of 13 ± 1 in the surface and 15 ± 2 in the deep horizon. When comparing MON *vs* SMLP, MON was significantly higher ($p < 0.05$) in the V30 surface and in the FOR deep horizon. Comparing the different land covers, at MON surface, the V30 was significantly higher ($p < 0.05$) than V15. As the C/N ratio represents the relationship between SOC and total N concentration (Costantini and Dazzi, 2013), the previous results are closely related to these two parameters.

Exchangeable acidity (H+Al; Fig. 16i) showed a range from 2.0 (V3, B horizon) to 34.9 $cmol_c\ dm^{-3}$ (V15, A horizon) at MON, with means of 12.6 ± 2.7 $cmol_c\ dm^{-3}$ in the surface and 11.5 ± 2.1 $cmol_c\ dm^{-3}$ in the deep horizon. In contrast, at SMLP, the H+Al values were generally lower, ranging from 0.0 (V30 and FOR, A and B horizons) to 16.1 $cmol_c\ dm^{-3}$ (FOR, B horizon), with mean approximately 2.4 times lower than those at MON in the surface (5.2 ± 1.1 $cmol_c\ dm^{-3}$) and about 2 times in the deep horizon (5.8 ± 1.6 $cmol_c\ dm^{-3}$). When comparing MON *vs* SMLP, different trends were observed. MON showed significantly higher ($p < 0.05$) H+Al than SMLP for V30 (both horizons) and in FOR (surface), as expected. However, it was observed an opposite for V3 (both horizons), in which SMLP > MON. These differences in SMLP could be related to agricultural management practices in the vineyard (V3), observing acid residuals derived from fertilizers. Comparing the different land covers, some significant differences ($p < 0.05$) were observed in the deep horizon at MON, with V15 showing higher H+Al than V3. The elevated H+Al in V15 can be attributed to the relatively lower pH in this land cover compared to the V3. Decreasing soil pH contributes to an increase of exchangeable Al, and given that Al typically coexists with hydroxyl groups, its solubility is directly linked to the concentrations of H^+ ions (Nair et al., 2019).

Exchangeable cations (Figs. 16j-m) at MON, ranged for Ca^{2+} from 0.4 (FOR, B horizon) to 11.9 $cmol_c\ dm^{-3}$ (FOR, A horizon), means of 5.9 ± 1.2 $cmol_c\ dm^{-3}$ for surface horizon and 5.1 ± 1.3 $cmol_c\ dm^{-3}$ for deep one; Mg^{2+}, from 0.6 (V30, A horizon; V15, V30 and FOR, B

horizon) to 3.5 $cmol_c\ dm^{-3}$ (V30, B horizon), means of 1.8 ± 0.3 $cmol_c\ dm^{-3}$ for surface and 1.9 ± 0.4 $cmol_c\ dm^{-3}$ for deep; Na^+ from 0.0 (V3, V15, V30, A horizon; V3 and V30, B horizon) to 0.4 $cmol_c\ dm^{-3}$ (V3, A horizon; FOR, B horizon), mean of 0.1 ± 0.0 $cmol_c\ dm^{-3}$ for both surface and deep; K^+ from 0.1 (V15, A horizon; V3, V15, and FOR, B horizon) to 1.2 $cmol_c\ dm^{-3}$ (V30, A horizon), means of 0.5 ± 0.1 $cmol_c\ dm^{-3}$ for surface and 0.3 ± 0.1 $cmol_c\ dm^{-3}$ for deep. At SMLP, the values were generally higher: for Ca^{2+}, it ranged from 5.4 (V3, A and B horizon) to 81.5 $cmol_c\ dm^{-3}$ (FOR, A horizon), with means of 17.7 ± 3.5 $cmol_c\ dm^{-3}$ for surface and 12.5 ± 1.5 $cmol_c\ dm^{-3}$ for deep horizon; for Mg^{2+}, ranged from 0.8 (V30, B horizon) to 10.9 $cmol_c\ dm^{-3}$ (FOR, A horizon), means of 2.6 ± 0.5 $cmol_c\ dm^{-3}$ in the surface and 1.7 ± 0.2 $cmol_c\ dm^{-3}$ in the deep; for Na^+, from 0.0 (V30, A and B horizon) to 2.0 $cmol_c\ dm^{-3}$ (V3, A horizon), means of 0.5 ± 0.2 $cmol_c\ dm^{-3}$ in the surface and 0.3 ± 0.1 $cmol_c\ dm^{-3}$ in the deep; and for K^+, from 0.4 (V3, B horizon) to 3.1 $cmol_c\ dm^{-3}$ (FOR, A horizon), means of 1.9 ± 0.1 $cmol_c\ dm^{-3}$ in the surface and 1.4 ± 0.1 $cmol_c\ dm^{-3}$ in the deep. Comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in some of the land covers for all exchangeable cations, in which SMLP > MON, except for V3-deep for the exchangeable Mg, which showed an opposite trend (MON > SMLP). The higher exchangeable cations at SMLP were expected since Luvisols on limestone present an intrinsically higher soil fertility (Costantini and Dazzi, 2013), consequently showing higher exchangeable cations compared to soils on granite. Some significant differences ($p < 0.05$) were observed when comparing the different land covers along the surface horizon. At MON-surface, the differences were observed only for exchangeable Mg and K, with V15 showing a higher concentration than V30 for Mg, while V30 showed the highest concentration for K. At SMLP-surface, 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 deep horizons, also some significant differences ($p < 0.05$) were observed. At MON-deep, differences were observed just for the K, with V30 higher than V15. At SMLP-deep, the differences were observed for almost all exchangeable cations (except for Na), with FOR exhibiting the highest concentrations. The higher concentrations observed in the vineyards at MON may be attributed to the influence of vineyard management practices, notably the application of fertilizers/amendments, especially in light of the low soil fertility in this soil. Conversely, the higher concentrations observed in the FOR land cover at SMLP may be attributed to the inherently greater soil fertility, partly derived from the parent material, along with the influence of OM inputs, contributing to an overall enhancement of soil fertility.

Cation exchange capacity (CEC; Fig. 16n) at MON ranged from 12.0 (V30, B horizon) to 40.0 $cmol_c\ dm^{-3}$ (V15, A horizon), with means of 20.9 ± 2.6 $cmol_c\ dm^{-3}$ and 18.9 ± 2.7 $cmol_c\ dm^{-3}$ in the surface and deep horizons, respectively. At SMLP, the ranges were broader, from 9.4 (V30, B horizon) to 95.3 $cmol_c\ dm^{-3}$ (FOR, A horizon), with means of 28.0 ± 4.2 $cmol_c\ dm^{-3}$ in the surface and 21.7 ± 1.8 $cmol_c\ dm^{-3}$ in the deep horizon. Comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in the V3 and FOR for both surface and deep horizons, in which SMLP > MON. These results could be related to the pH, SOM, and clay content in SMLP soils, exerting influence on the observed CEC values (Manrique et al., 1991). When comparing the different land covers within pedosystems and soil horizons, significant differences ($p < 0.05$) were observed in SMLP, with FOR > V3 = V15 = V30 in both horizons. The results are related to the previously mentioned soil parameters, and they play a significant role in influencing CEC values.

Base saturation (BS; Fig. 16o) at MON ranged from 9 (V15, A horizon; FOR, B horizon) to 87% (V3, B horizon), with means of 44 ± 8% in the surface and 42 ± 8% in the deep horizon. At SMLP, the values ranged from 46% (V3, B horizon) to 100% (V30 and FOR, A and B horizon), with means 1.7 times higher in the surface (75 ± 4%) and in the deep (72 ± 5%) horizon compared to MON. When comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed in V30 and FOR for both horizons, with SMLP > MON. Additionally, differences were also observed in the deep horizon of V3, but inversely, with MON > SMLP. Furthermore, significant differences ($p < 0.05$) were observed among the different land covers in the deep horizon for MON and in both horizons for SMLP. In the case of deep-MON, V3 > FOR; while in the surface-SMLP, FOR > V15 = V3, and in the deep-SMLP, V30 = FOR > V3 = V15. The various results are linked to soil pH, where elevated pH aligns with increased concentrations of certain or all exchangeable cations, consequently affecting BS (Yost & Hartemink, 2019).

Copper (Cu; Fig. 16p) at MON ranged from 2.3 (FOR, B horizon) to 99.0 mg kg^{-1} (V30, A horizon), with a mean of 22.5 ± 8.2 mg kg^{-1} in the surface and 21.0 ± 4.4 mg kg^{-1} in the deep horizon. At SMLP, it ranged from 21.0 (V3, B horizon) to 36.0 mg kg^{-1} (V15, A horizon), with means of 27.5 ± 0.8 mg kg^{-1} in the surface and 23.9 ± 1.1 mg kg^{-1} in the deep horizon. Comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed for V3 and V15 for both surface and deep horizons and in the FOR-deep horizon, in which SMLP > MON. Also, it was observed the contrary in the V30-deep horizon, i.e., MON > SMLP. The higher clay content in SMLP probably influenced the higher Cu concentration, since this fraction contributes significantly to Cu in soils (Kabata-Pendias and Pendias, 2001). When

comparing the different land covers within pedosystem and soil horizon, some significant differences ($p < 0.05$) were observed for both the surface and deep horizon at MON, and in the surface at SMLP. At MON, it was observed that V30 > V3 = V15 = FOR, while at SMLP V15 > V3 = V15 = FOR. The higher Cu concentrations in the vineyards are related to the application of copper-based fungicides to protect the vine against fungal diseases, resulting in the accumulation of Cu (Brunetto et al., 2016; Pietrzak and McPhail, 2004).

Iron (Fe; Fig. 16q) at MON ranged from 14.7 (V15, A horizon) to 51.3 mg kg^{-1} (V30, B horizon), with a mean of 18.5 ± 0.9 mg kg^{-1} in the surface and 21.9 ± 3.0 mg kg^{-1} in the deep horizon. At SMLP, it ranged from 23.3 (FOR, A horizon) to 43.4 mg kg^{-1} (FOR, B horizon), with a mean of 35.0 ± 1.5 mg kg^{-1} in the surface and 37.4 ± 1.3 mg kg^{-1} in the deep horizon. Comparing MON *vs* SMLP for both surface and deep horizon, significant differences ($p < 0.05$) were observed for almost all land covers (V30-deep horizon apart), in which SMLP > MON. When comparing the different land covers within pedosystem and soil horizon, it was observed significant differences ($p < 0.05$) just in the MON-surface, in which V3 > V15 = V30 = FOR. The results are related to the presence of a substantially high percentage of iron oxides in Luvisols on limestone, which are closely associated with clay minerals (Costantini and Dazzi, 2013).

Manganese (Mn; Fig. 16r) at MON showed contents ranging from 262.5 (V15, B horizon) to 880.6 mg kg^{-1} (FOR, A horizon), with a mean of 481.7 ± 34.2 mg kg^{-1} in the surface and 491.5 ± 47.6 mg kg^{-1} in the deep horizon. At SMLP, it ranged from 605.9 (V30, B horizon) to 1611.9 mg kg^{-1} (FOR, A horizon), with a mean of 1068.4 ± 84.5 mg kg^{-1} in the surface and 990.5 ± 75.0 mg kg^{-1} in the deep horizon. Comparing MON *vs* SMLP for both surface and deep horizon, significant differences ($p < 0.05$) were observed for almost all land covers (V30-deep horizon apart), in which SMLP > MON. Generally, the Mn concentration is related to clay content (Kabata-Pendias and Pendias, 2001), so for this reason, the higher concentration in the SMLP seems to be related to this. When comparing the different land covers within pedosystem and soil horizon, it was observed significant differences ($p < 0.05$) at MON in both soil horizons, in which FOR > V3 = V15 = V30 in the surface and V30 = FOR > V15. In these cases, the higher values seem to be related to the richness of SOM instead of clay content, once it is noticed that SOM can influence Mn contents (Kabata-Pendias and Pendias, 2001).

Zinc (Zn; Fig. 16s) at MON ranged from 37.3 (V3, B horizon) to 82.5 mg kg^{-1} (V30, B horizon), with means of 57.6 ± 4.9 mg kg^{-1} in the surface and 55.6 ± 5.8 mg kg^{-1} in the deep horizon. At SMLP, Zn ranged from 66.8 (V30, A horizon) to 120.0 mg kg^{-1} (FOR, A horizon; V3, B horizon), with a mean of 92.5 ± 5.0 mg kg^{-1} in the surface and 91.3 ± 3.8 mg

kg^{-1} in the deep horizon. Comparing MON *vs* SMLP, significant differences ($p < 0.05$) were observed for both surface and deep horizon in almost all land covers (except for V30), in which SMLP > MON. Among the different land covers, significant differences ($p < 0.05$) were observed in SMLP for both horizons, in which V3 = FOR > V30. The higher Zn concentrations at SMLP could be attributed to the influence of soluble Zn-organic complexes and complex anionic forms of Zn. These factors could contribute to the increased solubility and availability of Zn in soils characterized by a high pH range (Kabata-Pendias & Pendias, 2001).

3.3.4 MULTIVARIATE STATISTICS

Principal Factor Analysis (PFA)

PFA – Surface and deep soil horizons

As previously explained, by using a step-by-step approach, this is the last step in outcome discussion, i.e., the comparison between MON pedosystem *vs* SMLP one. For a statistically reliable comparison, as explained before (*vide supra*), only comparable land uses were taken into account; in particular, for both pedosystem, PFA was elaborated by only considering V3, V15, V30, and FOR, for the soil physical-chemical parameters.

For both investigated pedosystems, the eigenvalues, after the matrix rotation, were greater than 1, demonstrating again the high model statistical reliability. The PFA for MON and SMLP (Table 18) extracted a six- and five-component model, respectively. The MON-PFA accounts for an overall 84%, while 82% for SMLP. For the MON pedosystem, factor 1 (F1, 22%), reveals a positive correlation among pH, EC, exchangeable cations (Ca and Mg) and BS, while they were inversely related with BD and C/N. F1 confirms the key role played by the sandy acidic soil nature of the investigated pedosystem, where a decrease in pH (due to leaching processes commonly featuring sandy soils) brings to a generalized decrease in soil fertility. In the SMLP pedosystem, the situation completely differs, thus clearly showing how the different natures of soils can play a fundamental role from different points of view. Indeed, F1 (36%) extracted SOCs, total N, EC, all exchangeable cations, CEC, BS, and Mn, as all positively concordant, while negatively correlated with BD. This factor confirms what previously observed for SMLP in PFAs elaborated by taking into account (a) all land uses and horizons (Table 12) as well as (b) only surface (A) horizon together with litter and vegetation

(Table 13); in particular, the key role played by SOCs in improving general soil conditions. From this point of view, the F1 strongly differentiates the two pedosystems by showing completely different behaviors. As a matter of 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."* F2 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 concordant, while a negative correlation with clay, exchangeable K, Fe, and Zn was observed. Factor 2 for MON pedosystem has been already explained (please note Section 3.1.4; Table 7) as "*the influence of cation competition for exchangeable sites in influencing P behavior*"; and also, the same for SMLP (note Section 3.2.4; Table 12), that it can be named as *"the importance of the mineral colloidal fraction (clay) in cations exchangeable processes."* It is interesting to note that the second factor for both pedosystems clearly underlines the influence of soil physical feature (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 characterizes the MON site, while "clayey" Luvisols the SMLP one), it is interesting stressing that (a) the PFA clearly separates the two pedosystems also in terms of variability and that (b) their intrinsic genetic and physical-chemical nature has a great influence on the entire system variability, thus (c) soil nature determines differences in pedosystem behavior. F3 for MON (16%), extracted SOCs, total N, EC, and Mn as all positively correlated. In SMLP, F3 (11%), withdraws a humanly-induced geochemical correlation, with total and available P positively correlated with Cu. This is a well-known correlation due to the use of P fertilizers; indeed, P chemical fertilizers contain Cu as impurities (Kabata-Pendias & Pendias, 2001). Thus, comparing F3 in MON *vs* SMLP, we can name the first as (please note Section 3.1.4; Table 7) *"the role of SOCs in influencing some soil fertility-related parameters"*, while the second as "*the influence of human activities on investigated pedosystem*." Notably, the SOCs role in the MON pedosystem was highlighted just in the F3, thus assuming an extremely less important role inside the explained variability for the pedosystem itself and when compared with SMLP. All the other extracted factors are of minor statistical importance, merely showing already explained (*vide supra*) chemical and geochemical processes.

In general, the PFA unveiled several noteworthy findings. Both pedosystems exhibited a great influence of their parent material on the physical-chemical parameters, with a notable decrease in magnitude in the factor loadings, particularly in F1, when comparing SMLP to MON. In the 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 the SMLP (extracted at the F1 with a factor loading equal to 0.922) compared to MON (extracted at the F3 with a factor loading equal to 0.908), highlighting the importance of the SMLP pedosystem in terms of SOC and soil fertility.

Table 18

Factor loadings of a factor analysis (n = 32) for the MON and SMLP pedosystems considering surface and deep soil horizons; 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
Proportional variance (%)	22	19	16	12	9	6	36	19	11	10	6
Cumulative variance (%)	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

4 CONCLUSION

Over the last few years, studies on soil organic carbon stocks (SOCs) tremendously increased all over the world by investigating different ecosystems. Such studies are pivotal, for example (but not limited to), for the whole understanding of the complex role played by the pedosphere in climate change processes. The Mediterranean basin represents an important area hosting under-threat ecosystems. In managing such ecosystems, investigating involved pedosystems represents a fundamental step, since soil plays a pivotal role. However, most of the studies conducted in this context have been focused on SOCs quantification, modelization, or comparison among different land uses. Conversely, there is a lack of studies focusing on the understanding of how soil behavior, with particular reference to its genesis, development, classification, and soil physical-chemical features, can influence SOCs behavior and dynamics. This study, specifically, investigated contrasting Mediterranean pedosystems, in the Sardinia island (Italy). Cambisols on granite, i.e., the most common pedosystem featuring the Sardinian pedo-landscape was compared with one of the rarest: Luvisols on limestone.

Different land covers were compared, with a gradient varying from agricultural to more natural areas. Results revealed a substantial impact of human activities (predominantly in vineyards) in influencing soil behavior and, consequently, SOCs differences in terms of amounts and behavior. In the natural forests and close-to-natural ones (agroforestry) land covers exhibit noteworthy differences in SOCs compared to the more intensified and human-influenced land cover (vineyards), where SOCs are notably reduced or negligible.

The pedosystem developed on limestone (SMLP) exhibited higher SOCs, however showing a more pronounced impact of human activities on soil behavior when compared to the MON pedosystem. These differences arose from variations in substrate and subsequent soil formation processes between them, thus being intimately related to the soil's nature. In SMLP, it was underlined the pivotal role of the mineral colloidal fraction (clay) in facilitating cation-exchange processes and influencing the soil matrix, but also in showing less resilience when the influence of human activities, by the use of heavy machinery, are taken into account. Consequently, these factors appear to play a crucial role in the efficient sequestration and stabilization of SOC in this particular pedosystem.

These findings emphasized how SOCs are intimately linked to the soil's nature, highlighting their greater relevance compared to land cover. This specific aspect clearly demonstrates that SOCs studies, if not compared and related to the nature of the soil, may lead

to inaccurate or, even worse, wrong considerations. As a matter of fact, in this kind of research activities, merely quantitative, comparative, or modelization analysis are not enough to understand how carbon stock dynamics. Indeed, as we demonstrated, soil features strongly influence SOCs processes, behavior, and related complex mechanisms.

In conclusion, this study has provided valuable insights into the intricate behavior/relationships inside and between contrasting Mediterranean pedosystems. Further research and ongoing monitoring efforts are essential to improve our understanding of the complex vegetation-litter-soil relationships, thus in order to apply effective strategies for maintaining and enhancing SOCs in a different array of ecosystems.

ACKNOWLEDGEMENT

Embarking on a Ph.D. journey is not an easy thing. Working with research is often marked by challenges, uncertainties, setbacks, and intellectual puzzles. The difficulties in Ph.D. life encompass a myriad of aspects, including defining experimental design, conducting field sampling activities, working in a laboratory, reading research articles for hours, data analysis, writing a thesis, and many others. Sometimes these aspects are challenging, sometimes not, especially due to the remarkable people that you find in the middle of this path and help you in transforming this challenging journey into also funny, joyful, and beautiful phase of your life. So, now, here is my acknowledgment to all of those who contributed and were present in my life during this journey.

First, to God, for the gift of life, for always guiding my steps, and for showing me the right path. I am truly thankful for the guidance, protection, and the countless blessings that shape my journey.

To my dear parents (José and Marineide) and brothers (Nayara and Nicholas) for all the love, encouragement, trust, and support. You are everything in my life. Thank you for the wonderful family we have! If I arrived and reached this academic level, it is owed to you, for always telling me to pursue this path, even when I had doubts. You are always with me, in my heart.

To my dear family, for always being with me, even when I am far away.

To Francesco Floris, for supporting me and sharing life with me during the years of the PhD. You were the person who stayed by my side every time I needed, supporting me in the phases of sadness and homesickness.

To Prof. Gian Franco Capra, my supervisor, my sincere gratitude for the invaluable guidance and unwavering support throughout my academic journey. I am truly fortunate to have had the opportunity to learn under your mentorship and to have you so near to me. Prof. Capra, you have been a source of inspiration, and I am deeply appreciative of your contributions to my personal and academic development. I am very proud to say that you were my professor and my mentor on this journey and, beyond all that, my friend. Thank you for all that you did and do for me!

To Prof. Iraê Amaral Guerrini, my co-supervisor, for the guidance, patience, competence, professionalism, example of human being. Thank you for believing in me and for

all the words of encouragement. I am also very proud to say that you were my professor in both this journey and previous ones, and I am grateful for the friendship that has blossomed from our academic connection. Thank you for all that you did and do for me!

To Prof. Antonio Ganga, for the guidance and availability, for the helping in the field activities, and for always answering my requests for help. I am grateful not only for this, but also for all the informal conversations we have had, delving into a wide range of topics. Also, I really thank you for all the graphics and figures that you helped me to do and/or did to me. My debt with you is already substantial, but once again: *Metti nel conto*! Thank you Anto, for everything.

To the University of Sassari, especially the Department of Architecture, Design and Urban Planning, for being present in my personal and professional training during this journey.

To my postgraduate colleagues, for supporting me during the courses, seminars, lessons, events, research project activities, etc. In particular, to the colleagues who worked in our research group during my journey, and that now are my close friends, including Ilenia Murgia, Rafael Barroca, Enzo Paganini, and Sérvio Justino. Thank you, guys, for the friendship, for the supportive words, for listening my doubts and helping me to clarify them, and for sharing the beauty of life with me. To my other colleagues and professors from the Architecture and Environment School, for all the time that we spent together talking about research, life, events, and much more.

To Maria Chiara Ruggiu, Angelo Manca, and Nicoletta Melis, for helping us to find the study areas. You are amazing and I am grateful for your availability, for managing talking with the landowners, and for having their permission to sample in their areas.

To Marco Marrosu, from AGRIS, for managing the permission to sample in their area.

To the landowners of the study areas.

To Roberto Mattu, Gian Franca, Elisa Marras, Ilaria Incollu, and Mara Mameli, for helping in the field sampling activities and for the hard work in collecting the samples. Thank you very much!

To Prof. Emmanuele Farris and researcher Alfredo Maccioni, for conducting the vascular plants investigation and for your availability in helping us with this. Thank you very much!

To Mario Deroma and Linda Canu, from the Laboratory of Pedology of the University of Sassari, for supporting me during the laboratory activities, for having the patient

to teach me all the methodology for the analysis, for always being available. Thank you, Mario and Linda.

To all the colleagues that I had during my traineeship at the Swedish University of Agricultural Sciences (SLU). In particular, to the post-doc Lorena Chagas Torres and Prof. Thomas Keller, for having me in their research group, and for including me in all the activities carried out by them during the period I was there. I am really thankful.

To all the colleagues that I also had during my traineeship at the São Paulo State University. In particular, to my co-supervisor, for following me also during this important step.

To my Brazilian friends (better saying: family) in Sardinia: Neto, Jaque and Rodolfo, Marga and Salvatore, Roberta, Silvia and Antonello, Neia and family, Sol, Nina and family, Iara and Francesco, Padre Valdomiro. Guys, you made this journey less difficult, by being by my side when I needed it and when I did not. Thank you for everything. You are in my heart!

To the "*Banda Musicale Antonio Dalerci*" from Alghero and all its components. Thank you for all the moments that I had while playing with you in both rehearsal and presentations, for welcoming me so well in the band, and for sharing with me amazing moments of the Sardinian culture.

To all those who contributed, directly or indirectly, to this thesis.

To all those that I missed mentioning.

With deepest love and gratitude,

Ludmila

REFERENCES

Agenzia Regionale per la Protezione dell'Ambiente della Sardegna ARPAS. (2020). Relazione Tecnica: Climatologia della Sardegna per il trentennio 1981-2010.

Aru, A., Baldaccini, P., Delogu, G., Dessena, M. A., Madrau, S., Melis, R. T., ... & Vacca, S. (1990). *Carta dei suoli della Sardegna, in scala 1: 250.000*. Assessorato alla programmazione e all'assestamento del territorio, Centro Regionale Programmazione, Dip. Sc. della Terra, Universita di Cagliari, Italy.

Aru, A., Baldaccini, P., Vacca, A., Delogu, G., Dessena, M.A., Madrau, S., Melis, R.T. &Vacca, S. (1991). *Nota illustrativa alla carta dei suoli della Sardegna*. Dip. Sc. Terra Univ. di Cagliari, Ass. Reg. Progr. Bil. ed Asset. Terr., Cagliari.

Berg, B., & McClaugherty, C. (2008). Plant litter: decomposition, humus formation, carbon sequestration (second ed.). Berlin: Springer.

Brady, N. C., & Weil, R. R. (2010). *Elements of the nature and properties of soils*. Pearson Prentice Hall.

Braun-Blanquet J. (1928). Pflanzensoziologie, 1° ed. Berlin.

Barsotti, J. L., Sainju, U. M., Lenssen, A. W., Montagne, C., & Hatfield, P. G. (2013). Crop yields and soil organic matter responses to sheep grazing in US northern Great Plains. *Soil and Tillage Research*, *134*, 133–141. https://doi.org/10.1016/j.still.2013.07.015

Brunetto, G., Bastos De Melo, G. W., Terzano, R., Del Buono, D., Astolfi, S., Tomasi, N., Pii, Y., Mimmo, T., & Cesco, S. (2016). Copper accumulation in vineyard soils: Rhizosphere processes and agronomic practices to limit its toxicity. *Chemosphere*, *162*, 293–307. https://doi.org/10.1016/j.chemosphere.2016.07.104

Caloiero, T., & Guagliardi, I. (2021). Climate change assessment: Seasonal and annual temperature analysis trends in the Sardinia region (Italy). *Arabian Journal of Geosciences*, *14*(20), 2149. https://doi.org/10.1007/s12517-021-08527-9

Camponi, L., Cardelli, V., Cocco, S., Serrani, D., Salvucci, A., Cutini, A., Agnelli, A., Fabbio, G., Bertini, G., Roggero, P. P., Weindorf, D. C., & Corti, G. (2023). Holm oak (Quercus ilex L.) cover: A key soil-forming force in controlling C and nutrient stocks in long-time coppice-managed forests. *Journal of Environmental Management*, *330*, 117181. https://doi.org/10.1016/j.jenvman.2022.117181

Cappai, C., Kemanian, A. R., Lagomarsino, A., Roggero, P. P., Lai, R., Agnelli, A. E., & Seddaiu, G. (2017). Small-scale spatial variation of soil organic matter pools generated by cork oak trees in Mediterranean agro-silvo-pastoral systems. *Geoderma*, *304*, 59–67. https://doi.org/10.1016/j.geoderma.2016.07.021

Capra, G. F., Coppola, E., Odierna, P., Grilli, E., Vacca, S., & Buondonno, A. (2014). Occurrence and distribution of key potentially toxic elements (PTEs) in agricultural soils: A paradigmatic case study in an area affected by illegal landfills. *Journal of Geochemical Exploration*, *145*, 169–180. https://doi.org/10.1016/j.gexplo.2014.06.007

Capra, G. F., Tidu, S., Lovreglio, R., Certini, G., Salis, M., Bacciu, V., Ganga, A., & Filzmoser, P. (2018). The impact of wildland fires on calcareous Mediterranean pedosystems (Sardinia, Italy) – An integrated multiple approach. *Science of The Total Environment*, *624*, 1152–1162. https://doi.org/10.1016/j.scitotenv.2017.12.099

Capra, G. F., Vacca, S., Cabula, E., Grilli, E., & Buondonno, A. (2012). Human-Altered and Human-Transported Soils in an Italian Industrial District. *Soil Science Society of America Journal*, 76(5), 1828-1841.

Cerdà, A., Lavee, H., Romero-Diaz, A., Hooke, J., & Montanarella, L. (2010). Soil Erosion and Degradation in Mediterranean-Type Ecosystems. *Land Degrad. Develop*. 21, 71-74.

Chowdhury, S., Bolan, N., Farrell, M., Sarkar, B., Sarker, J. R., Kirkham, M. B., Hossain, M. Z., & Kim, G.-H. (2021). Role of cultural and nutrient management practices in carbon

sequestration in agricultural soil. In *Advances in Agronomy* (Vol. 166, pp. 131–196). Elsevier. https://doi.org/10.1016/bs.agron.2020.10.001

Coppola, E., Capra, G. F., Odierna, P., Vacca, S., & Buondonno, A. (2010). Lead distribution as related to pedological features of soils in the Volturno River low Basin (Campania, Italy). *Geoderma*, 159(3-4), 342-349. https://doi.org/10.1016/j.geoderma.2010.08.010

Corwin, D. L., & Lesch, S. M. (2005). Apparent soil electrical conductivity measurements in agriculture. *Computers and Electronics in Agriculture*, *46*(1–3), 11–43. https://doi.org/10.1016/j.compag.2004.10.005

Costantini, E. A. C., & Dazzi, C. (Eds.). (2013). *The Soils of Italy*. Springer Netherlands. https://doi.org/10.1007/978-94-007-5642-7

Cuttelod, A., García, N., Malak, D. A., Temple, H. J., & Katariya, V. (2009). The Mediterranean: a biodiversity hotspot under threat. *Wildlife in a Changing World–an analysis of the 2008 IUCN Red List of Threatened Species*, *89*(9).

Dazzi, C. (2021). *Fondamenti di Pedologia* (3 edition). Le Penseur.

Dazzi, C., & Monteleone, S. (2007). Anthropogenic processes in the evolution of a soil chronosequence on marly-limestone substrata in an Italian Mediterranean environment. *Geoderma*, *141*(3–4), 201–209. https://doi.org/10.1016/j.geoderma.2007.05.016

Díaz-Villa, M. D., Marañón, T., Arroyo, J., & Garrido, B. (2003). Soil seed bank and floristic diversity in a forest-grassland mosaic in southern Spain. *Journal of Vegetation Science*, 14(5), 701-709.

Facelli, J. M., & Pickett, S. T. A. (1991). Plant litter: Its dynamics and effects on plant community structure. *The Botanical Review*, *57*(1), 1–32. https://doi.org/10.1007/BF02858763

Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and

consequences. *Science of The Total Environment*, *805*, 150106. https://doi.org/10.1016/j.scitotenv.2021.150106

Filippelli, G.M. (2008). The global phosphorus cycle: past, present, and future. *Elements* 4, 89–95.

Filzmoser, P., Hron, K., & Reimann, C. (2009). Univariate statistical analysis of environmental (compositional) data: Problems and possibilities. *Science of The Total Environment*, *407*(23), 6100–6108. https://doi.org/10.1016/j.scitotenv.2009.08.008

Francaviglia, R., Benedetti, A., Doro, L., Madrau, S., & Ledda, L. (2014). Influence of land use on soil quality and stratification ratios under agro-silvo-pastoral Mediterranean management systems. *Agriculture, Ecosystems & Environment*, *183*, 86–92. https://doi.org/10.1016/j.agee.2013.10.026

Francaviglia, R., Renzi, G., Ledda, L., & Benedetti, A. (2017). Organic carbon pools and soil biological fertility are affected by land use intensity in Mediterranean ecosystems of Sardinia, Italy. *Science of The Total Environment*, *599–600*, 789–796. https://doi.org/10.1016/j.scitotenv.2017.05.021

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Bates, N. R., Becker, M., Bellouin, N., … Zeng, J. (2022). Global Carbon Budget 2021. *Earth System Science Data*, *14*(4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022

Hong, S., Gan, P., & Chen, A. (2019). Environmental controls on soil pH in planted forest and its response to nitrogen deposition. *Environmental Research*, *172*, 159–165. https://doi.org/10.1016/j.envres.2019.02.020

Intergovernmental Panel on Climate Change (Ipcc). (2022). *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in*

Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157940

Intergovernmental Panel On Climate Change (Ipcc). (2023). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844

IUSS Working Group WRB. (2022). World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Kabata-Pendias, A., & Pendias, H. (2001). *Trace elements in soils and plants* (3rd ed). CRC Press.

Keller, T., & Håkansson, I. (2010). Estimation of reference bulk density from soil particle size distribution and soil organic matter content. *Geoderma*, *154*(3–4), 398–406. https://doi.org/10.1016/j.geoderma.2009.11.013

Köberl, J., Prettenthaler, F., & Bird, D. N. (2016). Modelling climate change impacts on tourism demand: A comparative study from Sardinia (Italy) and Cap Bon (Tunisia). *Science of The Total Environment*, *543*, 1039–1053. https://doi.org/10.1016/j.scitotenv.2015.03.099

Köppen, W. (1936). *Das geographische System der Klimate (1936)*.

Krishna, M. P., & Mohan, M. (2017). Litter decomposition in forest ecosystems: A review. *Energy, Ecology and Environment*, *2*(4), 236–249. https://doi.org/10.1007/s40974-017-0064-9

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, *304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 815–830. https://doi.org/10.1098/rstb.2007.2185

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, *15*, 79–86. https://doi.org/10.1016/j.cosust.2015.09.002

Liu, X., Meng, W., Liang, G., Li, K., Xu, W., Huang, L., & Yan, J. (2014). Available Phosphorus in Forest Soil Increases with Soil Nitrogen but Not Total Phosphorus: Evidence from Subtropical Forests and a Pot Experiment. *PLoS ONE*, *9*(2), e88070. https://doi.org/10.1371/journal.pone.0088070

Lozano-García, B., Francaviglia, R., Renzi, G., Doro, L., Ledda, L., Benítez, C., González-Rosado, M., & Parras-Alcántara, L. (2020). Land use change effects on soil organic carbon store. An opportunity to soils regeneration in Mediterranean areas: Implications in the 4p1000 notion. *Ecological Indicators*, *119*, 106831. https://doi.org/10.1016/j.ecolind.2020.106831

Manrique, L. A., Jones, C. A., & Dyke, P. T. (1991). Predicting cation-exchange capacity from soil physical and chemical properties. *Soil Science Society of America Journal*, 55(3), 787-794.

Mercenaro, L., Nieddu, G., Porceddu, A., Pezzotti, M., & Camiolo, S. (2017). Sequence Polymorphisms and Structural Variations among Four Grapevine (Vitis vinifera L.) Cultivars Representing Sardinian Agriculture. *Frontiers in Plant Science*, *8*, 1279. https://doi.org/10.3389/fpls.2017.01279

Migheli, Q., Balmas, V., Komoñ-Zelazowska, M., Scherm, B., Fiori, S., Kopchinskiy, A. G., Kubicek, C. P., & Druzhinina, I. S. (2009). Soils of a Mediterranean hot spot of biodiversity and endemism (Sardinia, Tyrrhenian Islands) are inhabited by pan-European, invasive species of *Hypocrea/Trichoderma*. *Environmental Microbiology*, *11*(1), 35–46. https://doi.org/10.1111/j.1462-2920.2008.01736.x

Ministero delle Politiche Agricole e Forestali – MIPAF (1999). Approvazione dei "Metodi ufficiali di analisi chimica del suolo". Decreto Ministeriale 13-09-99, Gazzetta Ufficiale Serie Generale n.248 del 21-10-1999, Supplemento Ordinario n. 185. Available at <http://www.gazzettaufficiale.it/eli/id/1999/10/21/099A8497/sg>.

Moreno, G., Aviron, S., Berg, S., Crous-Duran, J., Franca, A., De Jalón, S. G., Hartel, T., Mirck, J., Pantera, A., Palma, J. H. N., Paulo, J. A., Re, G. A., Sanna, F., Thenail, C., Varga, A., Viaud, V., & Burgess, P. J. (2018). Agroforestry systems of high nature and cultural value in Europe: Provision of commercial goods and other ecosystem services. *Agroforestry Systems*, *92*(4), 877–891. https://doi.org/10.1007/s10457-017-0126-1

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858. https://doi.org/10.1038/35002501

Nair, K. M., Anil Kumar, K. S., Lalitha, M., Shivanand, Ramesh Kumar, S. C., Srinivas, S., Koyal, A., Parvathy, S., Sujatha, K., Thamban, C., Mathew, J., Chandran, K. P., Haris, A., Krishnakumar, V., Srinivasan, V., Jessy, Jacob, J., Nagaraj, J. S., D'Souza, M. V., … Singh, S. K. (2019). Surface Soil and Subsoil Acidity in Natural and Managed Land-Use Systems in the Humid Tropics of Peninsular India. *Current Science*, *116*(7), 1201. https://doi.org/10.18520/cs/v116/i7/1201-1211

Nave, L., Marín-Spiotta, E., Ontl, T., Peters, M., & Swanston, C. (2019). Soil carbon management. In *Developments in Soil Science* (Vol. 36, pp. 215–257). Elsevier. https://doi.org/10.1016/B978-0-444-63998-1.00011-2

Nelson, D. A., & Sommers, L. (1983). Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 2 chemical and microbiological properties*, 9, 539-579.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils—A review. *Geochemistry*, *76*(3), 327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Osservatorio Regionale Suoli della Sardegna ORSS. (2023). Carte dei Suoli, Portale del Suolo, AGRIS, Cagliari. Available on: <http://www.sardegnaportalesuolo.it/cartografia/carte-dei-suoli>.

Perakis, S. S., Sinkhorn, E. R., Catricala, C. E., Bullen, T. D., Fitzpatrick, J. A., Hynicka, J. D., & Cromack Jr, K. (2013). Forest calcium depletion and biotic retention along a soil nitrogen gradient. *Ecological Applications*, 23(8), 1947-1961.

Pietrzak, U., & McPhail, D. C. (2004). Copper accumulation, distribution and fractionation in vineyard soils of Victoria, Australia. *Geoderma*, *122*(2–4), 151–166. https://doi.org/10.1016/j.geoderma.2004.01.005

Pignatti, S. (1976). Geobotanica. "*Trattato di botanica*" (Cappelletti C ed). UTET, Turin, Italy, pp. 801-997.

R Core Team. (2023). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/. (Accessed 2 July 2023).

Ramachandran Nair, P. K., Nair, V. D., Mohan Kumar, B., & Showalter, J. M. (2010). Carbon Sequestration in Agroforestry Systems. In *Advances in Agronomy* (Vol. 108, pp. 237–307). Elsevier. https://doi.org/10.1016/S0065-2113(10)08005-3

Reimann, C., Filzmoser, P., & Garrett, R. G. (2002). Factor analysis applied to regional geochemical data: Problems and possibilities. *Applied Geochemistry*, *17*(3), 185–206. https://doi.org/10.1016/S0883-2927(01)00066-X

Roder, L. R., Guerrini, I. A., Lozano Sivisaca, D. C., Yaguana Puglla, C. A., Góes De Moraes, F., Pinheiro Da Silva, J., Batista Fonseca, R. C., Umbelino, M. T., James, J. N., Capra,

G. F., & Ganga, A. (2023). Atlantic rainforest natural regeneration in fragmented formations affected by increasing human disturbance. *Journal of Environmental Management*, *325*, 116521. https://doi.org/10.1016/j.jenvman.2022.116521

RStudio Team. «RStudio: Integrated Development for R». Boston: RStudio Team (2020), 2023. http://www.rstudio.com/.

Schröter, D., Cramer, W., Leemans, R., Prentice, I. C., Araújo, M. B., Arnell, N. W., Bondeau, A., Bugmann, H., Carter, T. R., Gracia, C. A., De La Vega-Leinert, A. C., Erhard, M., Ewert, F., Glendining, M., House, J. I., Kankaanpää, S., Klein, R. J. T., Lavorel, S., Lindner, M., … Zierl, B. (2005). Ecosystem Service Supply and Vulnerability to Global Change in Europe. *Science*, *310*(5752), 1333–1337. https://doi.org/10.1126/science.1115233

Seddaiu, G., Porcu, G., Ledda, L., Roggero, P. P., Agnelli, A., & Corti, G. (2013). Soil organic matter content and composition as influenced by soil management in a semi-arid Mediterranean agro-silvo-pastoral system. *Agriculture, Ecosystems & Environment*, *167*, 1–11. https://doi.org/10.1016/j.agee.2013.01.002

Sequeira, C. H., Wills, S. A., Seybold, C. A., & West, L. T. (2014). Predicting soil bulk density for incomplete databases. *Geoderma*, *213*, 64–73. https://doi.org/10.1016/j.geoderma.2013.07.013

Singh, B., & Sapkota, T. B. (2022). The effects of adequate and excessive application of mineral fertilizers on the soil. *Encyclopedia of Soils in the Environment*; Goss, M., Oliver, M., Eds, 1-14.

Sirigu, S., & Montaldo, N. (2022). Climate Change Impacts on the Water Resources and Vegetation Dynamics of a Forested Sardinian Basin through a Distributed Ecohydrological Model. *Water*, *14*(19), 3078. https://doi.org/10.3390/w14193078

Soil Survey Staff. (2011). Soil Survey Laboratory Information Manual. Soil Survey Investigations Report No. 45, Version 2.0. R. Burt (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.

Sonoda, K., Hashimoto, Y., Wang, S.-L., & Ban, T. (2019). Copper and zinc in vineyard and orchard soils at millimeter vertical resolution. *Science of The Total Environment*, *689*, 958–962. https://doi.org/10.1016/j.scitotenv.2019.06.486

Staaf, H., & Berg, B. (1981). *Plant litter input to soil*. *33*, 147–162.

StatSoft Inc Development (2006). Statistica 7.1. StatSoft Italia SrL, Padova.

Torrent, J. (2005). MEDITERRANEAN SOILS. In *Encyclopedia of Soils in the Environment* (pp. 418–427). Elsevier. https://doi.org/10.1016/B0-12-348530-4/00023-0

USDA. (2017). Soil survey manual. In: Soil Science Division Staff; *Agriculture Handbook No. 18*. U.S. Department of Agriculture.

Van der Maarel, E. (1979). Transformation of cover-abundance values in phytosociology and its effects on community similarity. *Vegetatio*, 39: 97-114.

Vogiatzakis, I. N., Griffiths, G. H., & Bacchetta, G. (2005). *Human impacts on Quercus suber habitats in Sardinia: Past and present*.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., Von Lützow, M., Marin-Spiotta, E., Van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H.-J., & Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales. *Geoderma*, *333*, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026

Wood, C. W., Adams, J. F., & Wood, B. H. (2005). Macronutrients. Encyclopedia of Soils in the Environment; Elsevier: Amsterdam, The Netherlands, 387-393.

Xu, Y., Liu, K., Yao, S., Zhang, Y., Zhang, X., He, H., Feng, W., Ndzana, G. M., Chenu, C., Olk, D. C., Mao, J., & Zhang, B. (2022). Formation efficiency of soil organic matter

from plant litter is governed by clay mineral type more than plant litter quality. *Geoderma*, *412*, 115727. https://doi.org/10.1016/j.geoderma.2022.115727

Yost, J. L., & Hartemink, A. E. (2019). Soil organic carbon in sandy soils: A review. In *Advances in Agronomy* (Vol. 158, pp. 217–310). Elsevier. https://doi.org/10.1016/bs.agron.2019.07.004