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Grazing effects on soil compaction in mediterranean oak woodlands

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Abstract This study evaluates the impact of grazing on soil compaction in two Mediterranean oak woodlands (*Quercus rotundifolia Q* and *Quercus pyrenaica Qp*) in the Montesinho Natural Park in north-eastern Portugal. In each habitat, paired fenced plots (grazed versus ungrazed) were monitored. Soil samples were collected at depths of 0–10 cm and 10–30 cm in order to assess texture, bulk density, moisture content and penetration resistance. The *Qr* plot was grazed by goats at a moderate intensity for 15 consecutive days. Meanwhile, the *Qp* plot was grazed by sheep at a higher intensity for 55 intermittent days over an extended period. Soil resistance was measured using an impact penetrometer and analysed using two-way ANOVA—SS Type III, principal component analysis (PCA) and Pearson correlations. Grazing significantly increased soil compaction in the *Qr* plots (3.03 ± 0.23 vs. 1.87 ± 0.1 Mpa), but not in the *Qp* plots (2.03 ± 0.2 vs. 1.70 ± 0.1 Mpa). Penetration resistance was positively correlated with clay content and bulk density, and negatively with silt content and moisture content. This study, conducted in Mediterranean mountain forests with *Q. pyrenaica* established on Umbric Leptosols and *Q. rotundifolia* on stony Leptosols derived from basic rocks, demonstrates that the effects of grazing on soil compaction are more closely linked to the intrinsic properties of the soil than to grazing stocking rate itself. These findings demonstrate that pre-existing soil properties modulate the effects of grazing on soil compaction, underscoring the importance of site-specific conditions in the sustainable management of Mediterranean silvopastoral systems.

Keywords Silvopastoral systems · Penetration resistance · Soil physical properties

Introduction

Soil compaction, as measured by soil penetration resistance, plays a crucial role in determining root growth potential, water infiltration and overall soil health. Higher resistance generally indicates limited aeration and restricted root development (Batey 2009; Shah et al. 2017; Pandey and Bennett 2023). Compaction induces substantial changes in the physical structure of soils and is considered one of the main research priorities topics in soil protection across Europe (Virto et al. 2015; Bolat et al. 2015).

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The magnitude of this process is commonly assessed using indicators such as bulk density, penetration resistance and porosity (Cambi et al. 2015).

Silvopastoral systems, which combine trees, pasture and animals within the same area provide a wide range of environmental, economic and social benefits. These include enhanced biodiversity, improved soil quality, increased carbon sequestration, microclimate regulation, and greater production diversification (Mosquera-Losada et al. 2018; Matthew et al. 2022; Fornara et al. 2018; Ruiz et al. 2020). Among these benefits, improvements in soil physical properties are particularly relevant when compared to conventional pastures, where surface compaction tends to accumulate over time due to limited plant diversity (Cambi et al. 2015). In contrast, the presence of trees in agroforestry systems contributes to enhanced soil macroporosity, water infiltration, and biological activity, ultimately reducing bulk density and improving structural stability (Mosquera-Losada et al. 2016; Spinelli et al. 2018; Marques et al. 2022). Consequently, the adoption of more diverse and structurally complex systems emerges as an effective strategy for preserving soil physical functions under increasing anthropogenic pressures.

However, when poorly managed, grazing within silvopastoral systems can lead to negative outcomes, particularly soil compaction resulting from intensive trampling—especially under high stocking rates (Sharrow 2007; Greenwood and McKenzie 2001). Although soil compaction is often associated with mechanised operations in intensively managed forests, the pressures generated by grazing animals—particularly under high stocking densities—can reach comparable levels. For instance, sheep can exert up to 80 kPa when trampling the soil (Sharrow 2007; Jordon 2021), a value similar to that of tractor wheels (Medina 2016), while cattle and goats exert pressures of approximately 190 and 60 kPa, respectively (Willatt and Pullar 1983). Under moist conditions or in cases of overgrazing, livestock trampling may result in compaction levels equivalent to those caused by forestry machinery such as skidders, which typically exert pressures between 30 and 85 kPa (Greacen and Sands 1980).

To enable rapid diagnosis of soil compaction in the field, penetration resistance is commonly measured using penetrometers. These instruments are valued for their practicality and speed. They offer a reliable index of compaction levels, enabling comparisons across different land uses and forest management systems (Suzuki et al. 2022; Reichert et al. 2021; Pinzón-Gómez et al. 2016; Mohieddinne et al. 2019; Jiang et al. 2020; Souza et al. 2015, 2018; Magalhães et al. 2018; Florentim et al. 2020; Moraes et al. 2013; Bratti et al. 2021; Oliveira et al. 2022). Recent technological developments have lowered costs and increased access to this type of equipment. For instance, Marques-Filho et al. (2022) developed a model up to 800% cheaper than commercial alternatives, facilitating large-scale application.

Although soil penetration resistance is an easily obtainable parameter, it is influenced by a range of edaphic and environmental factors, including moisture content, bulk density, texture, mineralogy, and organic matter. Therefore, its interpretation requires methodological rigor and familiarity with local soil conditions (Constantini 1996; Pinzón-Gómez et al. 2016; Silva et al. 2008; Vaz et al. 2011; Moraes et al. 2012; Vaz et al. 2013; Suzuki et al. 2024). In addition, land use practices—particularly the type and intensity of management—directly affect these soil attributes, shaping compaction patterns, hydrological processes, and root development (Suzuki et al. 2022; Strock et al. 2022).

This study was conducted in silvopastoral systems within the Montesinho Natural Park, north-eastern Portugal, on shallow Leptosols known for their vulnerable to compaction (FAO 2015; Batey 2009). Although previous research has addressed soil resistance to penetration in Mediterranean silvopastoral systems of the dehesa kind (Gómez-Rey et al. 2012; Díaz-Hernández et al. 2021; Moreno and Pulido 2009; Olea and San Miguel 2006), there are still gaps in the literature when it comes to comparing different *Q. rotundifolia* habitats and, above all, analysing them directly in relation to *Q. pyrenaica* stands in north-eastern Portugal. Despite the ecological importance of Mediterranean oak forests, the effects of grazing on soil compaction remain unclear: most studies are dedicated to general ecosystem services, soil carbon dynamics or the broad impacts of management and grazing (Guimarães et al. 2023; Mayerfeld et al. 2022; Gomez et al. 2022), rather than detailed investigations linking habitat, soil physical properties and grazing regimes. This study fills this gap by correlating penetration resistance values with soil physical attributes and management practices in both Mediterranean oak ecosystems, offering insights into how grazing intensity and habitat type condition soil health.

Therefore, this study aimed to assess the influence of grazing on soil compaction, using penetration resistance as an indicator, in two oak-based silvopastoral systems. The first system consisted of *Q. pyrenaica* woodlands grazed by sheep at higher intensity over 35 intermittent days over an extended period of six months. The second involved *Q. rotundifolia* stands grazed by goats at moderate intensity for 15 consecutive days. Soil resistance was measured at two depths: 0–10 cm and 0–30 cm.

In addition, the study sought to characterise the main physical properties of the soil—namely bulk density and particle size distribution—as well as the soil's water condition at the time of sampling, analysing its relationship with penetration resistance.

Material and methods

Study area

The research was conducted in north-eastern Portugal (41°53.59' N; 6°52.8' W), within the Montesinho Natural Park (PNM; Fig. 1). The study focused on two forest habitats of Community interest, as defined under the Habitats Directive (92/43/EEC): the Galician-Portuguese oak woods with *Quercus robur* and *Quercus pyrenaica* (habitat 9230), and the evergreen oak forests dominated by *Quercus ilex* and *Quercus rotundifolia* (habitat 9340). Within these habitats, we specifically studied stands of *Q. pyrenaica* and *Q. rotundifolia*. Both habitats are of natural origin, having developed without silvicultural intervention, and are occasionally subjected to extensive grazing.

The territory of PNM is characterised by a markedly heterogeneous relief, consisting of plateaus

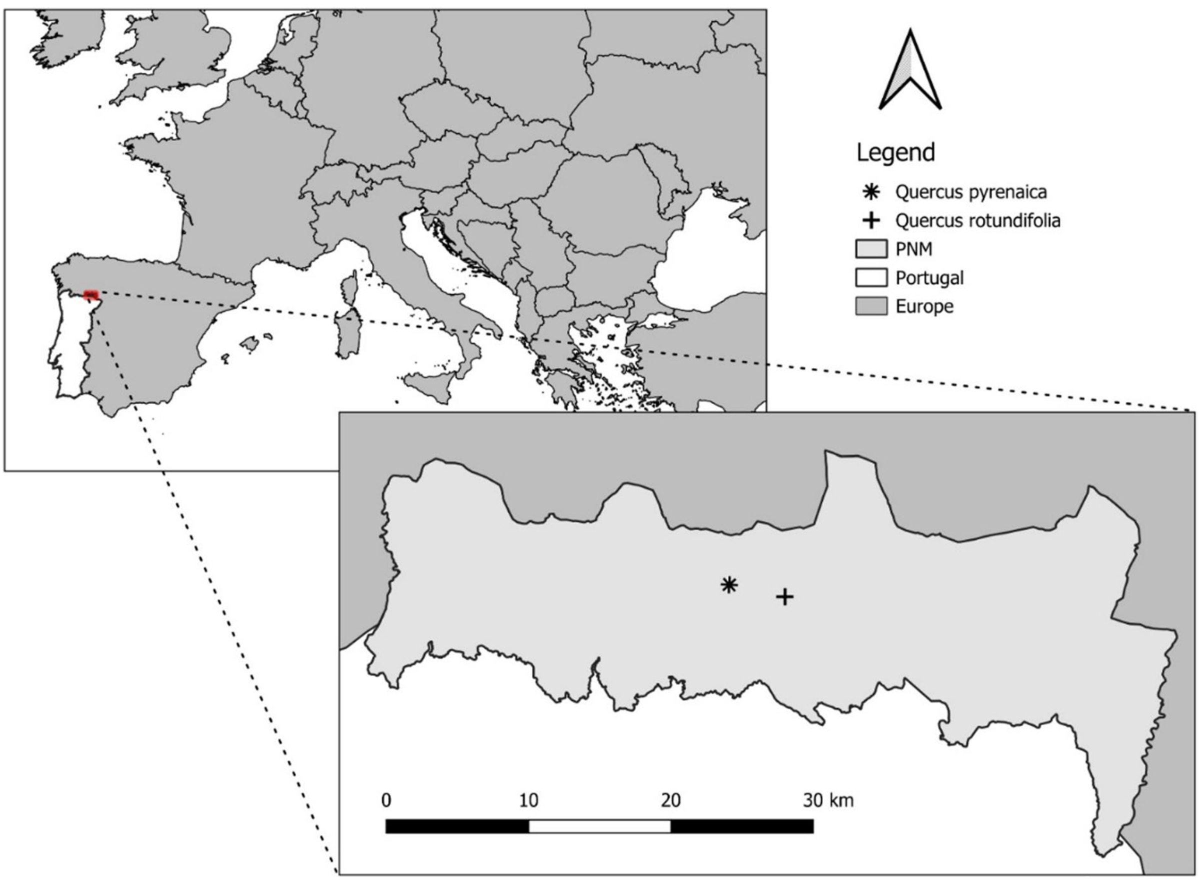

Fig. 1 Location of the study area in Montesinho Natural Park (PNM), NE Portugal

interspersed with deep valleys and mountainous formations (Castro et al. 2021). The slopes vary from flat to very steep, with altitudes ranging from 438 to 1,486 m asl. Most of the territory falls within the supra-Mediterranean bioclimatic zone, with an average annual temperature of between 8 and 12 °C and, annual rainfall of between 1,000 and 1,600 mm, mostly concentrated between the months of October and March (Fonseca et al. 2012) (See climate graphs for the year 2024 in the supplementary material, IPMA, 2020).

Experimental sites

The areas consists of a multifunctional natural forest that has historically been used for indirect purposes, including firewood collection, grazing, and mushroom harvesting. Approximately 30 years ago, it underwent traditional small-scale firewood and timber extraction, mainly involving the selective removal of branches or a limited number of trees. These interventions resulted in low-intensity timber extraction, although no quantitative records are available. The PNM is characterised by a mosaic of small land use fragments, with forest areas interspersed between agricultural fields and pastures, in a landscape shaped by a long tradition of transhumance (Pousa et al. 2025).

One of the sites includes two fenced plots of 1.3 hectares each, located within a stand dominated by *Q. rotundifolia*, with an estimated density of approximately 965 trees per hectare. The tree layer is accompanied by a relatively dense understory with approximately 51% shrub cover, composed of *Genista falcata* Brot., *Pterospartum tridentatum* (L.) Willk., *Cistus salviifolius* L., *Halimium lasianthum* subsp. *alyssoides*, *Cytisus multiflorus* (L'Hér.) Sweet, and *Erica australis* L. A sparse herbaceous layer is also present, consisting mainly of annual grasses.

Soil is classified as derived from basic rocks (Agroconsultores and Coba 1991), which are the dominant soil in the region. These soils are poorly developed and have a shallow profile with a surface A horizon varying between 10 and 30 cm (Calzolari et al 2021). The soil has a sandy loam texture, with an average clay content of 11.15%, and is often gravelly. The underlying C horizon consists mainly of fragmented parent material with a low proportion of fine earth. Coherent bedrock is typically found at depths of less than 50 cm, constraining both water retention and root development. Chemically, the soil is moderately acidic, with an average pH (H_2O) of 5.3.

In July of 2024, a herd of 25 goats of the *Preta de Montesinho* breed in the last third of pregnancy (weighing between 45 and 50 kg) grazed the treatment plot for 15 consecutive days. The animals spent approximately 15 h per day on the plot and were gathered at night due to the presence of wolves in the area. Their diet was estimated to consist of approximately 85% natural vegetation and 15% supplementary feed. During the grazing period 5 kg of energy-rich concentrate feed (crude protein 18.4%, crude fiber 11.4%, crude fat 3.1%, crude ash 8.5%, calcium 1.32%) was distributed in the plot to stimulate the goats' appetite. In short, grazing in the *Q. rotundifolia* habitat can be characterised as low-intensity and short-duration.

The other experimental site consists of two fenced plots of approximately 1.3 hectares each, located within a stand dominated by *Q. pyrenaica*, with an estimated tree density of approximately 1,545 trees per hectare. The understory, with approximately 32% shrub cover, is mainly composed of *Cytisus striatus* (Hill) Rothm. and *Rubus ulmifolius* Schott. The soil is predominantly classified as Umbric Leptosol, characterised by a low degree of pedogenetic development (Agroconsultores and Coba 1991). It features a dark-coloured, humic A horizon with a sandy loam texture (average clay content = 8.91%) and frequent gravel inclusions. This horizon overlies a C horizon composed mainly of coarse fragments resulting from the physical weathering of bedrock, with a low proportion of fine earth. A sharp lithological discontinuity is present, with unweathered bedrock occurring abruptly at depths between 10 and 50 cm. These conditions significantly limit the effective soil depth, constraining both root development and water retention capacity. Chemically, the soil is acidic, with an average pH (H_2O) of 5.1. A flock of 220 pregnant *Churra Galega Bragançana* ewes, each weighing between 50 and 60 kg, grazed on the *Q. pyrenaica* site. Between May and October 2024, the animals grazed on the plot for a total of 55 days, which were not consecutive. They spent around 17 h a day on the plot. In short, the *Q. pyrenaica* habitat can be characterised by high grazing intensity on non-consecutive days.

Soil sampling

Soil sampling was carried was carried out out before grazing, samples were collected at depths of 0–10 cm and 10–30 cm in order to analyse bulk density and granulometry (texture). To ensure representativeness and capture spatial variability, five samples were collected per treatment, the composite sampling method was adopted, in which each composite sample was made up of the homogenisation of three simple samples. Soil samples were collected using a probe sampler, which is appropriate for preserving the natural soil structure, particularly when assessing bulk density. After collection, the samples were placed in labelled containers and transported to the laboratory for drying, sieving, and subsequent physico-chemical analysis.

Soil resistance and soil moisture measurements

Soil resistance to penetration was measured in the field using an impact penetrometer, under field capacity conditions (neither too dry nor saturated) after grazing, following the method described by Stolf et al. (1983). Measurements were taken to the maximum depth of the soil profile, with five repetitions per sample and a total of 25 repetitions per treatment (habitat species and grazing or not). The procedure involved repeatedly dropping a 4 kg weight from a height of 40 cm onto the penetrometer rod. This was continued until either the maximum depth of 60 cm was reached, or the rod could no longer penetrate the soil. The number of impacts (knocks) required to drive the rod through each centimetre of soil was recorded, serving as an indicator of soil resistance (Eq. (1)).

Soil resistance was calculated using Eq. (1):

$$F = 5.6 + 6.89xN \tag{1}$$

where: F is the soil resistance (kgf $cm^{-2} \times 0.098 = MPa$), N is the number of impacts ÷ deepening (cm).

In both study areas, soil resistance was assessed through randomized sampling, ensuring a more accurate and comprehensive representation of the local edaphic conditions. The average penetration resistance of the soil layers at 0–10 cm, 10–20 cm, and 20–30 cm depths was used to establish correlations with other physical and mechanical soil properties measured in the soil samples. The soil resistance data in the 0 to 30 cm range was used to draw up the resistance profile, while the moisture content values, collected in the same depth range, served as the basis for constructing the soil moisture profile.

The soil moisture content was determined at the 0–10 cm, 10–20 cm and 20–30 cm depths, simultaneously with the penetration resistance measurements, in order to ensure that the field conditions were representative at the time of the assessments. Soil moisture (SM) was measured using a capacitive sensor model SM150T, positioned at the same place and time of collection for each depth analysed.

Statistical analysis

To study the influence of grazing on soil compaction in *Q. rotundifolia* and *Q. pyrenaica* habitats, penetration resistance at 10, 20, and 30 cm depths (as an indicator of soil compaction) was analyzed in response to habitat type, grazing (grazed vs. ungrazed), their interaction, and soil characteristics (moisture, density, sand, silt, clay, and maximum soil depth). Statistical analysis was carried out using two-way ANOVA—SS Type III, with habitats and the presence or absence of grazing as sources of variation. Tukey's honestly significant difference test was used for paired comparisons between the groups ($p < 0.05$), considering the different habitats and the presence or absence of grazing. These statistical analyses were conducted using SYSTAT® software version 13.2. Principal Component Analysis (PCA) using the PCA function from the "FactoMineR" package (Lê et al. 2008), and Variance Inflation Factors (VIF) were used to assess collinearity, retaining only variables with $VIF < 3$ (Zuur et al. 2010). All soil parameters measured at the target and overlying depths were considered as candidate predictors. Backward model selection based on Akaike's Information Criterion (AIC) was applied to identify the final model. Model validation was conducted using residual diagnostics from the simulate Residuals function in the "DHARMa" package.

Results

Effect of habitat and grazing on soil penetration

Soil penetration resistance differed significantly between habitats (*Q. rotundifolia* vs. *Q. pyrenaica*) at all depths (0–10 cm: $p < 0.004$; 10–20 cm: $p < 0.001$; 20–30 cm: $p < 0.001$). A significant interaction between habitat and grazing treatment was detected across all three soil layers (Table 1, supplementary material). Penetration resistance was higher in grazed *Q. rotundifolia* plots across all three soil layers, especially in the 0–10 layer, while grazed *Q. pyrenaica* plots showed the lowest values at 20–30 cm depth (Table 1, supplementary material).

There was a pattern, albeit not statistically significant, of soil resistance to penetration increasing with depth at all the sites evaluated, in decreasing order: *Q. rotundifolia with grazing* > *Q. pyrenaica without grazing* > *Q. rotundifolia without grazing* > *Q. pyrenaica with grazing* (Fig. 2).

Soil moisture showed an inverse pattern to penetration resistance, decreasing with depth in both habitats. The widest variation was observed in the grazed *Q. rotundifolia* site, where moisture content dropped from 28.2 ± 3.15% at 0–10 cm to 16.6 ± 1.64% at 20–30 cm depth (Fig. 3).

Table 1 Soil penetration resistance and moisture content by depth in grazed and ungrazed plots of *Q. rotundifolia* and *Q. pyrenaica*

Habitat		Penetration Resistance 0-10 cm (MPa)	Penetration Resistance 10-20 cm (MPa)	Penetration Resistance 20-30 cm (MPa)	Moisture 0-10 cm (%)	Moisture 10-20 cm (%)	Moisture 20-30 cm (%)
Q. rotundifolia	**Grazed**	3.03 (±0.23) A	6.99 (±0.71) A	8.68 (±0.28) A	28.20 (±0.63) B	24.40 (±0.50) B	16.60 (±0.33) C
	Ungrazed	1.87 (±0.11) B	4.57 (±0.37) B	6.01 (±0.61) C	30.40 (±0.50) B	26.60 (±0.49) B	21.00 (±0.39) B
Q. pyrenaica	**Grazed**	2.03 (±0.24) B	3.80 (±0.27) B	5.14 (±0.39) C	39.20 (±1.40) A	35.00 (±0.61) A	26.40 (±0.29) A
	Ungrazed	1.70 (±0.18) B	5.32 (±0.49) AB	7.23 (±0.31) B	38.60 (±0.89) A	37.00 (±0.39) A	24.52 (±0.53) A

Averages followed by different letters in the column indicate significant differences between habitats (*Q. rotundifolia* and *Q. pyrenaica*) and treatments (grazed and ungrazed) for each variable (penetration resistance and moisture) at the three depth layers (0–10 cm, 10–20 cm and 20–30 cm) according to Tukey's test at 5% probability, while the values in parentheses represent the standard error

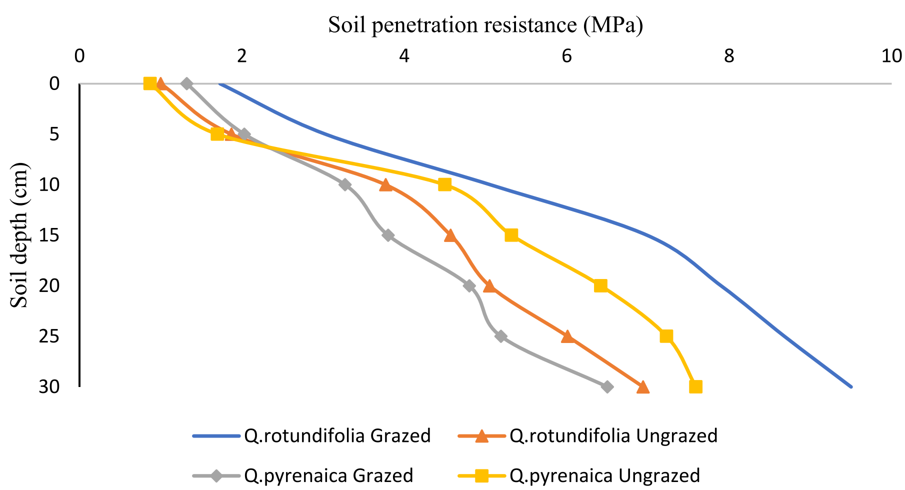

Fig. 2 Soil penetration resistance (MPa) by depth (cm) in grazed and ungrazed plots of *Q*. rotundifolia and *Q*. pyrenaica

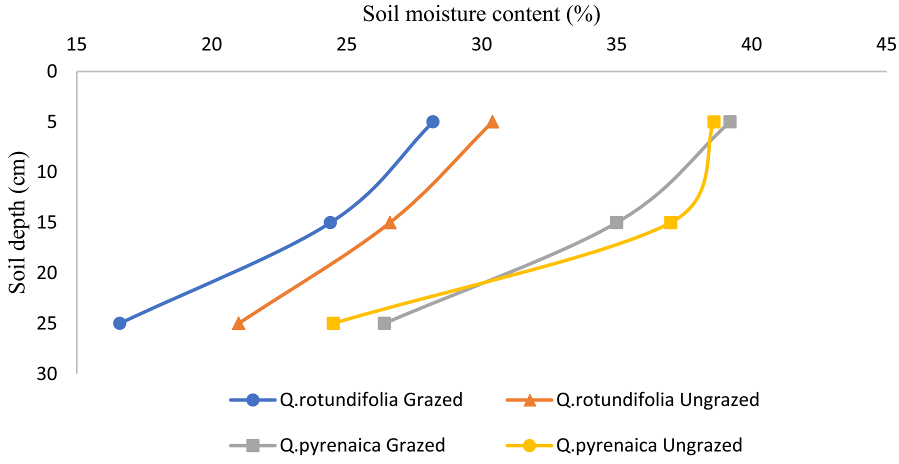

Fig. 3 Soil moisture content by depth in *Q. rotundifolia* and *Q. pyrenaica* habitats, with and without grazing

Multivariate analysis of soil texture and penetration resistance in surface layer (0–10 cm)

Principal component analysis (PCA) of soil texture and physical properties (moisture, density, sand, silt, clay, and maximum soil depth) at 0–10 cm depth showed a clear separation between treatments along the first two principal components, which together explained 62.1% of the total variance (Dim1: 43.3%, Dim2: 18.8%) (Fig. 4). The first principal component (Dim1) was strongly influenced by soil texture fractions. The sand content in the surface layer (Sand_10cm) made the largest contribution to this axis (relative contribution, ctr = 34.3%) and had high representation quality (cosine square, $cos^2 = 0.89$). Next were the silt content (Silt_10cm; ctr = 23.5%) and clay content (Clay_10cm; ctr = 14.9%). The bulk density of the soil (BD_10cm) also contributed moderately to Dim1 (ctr = 11.5%). Thus, Dim1 can be interpreted as a soil texture gradient, ranging from sandier to more clayey conditions.

The second principal component (Dim2) was primarily influenced by maximum depth reached (Max_depth), which had the highest contribution (ctr = 54%) and a strong correlation with the axis ($cos^2 = 0.60$), followed by clay content (Clay_10cm, ctr = 18.9%). This axis mainly reflects the variation in vertical penetration capacity in the soil, likely related to soil compaction or physical restrictions at depth. Soil moisture at 10 cm depth (Moisture_10cm) had a moderate influence on both axes (Dim1: ctr = 9.7%, $cos^2 = 0.25$; Dim2: ctr = 6.2%, $cos^2 = 0.07$), indicating a more diffuse contribution to the differentiation between habitats and treatments.

The biplot distribution reveals a clear separation between habitats and treatments. Plots under *Q. pyrenaica* with grazing (Q.pyr_Grazed) cluster predominantly in the negative quadrant of Dim1, associated with higher soil moisture and lower bulk density—conditions typically linked to reduced penetration resistance. In contrast, samples from *Q. rotundifolia*, particularly those without grazing (Q.rot_Ungrazed), are positioned in the positive quadrant of Dim1, corresponding to higher bulk density, increased clay content, and lower moisture levels, indicative of more compacted and resistant soil conditions.

Maximum penetration depth (Max_depth) was positively correlated with soil moisture and negatively correlated with bulk density, highlighting the influence of these factors on physical constraints to soil penetration. However, this relationship appears to be mediated not only by the availability of water in the soil, but also by the type of habitat dominated by *Quercus pyrenaica*, which provides specific conditions of vegetation cover and organic matter input, influencing the physical properties of the soil and cover conditions that affect soil properties. Soil texture also had a notable influence: higher silt content was associated with lower resistance to penetration, while increased proportions of sand and clay were linked to greater soil compaction.

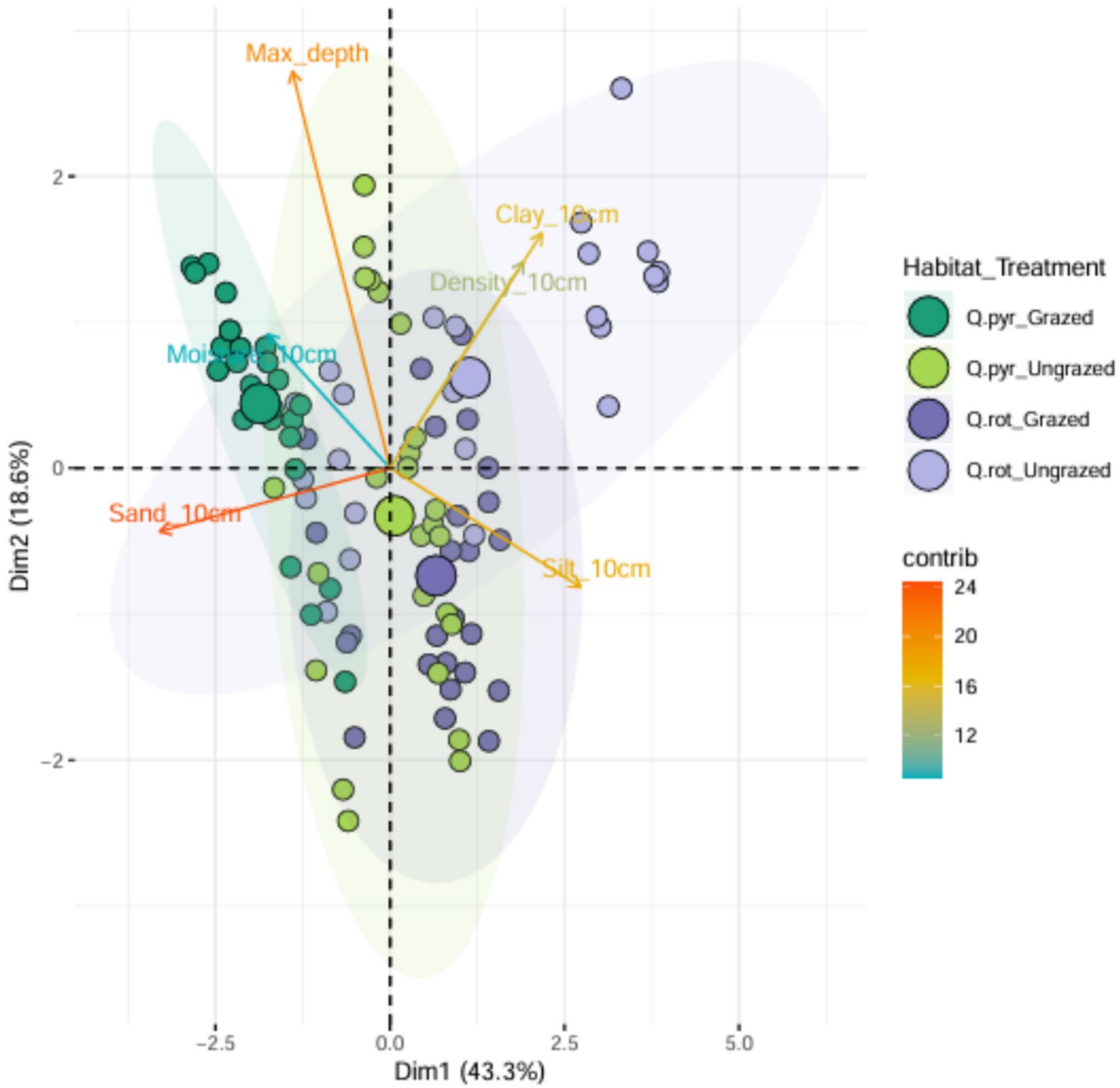

Fig. 4 Principal Component Analysis (PCA) biplot of soil physical attributes at 0–10 cm depth in different habitats and grazing treatments. Points represent samples; colours indicate habitat–treatment combinations and ellipses indicate group dispersion. The arrows represent edaphic variables (e.g., texture, bulk density, and water condition), with their direction and length indicating their correlation with the Dim1 and Dim2 axes. The colour of the arrows ("contrib") indicates the relative contribution of each variable to these axes

Multivariate analysis of soil texture and penetration resistance in the total profile (0–30 cm)

In the multivariate analysis covering the entire soil profile (0–30 cm), the first two components explained 58.2% of the total variance, with 32.8% attributed to Dimension 1 and 25.4% to Dimension 2 (Fig. 5). Dimension 1 was strongly influenced by the moisture content at all depths (Moisture_10cm to Moisture_30cm), and by sand content at 30 cm depth (Sand_30cm, ctr = 13.96%, $\cos^2 = 0.76$). These results indicate that this axis reflects a gradient of moisture and sandier texture, with drier and less structured soils located at the negative ends of the axis.

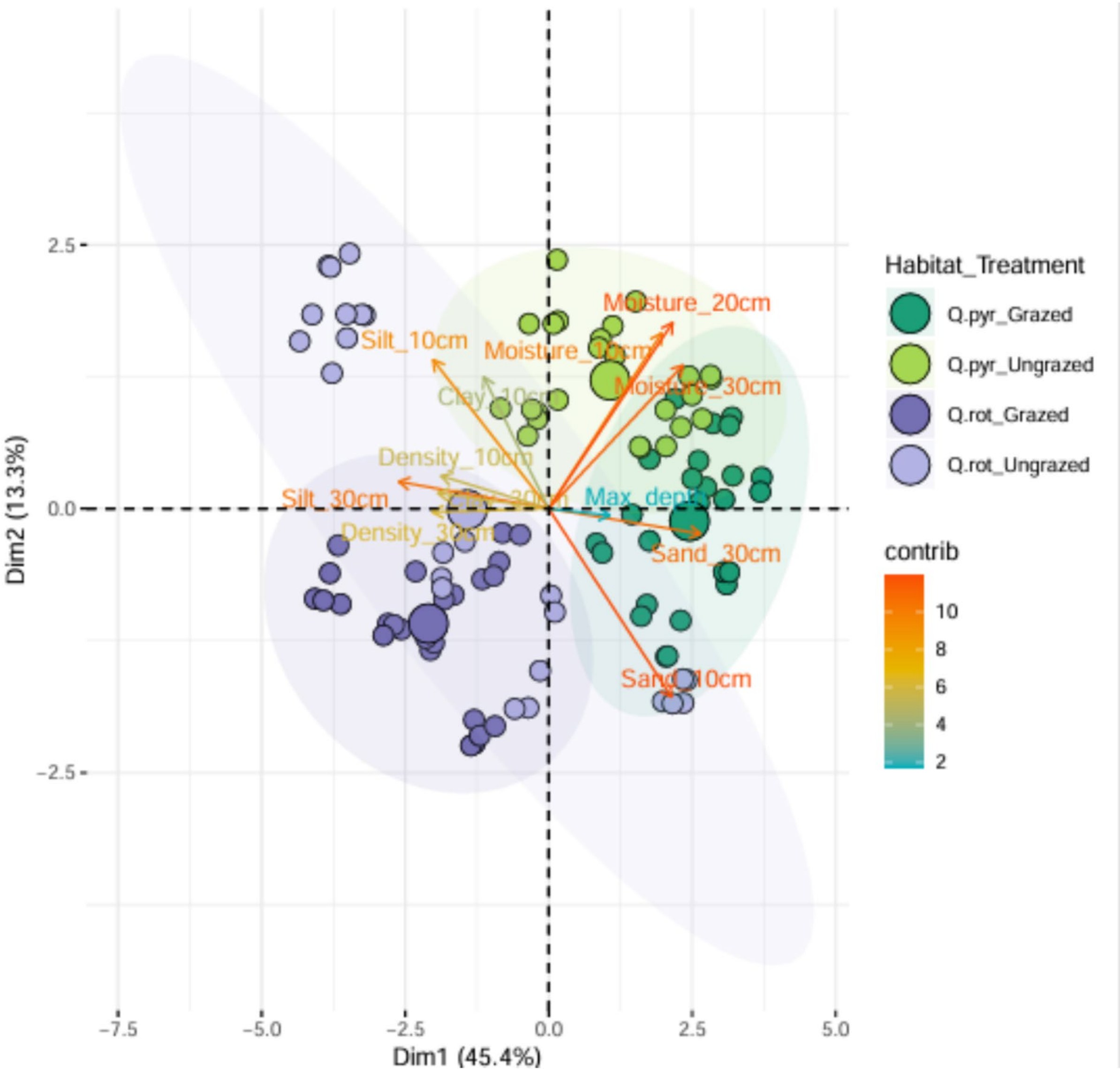

Fig. 5 Principal Component Analysis (PCA) biplot of soil texture other physical properties at 0–30 cm depth across different habitat and grazing treatments

Bulk density at 10 and 30 cm layers and silt content showed negative contributions, highlighting the contrast between light and compact soils.

Dimension 2 was primarily defined by textural variation in the surface layer, particularly the proportions of sand (Sand_10cm, ctr = 21.7%), silt (Silt_10cm, ctr = 13.5%) and clay (Clay_10cm, ctr = 10.6%) contents. Bulk density had a minimal influence on this axis. This dimension can be interpreted as a horizontal textural gradient, reflecting differences in surface conditions, possibly influenced by land use and management practices.

Overall, in the surface layer (0–10 cm), water availability and fine granulometry are the main determinants of mechanical impedance, with penetration resistance varying inversely with moisture and silt content and directly with bulk density and clay content. When the analysis is extended to the entire profile (0–30 cm) moisture and coarse granulometry—especially sand content at greater depths—plays an important role in limiting the penetrometer's advance. These findings show that although the soil's physical properties interact consistently at all depths, their effects vary in nuance according to the horizon considered.

The multivariate ordination reinforces this distinction: areas of *Q. rotundifolia* under grazing are grouped with soils with a higher density and lower moisture content, while those of ungrazed *Q. pyrenaica* are associated with wetter, silt-rich profiles. This contrast between habitats and management regimes highlights how the interactions between texture, moisture and compaction reflect not only intrinsic edaphic characteristics, but also the impacts of grazing on the physical structure of the soil in Mediterranean agroforestry systems.

Correlations between soil physical attributes and penetration resistance at the 0–10 cm and 0–30 cm depths.

Pearson's correlations confirmed the patterns identified in the PCA, demonstrating consistent relationships between soil physical properties and penetration resistance across the surface layer (0–10 cm) and the full profile (0–30 cm) (Fig. 6, supplementary material). In the 0–10 cm layer, penetration resistance was positively correlated with bulk density ($r=0.62$) and clay content ($r=0.49$), factors associated with greater resistance to mechanical penetration. Negative correlations of penetration were observed with soil moisture ($r=-0.59$) and silt content ($r=-0.54$), indicating that moisture and silt levels lower penetration resistance in the surface layer.

Within the full soil profile (0–30 cm), maximum penetration depth was moderately and positively correlated with soil moisture across depths ($r=0.18$–0.31), with the highest correlation at 30 cm ($r=0.31$). Negative correlations with bulk density were observed in deeper layers ($r=-0.26$–-0.30), indicating that increasing bulk density limits penetration depth. Sand content at 30 cm was positively correlated with penetration depth ($r=0.28$), while clay content showed a negative correlation at the same depth ($r=-0.24$). A strong negative correlation was also found between sand and silt content ($r=-0.92$), confirming the expected inverse relationship between these fractions. The results indicate that the greater surface resistance observed in the areas with *Q. rotundifolia* grazed is associated with lower levels of soil moisture and increased soil density. On the other hand, soils under *Q. pyrenaica* in areas without grazing maintained physical properties more favourable to penetration, showing greater porosity and water retention capacity.

Discussion

Co-variation of soil properties and tree species

The edaphic adaptations and morphological differences between *Q. rotundifolia* and *Q. pyrenaica* help to explain the contrasting soil responses observed in each habitat. In interaction with grazing, these differences modulate the patterns of soil compaction and structural dynamics observed under each habitat. *Q. rotundifolia* thrives in shallow, stony Leptosols derived from basic rocks. These soils are characterized by rapid drainage, low to moderate organic matter content, and neutral to alkaline pH (Alonso-Forn et al. 2020). They are poorly developed, typically featuring a surface A horizon of 0–30 cm over a fragmented C horizon, with a limited fine soil fraction (Calzolari et al. 2021). The root system of *Q. rotundifolia* is deep but sparsely branched near the surface. Combined with the drier microclimate under its canopy and limited litter input, this hampers aggregate formation, rendering the soil more vulnerable to trampling (Witzgall et al. 2024). As a result, even under low stocking rates, short-duration grazing tends to increase bulk density, reduce permeability, and raise mechanical resistance (Donovan and Monaghan 2021; Lai and Kumar 2020; Bastani et al. 2023).

In contrast, *Q. pyrenaica*, typically found in more favourable edaphic conditions, particularly Umbric Leptosols. These are marked by a dark, humic A horizon, sandy loam texture, and moderately acidic pH. Under its canopy, a dense network of fine surface roots and abundant litter accumulation promote bioturbation, nutrient cycling, and microbial activity. These biological processes enhance soil structure and promote porosity. As a result, even under high grazing intensity, compaction is significantly mitigated (Rakkar and Blanco-Canqui 2018; Hamza and Anderson 2005; Zhang et al. 2019; Han et al. 2019; Pulido-Moncada et al. 2019).

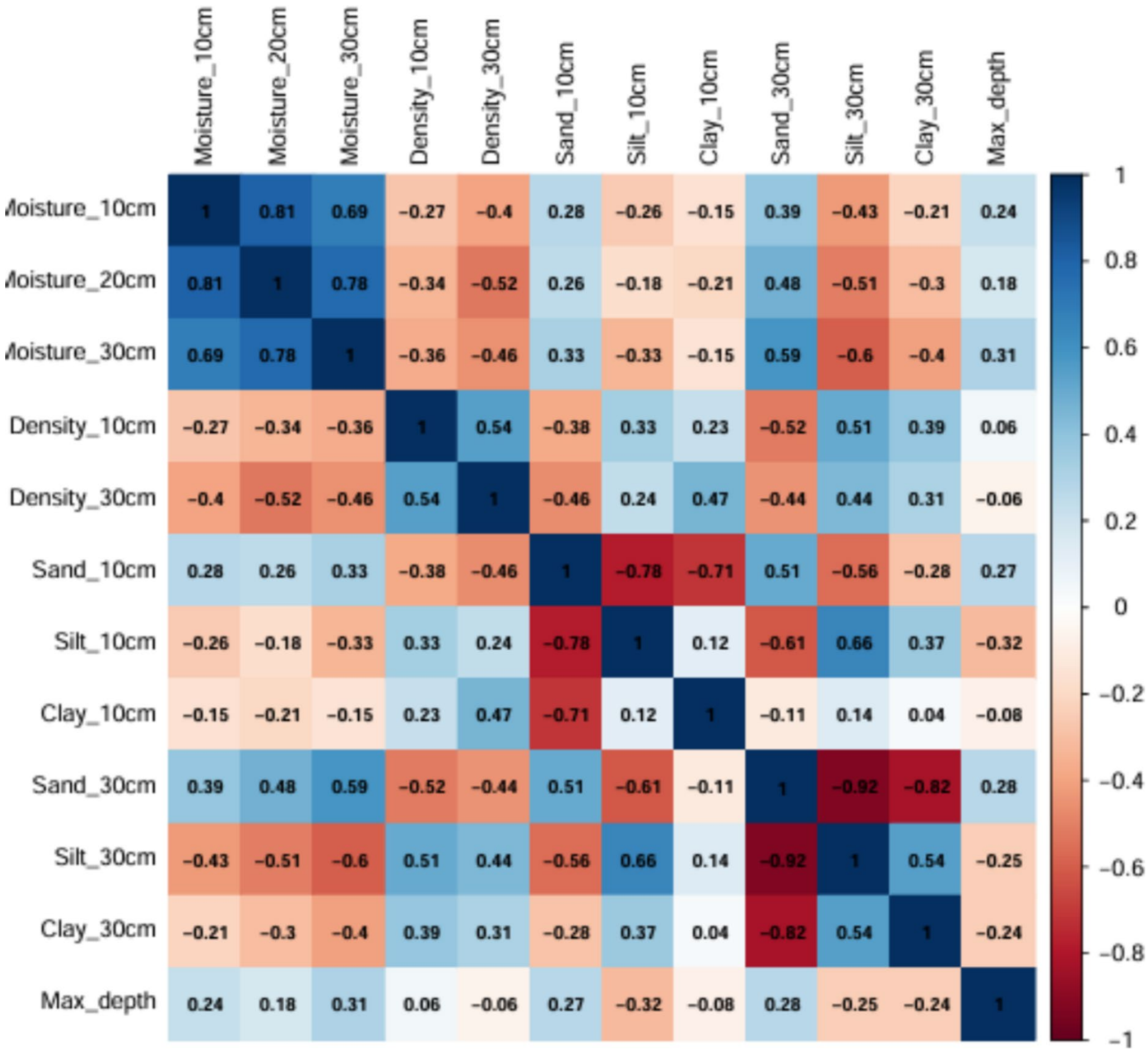

Fig. 6 Pearson correlation between habitat variables and resistance to penetration in 2024. Blue indicates positive correlations and red indicates negative correlations. Darker colors indicate higher correlations and lighter colors indicate lower correlations. Variables followed by "10 cm" or "30 cm" refer specifically to the respective soil depths analyzed

The differences in edaphic conditions between sites dominated by *Q. rotundifolia* and *Q. pyrenaica* reflect distinct combinations of texture, bulk density, and soil water condition associated with each habitat. These differences affect infiltration capacity, water storage and resistance of the soil to trampling, resulting in contrasting patterns of compaction under similar grazing regimes (Rapp et al. 1999). Correlation analyses reinforce these mechanisms, indicating that penetration resistance increases with bulk density ($r = 0.62$) and clay content ($r = 0.49$), and decreases with higher moisture and silt content ($r = -0.59$; $r = -0.54$). This highlights the structuring role of moisture and the silt fraction in mitigating the effects of livestock trampling, while clay content and compaction associated with reduced macroporosity act as mechanical limitations to rooting and infiltration (Vaz et al. 2011; Pinzón-Gómez et al. 2016). The strong negative relationship between sand and silt ($r = -0.92$) emphasises the role of textural gradients in regulating compaction in grazed systems. Multivariate ordination (PCA) clearly supports these patterns, showing that ungrazed *Q. pyrenaica* stands are clustered in wetter, silt-rich soils, whereas *Q. rotundifolia* areas are associated with denser, clayier and drier soils, demonstrating that edaphic characteristics-including soil moisture, porosity and structure are critical determinants of penetration resistance and resilience to trampling in Mediterranean agroforestry systems.

Animal–soil interactions in pastoral systems

Compared to similar studies conducted in southern Portugal, where *Q. rotundifolia* stands under similar sheep grazing conditions exhibited soil penetration resistance of around 1.7 MPa in the 0–10 cm layer (Serrano et al. 2023), our grazed *Q. rotundifolia* plots had substantially greater values, reaching 3.03 MPa within the same depth range. This difference suggests that the local edaphic conditions in our study area—namely the high stoniness, shallow effective depth and greater bulk density typical of Leptosols—intensify the compaction effect of grazing (Bissonnais et al. 2018). It is worth noting, however, that despite being elevated, the resistance values recorded in the surface layer remain close to the critical threshold of 2.5 MPa, which is considered restrictive for the root growth of *Q. rotundifolia* seedlings (Mancilla-Leyton et al. 2016).

Serrano et al. (2023) also reported that in *Q. rotundifolia* stands in southern Portugal, the greatest resistance to penetration was recorded in the 20–30 cm layer, with values around 3 MPa. In contrast, in the present study, resistance at the same depth reached 8.68 MPa. This difference is likely attributable to the distinct soil types involved: while the southern sites were characterised by Cambisols, which typically have deeper profiles and better aggregation (Turgut and Hangişi 2022), the soils evaluated here were Leptosols—shallow, fragmented, and inherently more prone to compaction (Pires-Sturm and DeJong 2023).

Conversely, the resistance values observed in *Q. pyrenaica* under grazing and in the absence of grazing were similar and remained below the critical threshold. This suggests that soil conditions in both situations were more favourable than those observed in *Q. rotundifolia* stands (Castro and Fernandez-Nuñez 2014). This may be explained by the presence of well-structured surface horizons with a higher organic matter content and substantial litter accumulation. These factors contribute to maintaining porosity and mitigating compaction, regardless of grazing activity (Jensen et al. 2019; Shepherd et al. 2021).

Management strategies should consider the functional complementarity between *Q. rotundifolia* and *Q. pyrenaica* in terms of soil structure and resistance to trampling. Grazing should be adjusted according to the soil requirements and seasonal dynamics of each species. In *Q. rotundifolia* stands, grazing intensity should be limited, rotational systems should be adopted with rest periods that coincide with phases of greater soil susceptibility (e.g. following rainfall and at the end of summer), and shrub cover should be promoted to support regeneration and protect the surface horizons (Monteiro-Henriques and Fernandes 2018). In contrast, *Q. pyrenaica* stands, which have higher tree density and, consequently, higher fine root density, as well as a more continuous supply of litter, tend to have structurally more stable soils, which may confer greater buffering capacity and flexibility of use under similar grazing regimes (Byrnes et al. 2018; Halde et al. 2011).

Although managers have capacity to adjust stocking density, allowing adequate plant recovery following grazing is a more effective means of mitigating soil compaction (Lai and Kumar 2020). However, defining optimal grazing pressure and defoliation intensity remains highly context-specific, depending on the ecosystem type and local environmental conditions (Ameray et al. 2022). Another important point to note is that grazing can contribute to litter accumulation in the soil when properly managed, through the trampling of plant material and the deposition of excreta. This controlled disturbance of the surface promotes the incorporation of organic matter into the topsoil (0–5 cm) (Souza et al. 2025).

The combined input of fragmented residues and manure—followed by humification—improves soil structure and fertility, enhancing vegetation recovery and resilience. Several studies have highlighted the positive role of well-managed grazing in maintaining soil functionality within pastoral systems (Herrero et al. 2016; Fonseca and Figueiredo 2018; Fielding 2022).

In summary, maintaining soil functionality in Mediterranean agroforestry systems requires more than adjusting grazing intensity alone—it demands an integrated approach that considers ecological variability, species-specific traits, and long-term management goals (Firn et al. 2013; Díaz Pereira et al. 2020). Practices that harmonise grazing pressure, tree cover, and silvicultural practices play a critical role in this balance (Moreno-Fernández et al. 2020; Carvalho 2023). Within such frameworks, well-planned strategies like rotational stocking or deferred grazing emerge as promising tools to minimise soil degradation and enhance ecosystem resilience (Serrano et al. 2023; Carreira et al. 2022).

Edaphic interactions: soil moisture, texture and depth

Soil penetration resistance was negatively correlated with soil moisture content, particularly in the upper 0–10 cm layer, indicating that a reduction in water content leads to a significant increase in mechanical penetration resistance (Vaz et al. 2002). Overall, the evidence suggests that soil moisture content is a key determinant of mechanical resistance, often overriding the direct effects of grazing management or vegetation characteristics (Suzuki et al. 2024; Souza et al. 2021). This relationship is well documented; for instance, studies conducted in *montado* systems in southern Portugal have shown that drier soils—such as grazed sites under *Q. rotundifolia*, where moisture values around 16.6% are recorded at depths of 20–30 cm—tend to exhibit greater penetration resistance. This highlights the strong influence of soil moisture on penetration resistance (Serrano et al. 2023), a pattern that was also observed in the present study when interpreted in conjunction with other physical indicators of soil structure.

This effect is particularly evident in Mediterranean and other semi-arid regions, where the variability of rainfall and its interception by tree canopies can reduce water infiltration, thereby exacerbating mechanical impedance (Souza et al. 2021). Monitoring soil moisture and penetration resistance is essential for understanding the dynamics of soil compaction, as these factors jointly determine the physical limitations for root growth and soil health (Benevenute et al. 2020; Paiva-Filho et al. 2024). In Mediterranean agroforestry systems, management practices that maintain or increase soil moisture, such as rotational grazing and the retention of shrub and herbaceous cover, can reduce soil penetration resistance and mitigate the risk of compaction. This contributes to the system's long-term resilience (Bratti et al. 2021).

Ecological and management implications

In a broader sense, type and intensity of land use exert a strong influence on the distribution and severity of soil compaction (Batey 2009; Shah et al. 2017; Nawaz et al. 2013). In general, unmanaged forest areas tend to maintain higher porosity and lower penetration resistance, reflecting minimal surface disturbance. In contrast, intensively grazed pastures often exhibit marked surface compaction due to the cumulative effect of repeated trampling by animals (Shah et al. 2017; Giacobbo et al. 2024). Agricultural systems based on annual cropping, particularly on sandy soils, can reach extreme resistance values—up to 14.4 MPa during dry periods—highlighting the combined impact of low soil moisture and mechanical stress associated with intensive management (Souza et al. 2021). Against this backdrop, agroforestry systems emerge as an intermediate use type, where the presence of trees may help buffer compaction—especially in subsurface layers—through the structural role of root systems and the protective effect of litter accumulation (Marques et al. 2022; Fahad et al. 2022; Ngaba et al. 2023).

However, long-term studies are needed to quantify the responses of different habitat types under varying climate scenarios, allowing for the assessment of both cumulative and seasonal impacts of management practices (Glindemann et al. 2009). In addition, such investigations should include the measurement of indicators related to ecosystem functioning, resilience, and service provision, offering an integrated perspective on how management and environmental conditions affect system sustainability (Ma et al. 2014; Wang et al. 2016). In this context, it is crucial that future research also advances the evaluation of grazing management practices and the definition of sustainable grazing and rest intervals, in order to preserve soil health in Mediterranean systems, where edaphic degradation remains a significant challenge (Guimarães et al. 2023).

In short, grazing influences soil quality and productivity in two key ways: through trampling, which can lead to compaction; and, by enhancing the input of organic matter through the fragmentation of litter and the recycling of nutrients via manure deposition

(Gilmullina et al. 2020). The net effect of these processes, however, largely depends on the intrinsic properties of the soil—such as texture, structure, organic matter content, and depth—which determine its susceptibility to compaction and its capacity to retain and process organic inputs (Wang et al. 2025; Lai and Kumar 2020). This dual impact highlights the importance of grazing management, by monitoring the effects of grazing and assessing the overall balance between the benefits and ecological impacts associated with this practice. If payment schemes for ecosystem services were to be implemented, such monitoring would play a pivotal role in ensuring transparency, informing public policies, and supporting sound management decisions (Maes et al. 2012). Furthermore, incorporating economic evaluations into grazing management provides land managers with the tools needed to assess trade-offs and make informed decisions, promoting the efficient and sustainable use of Mediterranean agroforestry systems in line with conservation, productivity, and resilience goals (Flinzberger et al. 2020).

Conclusion

This study, conducted in Mediterranean mountain forests with *Q. pyrenaica* established on Umbric Leptosols and *Q. rotundifolia* on stony Leptosols derived from basic rocks, demonstrates that the effects of grazing on soil compaction are more closely linked to the intrinsic properties of the soil than to grazing pressure itself. In *Q. pyrenaica* habitats, no measurable effect of grazing was observed on soil compaction in the surface layer (0–10 cm), indicating a high level of resilience to trampling under the conditions studied. In contrast, the highest values of penetration resistance were recorded under *Q. rotundifolia*, even with low-intensity, short-duration grazing. These values approached critical thresholds for root development, suggesting greater susceptibility of these soils to compaction due to their shallow profile, high stoniness, and lower organic matter content.

Soil texture, bulk density, and particularly moisture content were identified as key factors influencing resistance to penetration, with higher moisture clearly reducing compaction in surface layers by facilitating soil deformation and root penetration.

These findings indicate that, in Mediterranean mountain silvopastoral systems, the impact of grazing on soil structure is primarily governed by soil characteristics rather than by the presence of livestock per se. The results also highlight the value of penetrometers as practical and effective tools for assessing soil physical conditions in the field. However, accurate interpretation of penetration resistance data requires an integrated analysis that includes complementary variables such as soil moisture and texture. Such an approach improves the reliability of soil assessments and strengthens the knowledge base for land managers, farmers, foresters, and extension services.

Finally, the study confirms that Mediterranean forests dominated by *Q. pyrenaica* and *Q. rotundifolia* can support extensive grazing without causing degradation related to trampling or compaction. Even in cases where some degree of compaction was detected—such as under *Q. rotundifolia*—resistance values remained only slightly greater than those in ungrazed areas and were substantially lower than those typically recorded in open pastures lacking tree cover. These results reinforce the ecological compatibility of extensive livestock grazing with Mediterranean forests, creating favourable conditions for the implementation and development of genuine silvopastoral systems adapted to these landscapes.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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