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Multivariate assessment of the relationships between soil carbon stocks and plant communities in the Ait Hatem forest at the Moroccan central plateau

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ABSTRACT

This study was conducted to assess the carbon storage potential of forest soils under different vegetation types in the Moroccan Central Plateau, specifically in the Ait Hatem Forest. For each plant community, ten soil samples were collected from the top 30 cm and analysed in the laboratory to determine various physicochemical properties, including soil organic carbon (SOC). To characterize the relationships among soil properties, plant communities, and environmental variables, a multivariate factor analysis of mixed data (FAMD) was employed, combined with analysis of variance (ANOVA) to assess the effect of plant communities on soil physicochemical parameters. Our results revealed a strong influence of vegetation community composition on soil carbon stocks. The highest average SOC content was observed in the community dominated by stands of holm oak (*Quercus rotundifolia* Lam.) associated with more than one species of Cistus. Intermediate to high values were observed in the other plant communities, as well as in the community composed of stands of Barbary cedar (*Tetraclinis articulata* [Vahl] Masters), highlighting the major effect of floristic composition on SOC stocks. These findings suggest that differences in plant community composition, as well as potential interspecific interactions, are associated with variations in soil carbon stocks and must be taken into account when designing management and conservation strategies aimed at maintaining or enhancing soil carbon stocks.

Keywords: SOCS, environmental variables, plant communities, Central Plateau, Morocco.

INTRODUCTION

Against the backdrop of climate change, forest ecosystems play a crucial role in regulating the carbon cycle (Lorenz and Lal, 2009, 2014). Indeed, these ecosystems constitute a major carbon sink and manage to store around 861 gigatonnes of carbon globally, 44% of which is stored in forest soils (Mayer et al., 2020 ; Kocoglu et al., 2024), making soil organic carbon (SOC) one of the main terrestrial carbon reservoirs and thus playing a decisive role in climate regulation, the preservation of soil fertility and the enhancement of forest ecosystems' resilience to climate change (Heuvelink et al., 2021; Sakhaee et al., 2022; Zhang et al., 2022 ; Wadoux et al., 2023). Consequently, organic carbon sequestration is regarded as a key pillar in the long-term reduction of greenhouse gas emissions and contributes to the sustainable improvement of soil quality and resilience (Lal et al., 2013 ; Pouladi et al., 2019 ; Wang et al., 2024).

In forest soils, the continuous addition of decomposing plant residues to the soil surface, together with root growth and decomposition, are the main sources of organic carbon (COS) (Conforti et al., 2016). They possess significant carbon sequestration capacities, whether in vegetation, humus or soil (Bernoux et al., 2011). Rising levels of carbon dioxide (CO_2) in the atmosphere lead to increased carbon sequestration in terrestrial ecosystems (Norby et al., 2005), particularly in forests. These play a vital role in maintaining the planet's ecological balance. They not only preserve biodiversity, reduce soil erosion and protect catchment areas, but also promote surface and underground ecosystem services (Nandal et al., 2023). To achieve balanced growth whilst improving environmental quality, it is essential to have a thorough understanding of soils, including their properties, functions, ecological roles and management (Weil and Brady, 2017).

Globally, forests are major reservoirs of biodiversity, home to more than 70% of terrestrial species (FAO, 2020). However, deforestation, fragmentation and the degradation of forest ecosystems are leading to a significant decline in biodiversity. Large-scale experiments have demonstrated a significant positive impact of the diversity and composition of plant communities on processes such as biomass production, nutrient use, organic matter decomposition, etc. (Tilman et al., 1997).

The Mediterranean region, owing to its size, the complexity of its terrain and its climatic diversity, is a region of exceptional plant cover diversity. Over the past 10.000 years in the eastern Mediterranean, human activity has played a significant role in the degradation of these ecosystems. However, during the Holocene, the major changes in vegetation cover across the entire Mediterranean basin cannot be attributed solely to human activity (Sadori et al., 2008). In addition to human activity, climatic variations have also influenced the evolution of vegetation (Tahiri et al., 2013).

In Morocco, forest ecosystems act as strategic carbon sinks and play a crucial role in mitigating climate change, combating desertification and conserving soil (Rodrigues et al., 2020). In particular, the forests of Morocco's central plateau perform essential ecological functions by stabilising soils and regulating biogeochemical cycles (Ikraoun et al., 2022). However, these ecosystems are subject to increasing anthropogenic pressure, exacerbated by climatic aridity and the intensification of soil degradation processes (Dallahi, Boujraf, et al., 2023). These dynamic compromises their carbon sequestration capacity and highlights the urgency of in-depth scientific assessments (Dallahi, Boujraf, et al., 2023). Organic carbon stocks have been estimated primarily by taking into account the influence of either quantitative or qualitative factors; few studies have incorporated all factors, and their interaction remains insufficiently explored. Furthermore, most studies carried out in Moroccan Mediterranean forests have focused on vegetation formations rather than vegetation communities.

Although the forests of Morocco's central plateau are of major ecological importance, studies examining their capacity to store soil organic carbon remain insufficiently in-depth (Dallahi, Malaainine, et al., 2023, 2023; Ikraoun et al., 2022, 2024). Comparisons of sequestration potential between different plant communities are rare and often addressed in a fragmented manner (Friedlingstein et al., 2021). Furthermore, existing studies rarely incorporate, within a unified analytical framework, continuous variables such as the physico-chemical properties of soils and qualitative variables such as geology or topographic position. This lack of multivariate approaches suited to mixed data limits a comprehensive and hierarchical understanding of the factors controlling carbon dynamics in these forest ecosystems. Few studies have been carried out on the forests of the Moroccan plateau; the Ait Hatem Forest has not been the subject of any study on SCO within the various plant communities using a FAMD.

The evolution of techniques for assessing SOC stocks has been marked by a shift from traditional methods, such as direct sampling and laboratory analysis, to more integrated approaches utilising remote sensing, spatial modelling and artificial intelligence (Hund and Schroeder, 2020; Razali et al., 2024). Despite these advances, obtaining reliable data remains challenging due to the high complexity of the factors influencing SOC, such as variability in soil types, diversity of vegetation cover, vegetation type, soil physico-chemical properties, topographical conditions, geological substrate and climate (Yoo et al., 2006). In addition to soil depth and land management practices (Hobley and Wilson, 2016; Li et al., 2022; Zhuo et al., 2022), there are also biotic and abiotic factors (Doetterl et al., 2015). In semi-arid regions, these determinants exhibit high spatial heterogeneity, leading to marked variability in carbon stocks at different scales (Wang et al., 2021). Despite this complexity, integrative studies simultaneously combining quantitative and qualitative variables remain limited in these ecological contexts, which restricts a detailed understanding of carbon sequestration mechanisms (Ellert et al., 2008).

Analysing the results using the FAMD method allows both quantitative and qualitative variables to be incorporated into a single model; by contrast, the PCA method incorporates only quantitative variables, whilst the AFC method incorporates only qualitative variables.

Considering the importance of forest vegetation communities in carbon sequestration, the objectives of this study are: (i) to quantify the organic carbon stock in the top 30 centimetres of soil, (ii) to compare the physico-chemical properties of soils across different vegetation formations and plant communities, and (iii) to explore the multivariate relationships between environmental variables and organic carbon stock.

MATERIALS AND METHODS

Study area

This study was conducted in the Ait Hatem Forest, located in the Moroccan Central Plateau (Figure 1). This area covers 21 591 ha between latitudes 33°22’0”N and 33°37’0”N and longitudes 5°48’0”W and 6°00’0”W, at elevations ranging from 700 to 1 200 m. The area is characterized by a semi-arid to sub-humid bioclimate with high spatial and temporal variability in precipitation. The vegetation is dominated by forest stands of Barbary thuja (*Tetraclinis articulata*) and holm oak (*Quercus rotundifolia*), which cover more than 87% of the total area.

This forest is generally composed of holm oak coppice stands on mid- and upper slopes, a stump-remnant forest of Barbary thuja at lower elevations and on warm slopes and a mature cork oak forest scattered across two blocks in the southern and northern parts of the forest (Dallahi, 2017). Secondary tree species and forest clearings cover a significant area of approximately 750.09 ha, representing 3.47% of the total forest area. These secondary tree species consist mainly of *Pistacia lentiscus* (mastic tree), *Olea europaea* var. oleastrum (wild olive), *Cistus salviaefolius* (sage-leaved rockrose), *Arbutus unedo* (strawberry tree), *Rhus penthaphylla* (Tizgha), *Chamaerops humilis* (Doum), etc. They are scattered throughout the forest, either within the main stands or forming small patches in the cool lowlands. From a pedological perspective, there is a

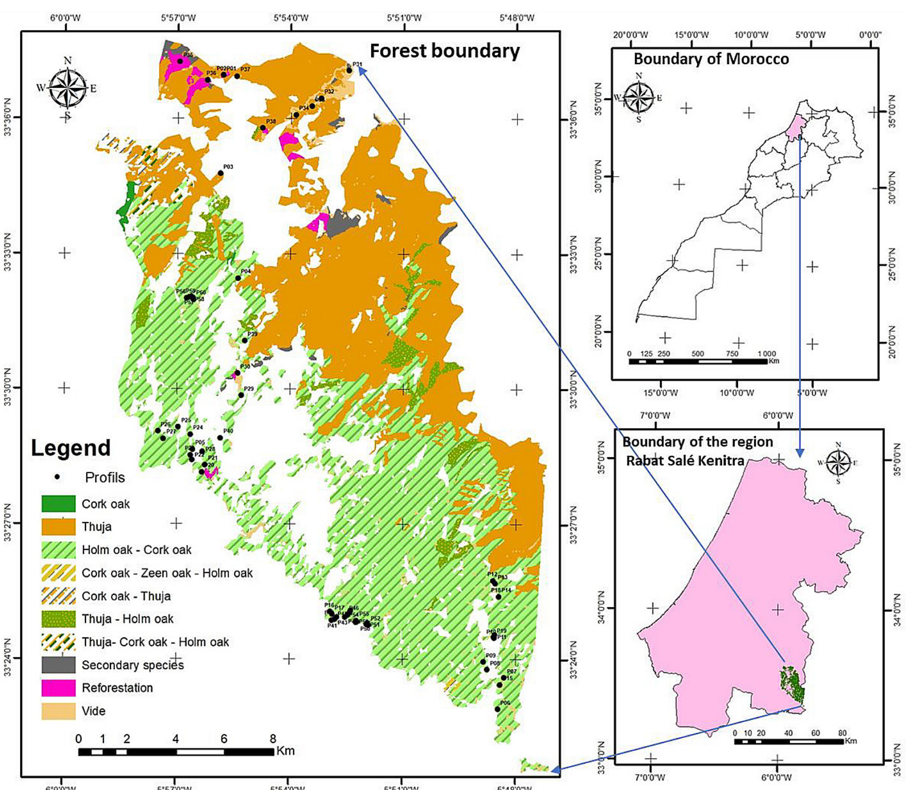

Figure 1. Study area showing the distribution of vegetation types and the selected sampling points

predominance of complex units, consisting of an association (of at least two soils types) of poorly developed regosolic erosion soils on schist, lithosols on sandstone and forest brown soils (MAPM, 1995). These soils generally develop under forest vegetation. They are followed by a complex of raw mineral soils and poorly developed soils (0.8%), and by poorly developed soils alone (0.2%), with a predominance of geological formations dating from the Paleozoic (Bouhdadi, et al., 2002; Izart et al., 2001a; Izart, et al., 2001b). The terrain is characterized by undulating relief.

Methodological approach

Sampling design and soil collection

The samples were selected using the map of stand types in the Ait Hatem Forest, following the identification of the six groups chosen on the basis of field observations in May 2023. Soil samples were collected according to a stratified sampling plan, using the main plant communities shown in Figure 2 as stratification units. A total of 60 samples were collected, 10 samples per plant community.

Sampling was conducted using an auger in the 0–30 cm soil layer (Figure 3), where root density is highest and exchanges between the soil and plant roots are significant (Ma et al., 2022; Zhao et al., 2021). This layer also receives substantial carbon inputs from surface litter, root exudates and the renewal of fine roots up to 30 cm deep in the soil profile (El Mderssa et al., 2024). Furthermore, this layer stores more than 80% of the carbon (Boulmane et al., 2010; Fonseca et al., 2012).

Assessment of soil physicochemical properties

The samples were analysed in the laboratory after being dried to constant weight, then ground and sieved through a 2-mm mesh. They were subsequently subjected to physicochemical characterization for the determination of soil properties and SOC stock. Carbon content was determined using the Walkley and Black method (Walkley and Black, 1934). Soil pH was measured in a soil-water suspension using a pH meter (Mclean, 1982). Total nitrogen was determined using the Kjeldahl method (Bremner and Jenkinson, 1960). Total phosphorus was determined after extraction with hot concentrated HNO_3, followed by concentrated $HClO_4$ and H_2SO_4 (Laurent and Brossard, 1991). Total potassium was extracted using boiling concentrated nitric acid and determined by flame photometry (Hesse, 1971). Particle size analysis was used to determine the proportions of clay, silt, and sand using the hydrometer method (Bouyoucos, 1962).

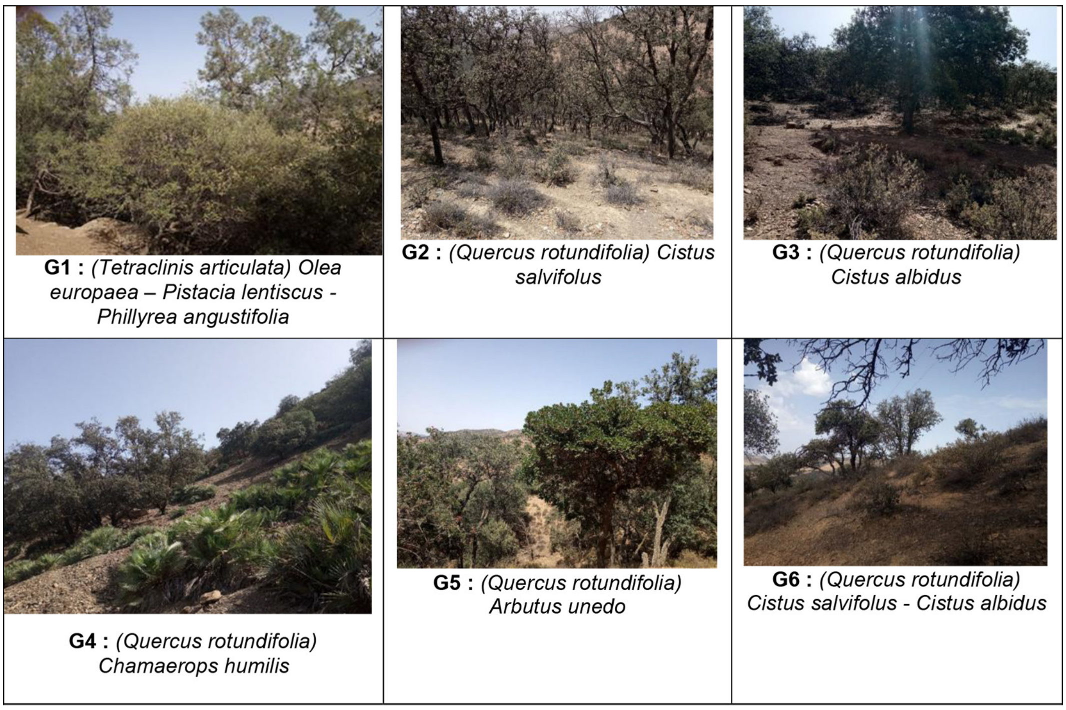

Figure 2. Photos of the different groups of plant communities in the study area

Taking a sample using an auger	Sampling at a depth of less than 30 cm	measuring the weight of the sample

Figure 3. Photographs of the field sampling procedure

Exchangeable cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) were extracted using a neutral normal ammonium acetate solution. Soil samples were also mineralized using aqua regia (Jackson, 1958), and these procedures provided the basis for determining exchange capacity. Dry matter content was determined as the fraction of material remaining after complete removal of water by oven drying. Organic matter was calculated according to the formula (Equation 1) found in the work of Solter (1988).

$$OM\ (\%) = C\ (\%) \times 1.724 \quad (1)$$

The carbon stocks of the sampled soils were calculated using bulk density (BD), organic carbon concentration, and sampling depth, according to the method (Equation 2) proposed by Batjes (1996). This approach estimates the amount of organic carbon stored per unit area, thus providing a standardized basis for comparing carbon storage among soils under different scenarios.

$$q(i) = 0.1 \times E(i) \times BD(i) \times C(i) \quad (2)$$

where: $q(i)$ is the soil organic carbon stock (t/ha), 0.1 is the conversion factor, $E(i)$ is the depth of layer i (cm), $C(i)$ is the organic carbon concentration in the fine soil fraction at depth i (g/kg), and $BD(i)$ is the bulk density of the fine fraction at depth i (g/cm^3).

Soil samples were collected using metal tins from a soil layer at a depth of less than 30 cm. The soil was then weighed and dried at 105 °C for 24 hours. Bulk density was calculated as the ratio of the dry mass of the sample to the volume of the cylinder used as shown in Equation 3.

$$BD = Ps / V_{cylinder} = Ps / \pi r^2 h \quad (3)$$

where: Ps is the dry weight of the sample, $V_{cylinder}$ is the volume of the cylinder, r is the radius of the cylinder, h is the height of the cylinder, and $\pi = 3.14$.

All analyses were conducted at the Research Unit for Environment and Conservation of Natural Resources at the National Institute for Agricultural Research (INRA) in Rabat. In addition to plant community, the explanatory variables considered in the analysis included topographic variables (altitude, slope, and aspect), derived from a digital elevation model (DEM), as well as edaphic variables, particularly geology and soil type. These variables were coded in accordance with Table 1 prior to statistical analysis.

Statistical analyses

In order to compare the physicochemical properties of soils across vegetation formations and plant communities and to explore the multivariate relationships between environmental variables and SOC, a Factor Analysis of Mixed Data (FAMD) was performed. This method is particularly suited to datasets that simultaneously include continuous and categorical variables (Lê et al., 2008). The analysis included all soil physicochemical parameters, two quantitative variables (altitude and slope) and four qualitative variables (vegetation community, geology, soil type, and aspect), the latter being considered potential explanatory factors of SOC variability. The results were interpreted on the basis of factor projections of individuals and variable categories, the relative contributions of the variables, the correlation matrix of the quantitative variables, as well as supplementary visualizations including boxplots of carbon stocks according to categorical variables and descriptive graphs of edaphic parameters. An analysis of variance (ANOVA) was used to study the effect of plant communities on soil physicochemical parameters. These are presented as degrees of freedom (df), the F statistic, and the

Table 1. Modalities codes for categorical variables included in the FAMD analysis

Variable	Modalities	Description
Geology	Geo1 Geo2 Geo3	Sandstone Schist and Limestone Schist and Sandstone
Soil type	Soil1 Soil2 Soil3 Soil 4	Burnished soils Complex soils Less developed soils Vertisols
Altitude	Alt1 Alt2 Alt3	Less than 700 m Between 700 and 1000 m More than 1000 m
Plant community	G1 G2 G3 G4 G5 G6	*Tetraclinis articulata – Olea europaea – Pistacia lentiscus – Phillyrea angustifolia* *Quercus rotundifolia – Cistus salvifolus* *Quercus rotundifolia – Cistus albidus* *Quercetum rotundifolio– Chamaerops humilis* *Quercus rotundifolia – Arbutus unedo,* *Quercus rotundifolia – Cistus salviifolius and Cistus albidus*
Aspect	ES NE SE WN	East South North East South East West North
Slope	Slope1 Slope2 Slope3	Less than 11% Between 11% and 25% Between 25% and 40%

p-value. The effect size (η^2) and its 95% confidence interval were calculated, and post hoc multiple comparisons using Tukey's test (HSD) were performed when the ANOVA was significant ($p < 0.05$). All statistical analyses were carried out in R (R Core Team, 2020) using the FactoMineR package (Lê et al., 2008)), with RStudio used as the development environment.

Figure 4 shows a summary workflow diagram illustrating the entire study process, from sampling through to laboratory analyses and statistical analysis.

RESULTS

Overview of soil physicochemical properties

The results shown in Figure 5 illustrate the distribution of the various soil variables measured, indicating significant variations in soil composition, whilst the calculated concentrations reveal marked physico-chemical heterogeneity in the soils of the different plant communities. This study showed that there is a variable distribution of cationic parameters (Ca^{2+}, Mg^{2+}, K^+, Na^+); the mean calcium value is 20.30 meq/100 g and that of magnesium is 7.94meq/100 g, with a maximum value for G6. Potassium has an average of 1.33 meq/100 g, whilst the average value for phosphorus is 28.29 meq/100 g and that for sodium is 2.84 meq/100 g. Groups 3 and 4 are characterised by high Na^+ concentrations; these two groups store less carbon. The cation exchange capacity (CEC) reaches a maximum value of 37.88 meq/100 g for G1. This same group records a maximum of 0.95 dS/m for electrical conductivity, indicating low salinity, which is favourable for plant growth. Total nitrogen has high values for groups characterised by high carbon storage. The pH values of the water range from 6.22 to 7.15, whilst those of the KCl solution range from 6.04 to 7.03; this indicates that our soils are slightly acidic, with the exception of G1, which is neutral, a condition that promotes the uptake of essential nutrients and ensures plant growth. Organic matter content ranges from 8.31% to 10.68%, playing a role in soil fertility and water retention, as does total carbon, which varies between 4.83 and 6.21 g/kg.

Soil texture analysis is determined by the proportion of sand, silt and clay. The sand fraction averages 32.46%, the silt fraction is 32.23%, whilst the clay fraction is 35.31%. The highest value is for clay, which influences soil structure and consequently carbon sequestration and soil stability. The average bulk density is 1.05 g/cm³, with a low value for G6, which has the highest carbon storage capacity; this indicates a fairly light and aerated soil that promotes root development.

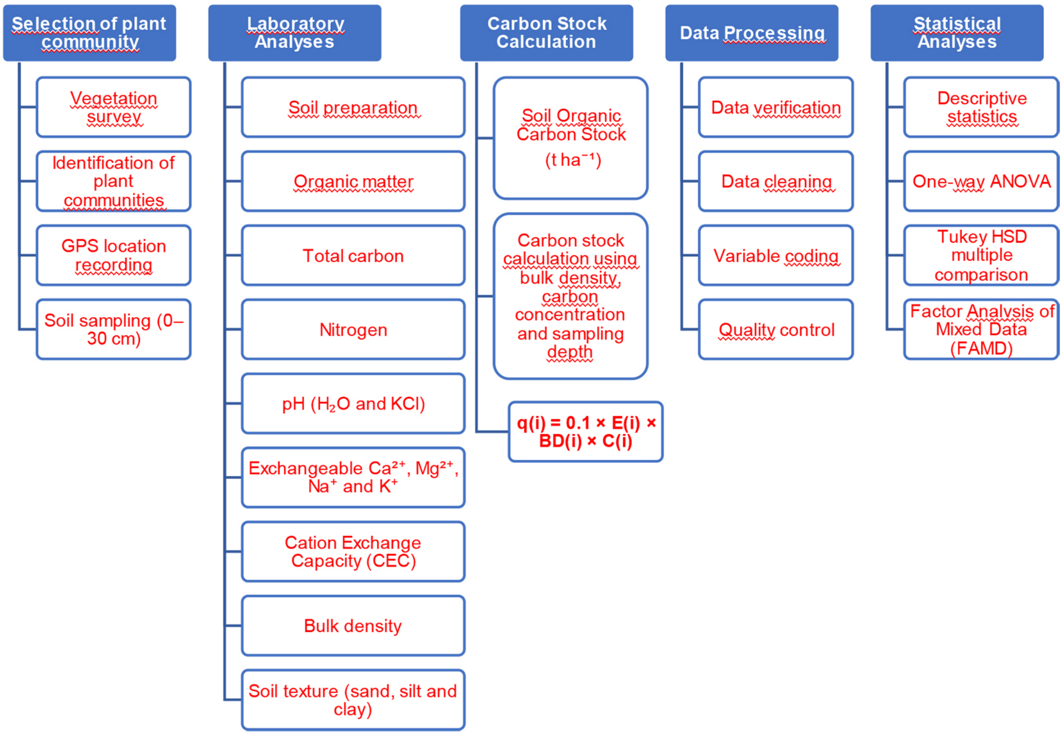

Figure 4. Summary diagram of the methodology used

Analysis of the effect size (Table 2) showed that plant community had a significant effect on the variable under study ($\eta^2 = 0.25$; 95% CI: 0.05–1.00), indicating that approximately 25% of the observed variance was explained by differences between plant communities.

The ANOVA analysis (Table 3) revealed significant differences between plant communities in terms of pH (water and KCl), Mg^{2+} content, electrical conductivity and phosphorus ($p < 0.05$). This difference indicates that these soil chemical properties vary according to plant community, whilst the other parameters were not significant.

According to Table 4, the post hoc comparisons carried out using Tukey's test revealed no significant differences between the various plant communities; values of $p > 0.05$ indicate the absence of a statistically significant difference between the groups in question. With the exception of Group 3, comprising G1, G4 and G5, as the comparisons with an adjusted p-value of less than 0.05 were considered significant.

Following an analysis of the soil's physico-chemical characteristics, the carbon stock will be assessed for the various plant communities selected.

Variation of organic carbon stock by vegetation types and plant communities

The results in Figure 6 show that carbon stock varies among vegetation types. In the holm oak stand, carbon stock ranges from 5.39 to 42.17 t/ha, with an average of 16.43 t/ha. Meanwhile, in thuja-dominated stands, values range from 11.44 to 29.37 t/ha, with an average of 17.82 t/ha.

Figure 3 highlights significant variability in SOC stocks across plant communities. The G6 community, dominated by *Quercus rotundifolia* in association with *Cistus albidus* and *Cistus salviifolius*, has the highest average value (18.95 t/ha). Intermediate levels are observed for G1 community, consisting of *Tetraclinis articulata* associated with *Olea europaea*, *Pistacia lentiscus*, and *Phillyrea angustifolia* (17.82 t/ha), as well as for G4 (17.04 t/ha), dominated by *Chamaerops humilis*, and for G5 (16.55 t/ha), characterized by association with *Arbutus unedo*. The G3 community (16.40 t/ha) and, even more clearly, the G2 community (13.41 t/ha), both dominated by *Quercus rotundifolia* in combination with *Cistus albidus* and *Cistus salviifolius*, recorded lower values.

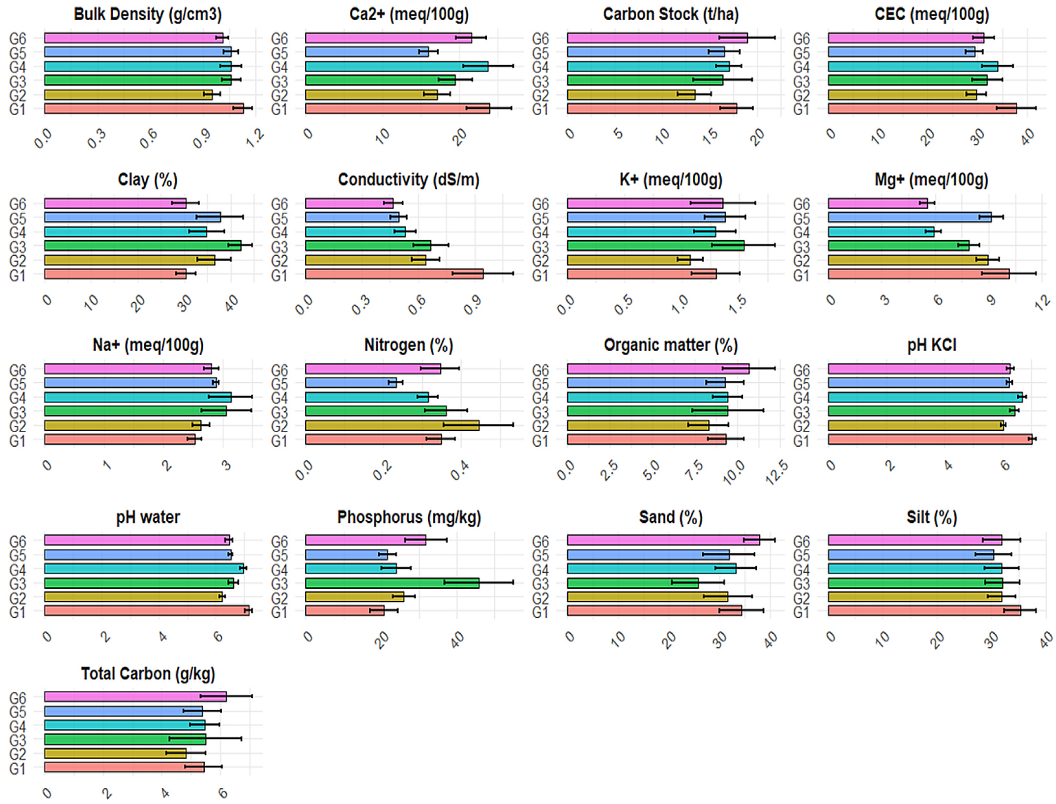

Figure 5. Soil physicochemical properties in different plant communities (ANOVA), *Means ± SE | ns $p > 0.05$, *$p < 0.05$, **$p < 0.01$, **$p < 0.001$

Table 2. Effect Size for ANOVA

Parameter	ETA²	CI	CI_Low	CI_High
Plantcomm	0.24530914	0.95	0.04625107	1

Table 3. ANOVA results for physicochemical parameters using Tukey's method

Paramètre	Df	Valeur F	Valeur p	Signification
Organic matter (%)	5	0.296	9.13e-01	ns
Total carbon (g/kg)	5	0.296	9.13e-01	ns
pH water	5	7.860	1.28e-05	***
pH KCl	5	7.580	1.88e-05	***
Ca^{2+} (meq/100 g)	5	2.008	9.22e-02	ns
Mg^{2+} (meq/100 g)	5	5.264	5.22e-04	***
Na^{+} (meq/100 g)	5	0.883	4.99e-01	ns
K^{+} (meq/100 g)	5	0.515	7.64e-01	ns
CEC (meq/100 g)	5	1.274	2.89e-01	ns
Nitrogen (%)	5	1.844	1.20e-01	ns
Bulk density (g/cm³)	5	1.351	2.57e-01	ns
Carbon stock (t/ha)	5	0.744	5.94e-01	ns
Sand (%)	5	0.750	5.90e-01	ns
Silt (%)	5	0.270	9.27e-01	ns
Clay (%)	5	1.620	1.70e-01	ns
Conductivity (dS/m)	5	3.823	4.89e-03	**
Phosphorus (mg/kg)	5	3.510	8.06e-03	**

Table 4. Tukey's post hoc multiple comparisons between plant communities

Contrast	Estimate	Se	Df	T. Ratio	P.Value
G1–G2	-5.238	7.14	54	-0.733	0.9769
G1–G3	-25.164	7.14	54	-3.523	0.0108
G1–G4	-3.206	6.98	54	-0.459	0.9973
G1–G5	-0.972	7.14	54	-0.136	1.0000
G1–G6	-11.088	7.34	54	-1.511	0.6590
G2–G3	-19.926	7.14	54	-2.789	0.0747
G2–G4	2.032	6.98	54	0.291	0.9997
G2–G5	4.266	7.14	54	0.597	0.9908
G2–G6	-5.850	7.34	54	-0.797	0.9668
G3–G4	21.958	6.98	54	3.146	0.0306
G3–G5	24.192	7.14	54	3.386	0.0159
G3–G6	14.076	7.34	54	1.918	0.4028
G4–G5	2.234	6.98	54	0.320	0.9995
G4–G6	-7.882	7.18	54	-1.098	0.8801
G5–G6	-10.116	7.34	54	-1.378	0.7396

Variation of organic carbon stock by edaphic and topographic factors

SOC shows marked variability depending on edaphic and topographic characteristics (Figure 6). Geologically, sandstone substrates have the highest average values (18.78 t/ha), followed by shale formations and mixed shale–sandstone substrates (15.82 t/ha), while calcareous contexts have the lowest levels (11.53 t/ha). Regarding soil types, complex soils (soil2) are characterised by a high average SOCS (18.07 t/ha), followed by poorly developed soils (soil3; 16.45 t/ha) and vertisols (soil4; 14.02 t/ha), while brown soils (soil1) have the lowest stocks (12.58 t/ha).

Topographic factors also confirm a significant variation in SOCS. Slopes of less than 11% have the highest values (18.51 t/ha), compared to slopes of 11–25% (15.49 t/ha) and 25–40% (17.03 t/ha). Furthermore, stocks are higher (17.35 t/ha) at altitudes below 700 m than those between 700 and 1000m (16.30 t/ha) and above 1.000 m (14.69 t/ha), indicating a gradual decrease in SOCS as altitude increases. Finally, aspect also influences carbon distribution: east–south (ES) slopes have the highest average values (19.11 t/ha), followed by southeast (16.43 t/ha), northeast (15.36 t/ha), and west–north (14.46 t/ha).

The correlation matrix between the various variables (Figure 7) shows a positive correlation between carbon stock and organic matter, as well as total carbon ($r = 0.95$). Moderate positive correlations are also observed with phosphorus, Ca^{2+} and CEC, whilst negative correlations are found with Na^{+}, K^{+}, bulk density and the sand and silt contents. Furthermore, a very strong positive correlation is recorded between CEC and calcium ($r = 0.93$), whilst the other relationships show moderate or weak correlations.

FAMD of soil gradients and plant community differentiation

Figure 8 shows the factor structure derived from the FAMD and the contribution of the first two dimensions. Dimension 1 (Dim 1), which explained 16.1% of the total variance, is primarily determined by soil chemical variables, particularly exchangeable cations (K^{+}, Mg^{2+} and Ca^{2+}), reflecting a gradient in soil fertility. Dimension 2 (Dim 2), which explained 11.4% of the variance, is primarily associated with soil physical properties, particularly bulk density and textural fractions (clay and sand), reflecting a gradient related to texture and compaction. Factor projections also suggested a correlation between plant communities and total carbon, organic matter, cation exchange capacity (CEC) and pH (water and KCl), indicating associations between plant communities and soil chemical properties related to carbon stock.

The color-coded representation by plant community type (Figure 9) showed a clear separation of group 1 (G1), dominated by *Tetraclinis articulata*, which is characterized by its association

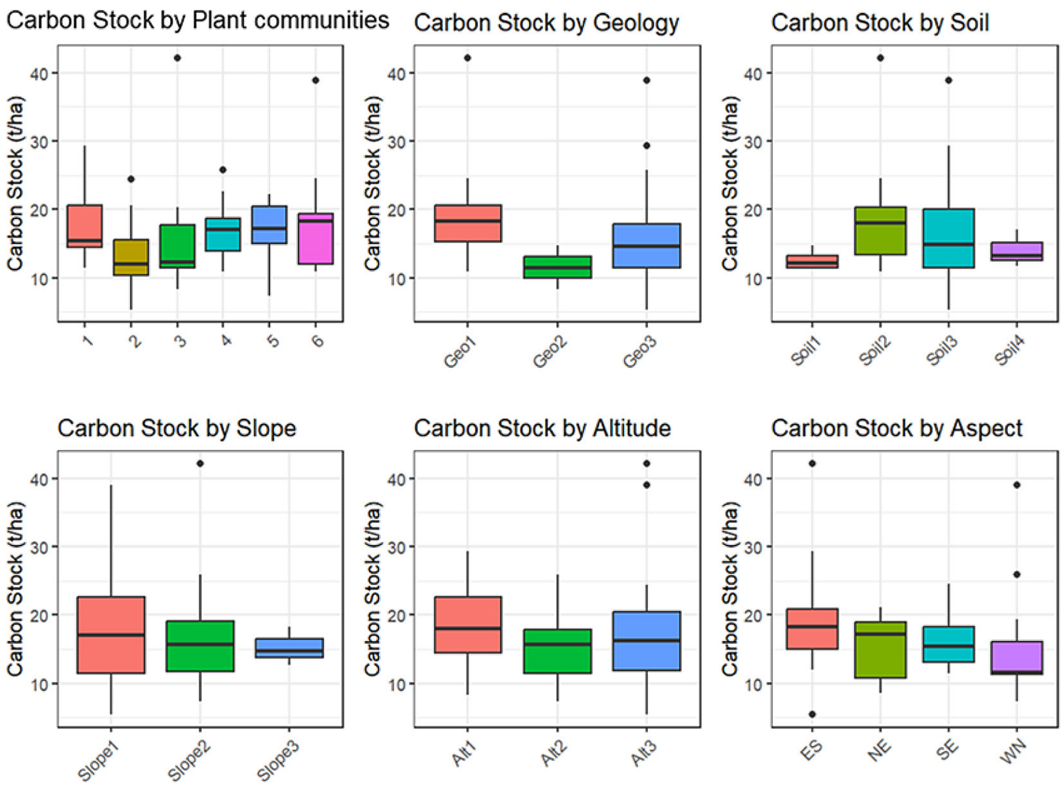

Figure 6. SOC stocks distribution in t/ha by categorical variables integrated in the FAMD

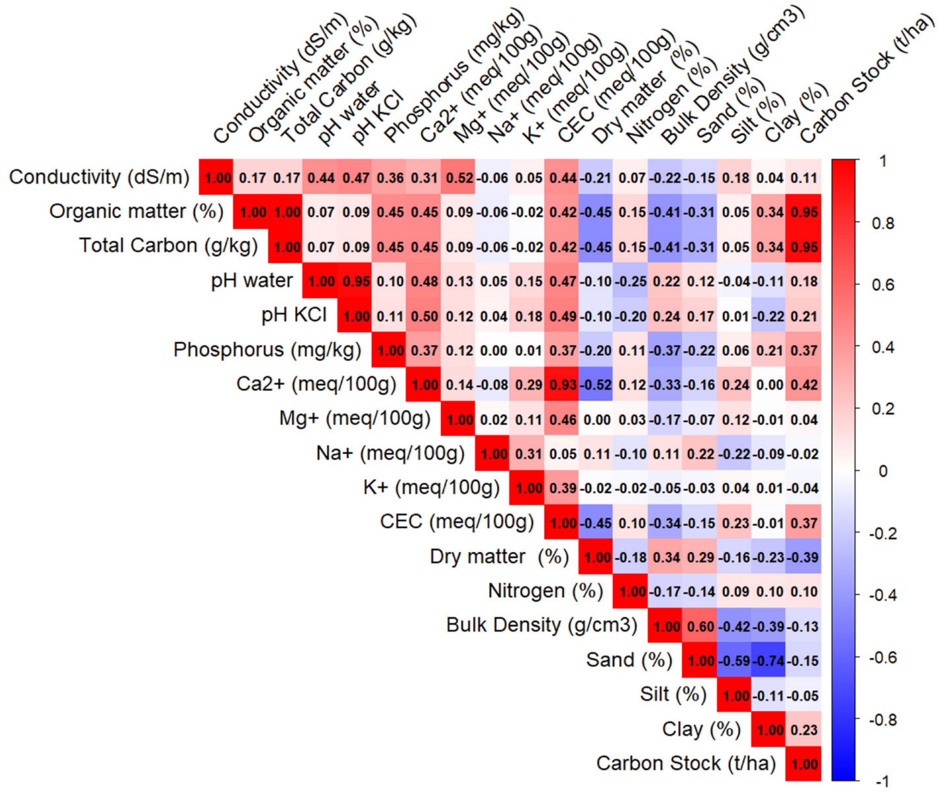

Figure 7. Correlation matrix for all quantitative variables

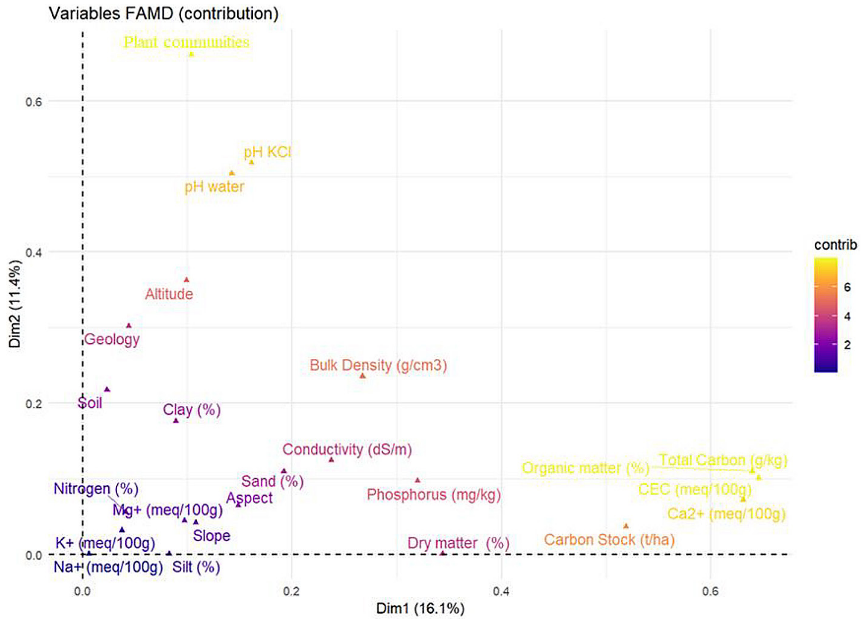

Figure 8. Projection of variables on the first two dimensions, showing the main chemical and physical gradients

with brown soils developed on schistose and calcareous substrates, located at altitudes below 700 m and on steep slopes (25–40%). The other communities dominated by *Quercus rotundifolia* are mainly located at an altitude of over 700 m and are associated with vertisols on schistose substrates, except for G5 and G6 communities, which are on complex soils. G3, G5, and G6 communities were mainly distributed on slight slopes (< 11%), while G2 and G4 are distributed across intermediate slopes (11–25%). Aspect was also shown to be an additional factor, contributing to the ecological differentiation of the communities.

An analysis of the correlations between the various variables (Figure 10) further clarified the influence of dimensions 1 and 2 (Dim 1 and Dim 2) on the distribution of pedological and chemical parameters. Organic carbon, organic matter and carbon stock were positively associated with Dim 1. The same was observed for phosphorus,

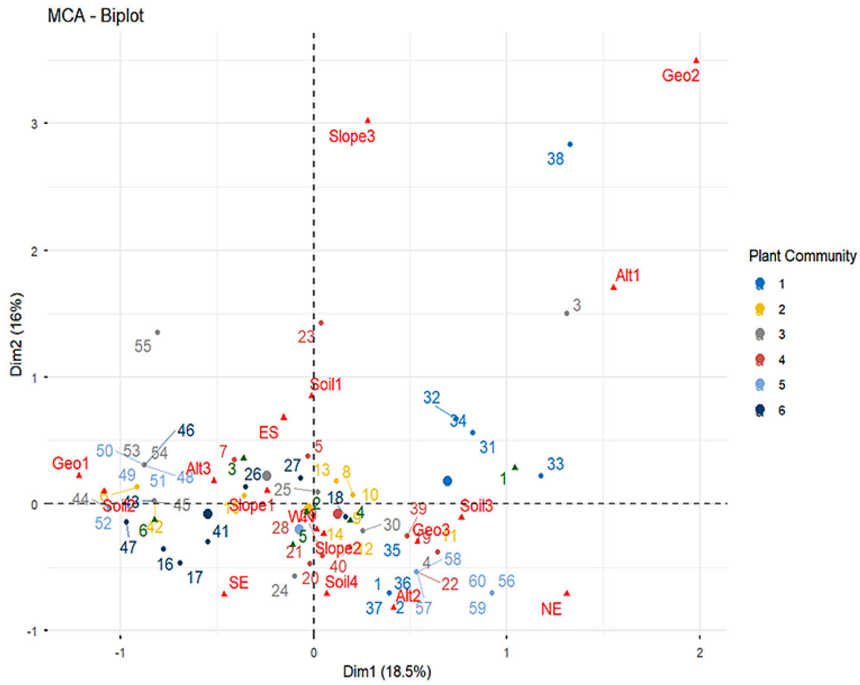

Figure 9. Projection of individuals and categories on the first two dimensions, coloured by plant community type

magnesium, electrical conductivity, nitrogen and pH. Dim 1 therefore appeared to be associated with the soil's chemical and nutrient characteristics, suggesting that this dimension reflects variation in soil chemical and nutrient status. Dim 2 is positively influenced by soil physical parameters such as sand, bulk density, dry matter, as well as sodium and potassium. This indicates that Dim 2 reflects variation related mainly to physical soil properties. Overall, these patterns suggest that differences in soil chemical quality and physical characteristics are associated with variation in carbon stock among the plant communities characterizing our study area.

DISCUSSION

The results obtained highlight substantial variability in soil organic carbon stocks, with values ranging from 5.39 to 42.17 t/ha. This range indicates significant carbon sequestration potential in the Ait Hatem Forest complex, underscoring the strategic role of forest soils in mitigating climate change. In a predominantly semi-arid context, these storage levels highlight the importance of soils as carbon reservoirs, echoing recent studies underlining the critical contribution of arid and semi-arid ecosystems to the global carbon cycle (L. Wang et al., 2024b).

The values obtained in this study are coherent with the ranges reported by (Ikraoun et al., 2022), who concluded that carbon storage in their study area, which is very close to ours, varies between 7 t/ha and 48 t/ha. Thus, in the holm oak (*Quercus ilex* L.) forests of the Middle and High Atlas, (Boulmane et al., 2015) estimated that the total soil organic carbon stock ranged from 141.4 t/ha at Ajdir to 24.6 t/ha at Asloul. In a previous study conducted in the Middle Atlas, (Boulmane et al., 2010) also reported values ranging from 63 t/ha at Tafachna to 47 t/ha at Reggada. Even higher values have been observed in other types of forest ecosystems. For example, (El Mderssa et al., 2024) estimated that the soil organic carbon stock ranged from 35 t/ha in treeless areas to 252 t/ha in mixed stands of Atlas cedar (*Cedrus atlantica*) and Canarian oak (*Quercus canariensis*). Similarly, in the cork oak (*Quercus suber*) ecosystem of the Maâmora forest, (Boujraf et al., 2023) reported values ranging from 55 t/ha to 95 t/ha, while (Oubrahim et al., 2016) estimated an average value of 121 Mg/ha in the north-western part of the same forest.

Furthermore, plant diversity promotes carbon sequestration in the soil (Qilong et al., 2023). Plant communities are often overlooked in carbon accounting, which led us to evaluate the SCOS in our study area by taking into account the various plant communities that exist there.

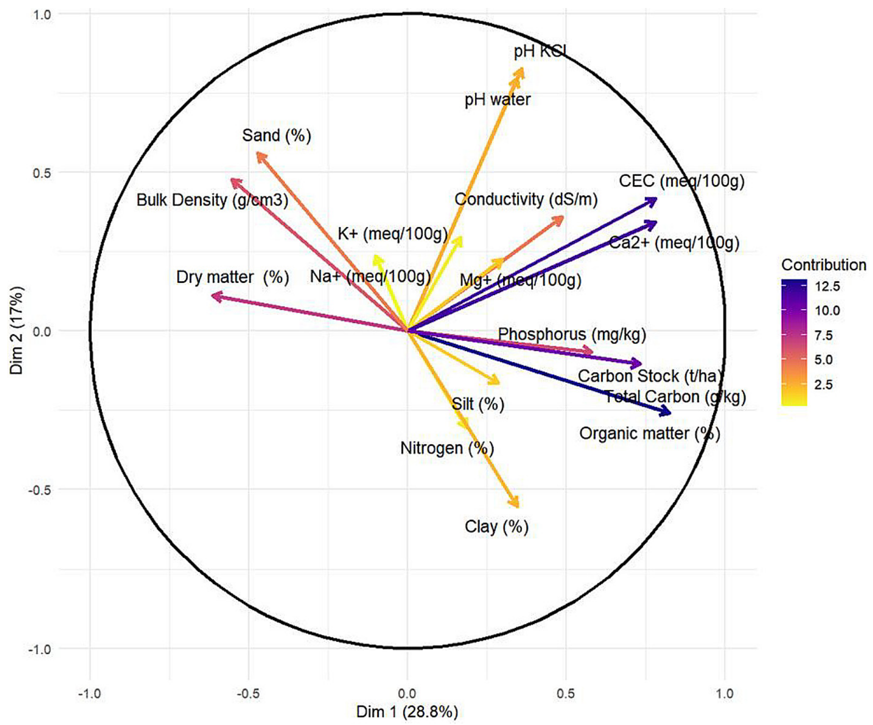

Figure 10. Correlation of quantitative soil and topographic variables on the first two dimensions

The results show that carbon sequestration is higher in Thuja types compared to holm oak stands, but when associated with shrub species, holm oak types store more carbon. Carbon stocks in broadleaf forests are among the highest (Monnoyer Smith, 2019). Studies in Spain shows that forests dominated by *Quercus ilex* have some of the largest carbon stocks and high sequestration capacities in dry Mediterranean climates (Lázaro-Lobo et al., 2023). Dense shrub understories also increase above-ground carbon stocks, but remain a minority compared to the tree and soil pools (van den Bor et al., 2024).

The species *Arbutus unedo*, which is found in very favourable site conditions, facilitates the establishment of *Quercus ilex* by creating a more shaded and humid microclimate (Richard et al., 2009), which explains the moderately high carbon storage rate for this group. Meanwhile, the group associated with the species *Chamaerops humilis* shows a lower increase in dry matter, indicates that this species was unable to increase its carbon sink intensity (Aranjuelo et al., 2009). Dense shrub layers also increase above-ground carbon stocks, but account for a smaller proportion compared with the carbon pools in trees and the soil (van den Bor et al., 2024).

Our analyses enable us to assess the capacity of soils to store carbon, support biodiversity and provide ecosystem services. They reveal considerable variability in soil parameters, which influence soil fertility and chemical properties. A high nitrogen content and a neutral pH are important for plant growth (Rawat et al., 2021).

Our soils are slightly acidic to neutral, which promotes the uptake of essential nutrients (phosphorus, calcium, magnesium and potassium) by reducing the solubility of toxic metals (Williston, 1978) and ensuring plant growth (Rawat et al., 2021). A variable distribution of cationic parameters (Ca^{2+}, Mg^{2+}, K^+, Na^+) plays a key role in soil fertility and chemical balance (Six et al., 2002; Sule et al., 2025; Weil and Brady, 2017). An excess of sodium in the soil causes salinisation, reduces fertility, degrades soil structure and impairs plant growth (Bello et al., 2021). The average nitrogen content is 0.34%; this value is similar to that found by (Tahiri et al., 2013) in the Quercus rotundifolia forest located in the Moroccan High Atlas, indicating the importance of nitrogen for soil fertility and plant growth (Govindasamy et al., 2023).

Our study has shown that there is a variable distribution of the measured parameters. Cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) play a key role in soil fertility and chemical balance (Sule et al., 2025). These cations are major soil elements that affect fertility (Weil and Brady, 2017) and carbon storage (Six et al., 2002). However, the uneven distribution of nutrients may be explained by stratification according to vegetation communities. It can be inferred from the present results that the physico-chemical properties of the soil vary with changes in vegetation composition.

Soil texture determines its ability to retain water and nutrients, its susceptibility to erosion, as well as its aeration and capacity to store carbon in the form of stabilised organic matter. It is a reliable variable as it is stable and changes only in response to long-term soil development (Gobat et al., 2004). The latter promote drainage and aeration and low water and nutrient retention capacity (Silva et al., 2021), while silt contributes to the retention of water and nutrients (Mengel et al., 1998). Both the clay and silt fractions play a double role in the formation and accumulation of stabilised soil organic carbon (Mao et al., 2024). The inverse relationship between sand and clay confirms their complementary roles in regulating soil properties and carbon sequestration (Franzluebbers, 2025). The fine fractions (silt and clay) retain most of the stabilised C and N due to their high specific surface area, high CEC and clay minerals (Churchman et al., 2020; A. Das et al., 2024; R. Das et al., 2019; Thabit et al., 2023). It has been demonstrated that the study conducted by (Martin Thiagaraja et al., 2025) focuses on the influence of the structural and chemical properties of clays on the preservation of organic carbon, which has implications for sustainable soil management and climate change mitigation.

The chemical and nutrient characteristics of the soil promote fertility and the sequestration of atmospheric carbon (Smagin et al., 2025), whilst the physical parameters of the soil are less conducive to carbon storage (Guarnieri et al., 2021; Alghamdi et al., 2023; Surda et al., 2024). These observations highlight the importance of striking a balance between chemical fertility and the physical structure of soils in order to optimise ecosystem management and their contribution to the carbon cycle.

Forest soils generally have a lower density than agricultural soils, which promotes porosity and water retention (Teepe et al., 2003). The Cistus community has the lowest density and is the most effective at storing carbon; it is also characterised by high levels of organic matter and total carbon.

Understanding their relationships and distribution helps to better manage forests and assess their carbon sequestration potential (Périé and Ouimet, 2008). The chemical and nutrient characteristics of the soil promote fertility and the sequestration of atmospheric carbon (Smagin et al., 2025), whilst the physical parameters of the soil are less conducive to carbon storage (Alghamdi et al., 2023; Guarnieri et al., 2021; Li et al., 2021 Surda et al., 2024). Our results are consistent with studies showing that changes in soil physicochemical properties are an important mechanism for regulating soil function and ecosystem resilience. Although conducted under different ecological conditions, studies by (Agbeshie et al., 2022) have shown that environmental disturbances alter several chemical and physical soil properties closely linked to nutrient availability and soil quality, highlighting the importance of considering these variables when interpreting soil organic carbon variability.

With regard to the effect of topography, a gentle slope allows organic matter to accumulate (Sanou et al., 2025) and consequently results in high carbon stocks at the foot of slopes, on slight slopes and in cooler aspects (L. Wang et al., 2024b). Indeed, the interaction between soil type and topographic level appears to be a key factor in assessing the soil organic carbon cycle (Sanou et al., 2025).

Numerous limitations have been identified and may concern both methodological aspects and the results obtained. Site selection was constrained by rugged terrain, leading to inaccessible locations, and the number of plots covered in this study remains relatively small.

CONCLUSIONS

This study highlights the importance of assessing soil organic carbon stocks in the Ait Hatem Forest on the Central Plateau and of identifying the impact of plant communities on this stock. The results confirm a relationship between plant communities and soil organic carbon stocks (SOC). However, it is important to note that this relationship cannot be understood without taking into account the impact of environmental factors. Soil characteristics, such as texture, pH and water-holding capacity, are essential for the stabilisation of organic carbon. Furthermore, topographical factors have an indirect influence on plant productivity and organic matter inputs. The type of geological substrate proves to be a determining factor, influencing both the physico-chemical properties of the soil and the development of plant communities. The relationship between these various elements creates significant spatial variability in SCOS, illustrating the complexity of ecological processes at the landscape scale. These results highlight the importance of developing carbon sequestration models for Mediterranean forest soils and provide crucial insights for sustainable management and targeted conservation in this semi-arid Mediterranean forest.

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