

# Pedodiversity as a Key Element of Geological Heritage in the Shouf Jezzine Geopark Project Lebanon

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## Research Article

**Keywords:** Geodiversity, pedodiversity, calcic horizon, forest soil, Shouf-Jezzine Geopark project

**Posted Date:** October 1st, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10996491/v1>

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**Additional Declarations:** No competing interests reported.

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# Pedodiversity as a Key Element of Geological Heritage in the Shouf Jezzine Geopark Project Lebanon

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## Abstract

Pedodiversity reflects the variability of soils in terms of composition, genesis, and properties, and it plays a role in terrestrial ecosystems. However, studies of Lebanese soils have largely overlooked the pedogenic accumulation of calcium carbonates ( $\text{CaCO}_3$ ), which limits our understanding of the formation of calcic horizons and the influence of past climatic and geochemical conditions.

This study examines the physical and chemical properties of soils under three forest species: *Pinus brutia* (*Pb*), *Pinus pinea* (*Pp*) and *Quercus calliprinos* (*Qc*), in the Shouf-Jezzine Geopark project, Lebanon. Fifteen soil profiles were analysed to determine their texture, carbonate content, organic matter, exchangeable cations and trace elements. Fieldwork enabled the identification and documentation of soil horizons, as well as the collection of soil samples from each horizon. Physico-chemical analyses carried out in the laboratory then revealed significant variations in soil parameters across different forest types. Calcic horizons, characterised by a high accumulation of  $\text{CaCO}_3$ , were most prevalent under *Pb* and *Qc*, whereas soils under *Pp* had lower carbonate contents. Furthermore, analysis of variance (ANOVA) and Pearson's correlations revealed no significant effect of soil depth or site on pH or electrical conductivity, but did show a positive correlation between silt content and  $\text{CaCO}_3$ . The soils under *Pb* trees had the highest organic carbon storage, highlighting their role in mitigating climate change.

These results provide a better understanding of how pedogenic carbonate dynamics vary across forest types, and highlight the ecological importance of forest soils for the conservation of biodiversity and the carbon sequestration.

**Keywords:** Geodiversity, pedodiversity, calcic horizon, forest soil, Shouf-Jezzine Geopark project

## 1. Introduction

Geodiversity encompasses all the geological, pedological, climatic, hydrological and geomorphological characteristics found on Earth [1]. Furthermore, it includes rocks, minerals, fossils, landforms, sediments and soils, as well as the processes that shape them [2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. Geodiversity plays an important role in ecosystem services by supporting biodiversity, water filtration, carbon sequestration, and soil formation. The abiotic components of geodiversity have a significant influence on biodiversity, thereby creating interdependencies that shape life on Earth [12, 13, 14].

Geodiversity includes not only the abiotic environment but also influences biotic diversity [12]. It is therefore regarded as the foundation of biodiversity [9, 13, 14]. There are thus close and positive links between biodiversity and geodiversity [3, 4, 9, 15, 16], which together sustain life on Earth's surface [17]. The relationships between geodiversity, biodiversity and human activity highlight the need to implement conservation and sustainable management practices.

Pedodiversity, an essential component of geology and ecosystem dynamics, refers to the variety and diversity of soils within a specific area or region [18, 19, 20]. Pedodiversity is a complex concept as it arises from the diversity of the atmosphere, biodiversity, hydrodiversity and lithodiversity within the ecosphere, which is altered by changes caused by human activity [18]. This concept highlights the role of pedodiversity in enhancing biodiversity, preserving geological heritage, increasing food production and carbon storage, conserving water, and its involvement in various ecological processes, making it a vital component of sustainable land management and biodiversity conservation [19, 21, 22].

Soil is a key element linking geodiversity and biodiversity. It contributes to plant growth, the regulation of hydrological processes and carbon sequestration, thereby influencing climate regulation [1, 19]. Among soil horizons, the calcic horizon is of particular importance due to its role in carbon storage and soil-forming processes. This horizon consists of secondary accumulations of calcium carbonate ( $\text{CaCO}_3$ ) [23, 24] that form during soil formation in arid and semi-arid regions [25, 26]. The presence of carbonate horizons provides information on soil genesis, climatic conditions, and geomorphological history.

The World Reference Base for Soil Resources (WRB) is an international soil classification system that standardizes the categorization of soils [27]. However, the WRB defines the calcic horizon as having a  $\text{CaCO}_3$  concentration of between 5 and 15% and a thickness of at least 15 cm. Consequently, the main findings suggest that the WRB classification appears to be essential for soil mapping and land-use planning, particularly in regions where carbonate-rich soils affect agricultural productivity and forest ecosystems.

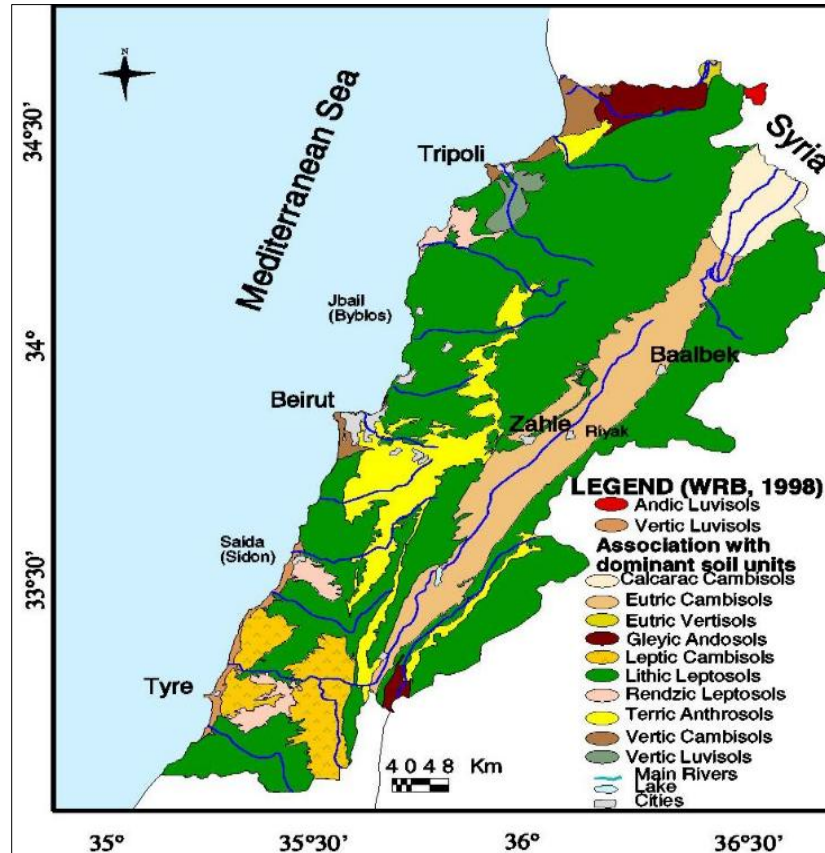


Fig. 1 Soil map of Lebanon (1:1,000,000) [28]

In Lebanon, the geological landscape consists mainly of carbonate rocks, notably limestone and dolomite, which cover 70 to 75% of the country's territory [29]. Given the existence of these formations, the available data indicate the presence of calcareous soils, which play a crucial role in hydrology, agriculture and forest ecosystems.

Furthermore, these results suggest that the country's topography encompasses different soil types. Moreover, shallow and stony soils, such as lithic leptosols and regosols, are common on rocky slopes, while deeper cambisols and other inceptisols develop in more stable mountainous areas [28] (Fig. 1). Terraced lands, often consisting of anthropogenic anthrosols, are traditionally used for growing fruit trees, whereas degraded lithic leptosols are used as pasture.

On moderate slopes, Mediterranean xeralfs (luvisols) occur, reflecting more advanced pedogenesis, whereas alluvial fluvisols and clay-rich vertisols dominate flat valley bottoms, where alternating wet-dry cycles influence root development and soil structure [28]. However, Lebanon's soils are increasingly threatened by deforestation, urban expansion, and overgrazing; major drivers of erosion in steep mountainous regions.

Although, Lebanon's forests, covering approximately 13% of the national territory, are predominantly composed of Mediterranean species such as *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos* [30, 31]. These data indicate that the interaction between

geology, soil properties, and forest ecosystems is a key factor in understanding ecological resilience and sustainability.

Despite the recognized importance of calcic horizons in soil formation and land management, these results show that their distribution, formation mechanisms and ecological implications in Lebanon remain largely unknown. Furthermore, this significant discrepancy could indicate that existing soil studies have not yet assessed variations in carbonate horizons across different forest types and along altitudinal gradients.

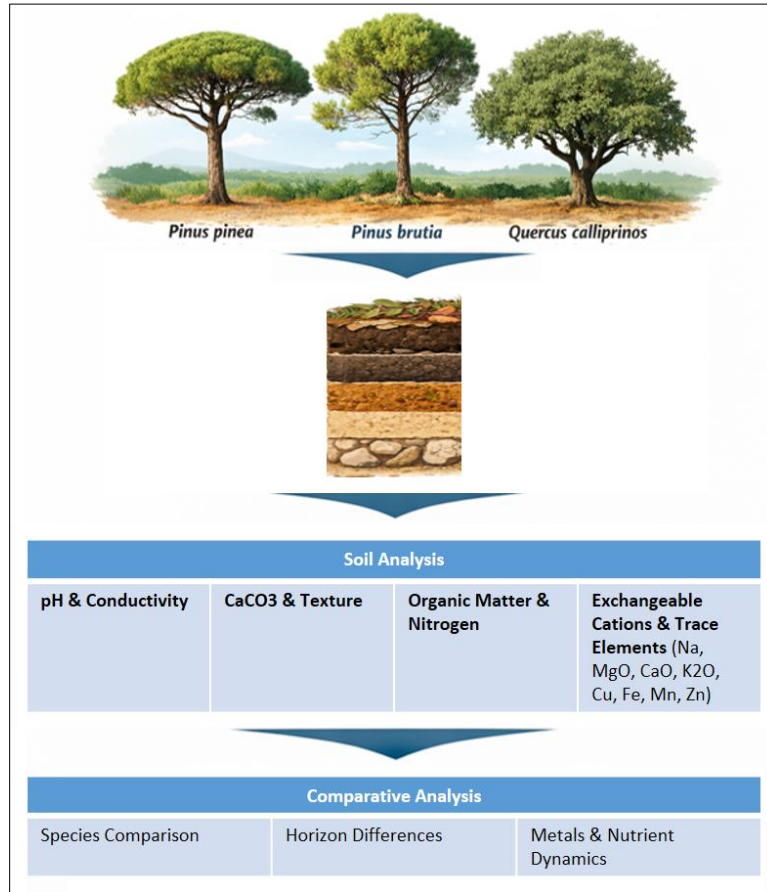


**Fig. 2** Horizon-specific variability of soil properties and elemental composition under different forest species

This study aims to address these gaps by assessing the physical and chemical properties of soils associated with three key forest species *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos*, within the Shouf-Jezzine Geopark project in Lebanon (Fig. 2). The objectives of the research are as follows:

1. To assess the physico-chemical properties of 15 soil profiles covering different horizons and forest species, with a focus on identifying calcic horizons.
2. To compare the soil parameters of the three forest species in order to understand their specific interactions with soil properties.

3. To analyze variations in soil carbon storage between the three forest types, exploring their role in mitigating climate change through the reduction of atmospheric carbon dioxide (CO<sub>2</sub>).

## 2. Materials and Methods

### 2.1. Study area

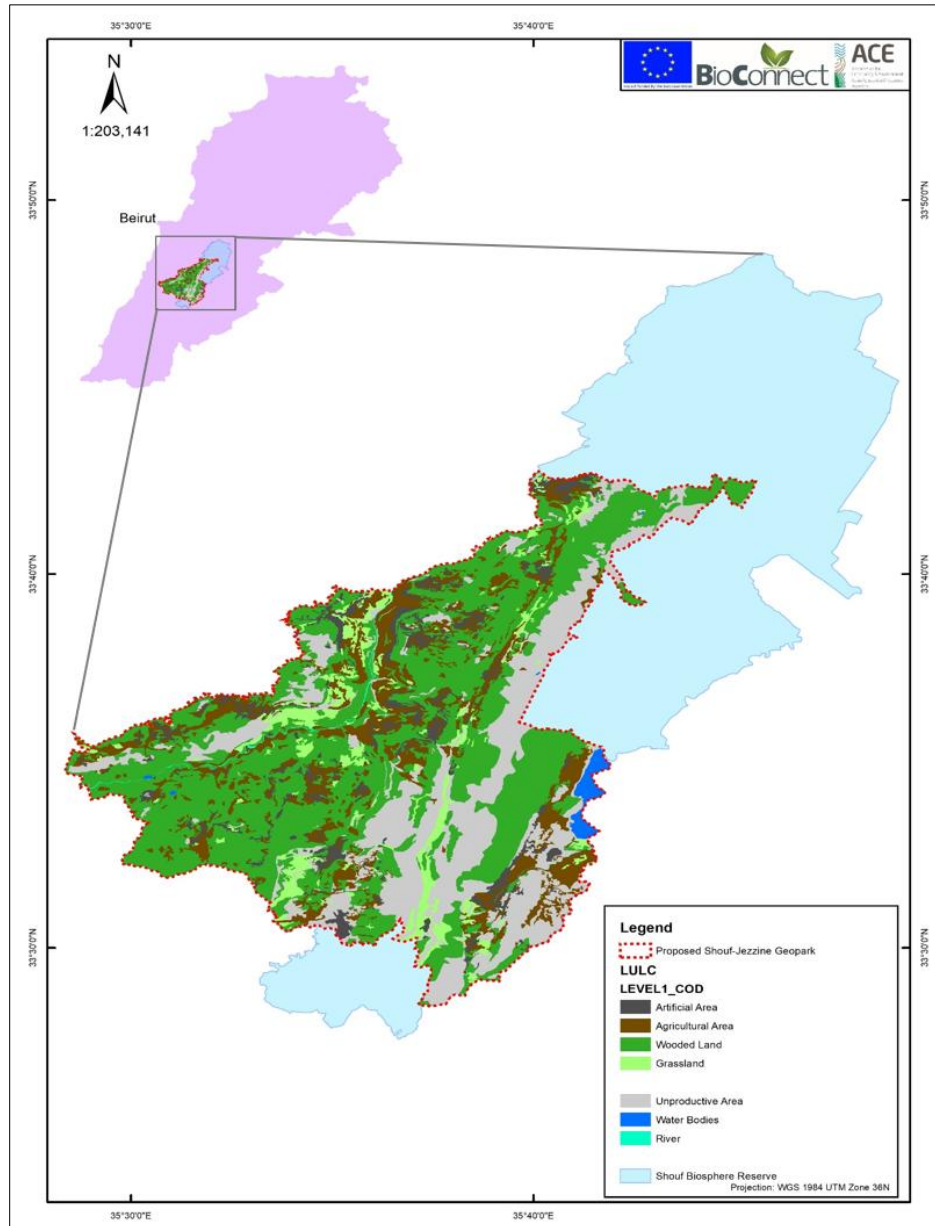


**Fig. 3** Location of the Shouf-Jezzine Geopark project and Land Use/Land Cover (LULC) within its boundaries

The study area is located in the central southern region of Lebanon, corresponding to the proposed Shouf-Jezzine Geopark project. This geopark encompasses the southern section of the Shouf Biosphere Reserve, parts of the cadastral areas of the Union of

Jezzine Municipalities, and additional areas within the Shouf district that extend beyond the biosphere reserve's boundaries to the west (Fig. 3). However, the defined boundaries of the geopark, which covers an estimated area of 289.83 km<sup>2</sup>, remain provisional. Furthermore, ongoing research as part of the BioConnect project, funded by the European Union, continues to refine its spatial extent.

This geopark boasts significant geological and ecological diversity, encompassing a wide variety of terrestrial fauna, including birds, mammals and bats. Furthermore, the Mediterranean climate, characterised by hot, dry summers and cool, rainy winters, could further enhance the ecological importance of this region.

The study focuses on three predominant forest species in the Shouf-Jezzine region: *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos*. However, these species were selected to facilitate the study of the soil horizons that appear to be associated with their habitats, given their ecological prevalence in the study area and throughout Lebanon.

## 2.2. Field Methodology

Fieldwork was conducted in October 2024 under dry weather conditions and high temperatures. Ten sites were selected within the Shouf and Jezzine districts to ensure representative coverage of three dominant forest species (Fig. 4), and a total of 15 soil pedons were examined using standard pedological techniques (Table 1).

**Table 1** Distribution of soil samples according to forest species and district

| Caza (district) | Sites         | <i>Quercus calliprinos</i> (Qc) | <i>Pinus pinea</i> (Pp) | <i>Pinus brutia</i> (Pb) |
|-----------------|---------------|---------------------------------|-------------------------|--------------------------|
| Jezzine         | Aazour (AZ)   |                                 |                         |                          |
|                 | Homsiyeh (HO) |                                 |                         |                          |
|                 | Sabbah (SA)   |                                 |                         |                          |
|                 | Bkassine (BK) |                                 |                         |                          |
| Shouf           | Niha (NI)     |                                 |                         |                          |
|                 | Dalboun (DL)  |                                 |                         |                          |
|                 | Mokhtara (MO) |                                 | common pedon            |                          |
|                 | Baadaran (BD) |                                 |                         |                          |
|                 | Mrusti (MR)   |                                 |                         |                          |
|                 | Bater (BT)    |                                 |                         |                          |
| <b>Total</b>    |               | <b>5</b>                        | <b>6</b>                | <b>5</b>                 |

One of these pedons where two forest species coexist within the same soil profile was purposefully chosen as a common pedon. In order to directly compare the impacts of vegetation under the same parent material, terrain, and microclimate, this pedon was included in the analysis. Therefore, the common pedon offers a special chance to separate the impact of tree species on soil characteristics, especially with regard to organic matter dynamics, nitrogen distribution, and exchangeable cations, by adjusting for edaphic and geomorphological variability.

The field process involved selecting sites based on forest composition and soil variability, recording each site's location and altitude using a GPS device, and delineating soil horizons by assessing carbonate presence through hydrochloric acid (HCl) effervescence testing. Soil horizon depths were measured using a measuring tape, and a scaled reference map was used to photograph soil profiles, which were later digitized in AutoCAD 2024. Soil samples, approximately 1 kg per horizon, were extracted using a shovel, placed in labeled nylon bags, and recorded with information including site name, forest species, horizon depth, and sample weight. The soil color was determined using the Munsell color chart before samples were transported to the laboratory for physical and chemical analysis. However, the selected and digitized soil profiles in AutoCAD illustrate the variation in soil horizons and their characteristics (Supplementary material - Annex 1).

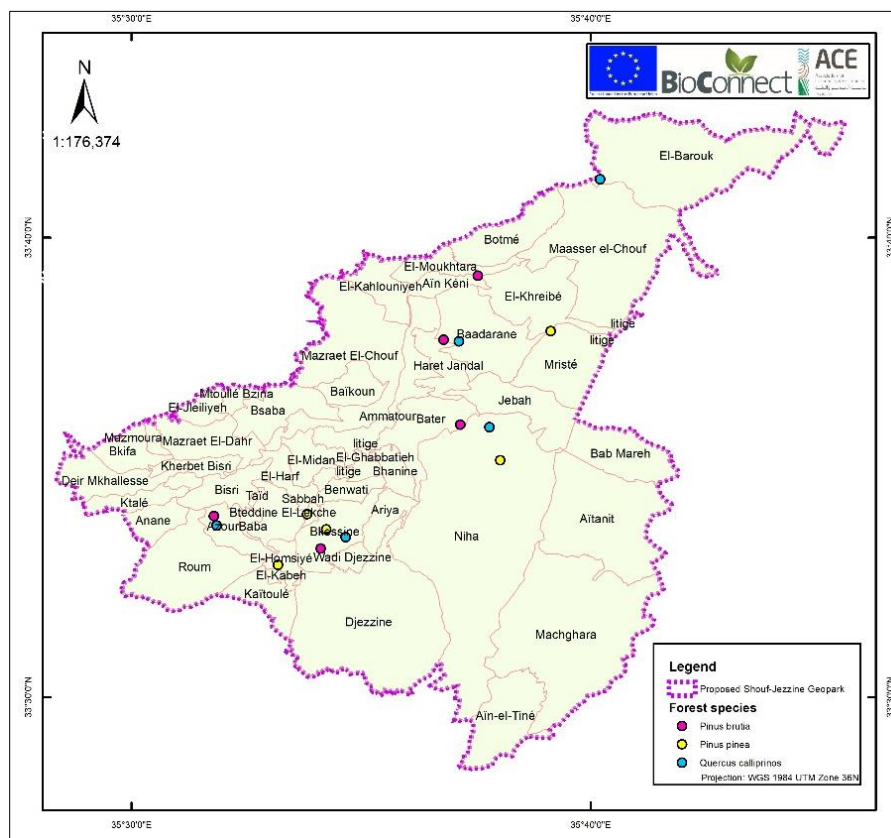


**Fig. 4** Soil sampling sites in the Shouf-Jezzine Geopark project

### 2.3.Laboratory Tests

Various laboratory tests were conducted on the 38 soil samples collected from all horizons of the 15 profiles within the Shouf-Jezzine Geopark project. Each sample was spread on a sterilized surface and left to air-dry for seven days in a well-ventilated room. Once dried, the soil was crushed using a mortar and pestle, then sieved through a 2 mm mesh to remove coarse particles such as roots, stones, and large organic debris.

The analyzed parameters included pH (ISO 10390:2005) and electrical conductivity (ISO 11265:1994), particle size distribution using the Bouyoucos hydrometer method (AFNOR X31-107:1983), water content determined by air-drying, and organic matter content measured using the Walkley and Black (1947) method. Organic nitrogen content was calculated, while total calcium carbonate content was determined using Bernard's calcimeter. Active calcium carbonate content was analyzed following the NF X31-106:1998 standard, and available phosphorus was assessed using the Olsen method (ISO 11263:1994). Exchangeable cations ( $K_2O$ , Na,  $MgO$ , and  $CaO$ ) were analyzed according to NF X31-108:1998, and trace elements (Cu, Fe, Mn, and Zn) were determined following ISO 14780:2001(E).

In addition, beyond fieldwork and laboratory tests, all collected data are used to generalize the various map layers generated in ArcMap 10.7.1, and statistical analysis of this data is performed using XLSTAT 2014 software. Furthermore, the analysis of soil carbon sequestration was conducted using satellite imagery from SoilGrids data.

### 3. Results and Discussion

#### 3.1. Altitudinal and Environmental Distribution of Forest Species

In October 2024, 38 soil samples were collected from three forest species: *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos*; across 15 soil profiles in the Shouf-Jezzine Geopark project.

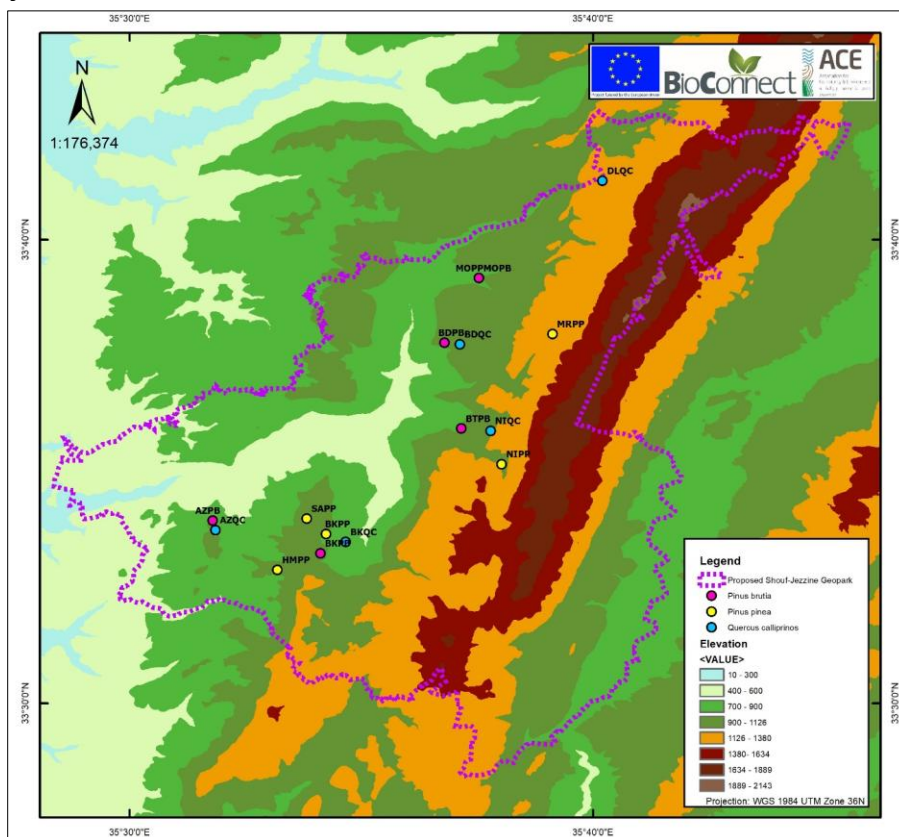


**Fig. 5** Distribution of forest species according to elevation

However, these species are found in different vegetation zones and at different altitudes (Fig. 5 and Fig. 6). For example, *Pinus brutia* was observed between 776 and 992 m, while *Quercus calliprinos* and *Pinus pinea* were recorded at altitudes of between 762 and 1,132 m and between 813 and 1,303 m, respectively. These altitudes therefore correspond to the eumediterranean (500–1,000 m) and supramediterranean (1,000–1,500 m) zones. This study supports recent findings that these three species belong to different vegetation zones and occupy specific altitudinal ranges, highlighting their biological requirements and demonstrating their ability to thrive under the environmental conditions of the study area, which are characteristic of their ecological niches.

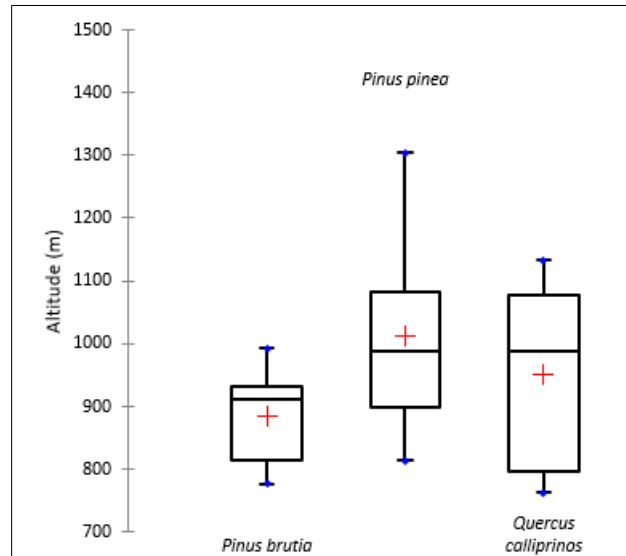


**Fig. 6** Elevation variation according to forest species

Geological analysis (Fig. 7) shows that *Pinus brutia* is predominantly found on C3 formations (alternating green marls and light limestones) and less frequently on C1 formations (Chouf sandstones), while *Pinus pinea* primarily inhabits C1 and occasionally C4 (light limestone) formations. *Quercus calliprinos* is particularly abundant on C4 limestone. Furthermore, hydrogeological data indicate that *Pinus brutia* and *Pinus pinea* grow in semi-aquiferous Quaternary and Cretaceous aquiferous formations, while *Quercus calliprinos* is generally found in Cretaceous aquiferous formations (Fig. 8), which may demonstrate that its dependence on permeable geological substrates retaining water facilitates its growth. Soil characteristics reveal that *Pinus brutia* favors red, sandy and mixed soils in hilly areas, while *Pinus pinea* prefers sandy soils, and *Quercus calliprinos* thrives on mixed soils in mountainous regions. However, after air-drying the collected samples, their final mass showed only very slight variation, indicating changes of less than 0.4%. Therefore, this minimal variation confirms that the soil was extremely dry at the time of sampling, as the soil particles were not bound together by a significant water content. These species probably possess ecological and physiological characteristics, such as a deep root system, low transpiration rates or efficient water-storage mechanisms, which enable them to withstand prolonged periods of drought.

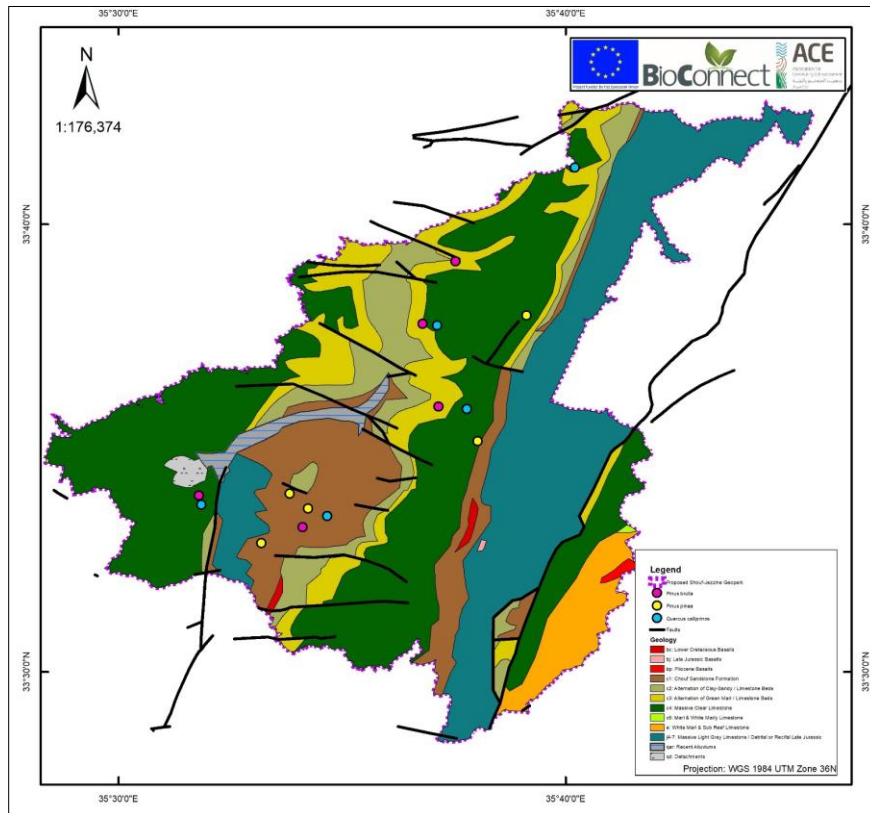


**Fig. 7** Distribution of forest species according to geology

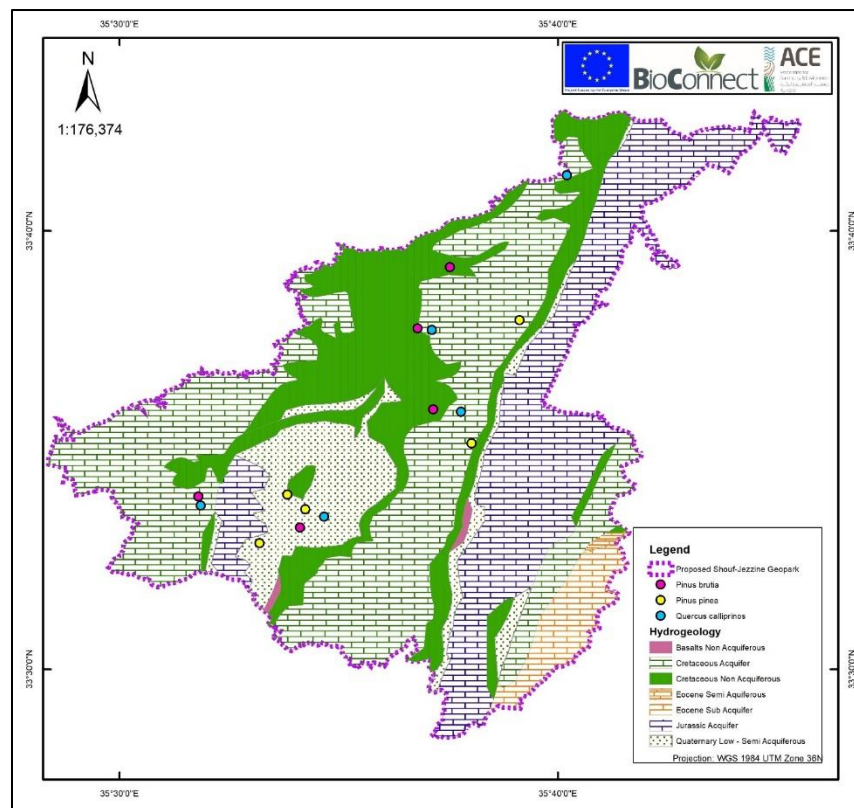


**Fig. 8** Distribution of forest species according to aquifers

To better understand these changes, a detailed analysis of soil properties such as pH, texture, organic matter content, and nutrient availability was conducted (Supplementary material - Annex 3). Laboratory test results for each forest species are presented below, allowing comparisons of parameter differences between species and soil depths. Multivariate statistical analyses, including analysis of variance (ANOVA) and Pearson correlation, were performed using XLSTAT 2014 to thoroughly assess the primary soil characteristics.

### 3.2.pH

Soil pH values showed minor fluctuations across depths, generally increasing with depth in the majority of soils studied for *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos*. This phenomenon is likely attributable to precipitation-induced leaching processes, leading to the movement of  $\text{Ca}^{2+}$  ions in alkaline soils from the surface to subsurface layers [32]. The pH values of the surface layer suggest that the soil is predominantly neutral to slightly alkaline (6.4–7.8) for *Pinus brutia*, and strongly acidic (2.3) to neutral to slightly alkaline (7.7) for *Pinus pinea*, and acidic (4.7) to neutral or slightly alkaline (8.0) for *Quercus calliprinos* (Fig. 9, Supplementary material - Annex 2). This trend can be attributed to the significant presence of carbonates inherited from the parent materials [32]. The uniformity of pH values across the different soil horizons and sites indicates limited leaching and suggests slow rates of weathering and soil development in these regions [33]. The results of the ANOVA tests showed no statistically significant effect of depth (p-value = 0.680 for *Pinus brutia*, p-value = 0.418 for *Pinus pinea*, and p-value = 0.391 for *Quercus calliprinos*) or site (p-value = 0.648 for *Pinus brutia*, p-value = 0.663 for *Pinus pinea*, and p-value = 0.649 for *Quercus calliprinos*) on soil pH, further confirmed by post-hoc tests, suggesting that the pH remained consistent (species grouped in the same category “A”) across depths and sites for all species.

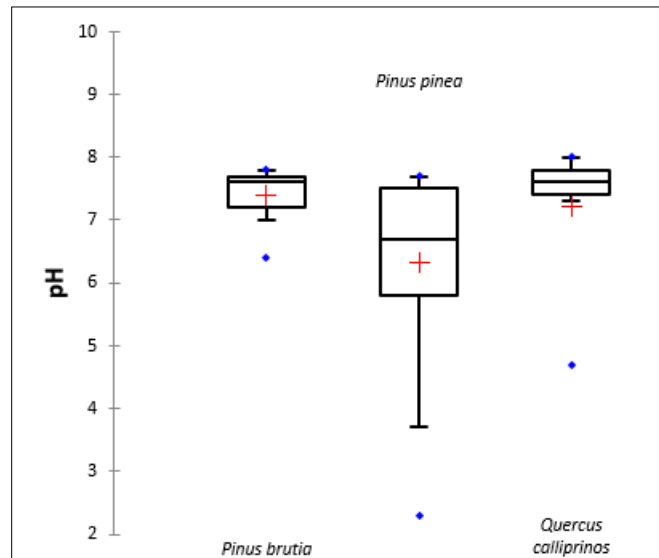


**Fig. 9** pH variation according to forest species

### 3.3. Electrical Conductivity

The presence of soluble salts in the soil solution is reflected by electrical conductivity (EC), which is commonly used as an indicator of soil salinity [34]. The absence of significant differences in EC and soluble cation values ( $p$ -value  $> 0.05$ ) between the horizons of each pedon suggests limited vertical movement of salts in the studied soils [33] (Fig. 10, Supplementary material - Annex 2). These results suggest that soil profiles exhibit limited vertical movement of salts, probably due to the Mediterranean climate with its seasonal water availability and the low solubility of certain salts. In the studied soils, the deep layer at Mrusti (associated with *Pinus pinea*) had the highest EC value at 0.8 mS/cm (Supplementary material - Annex 2); this was attributed to its relatively high organic matter content (5%), which contributes to the retention of salts and nutrients and ultimately increases the EC. The average EC of the other soils was much lower, ranging from 0.19 mS/cm for *Pinus brutia* to 0.13 mS/cm for *Pinus pinea* and 0.18 mS/cm for *Quercus calliprinos*. These values indicate that the soils are non-saline and generally favorable for plant growth, as salinity is not a limiting factor [33] (Fig. 10). For most soil profiles, EC was particularly high in the surface horizons, which can be explained by the accumulation of organic matter in these layers. Organic matter is an important factor influencing EC because it contains exchangeable ions that contribute to the soil's ionic conductivity. Nevertheless, EC remained largely constant across all horizons at Dalboun and Baadaran, where *Quercus calliprinos* predominates (Supplementary material - Annex 2). This consistency may be linked to the homogenisation of the clay caused by pedoturbation, a process which equalizes salt concentrations throughout the soil profile by redistributing clay particles and mixing the soil layers [33].

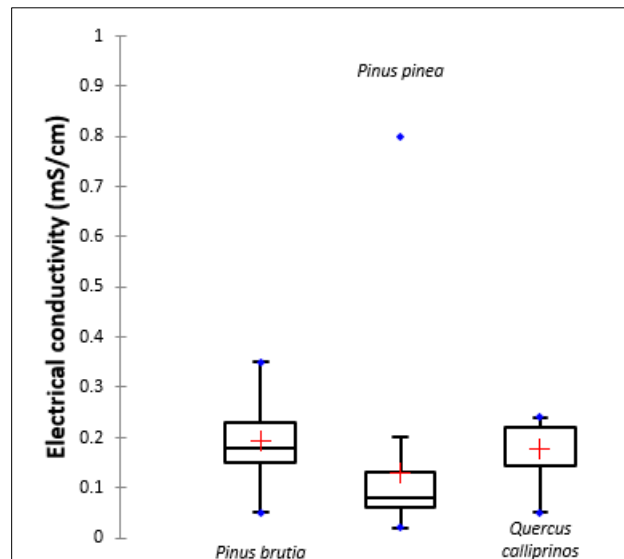


**Fig. 10** Electrical conductivity variation according to forest species

The ANOVA tests indicated no statistically significant effect of depth ( $p$ -value = 0.483 for *Pinus brutia*,  $p$ -value = 0.103 for *Pinus pinea*, and  $p$ -value = 0.455 for *Quercus calliprinos*)

or site (p-value = 0.215 for *Pinus brutia*, p-value = 0.398 for *Pinus pinea*, and p-value = 0.248 for *Quercus calliprinos*) on conductivity, with post-hoc tests confirming that all sites were grouped within the same category. However, a slightly significant relationship between conductivity and depth was observed at the 150-240 cm depth range at Mrusti, according to Fisher and Duncan tests. These results suggest that neither soil depth nor site significantly influences conductivity across the studied depths and sites.

### 3.4. Texture

For soil texture, the clay content in Aazour (associated with *Quercus calliprinos*), Bkassine (associated with *Quercus calliprinos*) and Niha (associated with *Pinus pinea*) ranges, respectively, from 16% at the surface to 36% at a depth of less than 80 cm, from 16% to 22% at a depth of less than 70 cm, and from 12% to 24% at a depth of less than 200 cm. The variation in clay content between the surface and subsurface horizons indicates the presence of a clay horizon buried at a depth of 70 cm or more. This clay horizon is particularly deep, with overlying calcareous materials, which suggests that it formed during wet periods [23, 33]. Furthermore, this was confirmed by the soil types determined according to the USDA for the sites, which are silty clay loam, sandy clay loam, and sandy clay loam, respectively (Fig. 11, Supplementary material – Annex 3). In contrast, in the other horizons, clay is uniformly distributed throughout the soil profile. The constant clay content implies that clay illuviation was not a dominant process in the upper horizons. This phenomenon is attributed to the flocculating effect of  $\text{CaCO}_3$ , which inhibits the movement of clay particles [33].

In the surface layers of the studied soils, a high silt content was consistently observed for all soil profiles and the three forest species (*Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos*). This phenomenon is caused by increased wind activity, which is essential for the deposition of fine particles such as silt, particularly in semi-arid and Mediterranean environments [23, 33]. Seasonal drought periods are common in the Shouf-Jezzine Geopark project, particularly in late summer and early autumn. During these periods, limited vegetation cover and dry, loose soil surfaces increase the susceptibility of the finest particles to wind erosion and redistribution. As there is less rainfall during these dry months, soil particles are less able to bind together, allowing the wind to transport and deposit finer silt fractions onto exposed surfaces.

Silt-rich soils often have a greater potential for nutrient adsorption, which benefits forest ecosystems such as Aazour associated with *Quercus calliprinos*, where the percentage of silt on the surface is 40%. The accumulation of silt on the surface can increase the availability of minerals necessary for tree growth, such as potassium, calcium, and magnesium.

Compared with finer soil fractions such as silt and clay, sand fractions showed a consistent distribution throughout the soil pedons, indicating minimal variability in their content. This uniformity suggests that sand particles are less affected by processes such as eluvation, illuviation, or wind deposition. The consistent sand fraction is likely derived from the underlying parent material, such as the sandstone formations frequently found

in the Shouf-Jezzine Geopark project, which are weather-resistant and constitute a reliable source of coarse particles.

Furthermore, as the sand particles are heavy and relatively large, they are less likely to be carried away by wind or water. This facilitates their stability and even distribution throughout the soil profile. This uniform distribution ensures good drainage and aeration, which benefits the root systems of tree species such as *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos*, which require well-drained soils to thrive. Soils with a higher proportion of sand are less prone to compaction, retaining their structure and promoting water infiltration and root growth; this is evident in all soil profiles of all species, based on the soil type determined according to the USDA (Fig. 11). Although sandy soils are well-drained, their reduced water-holding capacity could limit the availability of moisture for vegetation during prolonged periods of drought. This highlights the importance of having finer particles, such as silt and clay, to balance drainage and water retention. Furthermore, according to the WRB classification (2014), the majority of the soils studied are classified as cambisols (Supplementary material – Annexes 1 and 3), reflecting young soils with limited horizon development.

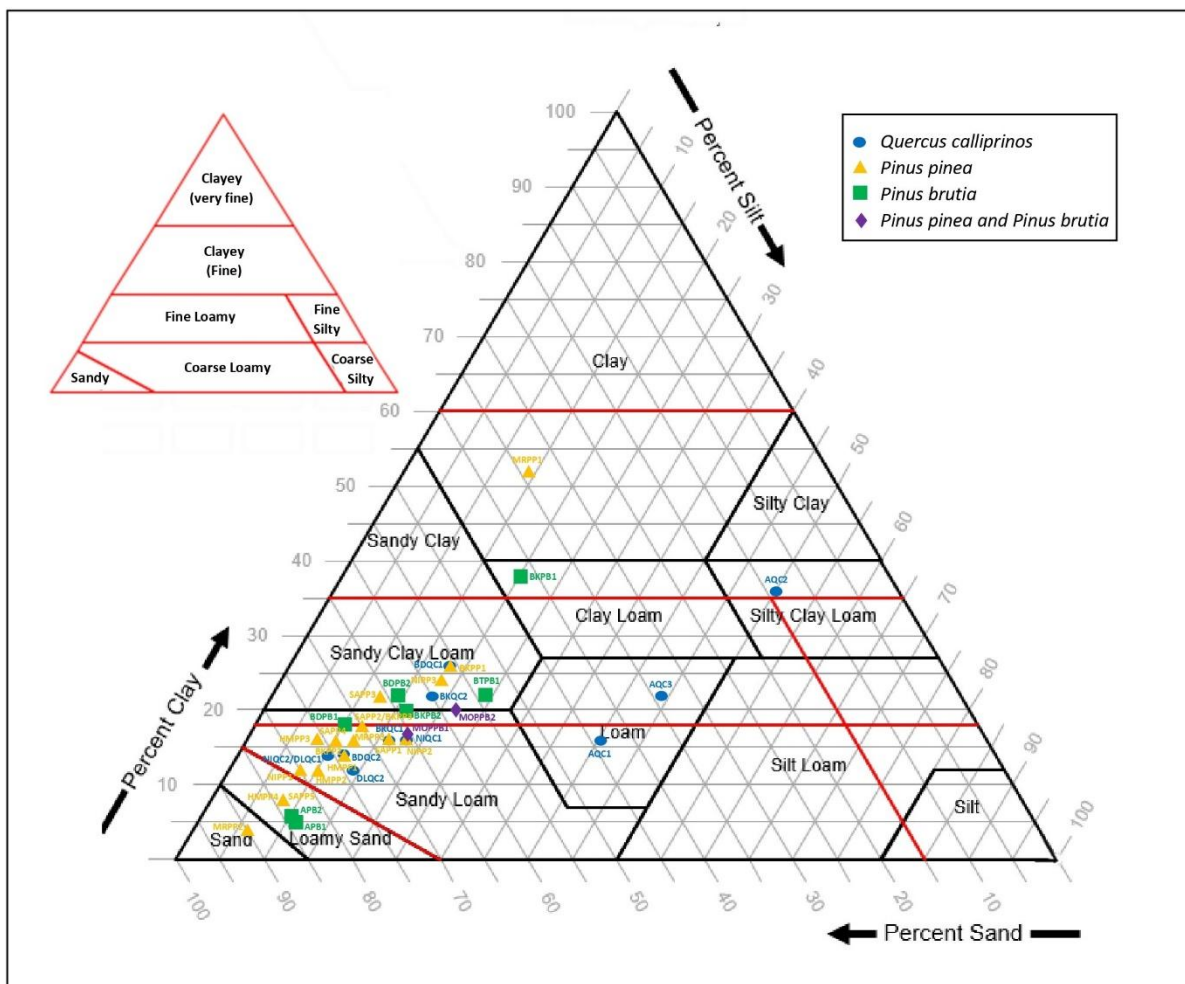


**Fig. 11** USDA soil texture classification of all soil horizons under three forest species across study sites

In contrast, those classified as luvisols, such as those at Bkassine and Bater under *Pinus brutia*, are characterized by an accumulation of clay in the B horizon, indicating advanced pedogenesis.

### 3.5. Calcium Carbonate

The horizons in the studied soil profiles that show carbonate accumulation are considered to be pedogenic [23, 33]. Calcium carbonate ( $\text{CaCO}_3$ ) percentages exceeding 15% are found in all soil profiles associated with *Pinus brutia* and *Quercus calliprinos*, suggesting the presence of a distinct calcic horizon (Fig. 12).

In contrast, the percentages of  $\text{CaCO}_3$  in the layers associated with *Pinus pinea* are significantly lower, ranging from 0.46% to 3.4%, indicating that there is no calcic horizon in these profiles. Notably, the percentage of calcium carbonate is higher at Mokhtara, where *Pinus pinea* and *Pinus brutia* coexist (Supplementary material – Annexes 2 and 3). This is probably due to the properties of the calcic horizon associated with *Pinus brutia*. Conversely, the horizons associated with *Quercus calliprinos* show lower percentages of  $\text{CaCO}_3$  at Bkassine, where sandstone formations predominate, highlighting the impact of the parent material on carbonate accumulation.

In Niha, Dalboun, and Baadaran, where *Quercus calliprinos* is present, the  $\text{CaCO}_3$  content increases with depth, rising from 13% at the surface to 51.2% at a depth of less than 120 cm, from 6.5% at the surface to 49.3% at a depth of less than 85 cm, and from 12% at the surface to 67% at a depth of less than 85 cm, respectively. Furthermore, the proportion of Aazour, Mokhtara and Baadaran associated with *Pinus brutia* at greater depths increased from 44% at the surface to 56% below 60 cm, from 49.5% at the surface to 53.9% below 120 cm, and from 30.7% at the surface to 62.3% below 55 cm, respectively.

The process of carbonate illuviation, in which carbonates are leached from surface layers and accumulate in deeper strata, is reflected in this increase with depth. It also highlights a significant interaction between tree species, soil depth and  $\text{CaCO}_3$  content.

Due to leaching processes caused by rainfall, the carbonate content of surface horizons is often lower. When water containing dissolved calcium carbonate percolates downwards and evaporates, carbonate deposits are left behind in the deeper layers. There is a close link between soil depth and the forest species present, as shown by the positive correlation between depth and calcium carbonate content. Due to their tendency to grow in alkaline environments, *Pinus brutia* and *Quercus calliprinos* are associated with calcic horizons, as evidenced by the increased carbonate concentration in their soils. In contrast, the low carbonate content of the soils associated with *Pinus pinea* suggests a preference for non-calcareous conditions. These results indicate a clear relationship between soil depth, tree species and  $\text{CaCO}_3$  accumulation. Statistical analysis (ANOVA) revealed that the  $\text{CaCO}_3$  content varies with depth depending on the forest species. It does not show significant variation between sites associated with the same species but differs notably between two different species.

However, soils rich in silt tend to show higher concentrations of  $\text{CaCO}_3$  ( $r=0.446$  – Pearson correlation), likely due to better carbonate retention, while sandy soils exhibit lower  $\text{CaCO}_3$  values ( $r=-0.231$  – Pearson correlation) due to increased leaching. These findings underscore the role of soil texture in the accumulation of carbonates and highlight the importance of pedogenic processes in shaping soil characteristics and nutrient availability in forest ecosystems.

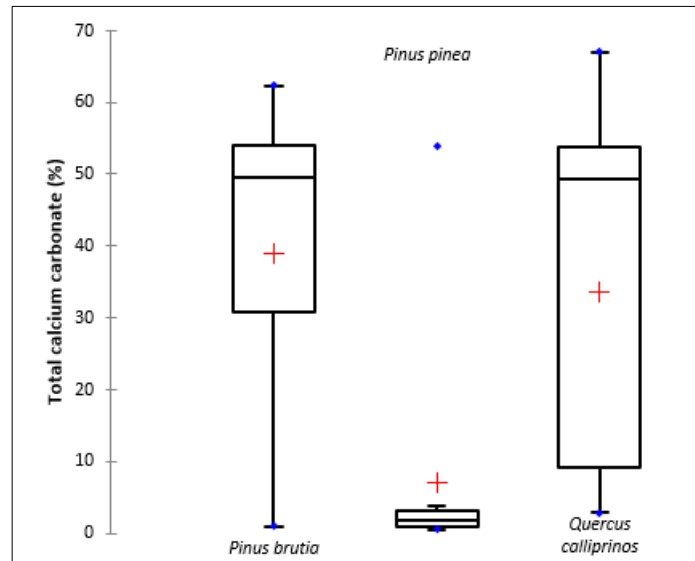


**Fig. 12** Total calcium carbonate variation according to forest species

### 3.6. Organic Matter and Organic Nitrogen

Johnson et al. [35] state that the majority of nitrogen (N) in soils is closely associated with organic matter. Organic matter is the most significant indicator of soil quality and is widely recognized as the primary soil component that supports the many activities of the soil ecosystem [19]. Furthermore, it originates from the addition of plant litter and is degraded, transformed, and respired by microbial communities. This has led to the hypothesis that nitrogen retention in forest ecosystems is primarily governed by biological processes.

For the forest species studied, soil organic matter content was consistently higher near the surface and decreased with depth. In terms of organic matter values, *Pinus brutia* had the highest content, followed by *Quercus calliprinos*, while *Pinus pinea* had the lowest values (Fig. 13).

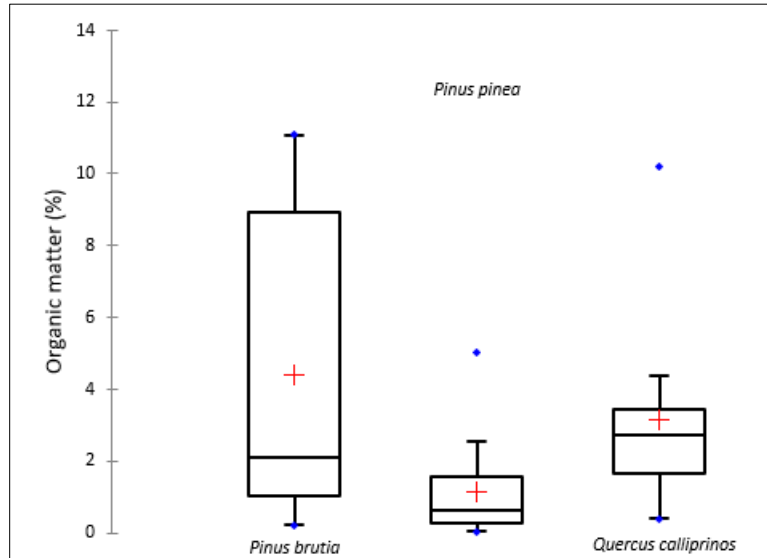


**Fig. 13** Organic matter variation according to forest species

In this study, a positive correlation was observed between soil organic matter content and the macro- and micronutrients present in the soil. The correlations (using Pearson's correlation coefficient) varied among the three forest species.

For macronutrients, *Pinus brutia* showed the strongest correlation observed between organic matter content and soil potassium ( $r=0.792$ ), indicating a close relationship, followed by correlations with soil calcium ( $r=0.616$ ), soil sodium ( $r=0.486$ ), and soil magnesium ( $r=0.275$ ). These results highlight the role of soil organic matter content in influencing the availability of these elements, particularly potassium and calcium, in soils under *Pinus brutia* (Fig. 14).

For *Pinus pinea*, the strongest correlation was also between organic matter content and soil potassium ( $r=0.327$ ), but this value was lower than that for *Pinus brutia*. The other correlations involved magnesium ( $r=0.351$ ), sodium ( $r=0.219$ ), and calcium ( $r=0.189$ ). These weaker correlations suggest that soil organic matter content has a less pronounced influence on nutrient availability in the soils of *Pinus pinea* (Fig. 15) than in those of *Pinus brutia*.

For *Quercus calliprinos*, a very strong correlation between organic matter content and soil potassium was observed ( $r=0.824$ ) among the species studied (Fig. 16). Substantial correlations were also found with sodium ( $r=0.820$ ), magnesium ( $r=0.643$ ), and calcium ( $r=0.233$ ). This pattern indicates a strong interaction between organic matter content and potassium, sodium, and magnesium, suggesting that soils under *Quercus calliprinos* are more influenced by organic matter content than those under the other two species.

As for micronutrients, *Pinus brutia* showed a positive correlation between soil organic matter and trace elements. The strongest relationship is with iron (Fe), with a correlation coefficient of  $r=0.695$ , indicating a significant association, followed by zinc (Zn) ( $r=0.666$ ), manganese (Mn) ( $r=0.428$ ), and copper (Cu) ( $r=0.306$ ). These results suggest that the availability of these trace elements, particularly Fe and Zn, tends to increase with higher organic matter content in soils under *Pinus brutia*.

For *Pinus pinea*, soil organic matter content also showed a strong positive correlation with Fe, with a coefficient of  $r=0.851$ , the strongest relationship among all trace elements, followed by Zn ( $r=0.688$ ), Cu ( $r=0.635$ ), and Mn ( $r=0.250$ ). These results highlight that Fe and Zn are most strongly influenced by organic matter levels in soils associated with *Pinus pinea*.

In the case of *Quercus calliprinos*, the relationships between soil organic matter and trace elements were weaker or even negative. A slight positive correlation was observed with Mn ( $r=0.441$ ), while the correlations with Zn ( $r=0.050$ ) and Fe ( $r=-0.073$ ) were minimal or negligible. It is interesting to note that Cu showed a negative correlation ( $r=-0.305$ ), suggesting that increased levels of soil organic matter may not improve copper availability in soils under *Quercus calliprinos*.

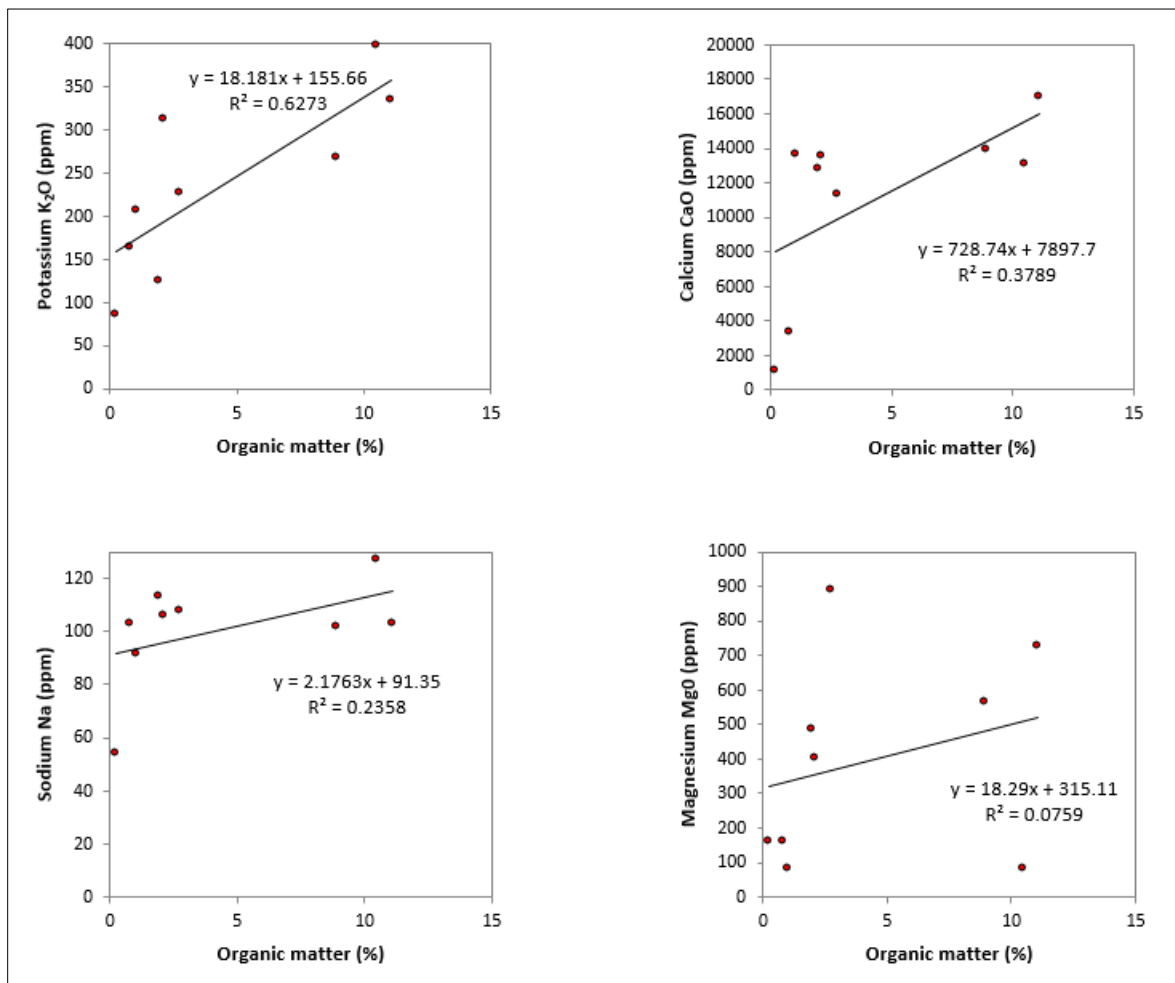


**Fig. 14** Correlation of organic matter with macronutrients for sites associated with *Pinus brutia* (Pearson correlation)

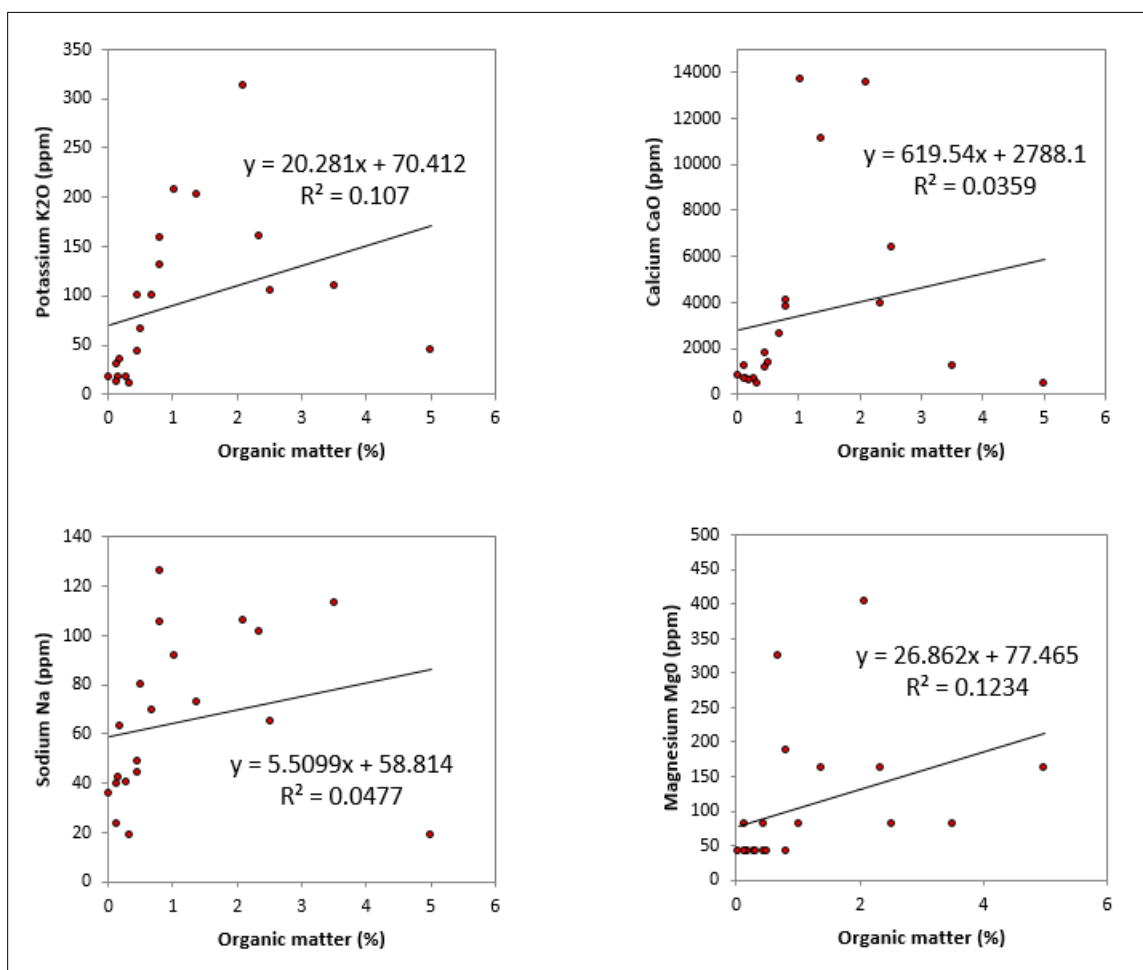


**Fig. 15** Correlation of organic matter with macronutrients for sites associated with *Pinus pinea* (Pearson correlation)

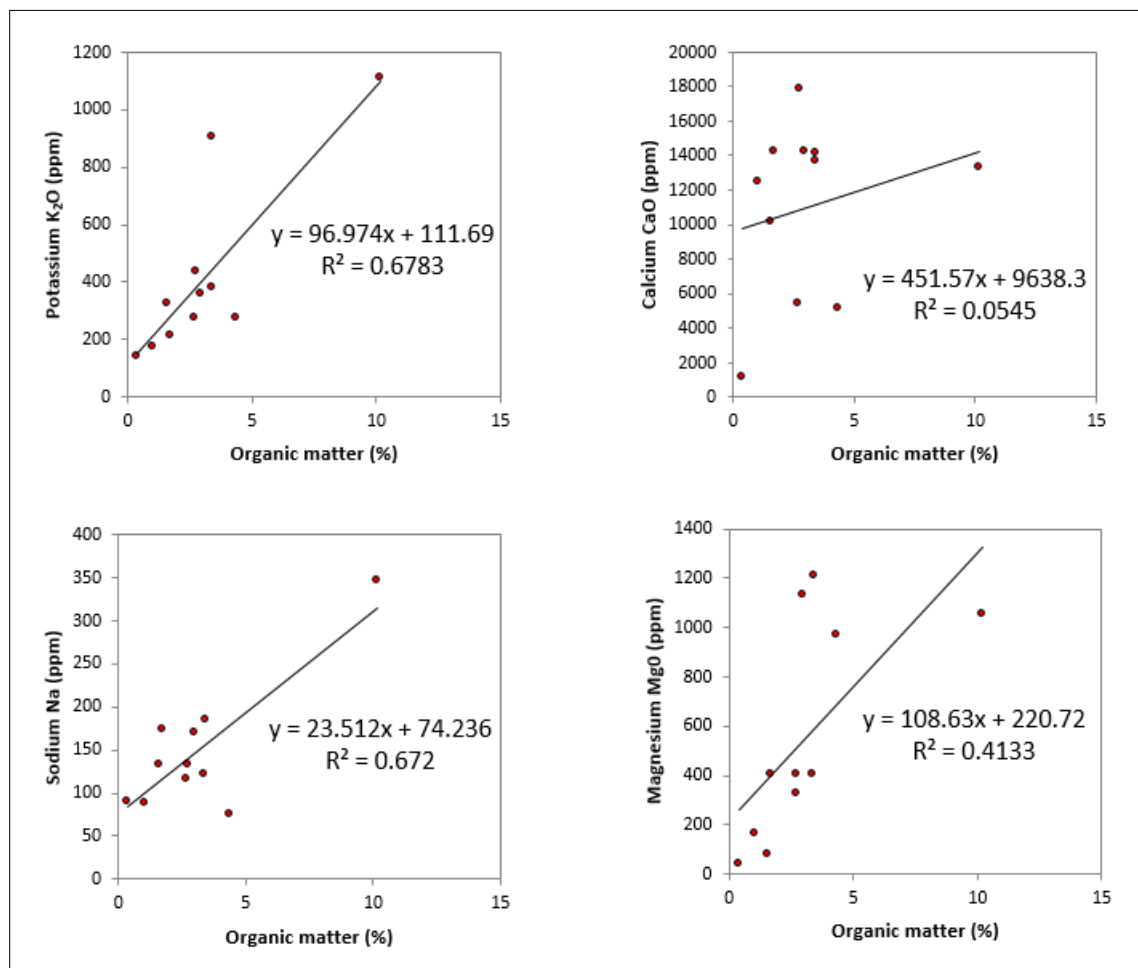


**Fig. 16** Correlation of organic matter with macronutrients for sites associated with *Quercus calliprinos* (Pearson correlation)

### 3.7. Phosphorus Availability

Phosphorus is a macronutrient that must be present in the soil in sufficient quantities for plant growth. Soil type, clay content, pH,  $\text{CaCO}_3$  content in the soil, organic matter, and other soil components can all affect the rate of phosphorus fixation phosphorus [36]. By forming a strong calcium phosphate bond on the surface of the lime, the  $\text{CaCO}_3$  in calcareous soil combines with the phosphorus in the soil solution phosphorus [36]. The phosphorus (P) values found in this study for the various forest species show values that remain relatively constant with depth However, the data may suggest that for *Pinus brutia*, phosphorus concentrations ranged from 7 ppm to 22.8 ppm, with values generally falling below the standard threshold of 35 ppm. On the other hand, *Pinus pinea* exhibits a wide range of phosphorus concentrations, ranging from 6.54 ppm to 60.8 ppm. With a notable maximum of 60.8 ppm in one of the deepest layers, the majority of readings fall between 6.54 ppm and 32.4 ppm.

This high concentration of phosphorus, particularly in the deeper layers of Mrusti (Supplementary material – Annex 2), is considered an outlier because it is much higher than the standard threshold and may contribute to the development of a distinct odor in the soil. This higher value suggests a potential accumulation of phosphorus in specific zones of the soil profile, possibly linked to the decomposition of organic matter, and may be used as a chemical fertilizer.

The phosphorus values, which range from 7.3 ppm to 22.5 ppm, suggest a relatively low phosphorus content at the various *Quercus calliprinos* sites. These values are consistent with the typical phosphorus content found in many forest soils, which is below the 35 ppm threshold.

### **3.8.Exchangeable Cations**

Exchangeable cations present in forest soils, such as calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na), play an important role in soil fertility and plant nutrition. In this study, calcium was the predominant extractable cation among the three forest species, followed by magnesium, potassium, and sodium. This distribution differs from some previous studies [33, 37, 38], in which sodium was found to be more abundant than potassium. The high concentration of calcium in the surface soil horizons is likely due to calcium input from processes such as wind deposition. The concentration of exchangeable potassium generally decreased with soil depth for all species, with the exception of *Pinus pinea* and *Quercus calliprinos*, for which potassium concentrations increased at certain specific sites such as Homsiyeh, Sabbah, and Aazour. Similarly, sodium and magnesium concentrations generally decreased with depth, except at certain specific sites. For example, at Aazour, both sodium and magnesium concentrations increased with depth, likely due to variations in soil pH. These results indicate that concentrations of exchangeable cations in forest soils are highly site-specific and influenced by both biological and environmental factors, including soil depth and pH variations.

### **3.9.Trace Metal Elements**

Soil pH, conductivity, and organic matter content significantly influence trace metal uptake by roots, affecting both root growth and pollutant mobility [39]. Moreover, the results indicate that trace metals accumulate at the surface in several cases, suggesting that erosion or sedimentation may drive this pattern. In light of the soil properties at these sites, these accumulations seem unlikely to stem from leaching. Nevertheless, seasonal fluctuations in shallow contaminated groundwater could transport metals to deeper layers, particularly those with greater mobility under reduced conditions. Trace metals pose environmental risks to groundwater and surface water even at low concentrations.

Typically, trace metals are immobilized or form insoluble compounds through adsorption or precipitation, with soil composition and environmental factors shaping this process [40]. Furthermore, permeable geological formations in the Shouf-Jezzine Geopark project may facilitate infiltration that affects metal transport and distribution. Most sites and species

examined showed low concentrations of micro-elements (Fe, Mn, Cu, Zn), likely because high pH in calcareous soils limits their availability to plants [36]. However, significant variation appeared at specific sites, such as Mrusti and Sabbah under *Pinus pinea*, where high Fe levels in deeper layers could indicate that reducing conditions promote accumulation (Supplementary material – Annex 2). Additionally, at Bkassine, elevated Fe in *Quercus calliprinos* soils might stem from lithological or biogeochemical processes.

Mn is elevated at the surface at Baadaran, Bkassine, Niha, and Dalboun, possibly reflecting interactions with organic matter [41]. Copper (Cu) shows limited mobility in alkaline soils. Given that acidic conditions raise Cu solubility, concentrations at Bkassine exceeded the conventional threshold [42]. Therefore, the movement of heavy metals through soil profiles could carry important implications for environmental assessments, since even slow migration may contaminate groundwater [43]. Groundwater level fluctuations complicate metal migration between soil and groundwater [44].

### **3.10. Organic Carbon Storage**

To achieve national and international greenhouse gas reduction goals and understand how forest soils can mitigate emissions, studying forest soils and measuring carbon stocks has become increasingly important [45]. Forest soils, which are among the largest terrestrial reservoirs of organic carbon, play an important role in atmospheric carbon dynamics. After fossil fuel reserves and the oceans, soils constitute the largest terrestrial carbon reservoir and the third-largest globally [46]. Photosynthesis and root respiration are two essential processes that transfer CO<sub>2</sub> from the atmosphere to the terrestrial ecosystem, contribute to the carbon flux between the soil and the atmosphere, and help moderate atmospheric CO<sub>2</sub> levels [46].

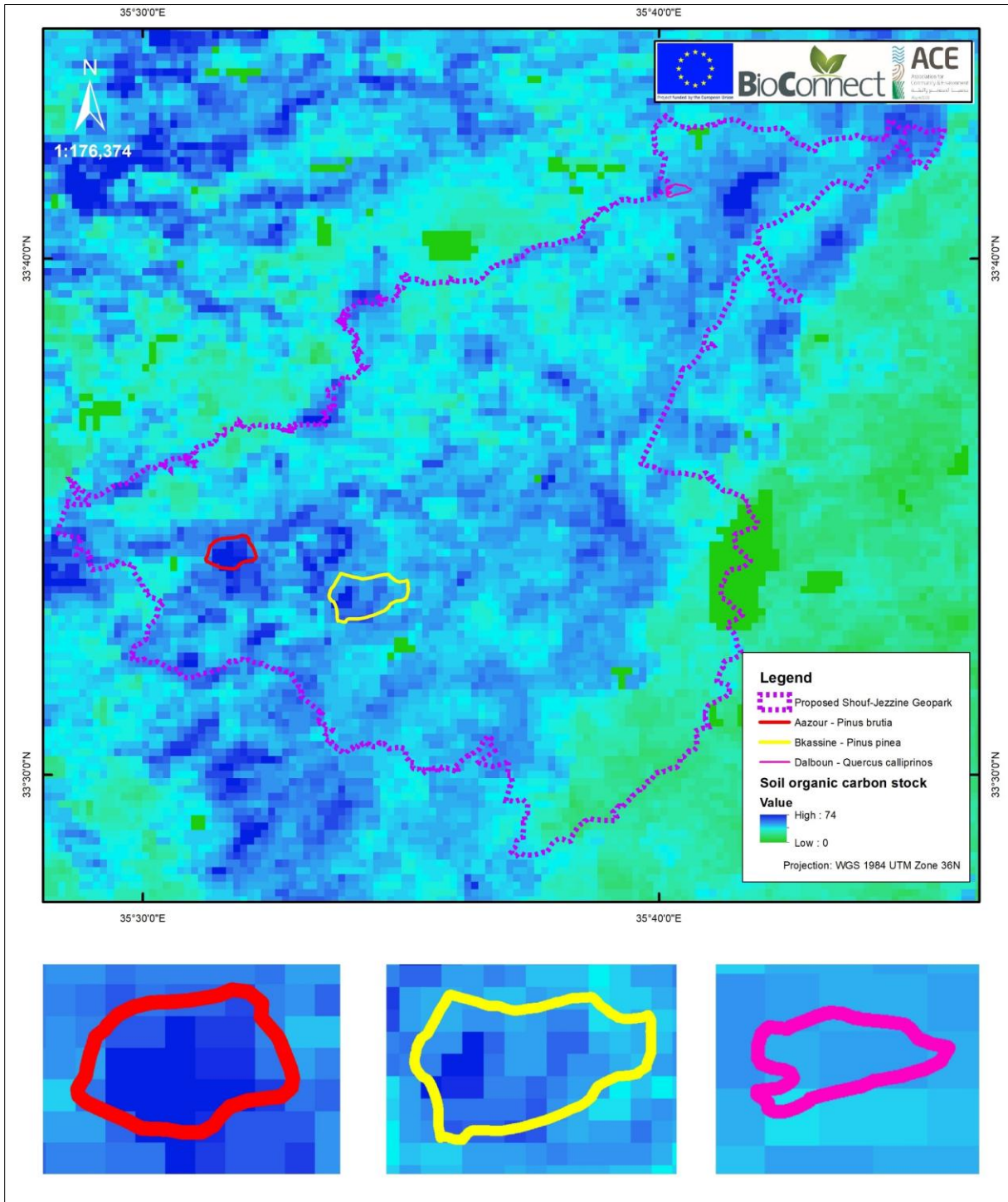


**Fig. 17** Differences in the amount of organic carbon stored in the soil between three forests of different species

Organic carbon storage levels in the soil are compared across three different forest types: Aazour, dominated by *Pinus brutia*; Bkassine, dominated by *Pinus pinea*; and Dalboun, dominated by *Quercus calliprinos*. Satellite imagery using SoilGrids data at a depth of 30

cm (Fig. 17) revealed that Aazour had the highest organic carbon storage, followed by Bkassine with moderate levels, and Dalboun with the lowest levels among the three sites.

Therefore, these results suggest that *Pinus brutia* plays a crucial role in enhancing organic carbon storage in the soil, thereby contributing to climate change mitigation by reducing atmospheric CO<sub>2</sub> levels through soil sequestration. This underscores the importance of forest management approaches that prioritize species such as *Pinus brutia* because of their carbon storage potential.

#### 4. Conclusions

This study aims to evaluate the physical and chemical properties of soils associated with three key forest species *Pinus brutia*, *Pinus pinea*, and *Quercus calliprinos* within the Shouf-Jezzine Geopark project in Lebanon. Fieldwork, conducted in October 2024, involved identifying the soil horizons present under these species and documenting them using AutoCAD, in accordance with FAO guidelines for soil characterization. A total of 38 soil samples were collected from 15 soil profiles and sent to the laboratory for analysis, including measurements of texture, carbonate content, organic matter, exchangeable cations, and trace elements. The analysis revealed unique relationships between these species and soil characteristics. *Pinus brutia* was found primarily at elevations of 500-1000 meters on green marls and limestone (C3 formation), *Pinus pinea* covered elevations of 500-1500 meters on Chouf sandstone (C1) and massive limestone (C4), while *Quercus calliprinos* was closely associated with massive limestone (C4).

The results showed that the soils under *Pinus brutia* and *Quercus calliprinos* stands exhibited significant calcic horizons, with a CaCO<sub>3</sub> content exceeding 15%, likely due to illuviation processes. In contrast, soils under *Pinus pinea* stands exhibited lower carbonate concentrations, suggesting species-specific effects or different soil-forming processes. Statistical analyses revealed that soil depth and site had a minimal impact on pH and electrical conductivity, although a positive correlation was observed between silt content and CaCO<sub>3</sub> accumulation, indicating that carbonate deposition is more likely in soils with a finer texture. Soil pH varies slightly among species: *Pinus brutia* prefers neutral to slightly alkaline soils, *Quercus calliprinos* adapts to soils ranging from acidic to neutral, and *Pinus pinea* tolerates conditions ranging from very acidic to slightly alkaline. The essential role of organic matter in nutrient availability and soil fertility has been highlighted by the positive correlation observed between organic matter content and essential macro- and microelements.

Higher levels of organic carbon storage were observed in soils under *Pinus brutia* trees, highlighting their role in mitigating climate change through the sequestration of atmospheric CO<sub>2</sub>. This study underscores the ecological importance of these tree species for preserving soil health, preventing erosion, and enhancing biodiversity in the Mediterranean region.

## Supplementary Information

The online version includes supplementary material containing the 15 pedons digitized in AutoCAD are provided, along with their characteristics. These pedons represent various soil profiles from different forest sites. Graphs illustrating the physicochemical variation with depth in the fifteen soil pedons across all study sites are also provided. In addition, the laboratory test results are also included, providing detailed data on soil properties such as pH, electrical conductivity (EC), calcium carbonate ( $\text{CaCO}_3$ ) content, organic matter content, and nutrient availability.

## Data Availability

All data generated or analysed during this study are included in this published article and its supplementary information file.

## Acknowledgments

This study was conducted as part of the BioConnect project, funded by the European Union, titled “Ensuring Effective Management and Governance in Sites of Ecological Importance and Expanding Biodiversity Protection in Southern Lebanon”. This project is implemented by a consortium led by the Al Shouf Cedar Society (ACS) in partnership with the Association for the Development of Rural Capacities (ADR), the Association for Community and Environment (ACE), and the Society for the Protection of Nature in Lebanon (SPNL).

The authors extend their sincere gratitude to the team of ACE for their invaluable contributions, including fieldwork coordination, data collection, and technical support throughout the research process.

## Author Contribution

**BOU GHOSN SALAMEH Reine:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **AYADI MAASRI Soumaya:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization, Project administration. **HASSOUN Georges:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **ABBOUD Maher:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **ERRAMI Ezzoura:** Writing – review & editing, Validation, Supervision, Data curation.

## Funding

This publication was funded by the European Union. Its contents are the sole responsibility of the Association for Community and Environment – ACE and do not necessarily reflect the views of the European Union.

## Declarations

**Conflict of Interest** The authors declare no competing interests.

**Ethical Conduct** This article contains no studies with human or animal subjects.

**Ethical approval:** not applicable.

**Consent to Participate declaration:** not applicable.

**Consent to Publish declaration:** not applicable.

## References

1. Jahan R. *Geodiversity and Biodiversity in the Himalaya Region: Quantifying Spatial Patterns and Exploring Linkages*. PhD thesis - Faculty of Mathematics, Informatics and Natural Sciences Institute of Geography of Universität Hamburg, Bangladesh; 2022. <https://ediss.sub.uni-hamburg.de/handle/ediss/9843>
2. Gray M. Geoconservation Geodiversity and Geoconservation : What, Why, and How ? *George Wright Forum*. 2005;22(3):3-12.
3. Gordon JE, Morrocco S, Ballantyne CK, Thompson DBA. Links between geodiversity and biodiversity on upland plateaux in Scotland : the importance of terrain sensitivity in managing change. Published online 2006.
4. Kozłowski S, Migaszewski ZM, Gałuszka A. Geodiversity conservation - Conserving our geological heritage. *Polish Geol Inst Spec Pap*. 2004;13:13-20.
5. Brilha J. Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: a Review. *Geoheritage*. 2016;8(2):119-134. doi:10.1007/s12371-014-0139-3
6. Sucyati N, Yani A, Nandi. Relationship Between Knowledge And Perceptions Of Geodiversity, Biodiversity, And Cultural Diversity With The Formation Of Students' Environmental Care Attitudes To The Existence Of The Ciletuh Pelabuhanratu Geopark Area. Published online 2021. doi:10.4108/eai.17-7-2021.2312158
7. Crofts R, Gordon JE, Brilha J, Gray M, Gunn J, Larwood J, Santucci V, Tormey D, Worboys GL. Lignes directrices pour la géoconservation dans les aires protégées et conservées. In *Lignes directrices pour la géoconservation dans les aires protégées et conservées*. 2021. <https://doi.org/10.2305/iucn.ch.2020.pag.31.fr>
8. Youm CI, Sow EH, Errami E, Diedhiou Y, Gueye A, Sarr R. Le géosite du Lac Rose (NE Dakar, Sénégal ): enjeux de la préservation d'un géopatrimoine exceptionnel menacé de disparition. *Open Ed Journals*. 2022;28(2):1-22.
9. Tukiainen H, Toivanen M, Maliniemi T. Geodiversity and Biodiversity. *Geol Soc London*. 2022;530(1):1-36. <https://doi.org/10.1144/SP530-2022-107%0ATo>
10. Ansori C, Setiawan NI, Warmada IW, Yogaswara H. Identification of geodiversity and evaluation of geosites to determine geopark themes of the Karangsambung-Karangbolong National Geopark, Kebumen, Indonesia. *Int J Geoheritage Park*. 2022;10(1):1-15. doi:10.1016/j.ijgeop.2022.01.001
11. Kaur G. Geodiversity, Geoheritage and Geoconservation : A Global Perspective. *Jour Geol Soc India*. 2022;98:1221-1228.
12. Shander SS. *A Social Impact Analysis of How Geoparks Contribute to Sustainable Economic Development: A Case Study of Meteorum Geopark in Dalarna, Sweden*. Master thesis in Sustainable Development, Uppsala University; 2014.
13. Alahuhta J, Toivanen M, Hjort J. Geodiversity–biodiversity relationship needs more empirical evidence. *Nat Ecol Evol*. 2019;4(1):2-3. doi:10.1038/s41559-019-1051-7

14. Ayadi-Maasri S. Geodiversity of Lebanon- A Resource for Sustainable Development & the Need for Geo-Education - Abstract. UNESCO IGD Geodiversity Workshop 5 -Geodiversity of The Middle East. The Association for Geoconservation, Hong Kong; 2022.
15. Bravo-Cuevas VM, González-Rodríguez KA, Cabral-Perdomo MÁ. Geodiversity and its implications in the conservation of biodiversity : Some case studies in central Mexico. *Cienc ergo-sum, Rev Científica Multidiscip Prospect.* 2021;28(3):15.
16. Ayadi-Maasri S. Geoconservation as a tool for ecosystem protection and local economic development - Abstract. Geodiversity science for society. The Royal Society London; 2023.
17. Record S, Dahlin KM, Zarnetske PL, et al. Chapter 10: Remote Sensing of Geodiversity as a Link to Biodiversity. In: *Remote Sensing of Plant Biodiversity.* ; 2020:1-595. doi:10.1007/978-3-030-33157-3
18. Mikhailova EA, Zurqani HA, Post CJ, Schlautman MA, Post GC. Soil diversity (Pedodiversity) and ecosystem services. *Land.* 2021;10(3):1-34. doi:10.3390/land10030288
19. Vittori Antisari L, De Feudis M, Trenti W, et al. Pedodiversity and Organic Matter Dynamics in the North Apennines (Italy): Relationships among Soil Types, Biodiversity, and Ecological Functionality. *Forests.* 2024;15:1-18. doi:10.3390/f15020353
20. Ayadi-Maasri S, Ghorra-Chamoun Y. A look at the soil, as a component of geodiversity and geoheritage, through viticulture. Centennial Celebration and Congress of the International Union of Soil Sciences - 100 years of soil science, Florence, Italy. 2024.
21. Ibanez JJ, Saldana A, Olivera D. Biodiversity and pedodiversity: A matter of coincidence ? *SJSS Spanish J Soil Sci.* 2012;2(3):8-12. doi:10.3232/SJSS.2012.V2.N3.01
22. Hartemink AE, Minasny B. Towards digital soil morphometrics. *Geoderma.* Published online 2014:1-13. doi:10.1016/j.geoderma.2014.03.008
23. Khresat SA. Calcic horizon distribution and soil classification in selected soils of north-western Jordan. *J Arid Environ.* 2001;47:145-152. doi:10.1006/jare.2000.0712
24. Bockheim JG. Soil geography of the USA: A diagnostic-horizon approach. In: *Soil Geography of the USA: A Diagnostic-Horizon Approach.* ; 2014:109-122. doi:10.1007/978-3-319-06668-4
25. Sobecki TM, Wilding LP. Calcic horizon distribution and soil classification in selected soils of the Texas Coast Prairie. *Soil Sci Soc Am J.* 1982;46:1222-1227.
26. Ebrahim SS, Abd El-Hady AA, Yousif IAH. The Use of Gis for Detection and Identification of Occurrence of Petrocalcic and Petrogypsic Horizons in the Cultivated Lands of Maryout Region, Egypt. *J Agric Sci Mansoura Univ.* 2009;34(5):5837-5852. doi:10.21608/jssae.2009.93140
27. FAO. *World Reference Base for Soil Resources 2014 - International Soil Classification System for Naming Soils and Creating Legends for Soil Maps.*; 2015. doi:10.1007/978-3-319-24409-9\_25
28. Darwish T. Chapter IX - Soil resources of Lebanon. In Y. Yigini, P. Panagos, & L. Montanarella (Eds.), *Soil resources of Mediterranean and Caucasus countries - Extension of the European soil database;* 2013:149-173.
29. Shaban A. *Water Resources of Lebanon.* Vol 7.; 2020. doi:10.1007/978-3-030-48717-1
30. Halabi A El, Mitri G, Jazi M. Chapter 2 - Fire Ecology: Monitoring post-fire forest regeneration of Pinus brutia in North Lebanon. In: *Advances in Forest Fire Research.* ; 2014:564-568. doi:10.14195/978-989-26-0884-6
31. Kildisheva OA, Aghai MM, Bouazza K, Davis AS. Improving restoration success through research-driven initiatives: case studies targeting Pinus pinea reforestation stock development in Lebanon. *Plant Ecol.* 2017;218(1):39-53. doi:10.1007/s11258-016-0632-7
32. Karim S. Calcium Carbonates Effect on Particle Size Distribution and Texture Classes in Calcareous Soils in Sulaimani Governorate. *Anbar J Agric Sci.* 2021;19(2):131-142. doi:10.32649/ajas.2021.175868
33. Khresat SA, Rawajfih Z, Mohammad M. Morphological, physical and chemical properties of selected soils in the arid and semi-arid region in north-western Jordan. *J Arid Environ.* 1998;40(1):15-25. doi:10.1006/jare.1998.0430
34. Sayyed MRG, Hundekari SM. Preliminary comparison of ancient bole beds and modern soils developed upon the Deccan volcanic basalts around Pune (India): Potential for palaeoenvironmental reconstruction. *Quat Int.* 2006;156-157:189-199. doi:10.1016/j.quaint.2006.05.030
35. Johnson DW, Cheng W, Burke IC. Biotic and Abiotic Nitrogen Retention in a Variety of Forest Soils. *Soil Sci Soc Am J.* 2000;64(4):1503-1514. doi:10.2136/sssaj2000.6441503x
36. Sakin E, Yanardağ IH. Chapter 6 - The advantages and disadvantages of calcareous soils. In:

*Agricultural Research Updates*. Vol 45. ; 2024:147-162.

37. Srivastava P, Bhattacharyya T, Pal DK. Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (Vertisols) of India. *Clays Clay Miner.* 2002;50(1):111-126. doi:10.1346/000986002761002874
38. Hattar BI, Taimeh AY, Ziadat FM. Variation in soil chemical properties along toposequences in an arid region of the Levant. *Catena*. 2010;83:34-45. doi:10.1016/j.catena.2010.07.002
39. Clemente R, Escolar Á, Bernal MP. Heavy metals fractionation and organic matter mineralisation in contaminated calcareous soil amended with organic materials. *Bioresour Technol.* 2006;97(15):1894-1901. doi:10.1016/j.biortech.2005.08.018
40. Jalali M, Khanlari Z V. Effect of aging process on the fractionation of heavy metals in some calcareous soils of Iran. *Geoderma*. 2008;143(1-2):26-40. doi:10.1016/j.geoderma.2007.10.002
41. Sherene T. Mobility and transport of heavy metals in polluted soil environment. *Biol Forum — An Int J.* 2010;2(2):112-121. doi:10.1097/00006454-199809000-00028
42. Fernández S, Seoane S, Merino A. Plant heavy metal concentrations and soil biological properties in agricultural serpentine soils. *Commun Soil Sci Plant Anal.* 1999;30(13-14):1867-1884. doi:10.1080/00103629909370338
43. Piłkuła D, Stępień W. Effect of the degree of soil contamination with heavy metals on their mobility in the soil profile in a microplot experiment. *Agronomy*. 2021;11(5):1-11. doi:10.3390/agronomy11050878
44. Darwish T.M, Jomaa I., Awada M B. Preliminary contamination hazard assessment of land resources in central bekaa plain of Lebanon. *Leban Sci J.* 2008;9(2):3-15.
45. Premrov A, Cummins T, Byrne KA. Assessing fixed depth carbon stocks in soils with varying horizon depths and thicknesses, sampled by horizon. *Catena*. 2017;150:291-301. doi:10.1016/j.catena.2016.11.030
46. Khalidy R, Arnaud E, Santos RM. Natural and Human-Induced Factors on the Accumulation and Migration of Pedogenic Carbonate in Soil: A Review. *Land*. 2022;11:1-13. doi:10.3390/land11091448

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