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Soil Physico-Chemical Properties and Below-Ground Carbon Storage: Insights from Natural Versus Plantation Forests in Northern Iran

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ABSTRACT

Aims: This study aimed to compare soil physico-chemical properties and evaluate below-ground carbon storage (soil and fine roots) in three plantations of *Quercus castaneifolia* C.A.M., *Alnus subcordata* C.A.M., and *Acer velutinum* Bioss., adjacent to a natural forest stand in the Hyrcanian region. There is limited site-specific data on carbon storage and its economic value in pure native plantation stands of Hyrcanian forests.

Materials & Methods: Across each stand (three plantations and one natural forest), five 400 m^2 (20 × 20 m) sample plots were established (20 plots in total). Composite soil samples were collected from two depths (0-5 and 5-15 cm) at five points per plot, yielding 10 composite samples per stand. The Laboratory analyses comprised soil texture, pH, organic carbon (OC), total nitrogen (TN), moisture content, and fine root biomass. The carbon storage in soil and fine roots was converted to CO_2 equivalents, followed by economic assessment based on a rate of USD 75 per ton. Finally, the soil parameters and the economic value of carbon storage were compared among the stands using one-way ANOVA followed by LSD test and different depths using independent T-test methods.

Findings: Soil moisture in our study site (29.37–46.80%) was significantly lower ($P \le 0.01$) in *Q. castaneifolia* stands. Both organic carbon (2.23–5.62%) and pH (5.94–6.36) varied significantly ($P \le 0.01$) among stands at both depths, while total nitrogen (0.12–0.25%) was highest in *A. subcordata* and lowest in *Q. castaneifolia*. Furthermore, the natural forest stand showed the highest root biomass values at both depths. Soil carbon storage correlated positively with bulk density ($R^2 = 0.32$) and moisture ($R^2 = 0.38$). Total below-ground carbon storage (0–15 cm) differed significantly ($P \le 0.05$), ranking as natural forest (99.40 $t.ha^{-1}$) and *A. velutinum* (95.18 $t.ha^{-1}$) > *A. subcordata* (81.72 $t.ha^{-1}$) > *Q. castaneifolia* (70.68 $t.ha^{-1}$). The economic values of CO_2 storage per hectare were USD 27,345 (natural forest), USD 26,197 (*A. velutinum*), USD 23,044 (*A. subcordata*), and USD 19,453 (*Q. castaneifolia*).

Conclusion: *Acer velutinum* demonstrated below-ground carbon storage levels comparable to those of natural forests, suggesting that this species should be prioritized in future reforestation projects aimed at maximizing carbon storage. The key drivers of soil bulk density and moisture content play a critical role in carbon storage in soil. However, further research is necessary to fully assess carbon stocks, including aboveground biomass (e.g., tree trunks and litter), to obtain a comprehensive understanding of the storage potential of these ecosystems.

Keywords: Reforestation; Carbon Economic Value; Climate Change; Ecological Valuation; Northern Iran.

CITATION LINKS

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Introduction

Global warming and the associated climate change portends most of the Earth's ecosystems. Forests, as the primary sources of carbon storage, absorb carbon through photosynthesis and store it in living tissues and soil. Sustainable forest management, including afforestation and reforestation, is thus a key strategy for mitigating the impacts of climate change worldwide [1]. According to the latest global forest assessment by FAO (2020), global plantation areas expanded by 123 million hectares between 1990 and 2020 [2]. The estimation of carbon stored in trees and soil in afforested serves as a key metric for assessing the economic value of forests in combating reducing greenhouse gas emissions [3].

The below-ground carbon storage has higher stability compared to carbon stored in aerial biomass. Fine roots also play a crucial role in the carbon cycle due to their high rates of production and decomposition. At the same time, by forming stable organic matter (such as humus), they make a significant contribution to the long-term stabilization of carbon in the soil and, subsequently, the reduction of greenhouse gas emissions into the atmosphere, ultimately reducing the effects of climate change worldwide [4].

In northern Iran's Hyrcanian forests, *Quercus castaneifolia*, *Alnus subcordata*, and *Acer velutinum* are ecologically and economically significant species. *Quercus castaneifolia*, a light-demanding, drought-tolerant oak, thrives at low to mid-elevations and is prized for its high-quality timber [5]. *Alnus subcordata*, a fast-growing nitrogen-fixing species, dominates riparian and humid zones. At the same time, *Acer velutinum*, a shade-tolerant maple, prefers deep, moist soils and is widely used in furniture production [6].

The type of species chosen for afforestation can impact soil pH, microbial activity, and the levels of essential nutrients, which are crucial for achieving sustainable soil fertility and forest management outcomes [7]. Furthermore, a considerate selection of tree species in reforestation projects can enhance soil carbon storage by 25%, which would be beneficial in mitigating the severe effects of climate change on the Earth [8].

Globally, studies have evaluated carbon storage in natural and planted forests. For example, Haghdoust et al. [9] reported 105 and 102 $t.ha^{-1}$ of carbon in 18-year-old *Acer velutinum* and *Alnus subcordata* plantations, respectively, in Mazandaran, Iran. Ostadhashemi et al. [10] found 52, 45, and 36 $t.ha^{-1}$ of aboveground carbon in 12-year-old *Alnus subcordata*, *Acer velutinum*, and *Quercus castaneifolia* stands in Hyrcanian forests. Comparative studies highlight disparities, as natural forests often outperform plantations, as evidenced by higher carbon stocks in natural stands compared to those of *Cryptomeria japonica* L., *Cupressus sempervirens* L., *Pinus taeda* L., and *Acer pseudoplatanus* L. plantations [11]. Similarly, *Quercus brantii* Lindl. stored higher soil carbon (29.45 $t.ha^{-1}$) than *Pinus eldarica* Medw. and *Cupressus arizonica* Greene. in Ilam, Iran [12]. Drivers of carbon storage also vary, with studies reporting correlations with nitrogen and soil moisture [13, 14], texture and bulk density [15], or pH [16].

Despite extensive global research, there is a lack of site-specific data on carbon storage and its economic value in pure native plantation stands of Hyrcanian forests. This study examines 30-year-old plantations of *Quercus castaneifolia*, *Alnus subcordata*, and *Acer velutinum* in Darabkola, Sari, northern Iran, with two objectives: (1) to compare soil physicochemical properties and below-ground carbon storage (soil and fine roots) among stands, and (2) to analyze relationships between soil properties and carbon stocks. We hypothesize that natural forests exhibit superior soil quality and carbon storage capacity compared to reforested stands.

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Materials & Methods

The study area is situated in Darabkola, southeast of Sari in Mazandaran Province (Figure 1), at an elevation of 330 m above mean sea level (Longitude 54° 14′ E and Latitude 36° 28′ N). The mean annual temperature in this area is 16.3°C, and the mean annual precipitation is 724 mm. Geologically, the area is characterized by marl-dominated parent material with gentle slopes (0–5%). The plantations in this area were established in 1995 (30 years old), consisting of *Quercus castaneifolia*, *Alnus subcordata*, and *Acer velutinum*, with 4×4 m spacing (almost 600 trees per hectare) with an mean coverage of 5 hectares for each stand. The main goal of forestry in this area was initially to restore degraded forests and, later, to produce wood for the lumber mills surrounding the forest. A nearby natural, mixed, uneven-aged forest spanning approximately 35 hectares served as a control. It is dominated by *Carpinus betulus* L., with associated species including *Parrotia persica* C.A.M., *Ulmus glabra* Huds., *Acer velutinum*, and *Quercus castaneifolia*. The understory vegetation comprised *Crataegus microphylla* K. Koch., *Mespilus germanica* L., *Rubus fruticosus* Agg., *Viola odorata* L., *Primula vulgaris* Huds., *Sorghum halepense* L., and *Urtica dioica* L [17].

After an initial visit to the study area, the pure plantation stands and mixed natural forests were identified. In each stand, five square sample plots of 400 m^2 (20 × 20 m) were established at a sufficient distance from boundaries to avoid edge effects. Soil samples from each plot were collected at five points (the four corners and the center) at two depths, 0–5 cm and 5–15 cm, using metal cylinders with diameters of

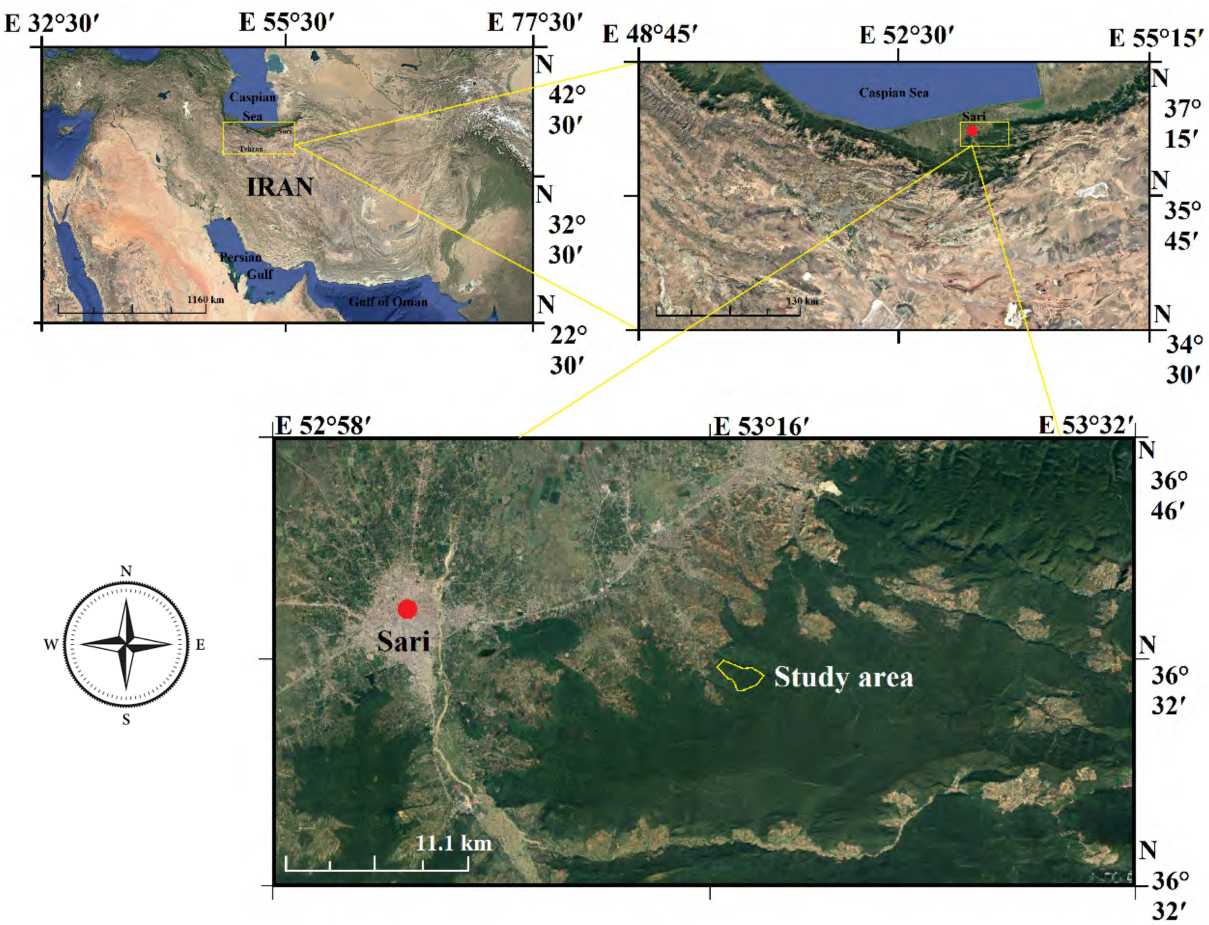

Figure 1) The geographical location of the study area in northern Iran.

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8 cm and lengths of 5 cm and 10 cm [18, 19]. The 0–5 cm layer was selected to capture surface organic inputs, while the 5–15 cm layer represented stabilized soil conditions [20]. Soil sampling for physical and chemical measurements, including moisture content, was conducted in January 2024. The samples from each plot were combined by depth, resulting in 10 composite samples from the two depths in each stand, which were then transferred to the laboratory for analysis.

The soil texture was determined using the hydrometer method [21], bulk density (BD) was measured using the clod method [22], moisture content was assessed through weighing and drying [23], pH was measured using the potentiometric method [24], organic carbon (OC) was determined using the Walkley-Black method [25], and total nitrogen (TN) was measured using the Kjeldahl method [26]. Additionally, the fine roots (<2 mm diameter) were manually separated, washed through a 2 mm sieve, oven-dried (70°C, 24 h), and weighed [27].

To calculate soil carbon storage, Eq. (1) was used [28]. To calculate fine root carbon storage, Eq. (2) was used [29]. To convert soil carbon storage to CO_2, Eq. (3) was employed [30, 31].

$$Cs\ (g.m^{-2}) = 10000 \times C\ (\%) \times BD \times D \qquad \text{Eq. (1)}$$

In this equation, 10,000 is the conversion factor ($gC.m^{-2}$), Cs is the carbon storage ($g.m^{-2}$), C is the carbon concentration (%), BD is the bulk density ($g.cm^{-3}$), and D is the soil layer thickness (cm).

$$C\ (t.ha^{-1}) = \text{Biomass}\ (t.ha^{-1}) \times 0.5 \qquad \text{Eq. (2)}$$

C is the carbon concentration ($t.ha^{-1}$).

$$\text{Sequestrated } CO_2\ (t.ha^{-1}) = \text{Stored carbon}\ (t.ha^{-1}) \times 3.67 \qquad \text{Eq. (3)}$$

To evaluate the economic value of stored carbon, we referred to economists who suggested that the value of carbon should be determined over a defined period, with the carbon price ranging from 40 to 80 USD per ton of CO_2 by 2020 and from 50 to 100 USD per ton of CO_2 by 2030 [32, 33]. In our study, the price of one ton of CO_2 was considered to be USD 75, which is the average of USD 50 and 100.

For data examination and statistical analysis, the normality of the data was first assessed using the Kolmogorov-Smirnov test, and the homogeneity of variances was tested using Levene's test. One-way ANOVA was used to compare the mean values of soil variables across different forest types, and the LSD test was applied for pairwise comparisons, with the natural forest serving as the control group. Additionally, the independent T-test was employed to compare different soil depths. The correlation between the data was calculated using Pearson's correlation coefficient. All statistical calculations and analyses were performed using SPSS version 26 [34].

Findings

- Soil Physical Properties

All four studied stands exhibited a loamy soil texture at the 0-5 cm depth, whereas the soil texture at the 5-15 cm depth was predominantly clay loam. The soil physical variables, including sand, silt, clay, and bulk density, did not show significant differences across the studied stands ($P \leq 0.05$, Table 1). However, the soil moisture content (WSM), which ranged from 29.37 ± 0.53 to 46.80 ± 1.05% at our study site, exhibited significant variation ($P \leq 0.01$) among the stands, with the *Quercus castaneifolia* stand showing the lowest values (Figure 2). Additionally, significant differences were observed between the two depths for sand, clay, and moisture content across all four investigated stands ($P \leq 0.05$). In contrast, no significant differences were found for silt and bulk density (Table 1, Figure 2).

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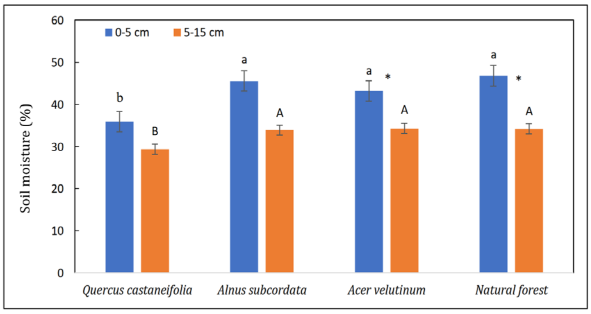

Figure 2) Weight of soil moisture of soil in the different depths at the forest stands.
Mean values within bars followed by different lower-case (0-5 cm) and upper-case (5-15 cm) letters indicate significant differences among forest stands. *: indicate significant differences between soil and depths.

- Soil Chemical Properties

Based on the results, the organic carbon (OC), which ranged from 2.23 ± 0.08 to 5.62 ± 0.10%, and the pH, ranging from 5.94 ± 0.06 to 6.50 ± 0.07 at our study site, showed significant differences (P ≤ 0.01) among the investigated stands at both depths (Figure 3). The highest OC values were observed in the natural forest at both depths, while the lowest values were recorded in the *Quercus castaneifolia* stand. The highest pH values were found at the first depth in the *Acer velutinum* stand, while at the second depth, the highest pH values were observed in the *Quercus castaneifolia* stand. The lowest pH values were observed at both depths in the *Alnus subcordata* stand (Figure 3). Additionally, the total nitrogen (TN), which ranged from 0.12 ± 0.01 to 0.25 ± 0.01% at our study site, showed a significant difference only at the first depth (P ≤ 0.01), with the highest values in the *Alnus subcordata* stands and the lowest in the *Quercus castaneifolia* stands (Figure 3). The OC and TN content in the soil exhibited significant differences among all four stands across the depths. At the same time, the carbon-to-nitrogen (C/N) ratio did not show significant differences either among the stands or between the depths (Table 2, Figure 3).

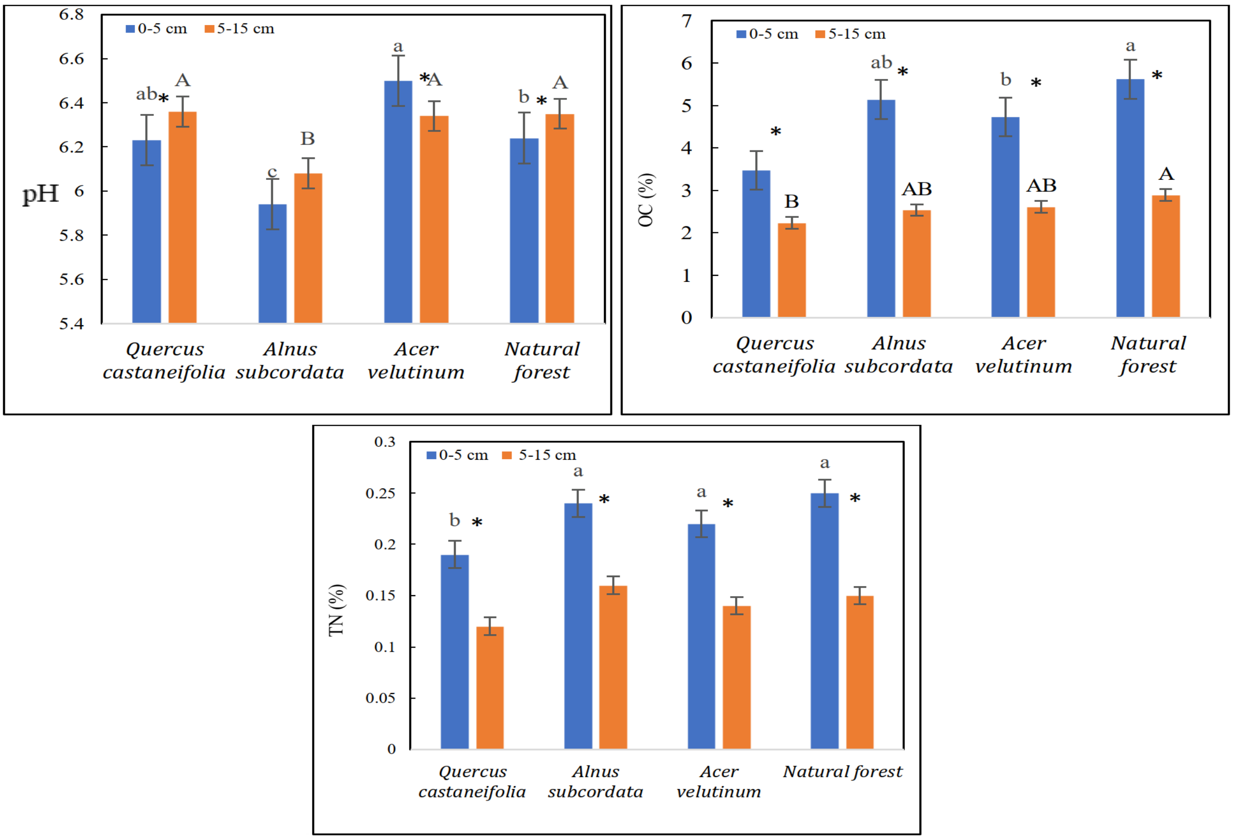

Figure 3) Organic carbon (OC), total nitrogen (TN), and pH of soil in different depths at the forest stands.
Mean values within bars followed by different lower-case (0-5 cm) and upper-case (5-15 cm) letters indicate significant differences among forest stands. *: indicate significant differences between soil and depths.

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- Fine Roots Biomass

The fine root biomass at both depths was significantly higher ($P \leq 0.01$) in the natural forest stand. At the same time, *Alnus subcordata* exhibited significantly lower values ($P \leq 0.01$) at both depths compared to the other stands (Table 3).

- Soil and Fine Roots Carbon Storage

At the first depth, the highest soil carbon storage was recorded in the natural forest stand, while at the second depth, the highest soil carbon storage was observed in the *Acer velutinum* stand. The lowest soil carbon storage was found at both depths in the *Quercus castaneifolia* stand. In terms of fine root carbon, the highest values were observed in the *Acer velutinum* stand at the first depth and in the natural forest stand at the second depth. Conversely, the lowest fine root carbon storage was measured at both depths in the *Alnus subcordata* stand (Table 4).

The results of the Pearson correlation analysis between soil properties and soil carbon storage, as well as fine root biomass across all studied stands, are shown in Table 5. A significant positive correlation was found between soil carbon storage and bulk density ($R^2 = 0.32$), as well as between soil carbon storage and soil moisture ($R^2 = 0.38$). Additionally, fine root carbon storage exhibited a significant positive correlation with pH ($R^2 = 0.26$, Table 5).

- Economic Value of Storage Carbon Dioxide

The highest soil carbon dioxide storage was observed at both depths in the *Acer velutinum* and natural forest stands (Figure 4). Furthermore, the highest root carbon dioxide storage was found in the natural forest, while the lowest was recorded in

Table 1) Comparison of means (± standard deviation) of physical variables amongst different stands in two depths.

		Forest Stands				
Depth (cm)	Soil Properties	*Quercus castaneifolia*	*Alnus subcordata*	*Acer velutinum*	Natural Forest	Significant Level
0-5	Sand (%)	40.21±1.23^{A}	42.66±1.30^{A}	44.31±2.10^{A}	44.03±2.07^{A}	0.192^{ns}
	Silt (%)	41.72±1.80	41.73±1.13	41.14±2.05	39.81±1.15	0.128^{ns}
	Clay (%)	18.07±1.23^{B}	15.61±0.82^{B}	15.54±1.43^{B}	16.16±1.48^{B}	0.532^{ns}
	BD (gr.cm^{-3})	1.80±0.17	1.70±0.11	1.84±0.21	1.73±0.05	0.405^{ns}
5-15	Sand (%)	29.26±2.19^{B}	33.34±2.49^{B}	31.18±1.79^{B}	32.71±0.17^{B}	0.224^{ns}
	Silt (%)	41.91±2.11	43.18±1.79	42.34±1.30	41.00±1.00	0.462^{ns}
	Clay (%)	28.82±1.80^{A}	25.48±2.30^{A}	26.47±1.06^{A}	26.28±0.63^{A}	0.254^{ns}
	BD (gr.cm^{-3})	1.73±0.13	1.72±0.17	1.89±0.16	1.68±0.10	0.773^{ns}

Mean values within columns followed by different upper-case letters indicate significant differences among the depths of soil. BD: bulk density. $^{ns}P \geq 0.05$

Table 2) Comparison of means (± standard deviation) of chemical variables amongst different stands in two depths

		Forest Stands				
Depth (cm)	Soil Properties	*Quercus castaneifolia*	*Alnus subcordata*	*Acer velutinum*	Natural Forest	Significant Level
0-5	C/N	18.11±1.90	20.72±0.69^{A}	21.13±0.71^{A}	21.15±0.23^{A}	0.148^{ns}
5-15		18.52±0.37	17.32±1.74^{B}	18.50±0.33^{B}	18.84±0.56^{B}	0.213^{ns}

Mean values within columns followed by different upper-case letters indicate significant differences among the depths of soil. C/N: organic carbon/total nitrogen. $^{ns}P \geq 0.05$

the *Alnus subcordata* stand (Figure 5). The economic value of the stored carbon dioxide in soil and root biomass was calculated as 27,345 USD.ha^{-1}, 26,197 USD. ha^{-1}, 23,044 USD.ha^{-1}, and 19,453 USD.ha^{-1} for the natural forest, *Acer velutinum*, *Alnus subcordata*, and *Quercus castaneifolia*, respectively (Figure 6).

Table 3) Comparison of means (± standard deviation) of fine roots biomass amongst different stands in two depths.

Forest Stands						
Depth (cm)	Soil Properties	*Quercus castaneifolia*	*Alnus subcordata*	*Acer velutinum*	Natural Forest	Significant Level
0-5	Fine Roots Biomass (g.m^{-2})	11.61±1.35^{ab}	6.15±1.22^{b}	28.88±3.12^{aA}	31.91±3.90^{aB}	0.000**
5-15		8.08±1.50^{c}	6.19±1.64^{c}	15.00±2.05^{bB}	56.34±4.95^{aA}	0.000**

Mean values within rows followed by different lower-case letters indicate significant differences among forest stands. Mean values within columns followed by different upper-case letters indicate significant differences among the depths of soil. **P ≤ 0.01, *P ≤ 0.05, nsP ≥ 0.05

Table 4) Comparison of the mean (± standard deviation) of Carbon Storage of soil and fine roots biomass at the 0-5 cm and 5-15 cm in forest stands.

Forest Stands						
Depth (cm)	Soil Properties	*Quercus castaneifolia*	*Alnus subcordata*	*Acer velutinum*	Natural Forest	Significant Level
0-5	Soil Carbon Storage (t.ha^{-1})	31.27±2.33^{c}	39.25±2.63^{b}	44.01±3.25^{ab}	47.28±1.24^{a}	0.006**
	Root Carbon Storage (t.ha^{-1})	0.29±0.04^{b}	0.15±0.03^{c}	0.79±0.12^{a}	0.77±0.14^{a}	0.000**
5-15	Soil Carbon Storage (t.ha^{-1})	38.72±2.35^{b}	44.02±2.75^{ab}	49.63±2.50^{a}	48.54±2.67^{a}	0.003**
	Fine Roots Carbon Storage (t.ha^{-1})	0.40±0.07^{b}	0.30±0.05^{b}	0.75±0.09^{b}	2.81±0.34^{a}	0.006**

Mean values within rows followed by different lower-case letters indicate significant differences among forest stands. Mean values within columns followed by different upper-case letters indicate significant differences among the depths of soil. **P ≤ 0.01, *P ≤ 0.05, ^{ns}P ≥ 0.05

Table 5) Pearson correlation coefficient (R^2) between soil and fine roots biomass Carbon Storage with soil variables amongst investigated stands.

Depth (cm)	Soil Variables							
0-15	Clay (%)	Sand (%)	Silt (%)	BD (g.cm^{-3})	pH	TN (%)	WSM (%)	C/N
Soil Carbon Storage (t.ha^{-1})	0.13^{ns}	0.14^{ns}	0.13^{ns}	0.32*	0.00^{ns}	0.05^{ns}	0.38**	0.06^{ns}
Root Biomass Carbon Storage (t.ha^{-1})	0.00^{ns}	0.02^{ns}	0.04^{ns}	0.00^{ns}	0.26*	0.01^{ns}	0.00^{ns}	0.01^{ns}

BD: bulk density, WSM: weight of soil moisture, TN: total nitrogen. **P ≤ 0.01, *P ≤ 0.05, ^{ns}P ≥ 0.05

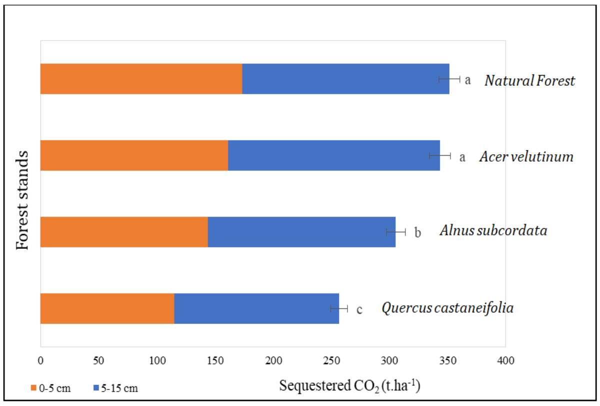

Figure 4) Sequestered soil carbon dioxide of soil (t.ha^{-1}) across natural and plantation forest stands at different depths.
Mean values by different lower-case letters indicate significant differences among forest stands.

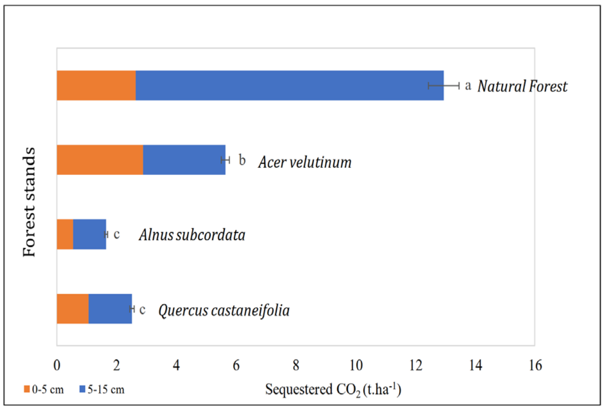

Figure 5) Sequestered carbon dioxide of fine roots (t.ha^{-1}) in fine roots across natural and plantation forest stands at different depths.
Mean values by different lower-case letters indicate significant differences among forest stands.

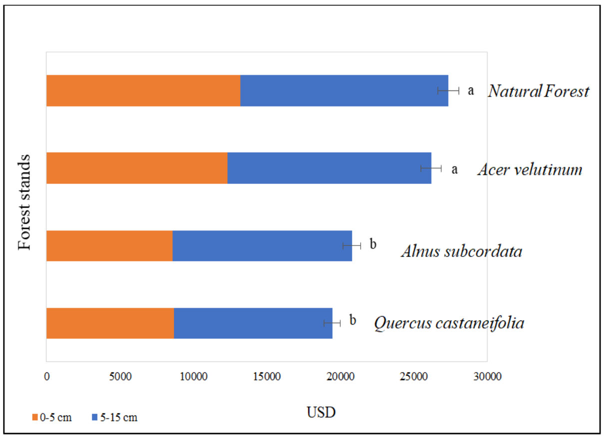

Figure 6) Economic value of sequestered carbon dioxide storage (USD) across natural and plantation forest stands at different depths.
Mean values by different lower-case letters indicate significant differences among forest stands.

Discussion

Overall, the natural forest demonstrated superior soil physicochemical properties compared to planted stands. However, *Acer velutinum* plantations exhibited comparable soil carbon storage to natural forests, a finding that aligns with studies highlighting the species' specific potential for carbon sequestration. Notably, *Quercus castaneifolia* showed the lowest soil moisture and organic matter content, consistent with its drought-tolerant traits. The role of organic matter in moisture retention is well-documented, as it reduces evaporation and enhances water infiltration —a mechanism corroborated by similar studies [35, 36]. Correspondingly, [37] demonstrated that soil organic matter significantly influences soil moisture content in 20-year-old plantations of *Quercus castaneifolia*, *Fraxinus excelsior* L., *Pinus brutia* Ten., and natural oak-beech stands in Darabkola of Sari.

Soil texture remained stable across stands, supporting the paradigm that short-term changes in physical properties are minimal [4,38]. Similarly, Moshki et al. [38] found no changes in soil texture in 40-year-old plantations of *Pinus eldarica* Medw. Moreover, *Robinia pseudoacacia* L., compared to the bare areas in the Sokan Forest Park of Semnan. However, [39] demonstrated variations in soil texture in a 35-year-old afforestation of *Fraxinus excelsior*, *Picea abies* L., *Pinus nigra* Arn., and *Quercus castaneifolia* in the northern forests of Iran, likely due to site-specific factors such as parent material or management history.

Alnus subcordata drove lower soil pH and higher nitrogen levels at 0–5 cm depth, which aligns with global observations that nitrogen-fixing species accelerate nitrification, acidifying soils while enriching nitrogen pools [40]. Consistently, Yamashita et al. [41] observed that areas afforested with *Acacia mangium* Wild. had lower pH

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values compared to areas dominated by species without nitrogen-fixing capabilities. Furthermore, the nitrogen levels at the first soil depth were highest in both the natural forests and *Alnus subcordata* stands. [42] The reported correspondingly higher nitrogen content in *Alnus subcordata* stands compared to those of *Acer velutinum*, *Quercus castaneifolia*, *Cupressus sempervirens* L., and natural forests in the Sari Darabkola forests is attributed to its nitrogen-fixing ability.
Our results identified bulk density and moisture as primary determinants of soil carbon storage, contrasting with studies that emphasize the roles of nitrogen, soil texture, pH, and C/N ratio in carbon storage in soil [13-16, 43]. Moreover, the positive correlation between carbon storage in fine root biomass and soil pH in our study may be attributed to the fact that an alkaline environment is more conducive to root growth, promoting enhanced microbial activity and root development [44, 45]. Different findings, such as null correlations in *Pinus eldarica* and *Quercus brantii* stands, highlight context-dependent interactions between soil properties and carbon dynamics [12].
Generally, the type of vegetation and soil properties play a significant role in carbon storage within the soil, as the amount of carbon sequestered is influenced by the input from plant residues and associated decomposition processes [46,49]. While natural forests typically outperform plantations in carbon storage [50], our findings reveal that *Acer velutinum* stands store carbon at levels comparable to natural forests - contrary to our initial hypothesis. This contrasts with studies by [50], who reported higher carbon stocks in natural forests than in afforested stands of *Acer cappadocicum* Gled., *Cryptomeria japonica* (Thunb. ex.l.f.), and *Cupressus sempervirens* in Lavij, Mazandaran. Also, [51] observed reduced soil organic carbon in afforested *Quercus macranthera* F. et Mey. stands relative to natural forests in Khalkhal, Iran.
In our study, 30-year-old *Acer velutinum* and *Alnus subcordata* stands stored approximately 95 and 82 $t.ha^{-1}$ in the soil, respectively. However, Haghdoust et al. [9] reported higher values (105 and 102 $t.ha^{-1}$ for the same species in Chamestan, Mazandaran), likely due to their greater tree density (2,500 vs. 600 $tree.ha^{-1}$) compared to our study site). Furthermore, the lower carbon stock in *Quercus castaneifolia* compared to other investigated stands might be due to slower leaf decomposition, resulting from its lower nitrogen content and, consequently, higher C/N ratio [52, 53]. Our results align with [54, 55], who found elevated levels of soil organic carbon and nitrogen in *Alnus subcordata* plantations compared to *Quercus castaneifolia*.
Most studies on oak forests have focused on *Quercus brantii* Lindl. For instance, Soleimanipour et al. [56] estimated carbon storage at 14 t per 121 $trees.ha^{-1}$ in Chaharmahal and Bakhtiari Province, while Yousefi et al. [57] reported 8 t per 145 $trees.ha^{-1}$ in Kermanshah—both substantially lower than our *Quercus castaneifolia* value (70 $t.ha^{-1}$). These disparities likely arise from differences in tree density, species traits, soil properties, and regional climate.
The economic evaluation of various ecosystem services provided by reforestation serves as a valuable foundation for understanding the multiple benefits of natural ecosystems [58]. The mean economic value of carbon dioxide storage for the investigated stands in our study was 24,000 $USD.ha^{-1}$. Sheykholeslami et al. [59] estimated carbon storage values of 11,437 $USD.ha^{-1}$ (conifers) and 60,445 $USD.ha^{-1}$ (broadleaf species) in Marzanabad, while Bordbar [60] reported 6,193 $USD.ha^{-1}$ for *Quercus brantii* in Fars Province. Fathi et al. [61] further document devaluations of 3,792 $USD.ha^{-1}$, 2,972 $USD.ha^{-1}$, and

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1,938 USD.ha^{-1} for *Robinia pseudoacacia*, *Fraxinus excelsior*, and *Cupressus arizonica* Greene. stands in Tehran, respectively. Such variability underscores the impact of local environmental conditions, management practices, and methodological approaches on carbon valuation.

Conclusion

Contrary to our initial hypothesis, *Acer velutinum* demonstrated below-ground carbon storage levels comparable to those of natural forests, suggesting that this species can serve as an effective tool for restoring soil carbon stocks in degraded forest ecosystems. This finding challenges the conventional assumption that natural forests inherently possess superior soil carbon storage capacity relative to reforested stands. Given its performance, *Acer velutinum* should be prioritized in future reforestation initiatives aimed at maximizing carbon sequestration. Key drivers of carbon storage, including soil bulk density and moisture content, played a critical role in these dynamics. Based on soil and root biomass measurements, the estimated carbon storage value of these plantations reached approximately USD24,000 per hectare per stand. Extrapolated across the 15–hectare study area to USD360,000, underscoring the significant role of such reforestation efforts in mitigating atmospheric CO_2. These results provide a robust economic rationale for integrating carbon valuation into forest management strategies. By quantifying the ecosystem services offered by reforestation, policymakers and land-use planners can make data-driven decisions to optimize conservation and restoration efforts. However, further research is necessary to fully assess carbon stocks, including aboveground biomass (e.g., tree trunks and litter), to obtain a comprehensive understanding of the sequestration potential of these ecosystems. The focus of this study was on measuring carbon storage in soil and fine roots. However, measuring carbon in the aboveground biomass could also provide helpful information. This required the accurate sampling of available litter on the soil, as well as on trunks, branches, and leaves of trees, which necessitated a dedicated method that was beyond the scope of this study.

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