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Physicochemical characterization of soil occupied by carob tree (*Ceratonia siliqua* L.) in Morocco

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Carob tree cultivation requires a good understanding of soil nutrient availability. Therefore, several farmers and other stakeholders have little scientific knowledge in soil standards for carob cultivation. This study aims to characterize and assess the physicochemical quality of carob soils to improve crop production. Data collection involved soil sampling at 0-20 and 20-40 cm depth beneath carob trees in 19 different regions of Morocco for 2019 year. Obtained results on the physicochemical analyses of the soil (texture, pH (H_2O), electrical conductivity (EC), total limestone, organic matter (OM), organic carbon (OC), total nitrogen (TN), C/N ratio, assimilable phosphorus (P)) indicated that soils from various studied stations exhibited sandy loam texture, with neutral to slightly alkaline pH values (ranging from 6.39 to 7.62). Regarding other elements, the soils of all studied stations have a content of organic carbon not exceeding 5.11%, an organic matter ranging from 0.62 to 8.70% and a content of total nitrogen below 1.82%, while C/N ratio in soils is relatively higher. However, in all the stations, soil is considered low in available phosphorus. Total limestone contents are higher in different stations. Furthermore, soil electrical conductivity ranges from low value (0.15 mS/cm) to moderate value (2.34 mS/cm). For the most variables, small differences in soil physicochemistry are found between different stations. These findings may elucidate the carob trees' adaptability to various soil types.

Keywords: Carob tree, *Ceratonia siliqua* L., soil characterization, soil texture, nutrient availability, pH, electrical conductivity, Morocco.

INTRODUCTION

Cultivated in Mediterranean regions, the carob tree (*Ceratonia siliqua* L.), a woody tree belonging to the legume family, demonstrates remarkable growth capacity under diverse soil conditions (Correia and Martins-Loução, 2005). It is a species capable of thriving in nutrient-poor soils and resistant to drought thanks to its various physiological and morphological mechanisms, which involve the development of distinct tolerance strategies (Battle and Tous, 1997; Correia and Martins-Loução, 2005).

Currently, carob cultivation has become an industrial endeavor, and Morocco ranks as the world's second-largest carob producer, with nearly 22,000 tons (FAO, 2021). The carob tree holds significant economic importance in Morocco, serving as a source of stable income for the local population and contributing to the development of both regional and national economies (Sbay *et al.*, 2008). For millennia, its fruit, the carob pod, has been used for human and animal consumption, as its pulp is rich in sugar, dietary fiber, polyphenols, and proteins. However, its seeds remain the most widely used industrially. Moreover, the carob tree is considered one of the most versatile fruit and forest tree in the Mediterranean region, as almost all of its parts (leaves, flowers, fruits, wood, bark, and roots) have practical uses.

In Morocco, the carob tree is characterized by a wide range of habitats (semi-natural, orchards, traditional agroforestry systems) and a significant climatic variation from the northern to the southern regions of the country (Baumel *et al.*, 2018). It occupies an area of approximately 10,400 hectares (FAO, 2021). However, there is currently no distinct carob forest in

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the Kingdom; it is often found in association with olive, mastic, cedar, or Argan tree.

The carob tree is well adapted to different types of soils in Morocco, as long as there is good drainage; it does not thrive in waterlogged soils (Albanell, 1990; Sbay and Abourouh, 2006). The carob yield and quality may be significantly affected by soil quality. Generally, calcareous soils with moderate to high organic matter content are considered the best for carob cultivation, but less fertile soils can also be used, revealing the high ecological plasticity of this crop (Battle and Tous, 1997; Correia and Martins-Loução, 2005). The economic yield and long-term variation in gross income in different soil types have never been studied or compared.

This study aims to furnish users with information on the physical and chemical characteristics, specifically focusing on soil nutrients conducive to carob cultivation in Morocco. This information assist farmers, agricultural cooperatives, extension services, and managers in providing advisory support for integrated soil fertility management in order to improve carob production.

MATERIALS AND METHODS

***Study area*:** The study encompasses soil samples from 19 ecologically diverse regions in Morocco, with specific details outlined in Table 1. The studied stations are in the Oriental, Rif, and North Central regions. The selected sites exhibit significant bioclimatic variability, ranging from a sub-humid Mediterranean climate with mild winters to an arid climate. The average annual temperatures vary from approximately 16.7 °C in Taghjirt in the Oriental region to over 18.6 °C in Brikcha in the Rif region, with overall annual average rainfall ranging from 287 mm to 642 mm across all stations.

***Collection of the samples of soil*:** Soil samples were collected out during the first week of September 2019 using a manual auger at two depths: 0-20 cm and 20-40 cm below the carob tree. Three repetitions were carried out at each station to create a composite sample for each depth. All collected samples were dried and sieved through a 2 mm sieve to remove coarse elements.

***Physico-chemical analyses of the soil*:** The physico-chemical analyses were conducted at the soil laboratory of the Forest Research Center (CRF) in Rabat. Particle size analyses were determined using the Mériaux (1954) method. Soil texture classification was carried out according to USDA soil texture triangle (Miller and White, 1998; Buol *et al.*, 2011a; Buol *et al.*, 2011b). Analysis of organic carbon (OC) and total nitrogen (TN) was performed using Walkley and Black (1934) methods and Kjeldahl (1883) method. The percentage of organic matter (OM) was calculated using the following formula:

$$\text{OM}\ \% = \%\ \text{OC} \times 1.724.$$

Soil pH (H_2O) was measured using a pH-meter with electrodes (McKeague, 1978). Assimilable phosphorus (P) was determined according to Olsen and Sommers (1982). Total limestone was determined by the Bernard calcimeter method according to the AFNOR NF P 94-048 (1996). Electrical conductivity (EC) was measured using an electrical conductivity meter, expressed in mS/cm, with a soil-to-water ratio of 1:5 at 25 °C (He *et al.*, 2012). Soil analysis results were compared with reference values (Tables: 2 and 3).

Table 1. Geographic coordinates and climatic characteristics of the soils studied in different ecological regions of carob tree in Morocco.

Soil No.	Rural commune of studied site	Station	Bioclimatic stage	Elevation (m)	Geographical coordinates		Annual temp. (°C)	Annual rainfall (mm)
					Latitude	Longitude		
s.1	Rmal	Zemmourene	Sub-humid	315	34.810.890	-5.532.127	18.6	642.1
s.2	Brikcha	Brikcha	Sub-humid	235	34.917.590	-5.541.558	18.6	642.1
s.3	Tassift	Tirines	Sub-humid	204	35.343.323	-5.180.146	18.6	642.0
s.4	Imzouren	Bouskour	Semi-arid	64	35.228.300	-4.023.258	18.2	316.8
s.5	Boughriba	Zâara	Arid	708	34.804.722	-2.499.167	18.5	302.2
s.6	Mhajar	Ben Taïeb	Arid	624	35.120.327	-3.485.440	18.2	316.8
s.7	Temsamane	Temsamane	Arid	315	35.129.616	-3.579.993	18.2	316.8
s.8	Rislane	Zâara Jbel	Arid	753	34.787.834	-2.504.047	18.4	600.2
s.9	Chouihia	Chouihia	Arid	510	34.797.523	-2.574.386	17.7	355.0
s.10	Zkhanin	Zaïo Zkhanin	Arid	306	34.979.477	-2.665.239	18.5	302.2
s.11	Kariat Arekmane	Kariat Arekmane	Arid	269	35.020.610	-2.725.661	17.6	354.0
s.12	Ain Sfa	Taghjirt	Arid	843	34.868.540	-2.142.333	16.7	287.2
s.13	Smia	Douar Zadra	Sub-humid	711	34.037.910	-4.371.288	18.1	517.2
s.14	Rbaa el fouki	El Kalb	Sub-humid	596	34.388.589	-4.319.768	18.1	517.2
s.15	Imouzare	Ait salh	Sub-humid	1303	33.784.203	-4.992.487	17.1	468.2
s.16	Ahl Sidi Lahcen	Zgane	Sub-humid	1270	33.744.176	-4.721.297	17.1	527.9
s.17	Ahl Sidi Lahcen	Ahl Sidi Lahcen	Sub-humid	772	33.753.029	-4.636.718	17.1	468.2
s.18	Oualili	Bou assel	Semi-arid	492	34.027.798	-5.573.833	17.1	511.0
s.19	Oualili	Khabar Zerhoun	Semi-arid	695	34.058.784	-5.499.884	17.1	511.0

Table 2. Soil fertility standards (El Falaki and Lhadi, 2001; Bocoum, 2004; LCA, 2008).

Appreciation Level	pH (H_2O)	Total nitrogen (%)	Organic matter (%)	C/N Ratio	Organic carbon (%)	Assimilable phosphorus (ppm)
Very low	< 5	< 0.05	< 1	< 6	< 0.6	-
Low	5-6.5	0.05-0.10	1–2	6-8	0.6-1.025	< 20
Medium	6.5-7.5	0.10-0.15	2–4	8-12	1.026–2.05	20-40
High	7.5–8.7	0.15-0.3	4–6	12-14	2.051–3.05	> 40
Very high	> 8.5	> 0.3	> 6	> 14	> 3.05	-

Table 3. Soil classification based on total limestone and salinity (Richards, 1954; GEPPA, 1981).

Soil class	Total Limestone Content	Salinity range (EC (mS/cm))
Very low	< 1 %	< 4
Low	1 - 5 %	4-8
Medium	5 - 25 %	8-16
Strong	25 - 50 %	16-32
Very Strong	50 - 80 %	> 32
Excessive	> 80 %	-

***Statistical analyses of data*:** Statistical analysis of data was carried out using Microsoft Excel 2016 and IBM SPSS Statistics 26 software to determine the significant effects among the studied physicochemical parameters. Several measures were subjected to analysis of variance (ANOVA). Subsequently, the Tukey multiple comparison test was employed to identify groups with significantly different means. Correlation analyses using the Pearson test were also conducted to examine the relationships between various soil properties.

RESULTS

***Particle size distribution and soil texture of studied soils*:** The results of particle-size distribution and soil texture analysis for studied soils are presented in Table 4. The particle size analysis of the surface horizon shows that 57.89% of the soil samples have a sandy loam texture, 31.57% have a loam texture, and 5.26% each have silt loam and sandy loam textures. For the deeper horizon, the texture of the 19 studied soils is predominantly sandy loam, accounting for 63.15% of the samples, while 21.05% of the soil samples have a loam texture, 10.52% have a silt loam texture, and 5.26% have a sandy texture. None of the stations falls into the clayey texture class.

If we examine the distribution of particle sizes (clay, silt, and sand), we can observe that the contents of silt and sand are higher in all the studied soils, while the clay content is low, not exceeding 25.92%. The content of clay tends to increase slightly with depth in most stations, while the content of silt and sand decreases with depth in most of the studied stations.

The chemical parameters of the soil

***The pH(H_2O) of soil*:** The results of the pH (H_2O) analyses show that the soils are neutral to slightly alkaline, with the exception of the station s.8 at layer part (0-20 cm), which is slightly acidic (pH (H_2O) = 6.39). Overall, for the surface horizons, the values of the pH ranged from 6.39 to 7.62, and between 6.66 and 7.54 in the depth horizon (Figure 1a). While these values exhibit minimal variation between the two horizons, statistical analysis revealed significant differences in pH between the horizons in six stations (s.3, s.6, s.7, s.8, s.11, and s.13). Indeed, the highest pH (H_2O) values were recorded in the stations s.3 and s.5, respectively for the surface and depth horizon, while the lowest values were recorded in the station s.8 for both horizons. The average pH (H_2O) values in both layers indicate that 84% of the soil samples studied are neutral.

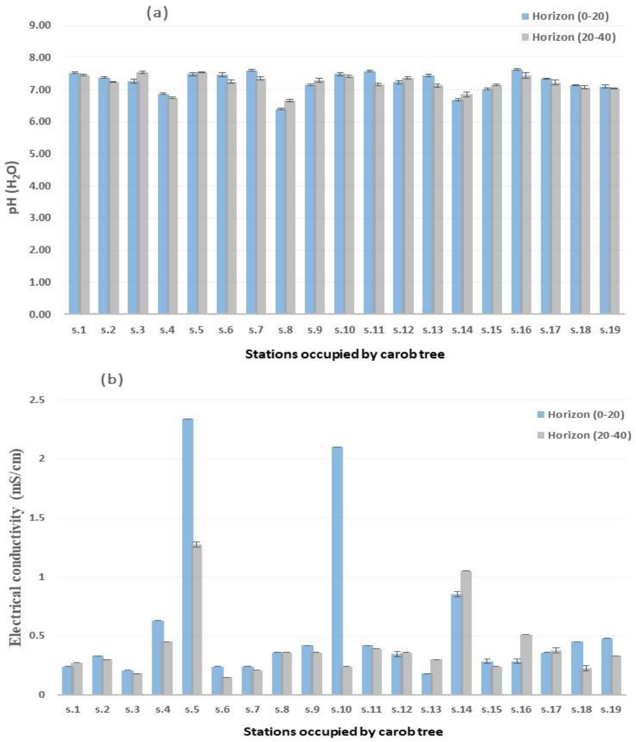

Figure 1. Distribution of soils of the 19 stations based on (a) their pH (H_2O) and (b) their electrical conductivity in different ecological regions of carob tree in Morocco.

Table 4. Texture classes and particle size distribution of analyzed soils of the 19 studied stations in different ecological regions of carob tree in Morocco.

Soil no.	Studied station	Soil depth (cm)	Particle size (%)					Texture
			Clay	Fine silt	Coarse silt	Fine sand	Coarse sand	
s.1	Zemmourene	0-20	12.98	41.12	9.54	7.80	28.53	silt loam
		20-40	17.66	37.69	11.49	9.06	24.10	loam
s.2	Brikcha	0-20	11.90	11.57	13.26	37.43	25.81	sandy loam
		20-40	13.87	7.18	12.26	41.67	25.02	sandy loam
s.3	Tirines	0-20	15.77	8.59	13.46	15.31	46.74	sandy loam
		20-40	9.24	11.34	9.34	20.16	49.92	sandy loam
s.4	Bouskour	0-20	13.88	18.97	7.93	41.23	17.42	sandy loam
		20-40	24.99	13.25	10.88	12.82	38.07	sandy loam
s.5	Zâara	0-20	14.37	9.62	10.46	51.58	13.90	sandy loam
		20-40	16.82	8.31	7.29	53.13	14.44	sandy loam
s.6	Ben Taïeb	0-20	1.72	25.58	9.62	12.03	51.01	sandy loam
		20-40	6.25	23.90	11.06	11.89	46.90	sandy loam
s.7	Temsamane	0-20	20.76	15.90	11.60	17.34	33.74	loam
		20-40	13.79	22.22	10.42	16.81	36.76	sandy loam
s.8	Zâara Jbel	0-20	12.59	19.34	9.61	16.87	41.56	sandy loam
		20-40	17.46	11.37	6.66	12.58	51.92	sandy loam
s.9	Chouihia	0-20	1.71	5.16	10.31	28.94	53.53	loamy sand
		20-40	1.05	6.46	3.38	24.75	64.36	sand
s.10	Zaïo Zkhanin	0-20	22.36	28.16	19.24	14.75	15.42	loam
		20-40	13.07	37.34	15.38	16.81	17.39	silt loam
s.11	Kariat Arekmane	0-20	17.11	27.13	14.49	16.88	24.37	loam
		20-40	19.83	33.86	11.15	15.50	19.67	loam
s.12	Taghjirt	0-20	7.19	25.05	11.77	20.64	35.32	sandy loam
		20-40	18.29	22.50	11.43	16.37	31.41	loam
s.13	Douar Zadra	0-20	10.88	28.68	10.20	26.92	23.29	loam
		20-40	9.03	12.04	7.41	27.83	43.69	sandy loam
s.14	El Kalb	0-20	18.06	28.91	17.06	20.02	15.92	loam
		20-40	6.59	44.75	11.60	12.94	24.12	silt loam
s.15	ait salh	0-20	6.33	14.46	6.61	30.45	41.41	sandy loam
		20-40	7.49	12.39	16.00	29.75	34.37	sandy loam
s.16	Zgane	0-20	15.36	6.34	19.26	25.14	33.84	sandy loam
		20-40	8.21	11.75	17.19	24.41	38.44	sandy loam
s.17	Ahl Sidi Lahcen	0-20	25.92	25.89	10.92	18.60	17.88	loam
		20-40	18.39	12.34	11.63	32.06	25.58	sandy loam
s.18	Bou assel	0-20	1.34	18.44	15.25	32.72	32.20	sandy loam
		20-40	10.73	20.94	14.05	31.41	22.86	sandy loam
s.19	Khabar Zerhoun	0-20	8.53	15.77	9.93	14.21	51.54	sandy loam
		20-40	18.84	28.13	7.56	8.67	36.80	loam

***Electrical conductivity of the soil*:** The electrical conductivity (EC) of soils determines their level of salinity, which in turn affects crop behavior in relation to salinity classes. The Richards scale (Table 3) was used to indicate the salinity class of soils in a 1/5 extract and its impact on crop yield. The results of salinity measurements vary significantly depending on the stations and depth horizon of soils. The values for the surface horizon range from 0.18 to 2.34 mS/cm and from 0.15 to 1.275 mS/cm for the depth horizon (Figure 1b). The electrical conductivity of the analyzed soils shows a significant decrease from the surface to depth horizons in the stations s.4, s.5, s.6, s.9, s.10, s.15, s.18, and s.19, and an increase in the stations s.13, s.14, and s.16. For the other stations, no remarkable variation was observed between the samples of the surface and depth horizons. After projecting the results of the analyses of this element onto the Richards salinity scale, we find that our soils belong to the category of non-saline soils regardless of the station.

***The content of total limestone in the soil*:** Obtained results showed that the content of total limestone in different stations vary significantly. The limestone contents range from 0.075 to 56.09 % for the surface horizon and from 0.145 to 51.935 % for the depth horizon (Figure 2a). It appears that these contents do not vary significantly between the two horizons for the most stations, except for stations s.8 and s.16, which show a significant difference between the two layers. The lowest values are found in stations s.1 for the surface horizon and s.7 for the depth horizon, while the highest values are in the station s.19 for both horizons. The analysis of the spatial distribution of total limestone reveals the existence of four soil categories for the surface horizon: moderate limestone soil (47.37%), high limestone soil (31.58%), non-limestone soil (15.79%), and very high limestone one (5.26%). For the depth horizon, there are five categories: high limestone soil (42.11%), moderate limestone soil (26.32%), low limestone soil (15.79%), non-limestone soil (10.53%), and very high limestone one (5.26%).

***Determination of the content of organic carbon in the soil*:** The content of organic carbon (OC) in the soil varies significantly depending on the studied stations. It ranges from 0.36 to 5.11 % for the surface horizon and from 0.78 to 5.06 % for the depth horizon (Figure 2b). Comparing the concentrations of this element in the two horizons shows that the OC content in the soil of the stations s4, s.6, s.13, s.14, s.15, and s.18 decrease with depth, unlike the stations s.1, s.10, and s.11where they increase with depth. For the other stations, no significant difference was recorded. According to soil fertilization standards (Table 2), the samples from the surface horizon (0-20 cm) in stations s.1 and s.7 have a very low OC content, making them very poor in this element. The soil samples from both horizons of station s.19 have the highest OC content, indicating that they are very rich in organic carbon. In general, more than 84% of the studied soils are well endowed with organic carbon.

***Determination of the content of organic matter in the soil*:** The content of organic matter (OM) in the soil follows the same trends of the content of organic carbon in the soil, with maximum and minimum contents found in the same stations for organic carbon. Overall, OM contents are highly variable, ranging from 0.62 to 8.79 % in the surface horizon and from 1.34 to 8.70 % in the depth horizon (Figure 3a). In the stations s.1, s.4, s.6, s.10, s.11, s.13, s.14, s.15, and s.18, OM contents show significant differences between the surface and depth layers of each station. Our results showed that OM contents are relatively higher in the surface horizon. In general, the OM averages in both layers of each station indicate that more than 68.42% of the studied samples fall within the range of soils rich in organic matter.

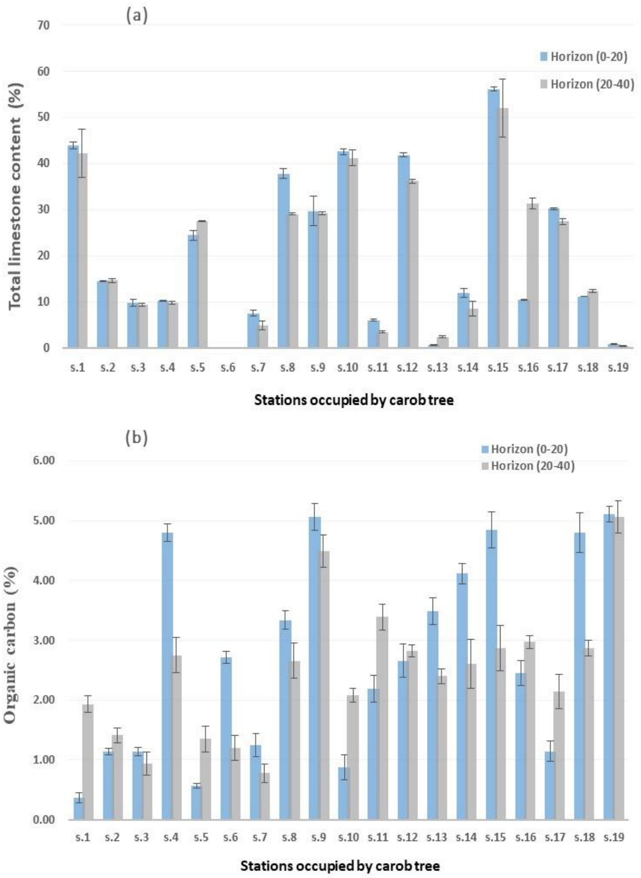

Figure 2. Distribution of soils of the 19 stations based on (a) their content in total limestone and (b) their content in organic carbon in different ecological regions of carob tree in Morocco.

Determination of the content of total nitrogen in the soil: Obtained results showed that the content of total nitrogen (TN) in the studied soil is variable. These contents range from 0.02 to 1.82 % in the surface horizon and from 0.02 to 0.24 % in depth one (Figure 3b). TN values are following the same trends as organic carbon, with percentages gradually decreasing with depth in 63.16% of the studied samples. However, there is no significant difference between the two depth levels for the various stations, except for stations s.8, s.12, s.14, and s.19. According to soil fertility standards (Table 2), the soils with the lowest TN content are those of stations s.2 for the surface horizon and s.14 for the depth horizon, while the highest values are recorded in stations s.8 for the surface horizon and s.9 for the depth horizon. Similar to organic matter, more than 84% of the mean TN contents in analyzed soils are rich in total nitrogen.

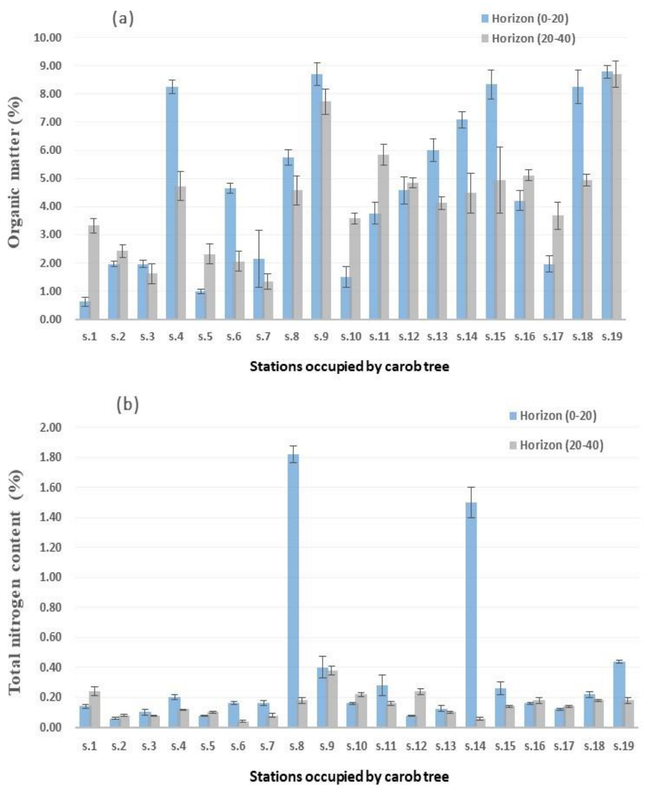

Figure 3. Distribution of soils of the 19 stations based on (a) their content in organic matter and (b) their content in total nitrogen in different ecological regions of carob tree in Morocco.

***Carbon/Nitrogen ratio*:** The carbon/nitrogen (C/N) ratio was calculated for both horizons of each station, and the values of the studied soils showed significant difference from one station to another and between the two horizons. The C/N ratio ranges from 1.84 to 33.28 in the surface horizon and from 8.14 to 29.92 in the depth horizon (Figure 4a). Within each station, the C/N ratio varies with depth, but the difference in not significant, except for the stations s.11, s.12, s.14, and s.19. Based on these results, the C/N ratio decreases with depth for the station s.12, while for the stations s.11, s.14, and s.19, it is slightly higher. The C/N ratio recorded in the stations s.8 (0-20cm) and s.1 (20-40cm) is lower, indicating rapid decomposition of organic matter, while the stations s.12 and s.14 have the highest values, respectively for the surface and depth horizons. The analysis of our results revealed that 42.11 and 63.16 % of the C/N ratios of the soil samples, respectively for the surface and depth horizons, fall within the range of high values (> 12), indicating that organic matter decomposition is slow, possibly due to a lack of nitrogen or an excess of organic carbon.

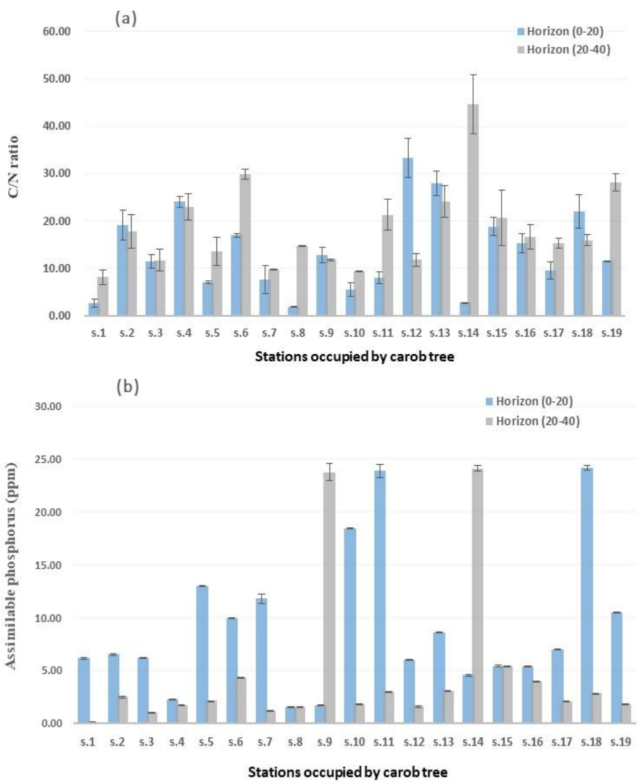

Figure 4. Distribution of soils of the 19 stations based on (a) their content in C/N ratio and (b) their content in assimilable phosphorus in different ecological regions of carob tree in Morocco.

***Determination of assimilable phosphorus*:** The content of assimilable phosphorus (P) in the soil is significantly different between the stations. It ranges from 1.54 to 24.18 ppm for the surface horizon and from 0.12 to 24.14 ppm for the depth horizon (Figure 4b). The content of P in the soil tends to decrease significantly with depth; this decrease is not significant in the stations s.4, s.8, and s.15, while in the stations s.9 and s.14 it is higher. The lowest P contents are recorded in stations s.8 and s.1, respectively, for the surface and depth horizons. These stations are considered as soils poor in P, while the highest contents in P are recorded in the station s.18 for the surface horizon and the station s.14 for the depth horizon. In general, the mean P contents in both horizons indicate poor soil fertility, regardless of the stations.

***Correlation between soil characteristics*:** Pearson correlation tests were conducted to measure the degree of association between various physical, chemical and geographical soil properties (Tables 5a and b). For all selected stations, the correlation analysis between soil chemical properties showed strong positive correlations between organic carbon and organic matter ($r = 1.00$, $P < 0.01$), as well as between organic carbon and total nitrogen. This correlation becomes stronger and significant in the depth horizon ($r = 0.627$, $P < 0.01$) but

Table 5. Pearson's correlations between physical, chemical contents and geographical parameters of soils.

(a): 0-20 cm depth horizon

	El	**MAR**	**MAT**	**Cl**	**FSi**	**CSi**	**FSa**	**CSa**	**pH**	**TN**	**OC**	**OM**	**C/N**	**P**	**$CaCO_3$**	**EC**
El	1															
MAR	0.041	1														
MAT	-0.612**	0.176	1													
Cl	-0.198	0.006	0.267	1												
FSi	-0.203	0.008	0.107	0.200	1											
CSi	-0.061	0.055	-0.015	0.347	-0.010	1										
FSa	0.058	-0.195	0.022	-0.184	-0.511*	-0.152	1									
CSa	0.218	0.148	-0.231	-0.626**	-0.384	-0.313	-0.351	1								
pH	-0.084	-0.235	0.022	0.183	0.044	0.248	-0.076	-0.132	1							
TN	0.124	0.272	0.131	0.046	0.100	0.040	-0.194	0.063	-0.810**	1						
OC	0.262	-0.055	-0.478*	-0.600**	-0.194	-0.254	0.174	0.382	-0.601**	0.341	1					
OM	0.262	-0.055	-0.478*	-0.600**	-0.194	-0.254	0.174	0.382	-0.601**	0.341	1.000**	1				
C /N	0.174	-0.190	-0.444	-0.499*	-0.123	-0.202	0.355	0.108	0.082	-0.465*	0.364	0.364	1			
P	-0.237	-0.273	-0.110	0.027	0.212	0.404	-0.033	-0.243	0.439	-0.304	-0.165	-0.165	-0.058	1		
$CaCO_3$	0.298	-0.019	-0.089	0.041	0.153	-0.183	-0.029	-0.063	-0.199	0.092	-0.138	-0.138	-0.139	-0.240	1	
EC	-0.102	-0.431	0.306	0.292	-0.033	0.286	0.379	-.533*	0.087	-0.023	-0.286	-0.286	-0.320	0.316	0.213	1

(b): 20-40 cm depth horizon

	El	**MAR**	**MAT**	**Cl**	**FSi**	**CSi**	**FSa**	**CSa**	**pH**	**TN**	**OC**	**OM**	**C/N**	**P**	**$CaCO_3$**	**EC**
El	1															
MAR	0.041	1														
MAT	-0.612**	0.176	1													
Cl	-0.306	-0.106	0.013	1												
FSi	-0.239	-0.091	0.049	0.123	1											
CSi	0.256	0.045	-0.269	0.017	0.269	1										
FSa	0.205	0.010	0.010	-0.138	-0.607**	0.016	1									
CSa	0.103	0.108	0.011	-0.451	-0.463*	-0.514*	-0.292	1								
pH	0.027	-0.115	0.072	-0.228	-0.069	0.159	0.342	-0.177	1							
TN	0.090	-0.114	-0.328	-0.091	-0.008	-0.197	-0.146	0.228	0.120	1						
OC	0.271	-0.040	-.599**	-0.011	0.079	-0.206	-0.257	0.216	-0.384	0.627**	1					
OM	0.271	-0.040	-.599**	-0.011	0.079	-0.206	-0.257	0.216	-0.384	0.627**	1.000**	1				
C /N	0.134	0.049	-0.088	-0.169	0.336	0.009	-0.225	-0.019	-0.558*	-0.480*	0.234	0.234	1			
P	0.083	-0.068	-0.053	-0.639**	0.137	-0.266	-0.048	0.286	-0.207	0.247	0.366	0.366	0.461*	1		
$CaCO_3$	0.432	0.011	-0.151	-0.045	-0.089	0.328	0.181	-0.146	0.279	0.532*	0.043	0.043	-0.511*	-0.024	1	
EC	0.155	-0.162	0.120	0.066	0.057	-0.164	0.386	-0.378	-0.042	-0.178	-0.003	-0.003	0.336	0.369	0.026	1

* Significant difference at $p < 0.05$; ** significant difference at $p < 0.01$.

The meaning of abbreviations indicated in the table: TN: total nitrogen; OC: organic carbon; OM: organic matter; C/N: C/N ratio; P: assimilable phosphorus; CaCO: total limestone; EC: electrical conductivity; El: elevation; MAT: mean annual temperature; MAR: mean annual rainfall; Cl: clay; FSi: fine silt; CSi: Coarse silt; FSa: Fine sand; CSa: coarse sand.

remains non-significant for the surface horizon (r = 0.341). There is also a significant correlation (r = 0.532, $P < 0.05$) between total nitrogen and total limestone content in the depth horizon. The C/N ratio was significantly negatively correlated with the total nitrogen contents in both surface and depth horizons (r = -0.465, -0.465, $P < 0.05$, respectively), as well as with pH (H_2O) and total limestone content in the depth horizon (r = -0.558, -0.511, $P < 0.05$, respectively). Similarly, pH (H_2O) is significantly negatively correlated with organic carbon and total nitrogen contents in the surface horizon (r = -0.601, -0.601, -0.810, $P < 0.01$, respectively). Assimilable phosphorus was significantly related to C/N ratio in the depth horizon (r = 0.461, $P < 0.05$). It is worth noting that electrical conductivity (EC) was not correlated with any chemical property.

Regarding physical properties, it is observed that clay, silt, and sand are correlated due to their mutually exclusive nature. Coarse sand is significantly negatively correlated with clay for the surface horizon (r = -0.626, $P < 0.01$), as well as fine silt and coarse silt content in the depth horizon (r = -0.463, $P < 0.05$ and r = -0.514, $P < 0.05$, respectively). There is also a negative correlation between fine sand and fine silt for the surface horizon (r = -0.511, $P < 0.05$), which becomes stronger in the depth horizon (r = -0.607, $P < 0.01$).

When examining the correlations between physical and chemical properties, it is noted that clay is significantly correlated with organic carbon, organic matter, and the C/N ratio for the surface horizon (r = -0.6, -0.6, $P < 0.01$, r = -0.499, $P < 0.05$, respectively), as well as coarse sand with electrical conductivity (r = -0.533, $P < 0.05$). Additionally, there is a negative correlation between clay and assimilable phosphorus in the depth horizon (r = -0.639, $P < 0.01$).

Furthermore, the correlation analysis between soil properties and altitude, average temperatures, and average rainfall shows that only the mean temperature is significantly negatively correlated with organic carbon and organic matter (r = -0.599,

$P < 0.01$). This correlation becomes weaker in the depth horizon ($r = -0.478$, $P < 0.05$).

DISCUSSION

The results of particle size analysis of studied soil indicate that over 57% of the samples of the surface horizon have a sandy loam texture, while over 63% of the samples from the depth layer also exhibit the same texture. Such sandy loam soils are often highly suitable for growing carob trees. The abundance of carob trees in the studied areas suggests that sandy to loamy soils are well suitable for carob cultivation. Most of the analyzed samples of soil consist of coarse particles, primarily coarse sand. These materials are highly permeable to water and air and their textural porosity promotes good aeration, drainage, and root development. Morton (1987) and Sbay *et al.* (2008) reported that well-drained and aerated sandy, loamy, and rocky soils, not too clayey, are excellent and suitable for carob cultivation.

The chemical analyses vary across the studied stations, this variation may be explained by various edaphic, morphological, land use, topographical, climatic, and vegetation cover factors (Jobbàgy and Jackson, 2000; Powers and Schlesinger, 2002; Evrendilek *et al.*, 2004 ; Wang *et al.*, 2012; Oueslati *et al.*, 2013; Wang *et al.*, 2015a and b). The pH (H_2O) values of the studied soils fall within the range of neutral to slightly alkaline soils. This parameter is a key element in the soil's chemical composition and determines nutrient availability for plants and soil microorganisms (Doucet, 2006; Borah *et al.*, 2010). It plays an important role in nutrient retention or release mechanisms (Farrah *et al.*, 1979). Similar studies have shown that carob trees thrive in soils with a neutral to slightly alkaline pH and do not tolerate acidic soils (Morton, 1987; Sbay, 2008). In Cyprus, a large carob tree plantation has been successfully developed on soil with a pH of = 9 (Morton, 1987). Sanchez *et al.* (2003) mentioned that a pH (H_2O) ranging between 6.0 and 7.5 creates optimal conditions for nutrient availability for most plants, and the values obtained in this study fall within this range. For electrical conductivity, the results indicate that the soils belong to the category of non-saline soils, with an electrical conductivity below 2 mS/cm. Correia *et al.* (2010) also reported that the carob tree can tolerate and maintain the majority of its physiological processes at a concentration of 40 mmol NaCl l^{-1}(or EC= 6,5 mS/cm). This demonstrates that carob tree can be planted in arid or semi-arid areas where salinity concentrations are relatively high.

Regarding the distribution of total limestone in the different studied stations, it is generally high. These results suggest that the carob tree may be considered a calciphilous plant capable of growing and developing in calcareous soils. According to Sbay and Abourouh (2006), carob tree prefers calcareous soils and Melgarejo and Salazar (2003) were able to locate carob plantations in areas with active limestone contents exceeding 22%. Ekwel *et al.* (2019) have shown that the presence of high limestone quantities in soils significantly increases seed and pod yields in the Mouola PG variety (varietie of cowpea). Its presence also enhances and facilitates the transfer of K+, Ca2+ and Mg2+ concentrations, and N into the leaves of the plants (Demidchik and Tester, 2002; Ekwel *et al.*, 2019) and increases plant tolerance to salinity (Liu and Zhu, 1998; Qiu *et al.*, 2002). In general, the presence of limestone in soils contributes to improve soil fertility and consequently increases carob yields (Correia and Pestana, 2018).

It appears that the organic matter content strongly influences the chemical fertility parameters value and evolution, such as total nitrogen, pH, and assimilable phosphorus, which is widely accepted (Piéri, 1989). The studied soils have a relatively good content in organic matter. They are well provided with total nitrogen and organic carbon, with a mean content ranging respectively between 0.07 and 1 % and between 0.96 and 5.09 %. However, more than 15.7 % of the studied samples of soil have a C/N ratio within the normative range (8 to 12). Indeed, the C/N ratio in these soils is relatively higher (C/N ratio > 12) due to the presence of coarse particles in the studied soils (Sedogo *et al.*, 1994; Kambiré *et al.*, 2001), which explains the low organic matter content in the studied stations. A C/N ratio that is too high (>12) in soil leads to low biological activity in the soil, thereby slowing down the mineralization of organic matter and the release of available nitrogen in the soil (Masson, 2012). In contrast, in soils with low C/N ratio (< 8), biological activity is high, resulting in significant nitrogen release. Although the analyzed soils are relatively rich in organic matter, it should be noted that the average assimilable phosphorus content is very poor across all studied stations. The lack of phosphorus in soils could be explained by the fact that this nutrient is taken up by the plants or due to the low abundance of bioreducers in the environment. Assimilable phosphorus is generally one of the most important soil nutrient parameters required for carob tree growth and, consequently, for good carob yield (Correia and Pestana, 2018).

In the vertical distribution of the analyzed elements, it is observed that the content of chemical elements in the studied soils gradually decreases with depth, but without significant difference between the considered layers in most of the stations. In general, the contents of organic carbon and total nitrogen in the soil are directly related to the significant content of organic matter mostly found in the top centimeters of the soil. Therefore, they are highly dependent on vegetation and humus form (Montuelle, 2003; Schilling *et al.*, 2009; Su *et al.*, 2010; Drouin *et al.*, 2011; Wiesmeier *et al.*, 2012 ; Wang *et al.*, 2015a). In depth horizon, this content decreases rapidly (Conant *et al.*, 2003; Liu *et al.*, 2012; Song *et al.*, 2016; Yu *et al.*, 2019). Schilling *et al.* (2009) also have shown that nutrient concentrations such as total nitrogen and organic carbon decrease with soil depth. However, there are stations where the contents of chemical elements are relatively low in the surface. This decline could be explained by erosion or leaching of these elements (Gurumurthy *et al.,* 2009; Liu *et al.,* 2011; Kumar *et al.,* 2012; Datta *et al.,* 2015; Saint-Laurent *et al.,* 2016; Jia *et al.,* 2017). The nature of the soil texture is also a factor explaining this variation (Montuelle, 2003; Schilling *et al.,* 2009); for example, the presence of a clay layer in the profile could alter the transport of chemical elements in the lower layers of the soil. Indeed, the texture of the studied soils, composed of coarser particles (sand), promotes vertical leaching of chemical elements (Don *et al.,* 2007). However, significant effects were not detected in our study regarding the vertical distribution of chemical elements between layers. This phenomenon is more pronounced for assimilable phosphorus; 84.21% of our soils have a higher assimilable phosphorus content in the surface horizon compared to the depth horizon. Moreover, Brooks (2002) demonstrated a decrease in several nutrient elements in the deeper layers of the soil profile, whereas Schilling *et al.,* (2009) have shown that phosphorus concentration does not seem to have specific ties to soil depth. Indeed, for the carob tree, the surface horizon is more important because its root system is active in the first 15 to 20 centimeters of the soil, which are generally more fertile and better aerated (Batlle and Tous, 1997).

The correlation between soil properties and climatic parameters was calculated not only for surface horizons but also for depth horizons. The correlation analysis between different soil properties revealed that organic carbon and total nitrogen contents in studied soils are positively correlated. Generally, soils that contain much organic carbon also have much total nitrogen (Brady & Weil, 2007; Rokosch *et al.,* 2009; Dai *et al.,* 2011). According to Wang *et al.* (2010), there is a strong correlation between organic carbon and total nitrogen due to their abundance in surface horizons. A non-significant negative correlation is observed between assimilable phosphorus and organic matter in the surface horizon. Indeed, the phosphorus present in organic residues can be associated with the solid constituents of the residue (Houot *et al.,* 2014). Furthermore, according to Provencher (2003), organic matter positively influences phosphorus assimilation by plants, which can explain the decrease in the content of P in the surface horizon, where the root system is more active. This correlation becomes positive in the deeper horizon, resulting in a significant positive correlation between assimilable phosphorus and the C/N ratio, as reported by El Boukhari *et al.* (2016). In addition, the presence of total limestone in soil leads to an increase in the content of total nitrogen in the soil. This is in line with the findings of Duchaufour (1950). Several authors also reported the positive effect of limestone (Duchaufour, 1988). Meanwhile, Marshner (1995) demonstrated that the presence of limestone directly or indirectly affects the chemistry and availability of nitrogen, phosphorus, and other soil nutrients. Providing adequate phosphorus to plants can be difficult in calcareous soils (Taalab *et al.,* 2019). It is also essential to mention that the content of organic carbon and phosphorus in the soil is negatively correlated with the percentage of clay in the soil. Contrary to the observations of several authors who indicated that soils with a higher percentage of fine particles tend to retain more organic carbon (Jobbàgy and Jackson 2000; Bedison *et al.,* 2013; El Boukhari *et al.,* 2016; Yu *et al.,* 2019). While Guppy *et al.* (2005) reported that phosphorus strongly binds to clay minerals, limiting its availability. Likewise, similar trends were also stated by Pothuluri *et al.* (1991). Furthermore, there is a strong negative correlation between the pH (H_2O) of soil and the content of organic carbon and nitrogen in soil, which are in concordance with the results of Saint-Laurent *et al.* (2016). Augusto *et al.* (2000) showed that the decomposition of biomass leads to the release of several acidifying compounds (e.g., fulvic and humic acids). This explains the negative relationship between the pH and the content of organic carbon and total nitrogen in soil. It is also noted that high content of sand in the soil was negatively correlated with the electrical conductivity of the soil. In contrast to our results, Piéri (1989) mentioned that the quantity of sand does not significantly influence electrical conductivity and that the presence of non-saline soils is associated with a dilution of the soil solution in clayey environments where water stays for a sufficient long time. Rahman *et al.* (2013) also reported a parallel result. According to Diallo *et al.* (2015) and Faye *et al.* (1995), soil salinization is attributed to rainfall deficit.

These studies have also not revealed any clear influence of climate on the overall balance of chemical elements in the soil, except for temperature, which is negatively correlated with organic matter, although this relationship is not significant for nitrogen. Jobbàgy and Jackson (2000) and Morris *et al.* (2010) mentioned that very high temperatures could lead to a loss of organic matter. Moreover, Hankin *et al.* (1982) showed that temperature might influence the growth of microorganisms, the quantity of extracellular enzymes released into the soil, and ultimately the rate of decomposition of organic matter and the release of nutrients for plants.

From a general perspective, obtained physicochemical results are very variable. Overall, studied soils range from poor to very rich in nutrients. These results explain that carob tree may adapt to a wide range of types of soil, from poor sandy soils and rocky hillsides to deep soils, as noted by Albanell (1990). Carob trees are not very demanding when it comes to type of soil; they have been cultivated on marginal lands with poor content in nutrients in very unfavorable conditions and in places where it is not possible to grow other species. In general, carob trees are found on poor, rocky, sandy, heavy loam, and clayey soils, with a preference for limestone terrain with a balanced texture and good drainage. They don't tolerate acidic soils (Albanell, 1990; Sbay and Abourouh, 2006) and tend to prefer shallow soils (Aafi, 1996).

The soil texture of studied soils occupied by carob tree in Morocco are suitable for the cultivation of this species since they promote good drainage and aeration and root development. Their nutrient retention of these calcareous soils and their content in nutrients and organic matter will improve the yield of carob trees in the country.

Conclusion: Detailed information on the physicochemical properties of studied soils for grouping and the characterization of soils is essential for effective land management planning and soil fertility enhancement, and also for stimulating carob production and cultivation in Morocco. This study is important for identifying the most appropriate soils for carob cultivation and estimating crop production and yield.

The studied carob soils exhibit great variety, primarily related to the geological and climatic diversity of the region. Soil quality in terms of chemistry and physics partly accounts for regional differentiation. This soil property has determined the specific types of carobs for each region. In general, studied soils have a coarser particles texture and a pH, which is favorable for carob cultivation. They are relatively well rich to low in total nitrogen and organic matter, which supports active microbial life. The C/N ratio indicates very slow mineralization of available organic matter. The nutrient balance reveals deficiencies in assimilable phosphorus.

The texture and the physicochemical quality of soils of the studied stations and the climatic conditions prevailing in the carob tree regions in Morocco will improve the production of carob and its quality in the country. Nevertheless, further studies are necessary to better understand the required agronomic environment for sustainable production and high yield of carob and to improve the income of the farmers of carob tree in Morocco.

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SDG's Addressed: Zero Hunger, Decent Work and Economic Growth, Responsible Consumption and Production, Climate Action.

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