ECODENDROMETRIC CHARACTERIZATION OF ALEPPO PINE (*PINUS HALEPENSIS* MILL.) STANDS IN THE BAÏNEM FOREST (ALGERIA)

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(Received 22nd Jan 2025; accepted 24th Mar 2025)

Abstract. The evaluation and monitoring of forest species can provide valuable data and useful information for sustainable forest management. In the present study, the ecodendrometric and pedological characteristics of Aleppo pine stands in the Baïnem Forest (Algeria) were determined. Four Aleppo pine plots (400 m^2 for each one) were installed and subjected to an ecological description (altitude, exposure, and slope), a complete dendrometric inventory (height, diameter, and circumference), and a pedological characterization (pH, conductivity, total limestone, and organic matter). Our dendrometric results revealed that Aleppo pine trees exhibit significant growth variability in height, diameter, and circumference and are distributed in a regular structure compared to the normal distribution. The relationships between dendrometric parameters varied significantly depending on the studied plots. The soils of the studied plots were rich in organic matter, non-saline, slightly acidic to neutral, and non-calcareous to slightly calcareous. The Principal Component Analysis highlighted that ecological and edaphic diversity is responsible for the growth heterogeneity in height, diameter, and circumference of the Aleppo pine trees within the studied plots. Our ecodendrometric and pedological data could be used as relevant and useful information for the sustainable management of Aleppo pine forests.

Keywords: *Pinus halepensis Mill., ecological description, dendrometric inventory, pedological characterization, multivariate analysis*

Introduction

The Aleppo pine (*Pinus halepensis* Mill.), belonging to the Pinaceae family, is one of the most characteristic species of the Mediterranean basin, particularly in North Africa, Italy, France, and Spain (Liphschitz and Biger, 2001; Fekih et al., 2014). The Aleppo pine forest covers more than 2.5 million hectares and is naturally widespread in semi-arid and arid regions at low altitudes and along the coast (Maestre and Cortina, 2004).

In Algeria, Aleppo pine, growing in all bioclimatic zones with a predominance in semi-arid zones, is considered the most important forest species, covering an estimated area of 1,158,533 ha (Benouadah et al., 2019). In addition, due to its low requirements, pyrophyte character and high plasticity to various eco-climatic conditions and poor soils, the Aleppo pine has been extensively used as a reforestation species to restore degraded areas (Liphschitz and Biger, 2001; Montero et al., 2001; Bello-Rodríguez et al., 2020).

As for growth and production, the Aleppo pine forests have been the subject of many studies in several Mediterranean countries, particularly in Tunisia (Souleres, 1969,

DOI: http://dx.doi.org/10.15666/aeer/2303_54995520

1975; Chakroun, 1986; Ayari et al., 2016; Bouachir et al., 2017; Jaouadi et al., 2019; Jaouadi et al., 2021; Mechergui et al., 2022), France (Bedel, 1986; Hover et al., 2017; Vennetier et al., 2018), Italy (Ciancio, 1986; Di Filippo et al., 2021), Morocco (Belghazi et al., 2000; Ben-Said et al., 2022; Benarchid et al., 2022, 2024) and Spain (Montero et al., 2001; De Luis et al., 2014; Camarero et al., 2020; Lerma-Arce et al., 2021; Cano et al., 2022). In Algeria, also, several studies have been conducted, notably on the description of forest stands (Boudy, 1950), productivity (Kadik, 1983; Bentouati, 2006; Sarmoum et al., 2020; Guit and Nedjimi, 2020), dendroecology (Kadik, 1983; Mederbel, 1992; Safar, 1994; Hani et al., 2020; Rached-Kanouni et al., 2020; Daoudi et al., 2022; Neghnagh et al., 2022; Ghalem and Zaidi, 2024), phytosociology, phytoecology, and phenology (Kadik, 2005; Brakchi, 2015; Djerrad, 2016; Djerrad et al., 2017; Djebbouri and Terras, 2020; Tebani, 2023; Lakhdari et al., 2024).

In fact, scientific research, such as dendroecology, phytosociology, climate modeling, biodiversity research, carbon sequestration research, Geographic Information System (GIS) applications, and long-term monitoring (Domingo et al., 2019; Segura et al., 2019; Gelabert et al., 2020; Vicent et al., 2024), plays a crucial role in helping forest management, ensuring its effectiveness and success.

In this context, the present study aims to determine the ecodendrometric and pedological characterization of Aleppo pine stands in the Baïnem Forest (Algeria), in sight to enhance the generation of forest ecosystem goods and services. For that, four Aleppo pine plots, with a surface area of 400 m^2 for each one, were subjected to an ecological description (altitude, exposure, and slope), a complete dendrometric inventory (height, diameter, and circumference) and a pedological characterization (pH, conductivity, organic matter, and total limestone). Indeed, our ecodendrometric and pedological study can provide valuable data and comprehensive information about the state and dynamics of forests, which allow promoting conservation, restoration, and sustainable management of Aleppo pine forest through integrated inclusive nature-based solutions to the climate change and to the strong human pressure, such as deforestation, illegal logging and fires.

Materials and methods

Description of the study area

The Baïnem forest is located in the Bouzareah massif, about 15 km west of Algiers, between 36° 48’ N and 3° 10’ W, with an altitudinal range of 80 to 500 m. It extends over an area estimated at 685.44 hectares, resulting from the merger of two sites: the state-owned Baïnem forest and the June 19 Forest. Such area makes this forest the largest wooded area in the Wilaya of Algiers (Algeria) (Teulieres, 1970).

Geographically, the Baïnem forest is bordered by Hammamet, Aïn Benian, Beni Messous, Bouzareah and Raïs Hamidou in the northwest of Algiers, overlooking the Algerian west coast (*Fig. 1*). It is managed by the Conservation of Algiers Forests (CFA) under the supervision of the General Directorate of Forests (DGF).

The Baïnem forest benefits from a warm sub-humid Mediterranean maritime climate, with irregular and low rainfall (on average, around 661 mm/year). The seasonal regime of our study area is of the HAPE type (winter, autumn, spring and summer), with summer as the driest season and winter as the wettest season. The temperatures vary greatly, the difference between the average maximum (M) and minimum (m) temperatures is between 11°C and 26°C. February is the coldest month of the year and

August is the hottest one. The dry period generally starts in mid-May and lasts until September (NMO, 2024).

The forest species contribute significantly (more than 65%) to the plant cover of our study plots, such as *Pinus halepensis* and *Eucalyptus camaldulensis*. The shrub layer, covering 30%, is dominated by *Pistacia lentiscus*, *Quercus coccifera*, *Arbutus unedo*, *Olea europaea* and *Erica multiflora*. The herbaceous layer, although less represented at 10%, hosts species such as *Ampelodesmos mauritanicum*, *Cistus salvifolius* and *Pinus halepensis* seedlings, indicating ongoing ecological regeneration processes.

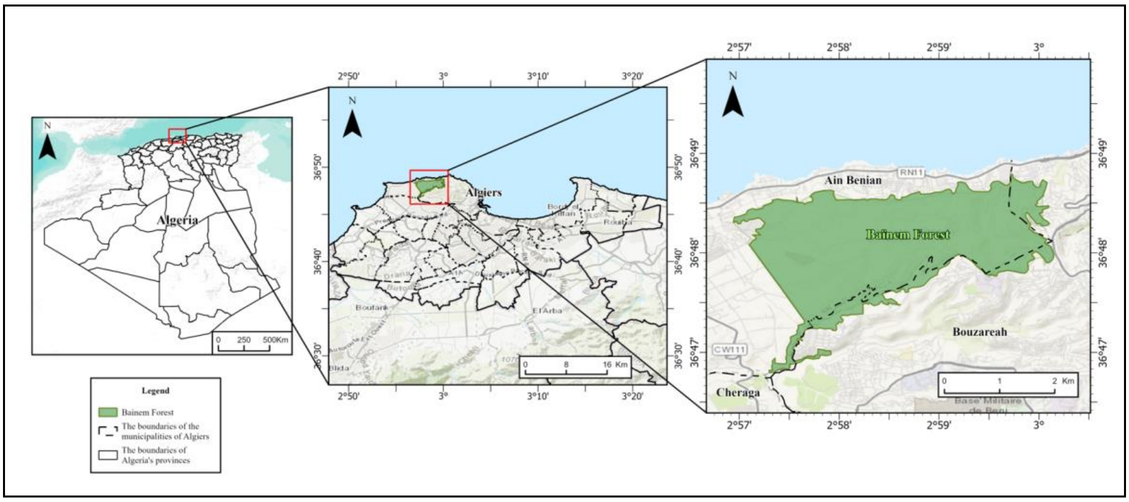


Figure 1. *Geographical location of the study area (The Baïnem forest)*

Dendrometric inventory and plots characterization

Four plots, circular in shape with a radius of 11.28 m (400 m^2) for each one (*Fig. 2*), were sampled subjectively, in March 2024, throughout the studied Aleppo pine stand in the Baïnem forest, taking into account the topographic characteristics, the stand density and the accessibility condition of the stand. The plots were ecologically and edaphically characterized and a complete dendrometric inventory was carried out.

Figure 2. *Installation of the plots*

Table 1 summarizes the ecological characteristics of the studied plots. The geographic coordinates and exposition were determined using a GPS (Global Positioning System) (Garmin, eTrex 20, France) and the slope was determined using a clinometer (Moineau Instruments, Clinometer 5000ME, France).

Table 1. *Ecological characteristics of the studied plots*

Plots		Longitude	Latitude	Altitude (m)	Slope (%)
South	S1	2°57’51”E	36°47’51”N	237	10
	S2	2°58’15”E	36°48’59”N	247	4
North	N1	2°58”97’E	36°48’12”N	265	2
	N2	2°58’11”E	36°48’41”N	235	15

Dendrometric measurements

The dendrometric measurements were described in field inventory sheets prepared for each plot. The total height of the tree, measured with a Blum-Leiss (Carl Leiss-Berlin, Germany), was defined as the distance from the base of the tree to its terminal bud. However, in case of trees with a tabular or rounded shape, this height was taken at the limit of the last twig of the crown. The circumference at 1.3 m from the ground was measured using a tape measure (Cloth tape measure 165 ft). The diameter at breast height (DBH) was measured using a forestry compass (Nestle Compas forestier Waldmeister Best. -Nr. 300 100, Germany). Trees with a trunk diameter of less than 5 cm were excluded from the survey. The basal area of a tree is the cross-sectional area of this tree at 1.30 m. In our present work, this basal area was estimated from the circumference at 1.3 m of the tree. Additionally, the sum of the basal areas of all trees within each plot allowed to determine the basal area per hectare. Density (number of stems per hectare (N/ha)) and total dominant height (defined as the arithmetic mean of the heights of the eight highest trees in each plot) were also determined.

Pedological characteristics

To assess the soil quality of the studied plots, some essential chemical parameters (Hydrogen Potential (pH), Electrical Conductivity (EC), Organic Matter (OM), and Total Limestone) were determined according to Mathieu and Pieltain (2003). The Hydrogen Potential was determined using a pH-Meter (Hanna Instruments, pH-Meter PH211, USA), the Electrical Conductivity was determined using a conductivity meter (Hanna Instruments, EC 214, USA), the Organic Matter was determined using a muffle furnace (Nabertherm, Muffle furnace L3/11, Germany), and the Total Limestone was determined using a Bernard Calcimeter (Gabbrielli Technology, Bernard Calcimeter, Italy).

Statistical analysis

During our inventory, 230 stems, distributed over four plots, were measured. The relationships between the different ecodendrometric and pedological variables of the studied plots were carried out using the following statistical methods:

Descriptive statistics, correlation and analysis of variance

The descriptive statistics includes the central tendency (arithmetic mean) and the dispersion (standard error, coefficient of variation). The coefficient of correlation was used to measure the relationship between two or more variables. The statistical evaluation, within the studied plots, was performed by one-way analysis of variance (ANOVA). Tukey's test was used to separate the means when the dendrometric variables are statistically significant ($P \leq 0.05$).

Overall plots structure

The normal distribution was opted for analyzing the overall structure of the Aleppo pine trees within the studies plots. The frequency histograms, according to diameter, circumference and height classes, were performed with the STATISTICA software; it should be noted that the graphical adjustment with the normal law, given by this software, allow to verify the nature of the distribution. Additionally, the Kolmogorov-Smirnov test and some parameters of shape (kurtosis coefficient (β) and Skewness coefficient (γ)) were also used to assess the normal distribution of the Aleppo pine trees within the studies plots.

Relationship between dendrometric variables

To adjust y to x of a cloud of points, it is to find a function f, whose representative curve, passes as close as possible to all the points of the cloud. In our study, we tested all the equations and retained only the one that provides the highest coefficient of determination R^2. This coefficient, with a value between 0 and 1, allow concluding the adequacy between the model and the observed data.

Multivariate analysis

The influence of ecological and pedological factors (slope, exposure, altitude, pH, conductivity, total limestone, and organic matter) on the growth and productivity of Aleppo pine, represented by dendrometric parameters (height, circumference, diameter, density, and basal area), was assessed using Principal Component Analysis (PCA), performed with SPSS software.

Results and discussion

Dendrometric characteristics

In total, 230 stems, distributed over four plots, were measured (S1 and S2 (South Slope), N1 and N2 (North Slope)). The overall descriptive analysis and one-way analysis of variance (ANOVA), followed by Tukey's test, of the dendrometric measurements (diameter, circumference, and height) are summarized in *Table 2*.

Our dendrometric inventory, for inter-plot comparison, showed no significant variability in growth according to diameters ($F_{obs} = 1.82 < F_{theo} = 2.64$; $P > 0.05$), significant variability in growth according to circumferences ($F_{obs} = 4.42 > F_{theo} = 2.64$, $P < 0.05$), and pronounced significant variability in growth according to heights ($F_{obs} = 8.40 > F_{theo} = 2.64$; $P < 0.01$).

Regarding the intra-plot comparison, our results showed a significant heterogeneity of growth according to the dendrometric characteristics within the studied plots. This significant heterogeneity of growth was confirmed by the coefficient of variation (CV values > 15%), and which was more pronounced within plots N1 and S1 according to the height parameter (CV values > 32%).

Table 2. *Overall descriptive analysis and ANOVA, followed by Tukey's test, of the dendrometric measurements*

Dendrometric variable	**Plots**	**Mean ± SD**	**CV (%)**	**ANOVA**		
				F	***P***	**Critical value for F**
Diameter (cm)	S1	13.42 ± 4.39 ^{a}	32.69	1.82	0.14	2.64
	S2	13.24 ± 3.95 ^{a}	29.82			
	N1	15.00 ± 5.15 ^{a}	34.31			
	N2	13.53 ± 3.89 ^{a}	28.78			
Circumference (cm)	S1	39.94 ± 14.44 ^{a**}	36.16	4.42*	0.005	2.64
	S2	42.03 ± 11.15 ^{a*}	26.52			
	N1	49.50 ± 16.91 ^{b}	34.16			
	N2	42.25 ± 14.25 ^{a*}	33.73			
Height (m)	S1	09.28 ± 2.13 ^{a**}	22.97	8.40*	0.0000	2.64
	S2	09.15 ± 2.15 ^{a**}	23.54			
	N1	07.57 ± 2.81 ^{b}	37.09			
	N2	09.83 ± 2.34 ^{a**}	23.76			
TDH (m)	S1	12.81 ± 1.00 ^{a}	0.08	0.50	0.68	2.95
	S2	12.44 ± 0.50 ^{a}	0.04			
	N1	12.56 ± 2.74 ^{a}	0.22			
	N2	13.31 ± 0.88 ^{a}	0.07			
Density (stem/ha)	S1	132,500 ^{a}				
	S2	192,500 ^{b}				
	N1	117,500 ^{c}				
	N2	132,500 ^{a}				
Basal area (m^2/ha)	S1	18.97 ^{a}				
	S2	28.94 ^{b}				
	N1	25.53 ^{c}				
	N2	20.93 ^{a}				

SD: Standard Deviation; CV: Coefficient of variation; TDH: Total dominant height. For each dendrometric variable, different letters represent significant differences according to Tukey's test (*$P \leq 0.05$; **$P \leq 0.01$)

Moreover, the graphical presentation of the standard deviations from the mean of the dendrometric variables showed homogeneous profile of growth in diameter and circumference for the Aleppo pine trees within the studied plots. While, the Aleppo pine trees within plot N1 showed different growth trend according to the height parameter (*Fig. 3*).

The density fluctuation of the studied plots (117,500 stems/ha (plot N1) – 192,500 stems/ha (plot S2)) could partly explain the observed heterogeneity of growth according to the dendrometric characteristics. In fact, our investigation showed that Aleppo pine growth in height is favored in dense stands (plots S1, S2, and N2) and Aleppo pine growth in diameter is favored in less dense stands (plot N1, with the lowest density (117,500 stems/ha)). In that sense, the closure of the crown and that of the stand promote competition at the crown level, hence the stimulation of growth in height of Aleppo pine trees.

On the other hand, our investigation showed that total dominant heights are insensitive to the density fluctuation of the studied plots (Fobs = 0.50 < Ftheo = 2.95; P > 0.05). In this sense, Lanner (1985) reported that trees growth in height within moderate dense stands is insensitive to spacing, because the elongation of the internodes formed in the buds is not influenced by current environmental conditions, but by the number of internode primordia formed in the previous year. On the other hand, the lateral meristems, as emphasized by Fritts (1976), have no preformation.

In conclusion, the observed variability in growth according to height, diameter and circumference of Aleppo pine trees, could probably result from human activities, such as safety cuts, deliberate or accidental fires, and past silvicultural interventions, as well as from the ecological and edaphic variability of the studied plots. Indeed, such factors strongly influence the structure and dynamics of the stands. For example, safety cuts could explain the high growth variability in diameter in plot N1, by creating openings that promote the rapid growth in diameter of Aleppo pine trees. Similarly, fires can eliminate older trees and promote regeneration, leading to a dominance of small-diameter trees in plots, such as plots S1, S2, and N2. Finally, past silvicultural practices, such as thinning or plantations, can also modulate the density and growth of the stands, thus affecting the observed dendrometric parameters.

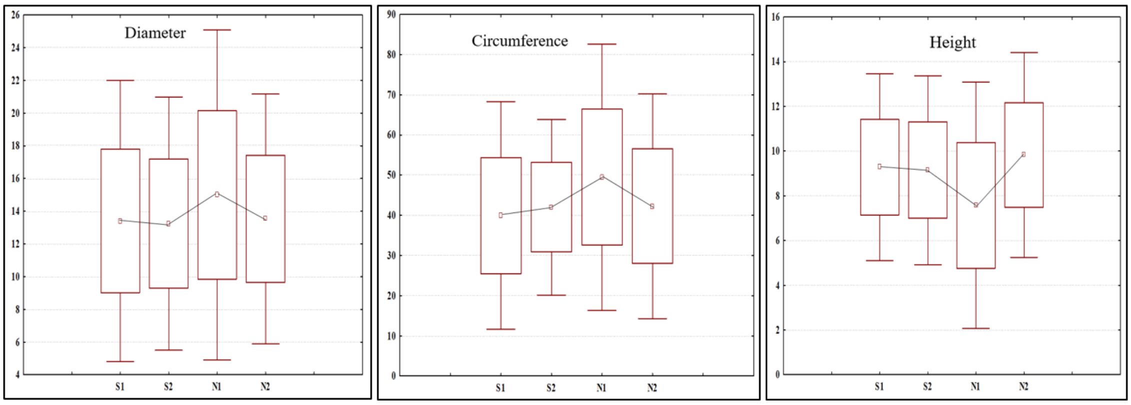


Figure 3. *Graphical presentation of standard deviations from the mean of the dendrometric variables*

Normality and structure of plots

When all countable stems in a stand are grouped by classes of diameters, circumferences and heights, a frequency distribution is defined. This frequency distribution is considered as an explanatory variable of growth, production and overall development of a stand. It also reflects the reaction of the stand to growth conditions and silvicultural operations (Stewart and Roustide, 1974; Barbeito, 2009). In this context, our dendrometric inventory could be used as an additional purpose to highlight the structure of the studied plots.

Thus, in an even-aged stand, the trees are distributed according to the Gaussian law (normal distribution), while in an uneven-aged stand, the distribution of the trees is represented by an exponential curve (Parde and Bouchon, 1988). To evaluate, quantitatively, such normal distribution, the Kolmogorov-Smirnov test and some parameters of shape (kurtosis coefficient (β) and Skewness coefficient (γ)) were used.

The Kolmogorov-Smirnov test compares the empirical cumulative distribution function of the sample data (observed K-S) to the distribution that could be expected if the data were normal (theoretical K-S). If this observed difference is sufficiently large, or the *P*-value of this test is less than the considered significance level ($\alpha = 0.05$), the test rejects the null hypothesis of normality and concludes that the stand structure is no normal. According to the values of this test (*Table 3*), the Aleppo pine trees within the studied plots were distributed in a regular structure, compared to the normal distribution, and this except for those classified by height within plot N1, where an irregular distribution was observed (observed K-S = 0.21932 > theoretical K-S (0.19420) and $P < 0.05$).

The Kurtosis *(β)* and Skewness *(γ)* coefficients revealed no significant irregular distribution compared to the normal distribution. Indeed, the Skewness coefficient values confirmed the normality revealed by the Kolmogorov-Smirnov test, and this except for plot N1, where the Aleppo pine trees distributed by heights classes were strongly skewed to the left ($\gamma = 1.77$). Such left skewness highlighted the predominance of low-height trees within plot N1, as is well shown in *Table 2*. Additionally, the Kurtosis coefficient values confirmed the normality revealed by the Kolmogorov-Smirnov test and the Skewness coefficient. According to the values of this coefficient, the distribution of trees within the studied plots was mainly mesokurtic, and this except for plot N1, where a leptokurtic distribution was observed with a Kurtosis coefficient value of 4.18.

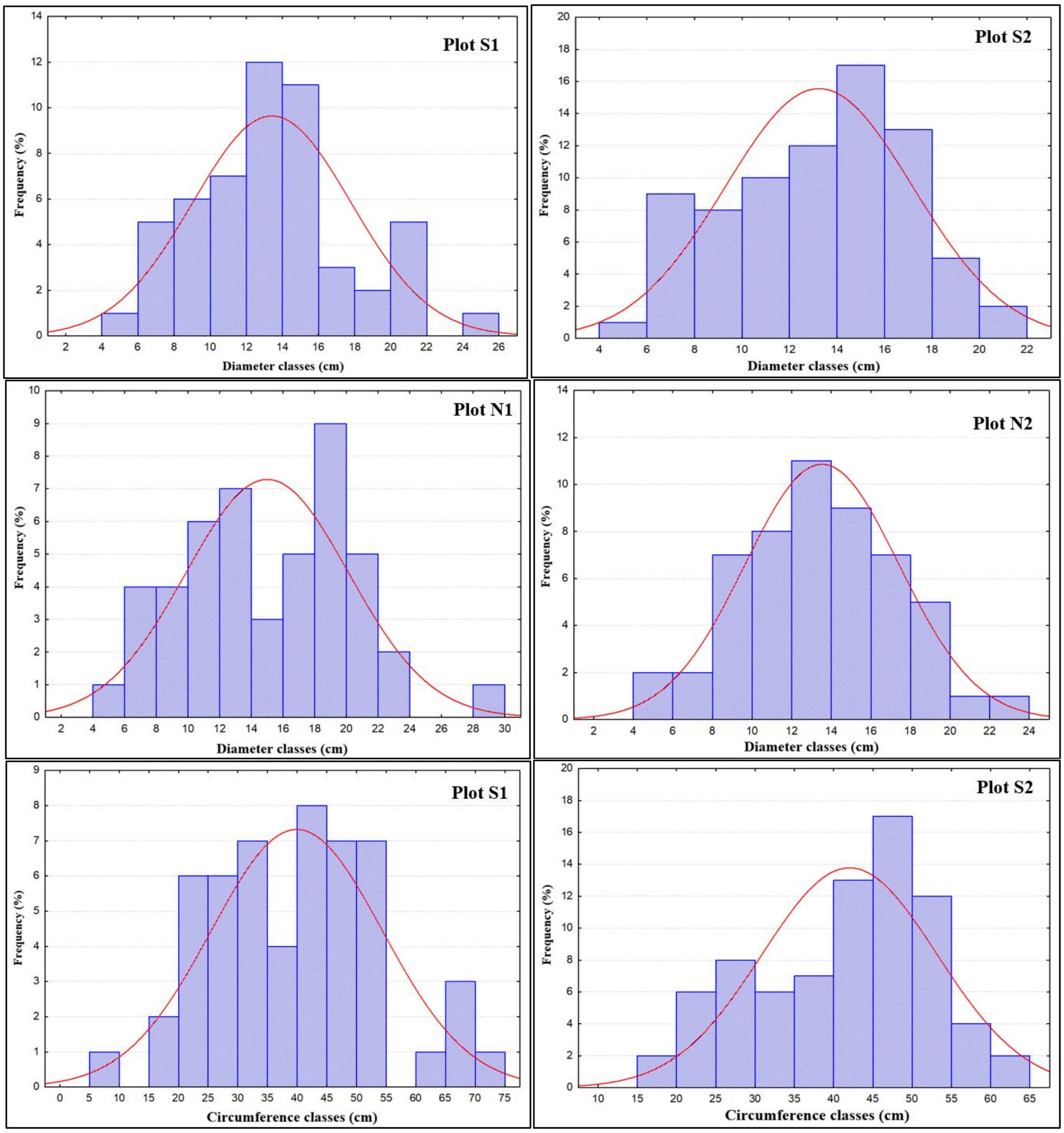
Table 3. *Assessment of the distribution of Aleppo pine trees within the studied plots using the Kolmogorov-Smirnov test, the Kurtosis and Skewness coefficients*

	Plot	**K-S observed**	**K-S theoretical**	**P**	**Kurtosis (*β*)**	**Skewness (*γ*)**	**Observation**
Diameter	S1	0.08969	0.18311	> 0.20	-0.07	0.45	ND
	S2	0.07989	0.15244	> 0.20	-0.90	-0.15	ND
	N1	0.09452	0.19420	> 0.20	-0.43	0.18	ND
	N2	0.05887	0.18311	> 0.20	-0.22	0.21	ND
Circumference	S1	0.07463	0.18311	> 0.20	-0.29	0.26	ND
	S2	0.13198	0.15244	< 0.15	-0.75	-0.40	ND
	N1	0.07300	0.19420	> 0.20	-0.26	0.21	ND
	N2	0.08078	0.18311	> 0.20	0.59	-0.12	ND
Height	S1	0.13462	0.18311	> 0.20	-0.24	0.40	ND
	S2	0.09904	0.15244	> 0.20	-0.57	-0.24	ND
	N1	0.21932	0.19420	< 0.05	4.18	1.77	ID
	N2	0.16806	0.18311	< 0.10	-0.84	0.17	ND

ND: Normal Distribution; ID: Irregular Distribution

In addition to this quantitative assessment, the frequency histograms, according to diameters, circumferences and heights classes (*Fig. 4*), allowed to draw the following observations:

- The presence of some classes in some plots and their absence in others, which could be attributed to the disturbances related to the secure logging and fires over the past decade.
- Trees in plot N1 appeared unbalanced and the structure showed the predominance of low-height trees within this plot.
- Trees in plot S2 appeared older due to the predominance of large circumferences, diameters, and heights classes. This predominance can be considered a sign of high production, but the deficit of small diameter trees within this plot can be considered an indicator of low regeneration.
- Trees within plots N2 and S1 appeared relatively the most balanced. The trees within these plots belonged mainly to the classes of medium diameters, circumferences and heights.



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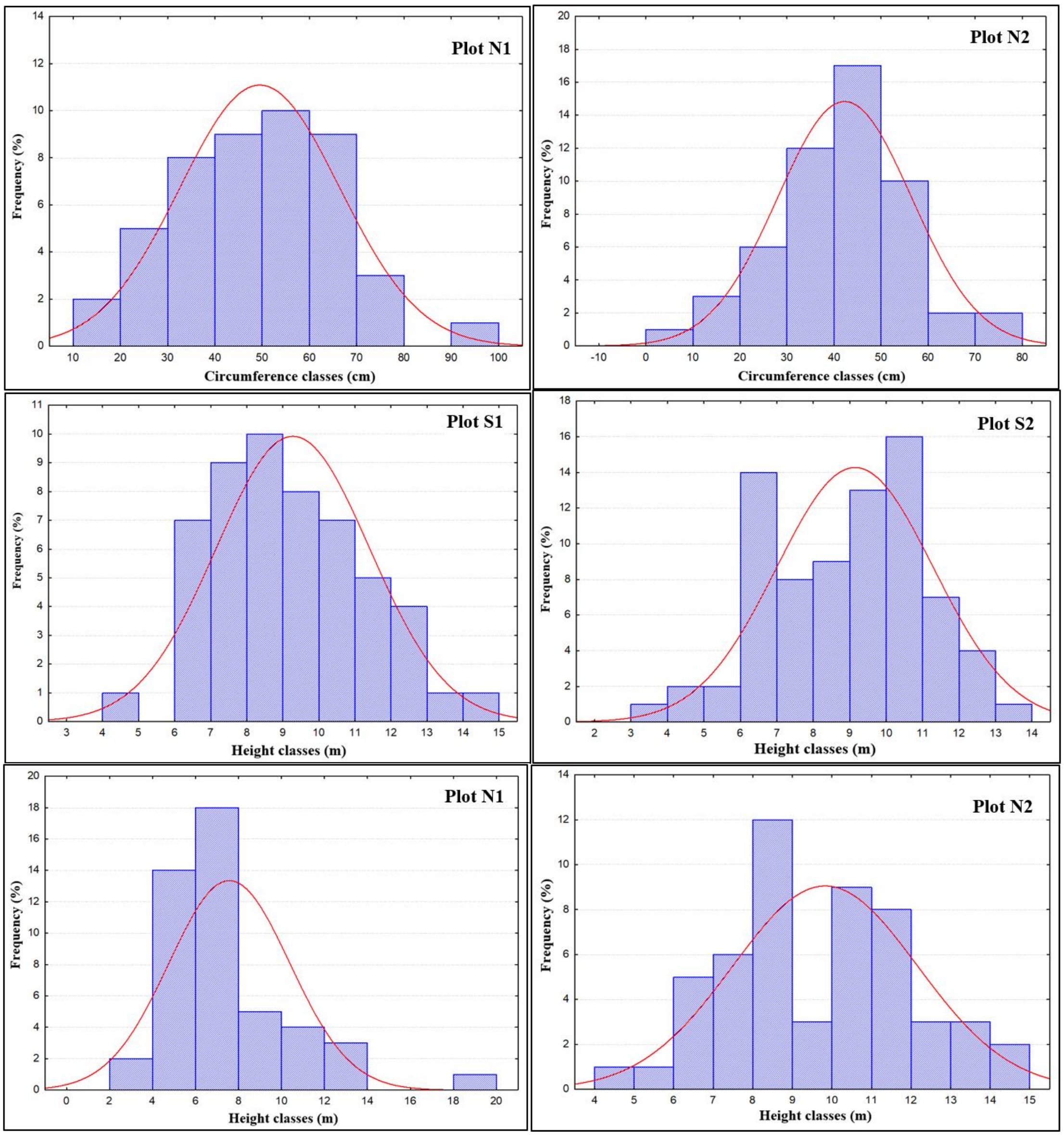
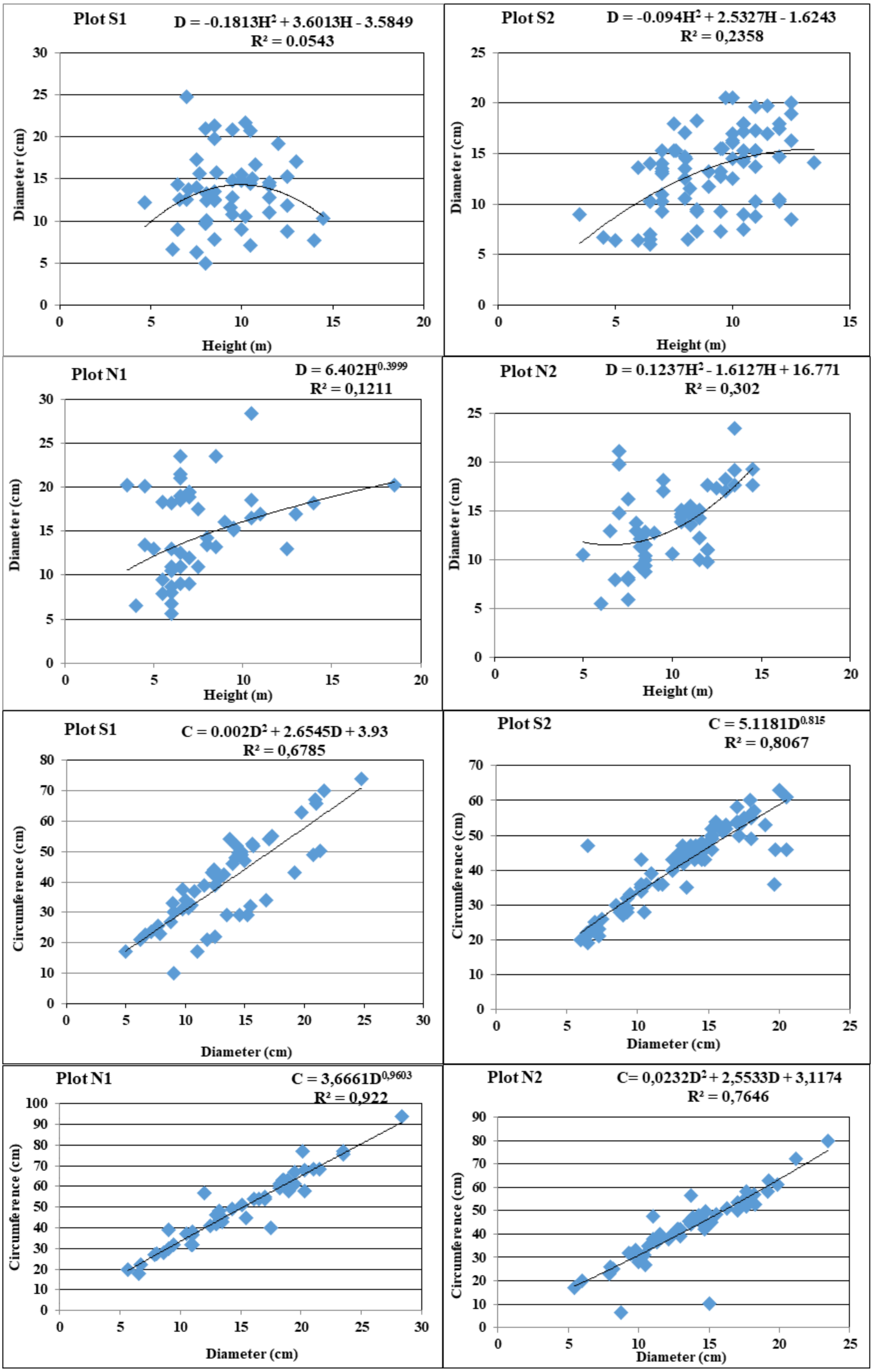


Figure 4. *Frequency histogram of Aleppo pine trees within the studied plots according to diameters, circumferences and heights classes*

Relationship between dendrometric parameters

In this part, the relationships between the different dendrometric parameters were established. We tested all the equations and retained only the one, which provides the highest coefficient of determination R^2. This coefficient is considered as an indicator that allows judging the quality of a linear regression, simple or multiple. With a value between 0 and 1, it measures the adequacy between the model and the observed data. According to the selected models, represented in *Figure 5*, the following observations could be drawn:

Diameters-heights relationship. Plot N2 showed a convex parabolic geometry with a low coefficient of determination ($R^2 = 0.302$). The parabola of this relationship showed that trees growth in diameter appears insensitive to the lower heights and very sensitive to the higher heights.



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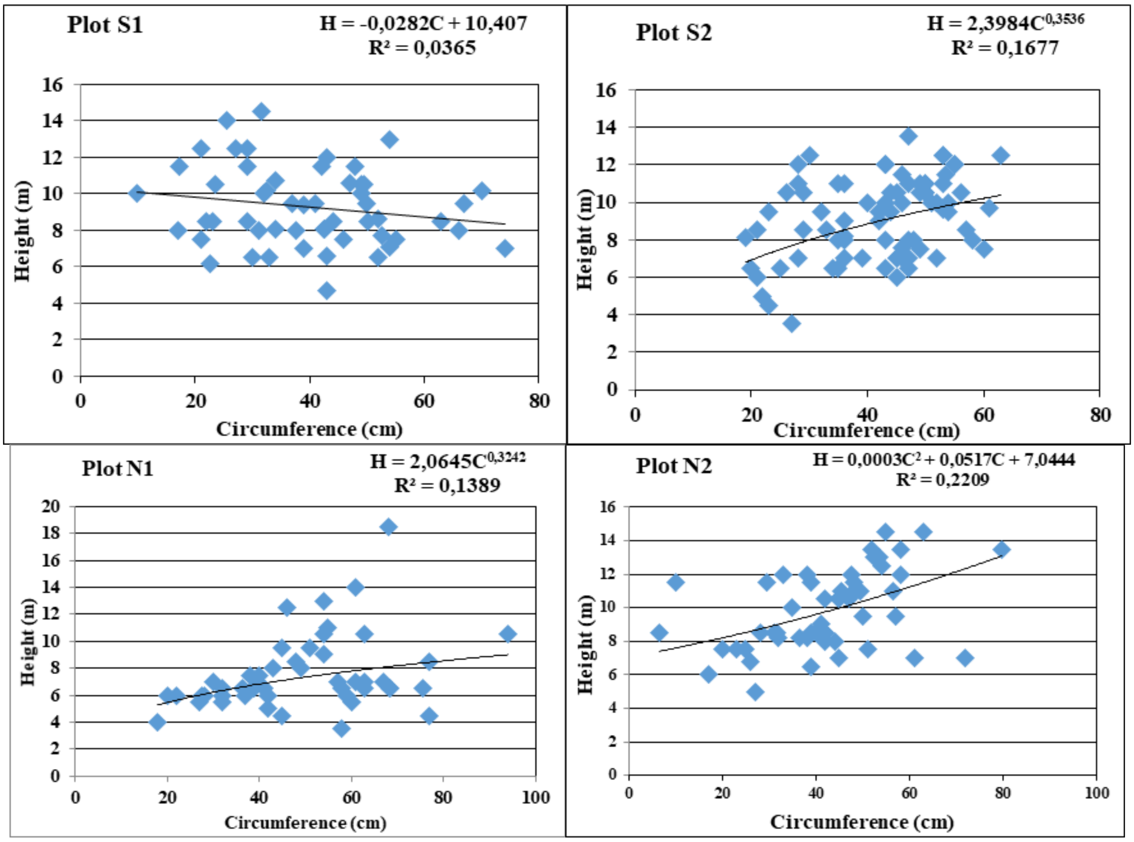

Figure 5. *Selected trend models for relationships between the different dendrometric parameters*

Plot N1 showed a power function with a low coefficient of determination ($R^2 = 0.1211$). Such modeling showed that the dynamics of trees growth in diameter and height, within this plot, are almost similar. Plots S2 and S1 showed a similar geometry (convex parabolic function), with a low coefficient of determination ($R^2 = 0.054$ f (plot S1); $R^2 = 0.236$ (S2)). These polynomial functions generally showed, for both plots, that trees growth in diameter increases rapidly and almost linearly with trees growth in height, then slows down for the higher heights.

Circumference-diameter relationship. Plot N2 and S1 showed a convex parabolic geometry, with relatively high coefficients of determination ($R^2 = 0.764$ (plot N2); $R^2 = 0.678$ (plot S1)). The parabolic trend towards linearity, for these plots, revealed a regular character of concomitant growth in diameter and circumference for the Aleppo pine trees in these plots. Plots N1 and S2 showed a power function, with relatively highest coefficients of determination ($R^2 = 0.922$ (plot N1); $R^2 = 0.807$ (plot S2)). Such power function revealed also a concomitant growth in circumference and diameter for the Aleppo pine trees within these plots.

Height-circumference relationship. Plot N2 showed a convex parabolic geometry, with relatively low coefficient of determination ($R^2 = 0.221$). The quasi-linear character of the parabola, for this plot, revealed similar height and circumference growth dynamics for the Aleppo pine trees within this plot. Plot S1 showed a simple linear model with a low coefficient of determination (0.036), which is rarely observed for such a relationship. Indeed, according to Dhote and De Herce (1994), the height-

DOI: http://dx.doi.org/10.15666/aeer/2303_54995520

circumference relationship is generally not linear. The negative slope for this linear model (a = -0.028) reflected that the circumference growth rate is higher than the height growth rate for the Aleppo pine trees within this plot, in other words, thickening was favored over slenderness. Density fluctuation, considered as an indicator of past silvicultural practices, could partly explain this growth trend within this plot. Plots N1 and S2 showed a power function with comparable power parameters and coefficients of determination. Such power function revealed a concomitant growth in height and circumference for the Aleppo pine trees within these plots.

Our findings allowed concluding that the relationships between the dendrometric parameters of forest species could differ between plots of the same forest.

Pedological characteristics

The results of soil parameter measurements of the studied plots are summarized in *Table 4*.

Table 4. *Measurements results for the pedological parameters of the studied plots*

Plot	pH	Conductivity (µS/cm)	Organic matter (%)	Total limestone (%)
S1	6.49	84.55	4.16	1.78
S2	6.34	62.15	5.46	0.44
N1	6.61	54.85	7.18	0.89
N2	6.36	43.10	6.45	1.78

The soil pH is considered as an expression for the acidity or alkalinity degree of a soil. According to the soil pH classification scale (Mathieu and Pieltain, 2003), our findings showed a slightly acidic to neutral character for the studied plots. In the forest, the pH is ranged between 3.5 (particularly acidic soil) to 8.5 (particularly basic soil) (Amécourt, 2015), which is in agreement with our results.

The slightly acidic character of the studied plots could be explained by the fact that conifers (e.g., Aleppo pine) have a strong tendency to acidify soils. As the litter falls to the ground, the vegetation around the pines dies, and the soils accumulate a layer of needles (dead cover). This layer of needles decompose much more slowly than the litter of herbs and grasses, as they are rich in lignin and phenolic compounds. This slow decomposition is accompanied by the production of acidic organic compounds, which gradually acidify the soil. Additionally, the soil acidification can be exacerbated by the pruning of trees, which represents an important source of needles and branches on the ground over a short period (Burner and Brauer, 2003).

Such acidified soils could have negative impacts on the availability of nutrients. Indeed, acidic conditions reduce microbial activity, resulting in a decrease in the nitrogen mineralization (nitrification) and other nutrients (Hawke and Percival, 1992; Burner and Brauer, 2003). Changes in soil fauna can be also noted as a negative impact of such acidified soils. Among other things, earthworm populations and insect diversity decrease as the soils become more acidic. It is well known that earthworm activity promotes greater stability of soil aggregates, better aeration and greater water-holding capacity. Therefore, soil quality can deteriorate in a situation where earthworm populations decline (Benavides et al., 2009).

The electrical conductivity measurement, at a fixed temperature, provides a quick way to estimate soil salinity, which is due to the various soluble salts in the soil (Aubert, 1978). According to the European salinity scale (Gros, 1979), the soils of the studied plots were classified as non-saline soils.

The organic matter content in soil provides information on soil fertility and aggregation (Bronick and Lal, 2005). According to the classification of Schaeffer (1975), the soils of the studied plots were qualified as being rich in organic matter, exceeding 4%, which made it possible to conclude that these plots can be considered as a very fertile and functional terrestrial ecosystem. Depending on the type of climate, soil and fresh organic matter input, the organic matter content can vary considerably from very low rate (0.5%) to very high rate (30%). The forest mineral soils have generally 1%–5% organic matter by weight (Osman, 2013), which is in agreement with our results.

An adequate level of organic matter is crucial for the ecosystem functions and the soil health. In fact, layers rich in organic debris or fresh organic matter, whether partially or fully decomposed by the biological activity of the soil, offer many essential ecological benefits. They increase soil fertility by giving rise to soluble and/or volatile mineral elements (mineralization) and numerous neo-formation products (humification). Such layers also improve the soil structure, increase the water-holding capacity, stabilize the soil microclimate and support the terrestrial biodiversity (Baize and Jabiol, 1995).

The total limestone content, which is the total limestone present in all its forms in the soil, makes it possible to specify the type of soil and to know the importance of its reserves in calcium carbonates. According to the classification of Baize (1988), the soils of the studied plots were classified as non-calcareous to slightly calcareous, suggesting a low presence of calcium carbonates in these plots. The low rate of calcium carbonates leads to avoiding excessively alkaline conditions that could limit the bioavailability of certain essential nutrients for the forest plants growth (e.g., iron, manganese).

Generally, the Aleppo pine is a very tolerant species from an edaphic point of view, adapting well to both calcareous and acidic soils. The most Aleppo pine soils have a sandy-silty texture with a low clay content, not exceeding 10%. Aleppo pine essentially favors, throughout its range, marly and calcareous-marly substrates where it finds a particularly deep soil, easily accessible to its root system. The Aleppo pine also appears on non-calcareous substrates, but essentially on schists and micaschists (Quézel and Barbero, 1992; Kadik, 1983).

In conclusion, our findings revealed that the soils of the studied plots are classified as non-saline, slightly acidic to neutral, non-calcareous to slightly calcareous and rich in organic matter.

Influence of ecological and pedological factors on the Aleppo pine growth and productivity

Understanding how forest stands function is an essential preoccupation in forest ecology. In this context, the Principal Component Analysis (PCA) was used to assess the influence of ecological and pedological factors (slope, exposure, altitude, pH, conductivity, total limestone, and organic matter) on the growth and productivity of Aleppo pine, represented by dendrometric parameters (height, circumference, diameter, density, and basal area). According to *Table 5,* the first two principal components explained 81.46% of the total variance.

Table 5. *Eigenvalues and total variance for the first three principal components*

Components	Eigenvalues	Total variance (%)	Cumulative	Cumulative (%)
PC1	6.37	53.14	6.37	53.14
PC2	3.40	28.32	9.77	81.46
PC3	2.22	18.54	12.00	100.00

The first principal component explained 53.14% of the total variance, indicating the degree of redundancy between variables. The variables projection on the 1*2 factorial plane (*Fig. 6*) revealed several interesting correlations.

The density of the studied plots was negatively correlated with exposure (-0.65), growth in diameter (-0.64) and circumference (-0.42)), as well as with soil fertility expressed in pH (-0.72), total limestone (-0.63), and organic matter (-0.32). In contrast, the density of the studied plots was positively correlated with basal area (0.65) and growth in height (0.33). According to Parde and Bouchon (1988), plot density is a crucial parameter for assessing competition between stands. It directly affects trees height and diameter, thereby influencing growth, production and stand structure.

Furthermore, the Aleppo pine growth in height was negatively correlated with growth in diameter (-0.90) and circumference (-0.89), as well as with soil fertility, expressed in pH (-0.84) and organic matter (-0.51), and with altitude (-0.97) as an ecological factor. On the other hand, there was a positive correlation between Aleppo pine growth in height and slope (0.83).

The positive/negative correlation between slope and Aleppo pine growth (height (0.83), diameter (-0.53), and circumference (-0.62)) could be explained by a disturbance of water supply in steep areas. Lemoine and Sartolou (1981) observed similar phenomena in maritime pine, thus highlighting the critical importance of this topographic factor.

The negative correlation between growth in height and basal area of Aleppo pine could partly explained by extreme climatic conditions, such as heavy hail and frost, especially in spring. These events can cause significant damage to flower buds and young shoots, thereby reducing the basal area of Aleppo pine plots (Mimouni, 2007). However, it should be noted that the relationship between trees growth in height and basal area is specific to each forest species. Indeed, according to Fortin et al. (2009), about 2.5 m difference in height was observed among the twenty most abundant species in southern Quebec when the basal area varied from 10 to 40 m^2.

Moreover, the basal area, considered a key indicator of a stand richness (Bouazza et al., 2017), was negatively correlated with total limestone (-0.983) and slope (-0.763). Such a result underlines the crucial importance of the topographic position of a forest stand and its adequate level of total limestone. Indeed, soild with high level in total limestone led to form a hard crust, due to repeated drying and wetting cycles, which hinders the trees growth by damaging their roots. Additionally, the topographic position influences the hydrology of the stand (lateral water losses and inputs) as well as the trees nutrition (erosion, transport of nutrients and accumulation at the bottom of the slope) (Lemoine and Sartolou, 1981).

The Aleppo pine growth in diameter and circumference was positively correlated with soil fertility, expressed in pH (0.86; 0.69) and organic matter (-0.72; 0.84), as well as with some ecological factors, such as altitude (0.86; 0.92) and exposure (0.66; 0.68). In this context, it is essential to note that an adequate level of organic matter is essential

DOI: http://dx.doi.org/10.15666/aeer/2303_54995520

for ecosystem functioning and soil health, and that an inadequate pH could have variable impacts depending on different forest species (Baize and Jabiol, 1995).

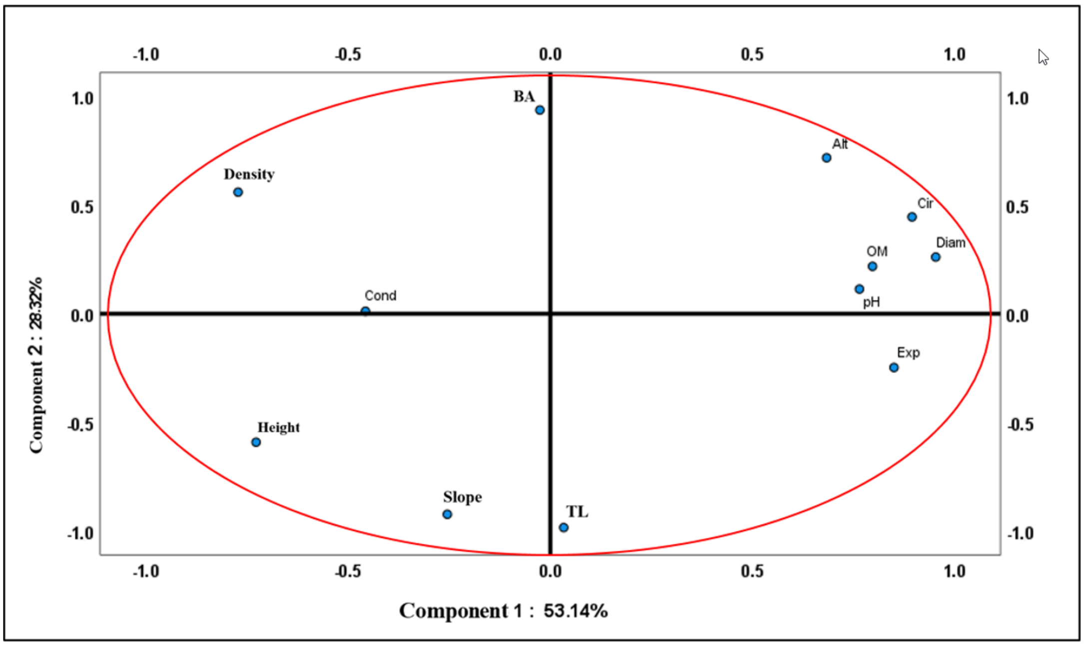

Figure 6. *Correlation circle showing the degree of correlation between dendrometric, ecological and pedological variables on the 1 * 2 factorial plane. Alt: Altitude; Exp: Exposure; OM: Organic matter; Cond: Conductivity; TL: Total limestone; Cir: Circumference; Diam: Diameter; BA: Basal area*

The projection of the studied plots on the selected factorial plane, with respect to variables, showed certain divergences and analogies between the studied plots (*Fig. 7*).

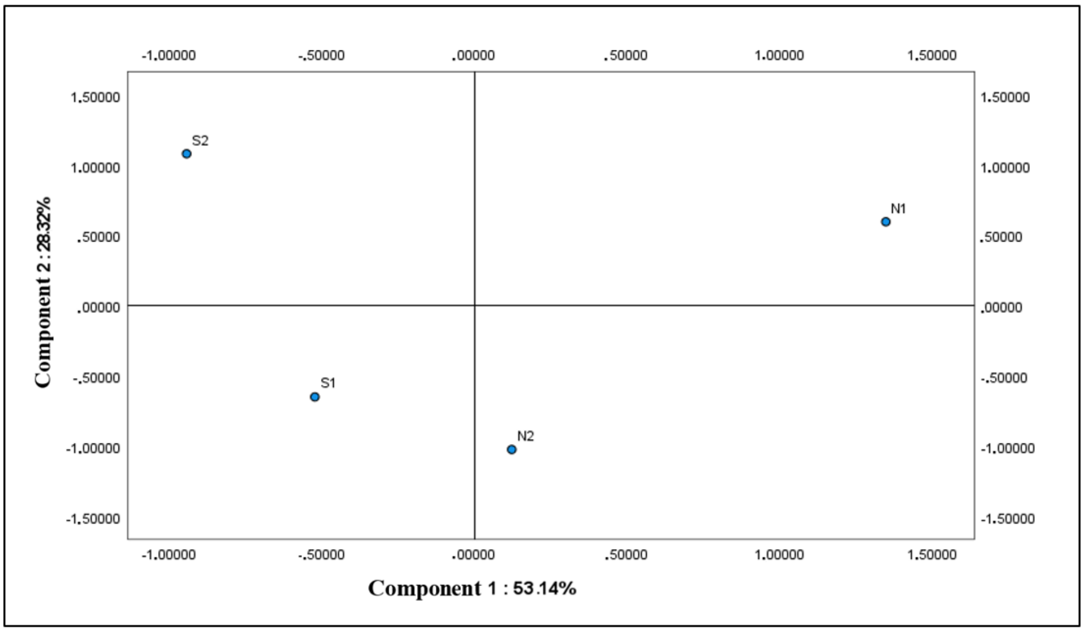

Figure 7. *Projection of the studied plots on the 1*2 factorial plane, with respect to the considered variables*

The plot N1 was positioned in the positive part of the first principal component. It is the most productive part, in terms of growth in diameter and circumference of Aleppo pine trees, where the ecological and pedological conditions are generally favorable.

The plot S2, positioned in the positive part of the second principal component, stood out from the other plots by its high density and its large basal area. In terms of growth, this plot showed the weakest growth in diameter. The Aleppo pine trees within this plot benefit from moderately favorable soil fertility conditions, expressed in pH and organic matter.

The plots S1 and N2, positioned in the negative part of the second principal component, converged with each other in terms of density and basal area. The Aleppo pine trees within these plots developed on a slightly calcareous soil with a steep slope and low altitude. Despite these similarities, the growth in height and diameter distinguished them. The winds, influenced by exposure, could explain partially this fluctuation in productivity between these two plots. In fact, according to several studies, the southwest winds, in November and December, could be very strong, which is a major challenge for the development of forest species in the south-facing exposure (Bariki, 1980; Bellili, 1981; Loukoumanou, 1999).

The first principal component appeared to reflect a growth gradient, closely linked to the soil fertility and altitude. As for the second principal component, it could reflect the effect of exposure, as an ecological gradient, highlighting the difference between north and south-facing plots.

At this stage of analysis, we can conclude that despite the presence of similarities between the plots studied, the ecological and pedological contrasts that characterize them have induced significant differences in growth, productivity and structure.

Conclusion

In this study, the ecodendrometric and pedological characteristics of four Aleppo pine plots in the Baïnem Forest were determined.

Our dendrometric results revealed that the Aleppo pine trees exhibit significant growth variability in height, diameter and circumference, and are distributed in a regular structure compared to the normal distribution.

Our findings allowed concluding that the relationships between the dendrometric parameters of Aleppo pine trees could differ between plots of the same forest. The growth in diameter appeared insensitive to lower heights and very sensitive to higher heights, the growth in diameter and in circumference was concomitant, and the growth in circumference was greater than growth in height in some plots and concomitant in other plots.

Our pedological findings revealed that Aleppo pine trees within the studied plots develop on soils rich in organic matter, non-saline, slightly acidic to neutral, and non-calcareous to slightly calcareous.

The PCA highlighted that ecological and edaphic diversity (slope, altitude, exposure, pH, conductivity, total limestone, and organic matter) are the factors responsible for the variability of growth in height, diameter and circumference of Aleppo pine trees in the studied plots. This PCA showed that Aleppo pine growth in height is opposed to its growth in diameter and circumference. Thus, the growth in height was negatively correlated with altitude and soil fertility, expressed in pH and organic matter, and positively correlated with slope. In contrast, the growth in diameter and circumference was positively correlated with altitude, exposure, and soil fertility expressed in pH and organic matter, and negatively correlated with slope.

Our findings are important for forest management. However, a broader study would provide even more relevant and useful information for the sustainable management of the Aleppo pine forest.

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DOI: http://dx.doi.org/10.15666/aeer/2303_54995520