

DEMOGRAPHIC STRUCTURE AND STAND DYNAMICS OF THE EL HAMIMET FOREST MODELED BY THE WEIBULL DISTRIBUTION

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Abstract: This study involved dendrometry analysis and modelling of the demographic structure of stands in the El Hamimet forest (Oum El Bouaghi, Algeria), dominated by Aleppo pine (*Pinus halepensis* Mill.) and green cypress (*Cupressus sempervirens* L.). Four representative plots were studied in order to assess the variability of dendrometry and structural parameters. The average diameters observed ranged from 13.4 to 22.8 cm, and the average heights ranged from 3.2 to 4.5 m, reflecting marked heterogeneity between young and mature stands. The average basal area ranged from 15.2 to 27.6 m²/ha, with a density of 820-1,150 stems/ha, reflecting varying conditions of competition and growth. By fitting the diameter and height distributions to a three-parameter Weibull distribution, we characterized the demographic structure in detail. The values of the shape parameter (k) ranged from 1.46 (P2) to 2.70 (P4), indicating structures ranging from young, regenerating stands to mature, homogeneous stands. The scale parameter (λ), ranging from 3.22 to 4.53, reflects the dispersion of heights and diameters across development stages. These results show that plots P1 and P4 have stable structures with a predominance of mature trees, whereas P2 and P3 exhibit active regeneration dynamics. All of these observations highlight the structural complexity and functional diversity of the El Hamimet forest. The use of Weibull's law proved particularly effective for interpreting the distributions of heights and diameters, enabling assessment of the dynamics of stand growth and succession. These results provide an essential basis for guiding silvicultural practices toward sustainable, resilient management of Mediterranean forest ecosystems.

Keywords: El Hamimet forest; *Pinus halepensis*; *Cupressus sempervirens*; Dendrometry parameters; Weibull distribution; Demographic structure; Forest regeneration; Stand dynamics.

1. Introduction

The study of forest structure is an essential basis for understanding the dynamics, regeneration, and sustainability of forest ecosystems (Bravo-Oviedo *et al.*, 2022). Dendrometry parameters such as diameter at breast height (DBH), total height, density, basal area, and volume are significant indicators of the vitality, productivity, and ecological stability of stands (Schütz & Rosset, 2020; Vargas-Larreta *et al.*, 2021; Sa *et al.*, 2023). These variables enable the estimation of biomass and carbon sequestration capacity, as well as the characterization of forest demographic structure through the distribution of diameter and height classes (Sa *et al.*, 2023).

Analysis of demographic structure provides an integrated view of the state of development and internal functioning of a forest stand. Among the statistical models used for this purpose, the three-parameter Weibull function stands out as one of the most robust and flexible tools for describing the distribution of tree diameters and heights (Lopez-Martinez *et al.*, 2020; Vargas-Larreta *et al.*, 2021). This probabilistic model makes it possible to adjust the observed distribution to the different growth phases and to differentiate between young, irregular, or mature structures according to the values of the shape (k), scale (λ), and position (θ) parameters. The application of the Weibull distribution is particularly relevant to the study of

Mediterranean stands, where the dynamics of regeneration and intraspecific competition strongly influence the spatial structure and sustainability of ecosystems (Alemu et al., 2023; Sa et al., 2023; Suárez-Muñoz et al., 2023).

This study focuses on the El Hamimet forest, located in Oum El Bouaghi (North-eastern of Algeria). This forest, covering an area of around 1,460 ha, lies at altitudes between 800 and 1,039 m, in the heart of a mountainous landscape that forms part of the Aurès mountain range. Although the region belongs to the semi-arid bioclimatic zone, the topography favors locally higher rainfall, creating a microclimate conducive to the development of a diverse forest ecosystem. The plant cover is dominated by Aleppo pine (*Pinus halepensis*), a species emblematic of Mediterranean forests, accompanied by green cypress (*Cupressus sempervirens*) and blue acacia (*Acacia cyanophylla* Lindl.) (DGF, 2005).

For sustainable management and ecological evaluation, analyzing the demographic structure with the Weibull distribution serves as a decision-making tool to understand the vitality, growth dynamics, and regeneration potential of stands. This work aims to model the diameter and height distributions of stands in the El Hamimet forest using the three-parameter

Weibull distribution to determine their development stage and to suggest silvicultural guidelines that support the conservation and sustainability of this ecosystem.

2. Methods and materials

2.1. Presentation of the study area

The study was conducted in the El Hamimet forest, located in the wilaya of Oum El Bouaghi, Daïra, and commune of Aïn Babouche (35°58'26" N; 7°11'11.7" E) (Fig. 1). This forest massif covers a total area of around 78,000 ha, including 1,460 ha of reforested areas. The altitude ranges from 800 to 1,039 m, with an average of 848 m. The relief is composed of regions with high slopes ($\approx 20\%$ of the surface area, average gradient = 12.5%), low slopes (gradient = 3-5%), and plains (gradient = 0-3%).

The geological formations are dominated by clay-limestone to limestone soils, favoring sparse xerophytic vegetation (cover = 5-10%), mainly consisting of Alfa (*Stipa tenacissima* L.), Diss (*Ampelodesmos mauritanicus* Poir.) and White Mugwort (*Artemisia herba alba* Asso.). The artificial plantations, aged between 15 and 40 years, cover 1,893 ha, divided between Djebel Hamimet (1,313 ha), Khoudjel (150 ha), and Al-Azezeb (280 ha).

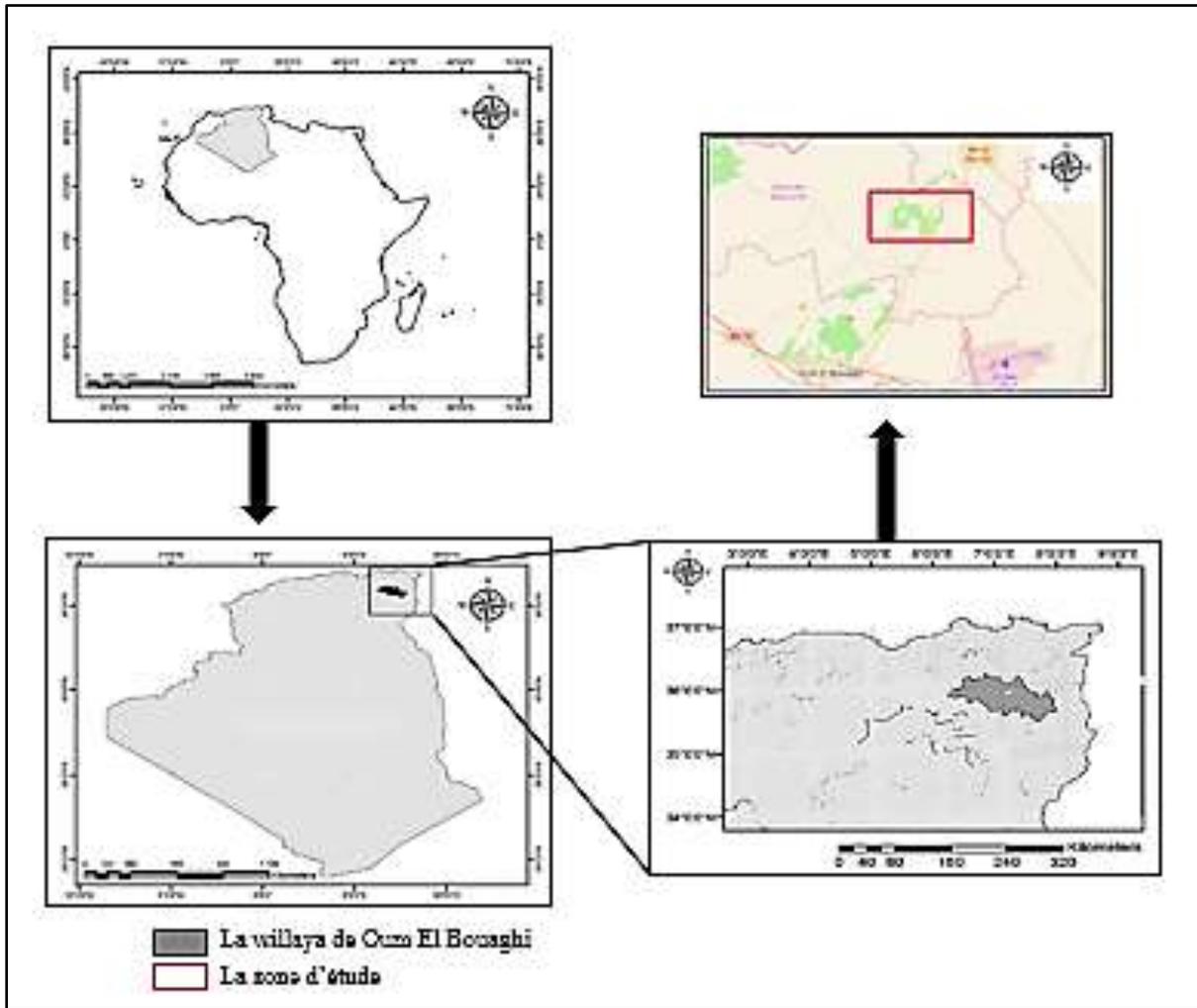


Figure 1. Geographical location of the study area (Yahi, 2021).

2.2. Choice and characterization of plots

The inventory was performed on random plots centered on adult stems of *Pinus halepensis* and *Cupressus sempervirens*. Each plot covered 900 m², with dimensions adapted to the stand’s morphology (Natta, 2003).

The dendrometry measurements included:

- Diameter at breast height (DBH) measured at 1.30 m from the ground for all trees with a DBH of 5 cm or greater.
- Total height (H) measured with a Sunto clinometer;
- Geographical coordinates taken with a Garmin 60 GPS.

These parameters were used to describe stand structure through density, basal area, and the distribution of individuals by diameter and height classes.

2.3. Dendrometry parameters

- The basal area is the sum of the cross-sections at man-height (1.30 m) of all the trees in the plot, per hectare. It is calculated according to the formula:

$$G = \pi D^2 / 4S$$

Where:

D is the diameter of the tree (in cm),
S is the surface area of the plot (in ha).

- Stand density (N, trees/ha) corresponds to the average number of living trees (DBH ≥ 5 cm) per hectare:

$$D = N/S$$

- The slenderness coefficient (SC), defined as the ratio between height and diameter (SC=H/D), assesses the mechanical stability and morphology of trees. The commonly accepted thresholds are as follows:

- $H/D < 80$: satisfactory stability;
- $80 < H/D < 100$: avoid heavy sunshine;
- $H/D > 100$: increased risk of breakage or uprooting (Gaudin, 1996).

2.4. Analysis of demographic structure

The demographic structure of the stands was studied based on the distribution of tree diameters (DBH ≥ 5 cm) and total heights (H ≥ 1.30 m). The diameter and height classes were used to construct frequency distribution histograms, which show the distribution of individuals according to their structural development.

The observed distributions were then fitted to the three-parameter Weibull distribution using Minitab 18 software (Rondeux, 1999; Goba et al., 2019). This distribution is commonly used to describe the structure of forest stands because of its flexibility and its ability to represent various forms of diametric or height frequency distributions.

The probability density function associated with the Weibull distribution is expressed as follows:

$$f(x) = \frac{k}{\lambda} (x - k/\lambda)^{\theta-1} \exp \left[- \left(\frac{x - k}{\lambda} \right)^{\theta} \right]$$

Where:

x represents the variable under study (diameter or height),

k is the shape parameter,

λ is the scale parameter,

θ is the position parameter.

Depending on the value of the parameter k , the distribution can exhibit different characteristic forms (Husch et al., 2003; GlèlèKakaï et al., 2016):

$k < 1$: “inverted J” distribution, typical of uneven-aged or multi-story stands;

$1 < k < 3.6$: predominance of young or small-diameter individuals;

$k > 3.6$: stands dominated by old trees or trees with a regular structure.

The Weibull distribution parameters were estimated using the Maximum Likelihood Estimation (MLE) method. The model fit to the observed data was evaluated using the Kolmogorov-Smirnov test and the coefficient of determination (R^2) to assess the statistical quality of the fit.

3. Results and discussion

3.1. Dendrometry parameters

Table 1 shows the main dendrometry characteristics of the four plots studied, including mean values for diameter (D), total height (H), slenderness factor (H/D), basal area (G), and density (N/ha).

Table 1. Dendrometry characteristics of the plots studied.

Plot	D (cm)	H (m)	H/D	G (m ² /ha)	N/ha
P1 <i>P. halepensis</i>	29,88	6,41	26,47	33,01	344
P2 <i>P. halepensis</i>	17,22	4,32	27,03	14,23	489
P3 <i>C. sempervirens</i>	11,88	5,55	41,83	3,16	222
P4 <i>C. sempervirens</i>	9,03	3,63	42,04	2,70	378

The two *Pinus halepensis* plots (P1 and P2) show apparent differences in structure and

vigor. Plot P1 has an average diameter of 29.88 cm and an average height of 6.41 m, compared to 17.22 cm and 4.32 m for P2. Despite these differences, H/D ratios stay similar (≈ 27), indicating comparable vertical shape. However, basal area is significantly higher in P1 (33.01 m²/ha) than in P2 (14.23 m²/ha), while density is inversely related (344 vs. 489 trees/ha).

These differences highlight the significant influence of site conditions and density on stand growth. Plot P1 appears to benefit from better edaphic or microclimatic conditions (deeper or better-drained soils), which favor radial growth and wood productivity. Conversely, the high density observed in P2 increases competition for light and water resources, restricting diameter development. These findings align with those of Bentouati *et al.* (2005) and Rabhi *et al.* (2023), which showed that Aleppo pine growth depends heavily on-site quality and stand density. Moderate density encourages better individual vigor and increased stand productivity.

In the case of green cypress, plots P3 and P4 exhibit generally lower dendrometric values than Aleppo pine, confirming slower growth. The average diameters are 11.88 and 9.03 cm, respectively, and the average heights are 5.55 and 3.63 m. The H/D ratios (41.83 and 42.04) indicate a slender form, typical of species that seek to compensate for low light availability through significant axial growth.

Basal area remains low (3.16 and 2.70 m²/ha), reflecting the youthfulness of the stands or an early stage of development. These low values are accompanied by moderate densities (222 and 378 trees/ha), indicating still limited competition but restricted total above-ground biomass. The differences between P3 and P4 could be explained by local variations in edaphic or hydric conditions: a deeper, better-drained soil in P3 would favor better growth

than in P4. These trends are consistent with the observations of Monjanel *et al.* (2019) and Abdessemed *et al.* (2022), which indicate that the growth of *C. sempervirens* in Mediterranean environments depends closely on water availability and soil fertility. In situations of water stress or high density, radial growth is reduced, leading to higher H/D ratios and greater vulnerability to mechanical stress.

An interspecific comparison reveals significant differences in growth patterns. *P. halepensis* has notably larger diameters and land areas, indicating a rapid growth strategy and a greater ability to utilize available resources. Conversely, *C. sempervirens* is characterized by slower growth, a slender morphology, and adaptation to vertical competition. These differences reflect the distinct ecological strategies of the two species: Aleppo pine, a pioneering, heliophilous species, prefers open, bright environments, while green cypress, more drought-tolerant, exhibits moderate initial growth but better resistance to arid conditions. Structurally, *P. halepensis* stands (P1 and P2) exhibit higher wood productivity (33.01 and 14.23 m²/ha) than *C. sempervirens* stands (3.16 and 2.70 m²/ha). These differences not only reflect variations in growth potential between the species but also the combined effects of site quality and density. The high density observed in green cypress increases intra-specific competition, limiting individual growth, while Aleppo pine benefits from lower density and better light exposure. These observations align with the findings of Quézel and Médail (2003), Bentouati *et al.* (2005), and Rabhi *et al.* (2023), who demonstrate that *P. halepensis* has remarkable ecological plasticity and a greater ability to adapt to favorable conditions, unlike green cypress, whose initial growth remains more limited.

3.2. Analysis of the demographic structure of El Hamimet forest stands

3.2.1. Analysis of demographic structure in diameter

Fitting diameter data to the three-parameter Weibull distribution is a robust statistical

method for describing the demographic structure and growth patterns of forest stands. In the present study (Fig. 2), the four analyzed plots show apparent differences between Aleppo pine stands (P1 and P2) and green cypress stands (P3 and P4), indicating significant variations in age structure, density, and local ecological conditions.

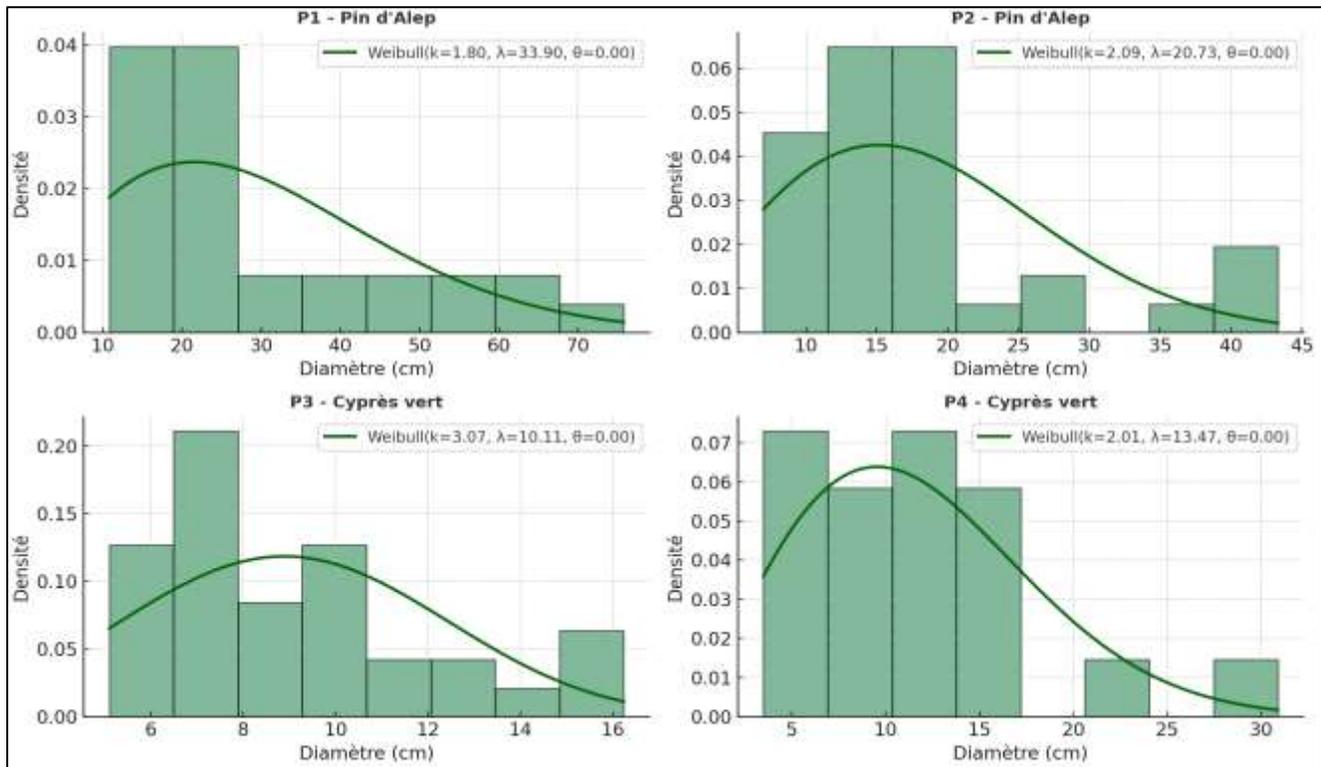


Figure 2. Weibull fitting of diameters for the four plots studied.

Aleppo pine stands show diameter distributions well fit by Weibull functions, with shape parameters $k > 2$, indicating a unimodal structure typical of regular, relatively mature stands. The shape parameter (k) represents the slope of the Weibull function, while the scale parameter (λ) relates to the central value of the diameter distribution.

A $k < 1$ indicates an inverted “J” shape typical of uneven-aged or young stands, whereas a $k > 3.6$ signifies stands dominated by older individuals. Therefore, the intermediate k values ($1 < k < 3.6$) observed here suggest stands where young and mature trees coexist,

with a dominance of medium-diameter individuals.

The density curve indicates a concentration in medium-to large-diameter classes, reflecting the dominance of mature individuals and limited natural regeneration. This pattern suggests an evolution toward later developmental stages, in which competition for resources (light, space, nutrients) results in selective mortality among young individuals (Hafiane *et al.*, 2022). Such structures are common in *Pinus halepensis* stands that have been previously logged or experienced moderate disturbances (fire, grazing), followed

by natural recolonization (Sahnoune *et al.*, 2023).

Conversely, *Cupressus sempervirens* stands have k inf values greater than 2, indicating an inverted “J” distribution, characteristic of irregular or young stands, where regeneration is active and small-diameter classes dominate. This type of structure reflects a dynamic of continuous renewal, typical of shade-tolerant species and expanding natural stands (Bencherif *et al.*, 2021).

In plot P4, the more dispersed distribution and the presence of more medium-diameter trees indicate a shift toward a more balanced structure, likely driven by favorable microclimatic conditions or reduced interspecific competition. This variability between P3 and P4 could be due to edaphic differences or contrasting disturbance regimes, as also observed by Zeraoula *et al.* (2023) in the Mediterranean forests of Algeria.

In comparison, Aleppo pine stands are more widely distributed, reflecting greater structural heterogeneity than that observed in green cypress. This difference can be explained by the distinct ecological characteristics of the two species: Aleppo pine, a pioneer species, tends to form monomorphic stands after post-fire colonization, whereas green cypress, an evergreen species, adopts a multi-layered structure, which favors its resilience in the face of climatic constraints (Laaribi *et al.*, 2024).

Weibull parameters also indicate that Aleppo pine stands have larger diameters, suggesting greater growth in height and diameter on well-drained soils. Conversely, green cypress adopts a strategy of slow but continuous growth, typical of Mediterranean species adapted to dry environments. These contrasts reflect

differentiated ecological dynamics: Aleppo pine, with its ecological plasticity, prefers dry, rocky sites, where it plays an essential pioneering role in soil stabilization, whereas green cypress contributes more to erosion protection and biodiversity conservation by maintaining a persistent plant cover (Boudiaf *et al.*, 2023).

From a silvicultural point of view, stands with a unimodal structure (Aleppo pine) require management aimed at promoting natural regeneration, notably by selective thinning or opening gaps. On the other hand, stands with an inverted “J” structure (green cypress) offer greater potential for sustainability, ensuring constant natural renewal. Fitting diameter distributions to Weibull’s law is therefore a reliable tool for assessing the stability and sustainability of Mediterranean forests, and a valuable aid for planning appropriate silvicultural management (Aït Mouheb *et al.*, 2022).

3.2.2. Analysis of demographic structure in height

The three-parameter Weibull distribution is a powerful statistical tool for modeling the vertical structure of forest stands. It provides a detailed characterization of the height distribution by integrating three parameters: the minimum threshold (position parameter θ), the concentration of individuals around the mean (shape parameter k), and the scale of height variation (scale parameter λ) (Weiskittel *et al.*, 2011 et Monjanel *et al.*, 2019). Its application to four plots in the El Hamimet forest reveals marked contrasts between the stands, reflecting differences in their growth dynamics and degree of maturity (Fig. 3).

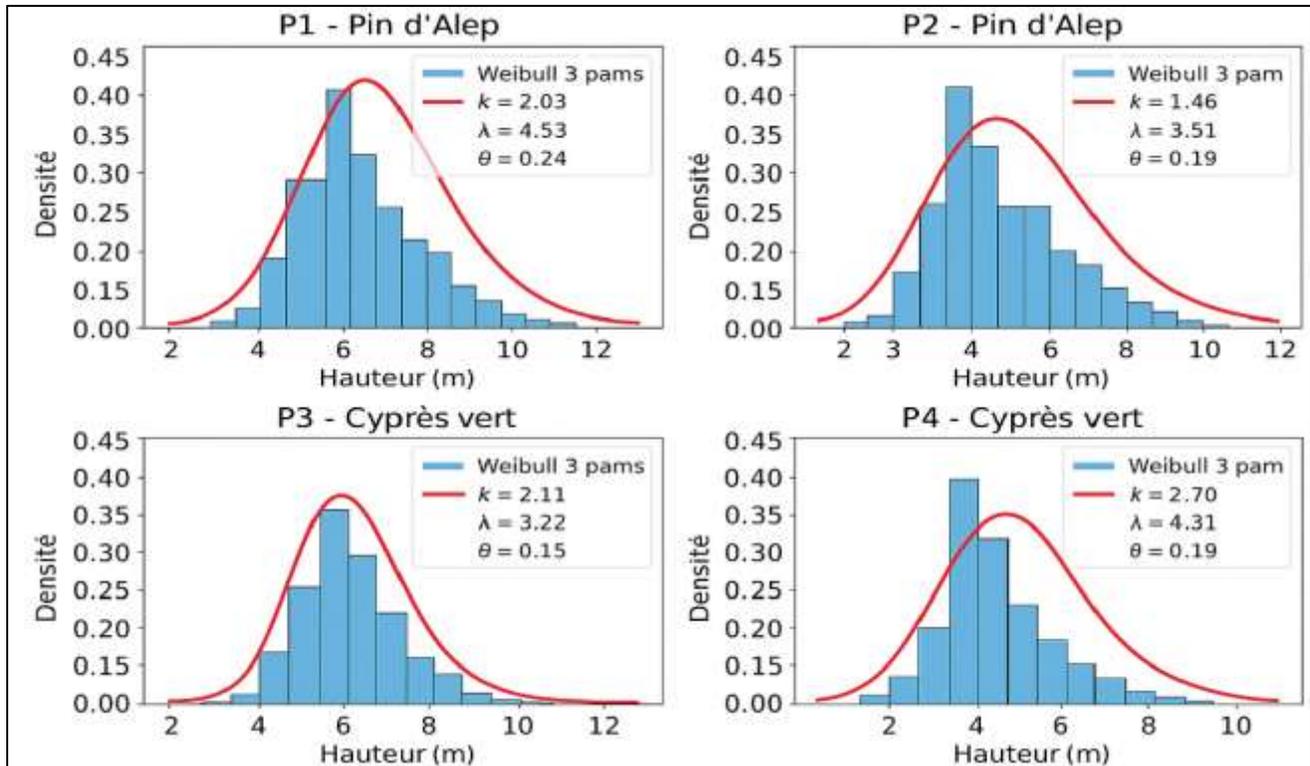


Figure 3. Weibull height adjustment for the four plots studied.

In plot P1, the shape parameter $k = 2.03$ indicates a unimodal distribution, typical of relatively homogeneous stands. This value reflects a high concentration of trees around the average height, with a balanced vertical structure. The scale parameter $\lambda = 4.53$ reveals the presence of large individuals, indicating a mature stand with sustained height growth. The position parameter $\theta = 0.24$ indicates that young shoots or seedlings are present, but in low proportions, reflecting moderate natural regeneration (Pommerening & Stoyan, 2006). These features suggest an ecosystem in relative equilibrium, where competition for light has stabilized height distribution around a dominant mean.

Plot P2 is distinguished by a shape parameter $k = 1.46$, lower than 3.6, indicating a more spread-out distribution and a higher proportion of low-height individuals. The scale parameter $\lambda = 3.51$ indicates a predominance of small to medium-sized trees, typical of a young stand or

one that has undergone recent disturbance. This structure, combined with active regeneration dynamics, suggests a process of recolonization or post-disturbance growth (Hou *et al.*, 2020). The development of young stems and the diversity of height classes confirm the vitality of the stand and its capacity for renewal.

In plot P3, the shape parameter $k = 2.11$ reflects a moderate concentration around the average height, while the scale value $\lambda = 3.22$ indicates a lesser presence of large trees. This configuration corresponds to an intermediate stage of development, characterized by increased competition for light, likely to limit the growth of dominant individuals. The position parameter $\theta = 0.15$ suggests that regeneration has begun but is still limited, reflecting a transitional phase of forest succession (Pommerening, 2002).

Plot P4, on the other hand, has the most homogeneous structure, with a shape parameter $k = 2.70$, indicating a high concentration of

trees around a dominant height. The scale value $\lambda = 4.31$ indicates the presence of large trees, reflecting a mature, stable stand. The position parameter $\Theta = 0.19$ confirms the limited but constant presence of seedlings, indicating a balance between growth and regeneration (Landsberg & Waring, 1997). This vertical homogeneity reflects ecological stability, probably favored by site conditions and low disturbance intensity.

The comparison of the four plots reveals significant structural heterogeneity within the El Hamimet forest. Plots P1 and P4, characterized by k -values greater than 2, show homogeneous vertical structures associated with mature, lightly disturbed stands. Conversely, plots P2 and P3, where k values are lower and λ values are reduced, reflect phases of active regeneration or stands undergoing reconstitution.

The low Θ values across all plots indicate the presence of young shoots, but their proportion varies with the stage of succession. This diversity of vertical structures reflects a complex forest dynamic, characteristic of Mediterranean ecosystems where young and mature individuals coexist under the effect of natural or anthropogenic disturbances. These results confirm the importance of vertical structure as an indicator of the productivity, resilience, and biodiversity of Mediterranean forests (Vallejo et al., 2017).

In summary, Weibull function parameters applied to tree heights clearly distinguish stands by stage of development and ecological status. The joint interpretation of k , λ , and Θ values provides a fine quantitative reading of vertical structure. It constitutes a reliable silvicultural and ecological diagnostic tool for the sustainable management of El Hamimet forests.

4. Conclusion

Dendrometry analysis and modeling of demographic structure using the three-parameter Weibull distribution were used to characterize structural variability and stand dynamics in the El Hamimet forest. The main dendrometry parameters, diameter, height, basal area, and density, show significant differences between stands of Aleppo pine (*Pinus halepensis*) and green cypress (*Cupressus sempervirens*). These variations reflect contrasting ecological conditions and different stages of development, ranging from young, regenerating stands to older, stabilized formations. Fitting the diameter and height distributions to Weibull's law confirmed the relevance of this law for describing stand structure. The study of height distribution confirms the presence of a vertical stratification characteristic of natural Mediterranean forests. The coexistence of dominant, co-dominant, and young trees reflects a balance between growth, mortality, and regeneration. This vertical and horizontal organization reflects the ecological complexity of the El Hamimmet massif, influenced by site conditions, natural disturbances, and past silvicultural practices.

Overall, Weibull modelling is an effective tool for assessing the structure and dynamics of forest stands. It enables linking dendrometry characteristics to growth and regeneration processes and guiding management decisions. The results obtained suggest the need for differentiated management tailored to each stand to maintain structural and functional diversity, an essential condition for the ecological resilience and sustainability of Mediterranean forest ecosystems.

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