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Structural Dynamics of Atlas Cedar in the Tala Guilef Forest: A Favorable Situation that can be Improved by Controlling Anthropogenic Pressure

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ABSTRACT

Understanding stand structure and regeneration dynamics is essential for assessing the functioning, resilience, and conservation status of Mediterranean forest ecosystems. Atlas cedar (*Cedrus atlantica*), a keystone species of high conservation concern, has experienced significant decline across its natural range. This study examines the structural dynamics and regeneration patterns of *C. atlantica* in the Tala Guilef forest (northwestern Djurdjura, Algeria) under varying local ecological conditions and disturbance regimes. Field data were collected from 32 square stands (625 m^2 each), representing a range of elevations, slopes, exposures, vegetation cover classes, and stand compositions. Structural attributes were assessed using dendrometric measurements (diameter at breast height, total height, crown dimensions, basal area, and density), while regeneration was evaluated across four developmental stages. Cone production was quantified as an indicator of reproductive potential, and disturbance factors were recorded through direct field observations. The results indicate that *C. atlantica* dominates all stands and is associated with low to moderate woody species diversity. Regeneration was present across all sites, although its density varied significantly with ecological conditions. Seedlings were more abundant on north-facing slopes, whereas advanced regeneration stages were more frequent on south-facing slopes. Regeneration density peaked at higher elevations and under intermediate vegetation cover (25–50%). Cone production was widespread and did not limit regeneration. Diameter distributions consistently exhibited an inverted J-shaped structure, indicating continuous recruitment. Structural attributes such as diameter, height, and basal area were generally higher in mixed stands and at medium elevations. Grazing was identified as the dominant disturbance factor, affecting more than 80% of the surveyed stands and likely constraining regeneration success. Despite these pressures, the overall structural patterns suggest that *C. atlantica* populations in Tala Guilef maintain active dynamics and regeneration capacity. Reducing anthropogenic pressure, particularly grazing, and prioritizing the protection of stands with high regeneration potential may enhance natural regeneration processes and support sustainable forest management.

Keywords: anthropogenic disturbance, *Cedrus atlantica*, Djurdjura National Park, ecological factors, stand structure, woody species diversity

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INTRODUCTION

Forest structure reflects both species composition and their spatial organization within ecosystems and is a fundamental attribute for understanding forest functioning, dynamics, and management (Franklin et al. 2002, McElhinny et al. 2005, Gao et al. 2014). It is shaped by the combined influence of natural drivers, including ecological succession, fire, and climatic variability, as well as anthropogenic pressures such as grazing, logging, and land use change (Franklin et al. 2002, Bassil et al. 2018, Allen et al. 2024, Coskuner et al. 2025).

In Mediterranean ecosystems, these interacting factors strongly influence forest resilience, regeneration capacity, and long-term persistence (Quézel and Médail 2003, Navarro-Cerrillo et al. 2019).

Atlas cedar (*Cedrus atlantica* (Endl.) G.Manetti ex Carrière) is a keystone species of Mediterranean mountain forests and is currently classified as Endangered on the IUCN Red List of Threatened Species due to extensive range contraction and long-term degradation (Cheddadi 2009). Present-day cedar forests represent fragmented remnants of formerly extensive stands that have been affected by deforestation, recurrent fires, and overexploitation. Understanding their structural dynamics and regeneration processes is therefore essential for developing effective conservation and management strategies.

The Djurdjura Mountains, located in northern Algeria, fall within the natural distribution range of *C. atlantica* and include Djurdjura National Park, established in 1983 and covering approximately 18,550 hectares (JORA 1983). This protected area is of high ecological value due to its biodiversity, landscape diversity, and hydrological function linked to its karstic substratum. Despite its protected status, the forest cover remains highly fragmented, consisting of isolated patches dominated primarily by Atlas cedar and holm oak, which cover approximately 2234 ha and 3344 ha, respectively (internal DNP data).

The degradation and fragmentation of these forests highlight the need for restoration strategies aimed at stabilizing soils, reducing erosion and downstream flood risks, supporting biodiversity recovery, and enhancing carbon sequestration under changing climatic conditions (García-Ruiz and Lana-Renault 2011, Crouzeilles et al. 2016, El Mderssa et al. 2019). Reforestation programs using Atlas cedar have been implemented across the Djurdjura massif; however, their success has been uneven, with limited establishment in some areas despite favorable growth in others (Rabhi 2015). These outcomes point to the need for a better understanding of local structural dynamics and regeneration patterns.

Previous research on Atlas cedar forests has addressed individual aspects such as: phytodynamics (Mediouni and Yahi 1994), silvicultural practices (Navarro-Cerrillo et al. 2013), growth dynamics (Sarmoum et al. 2018), climate-growth relationships (Navarro-Cerrillo et al. 2019), regeneration ecology (Alileche et al. 2021), reproductive biology (Toth 1978, Derridj 1990, Krouchi et al. 2004), and in situ seed germination and seedling survival (Ezzahiri and Belghazi 2000, Addar et al. 2016). However, integrated analyses combining stand structure, regeneration stages, reproductive potential, and disturbance indicators within the natural range of the species remain limited, particularly at the local scale in the northwestern Djurdjura.

In this context, the Tala Guilef cedar forest provides a relevant case study for examining how local ecological conditions and disturbance regimes shape the dynamics of *C. atlantica* stands. A detailed assessment at this scale can provide actionable insights for both conservation and forest management.

The present study investigates the structural dynamics and regeneration processes of *C. atlantica* in the Tala Guilef forest (northwestern Djurdjura, Algeria). It specifically aims to (i) evaluate the influence of elevation, aspect, slope, canopy cover, and stand composition on stand structural attributes; (ii) analyze the spatial distribution and density of regeneration stages across ecological gradients; (iii) quantify cone production as an indicator of reproductive potential; (iv) characterize the diversity and composition of associated woody species; and (v) assess the impact of anthropogenic and natural disturbances on current forest dynamics. We hypothesize that variations in local ecological conditions and disturbance intensity significantly influence stand structure, regeneration patterns, and reproductive performance.

MATERIAL AND METHODS

Study Area and Sampling Procedure

The study was conducted in the Atlas cedar forest of Tala Guilef (northwestern Djurdjura, Algeria), which is characterized by a Mediterranean climate within the humid to per-humid bioclimatic zone (Figure 1). The geological substratum is dominated by limestone formations, including Eocene and Oligocene deposits interspersed with marls and conglomerates (Flandrin 1952).

The forest is composed of two main vegetation types: stands dominated by *Quercus ilex* L. (approximately 438 ha) and stands dominated by *C. atlantica* (over 509 ha), according to forest administration data. Mixed stands occur at the interface between these two vegetation types. To capture local variability in stand conditions, 32 square sampling plots (625 m^2 each) were established across the study area. In each plot, the following variables were recorded: geographic coordinates, elevation, slope, aspect, stand composition (pure vs mixed), vegetation cover, and all woody individuals.

Slope was classified according to Anbalagan (1992) as follows: gentle (15–25°), moderately steep (25–35°), steep (35–45°), and escarpment (>45°). Vegetation cover was estimated visually and categorized according to Long (1975) into three classes: very light (0–25%, R1), light (25–50%, R2), and fairly light (50–75%, R3). The dense class (75–100%, R4) was not observed in the study area. Elevation was grouped into three classes: low (<1400 m a.s.l.), medium (1400–1600 m a.s.l.), and high (>1600 m a.s.l.).

Woody Species Diversity and Abundance

All woody species present within each plot were recorded. Botanical identification was verified using the African Plant Database. Life forms were assigned according to the Raunkiaer classification system (Raunkiaer 1937). Phanerophytes were classified according to height into megaphanerophytes (over 30 m), mesophanerophytes (8–30 m), microphanerophytes (2–8 m), nanophanerophytes (under 2 m) and lianas (no height limit). Chamaephytes were defined as

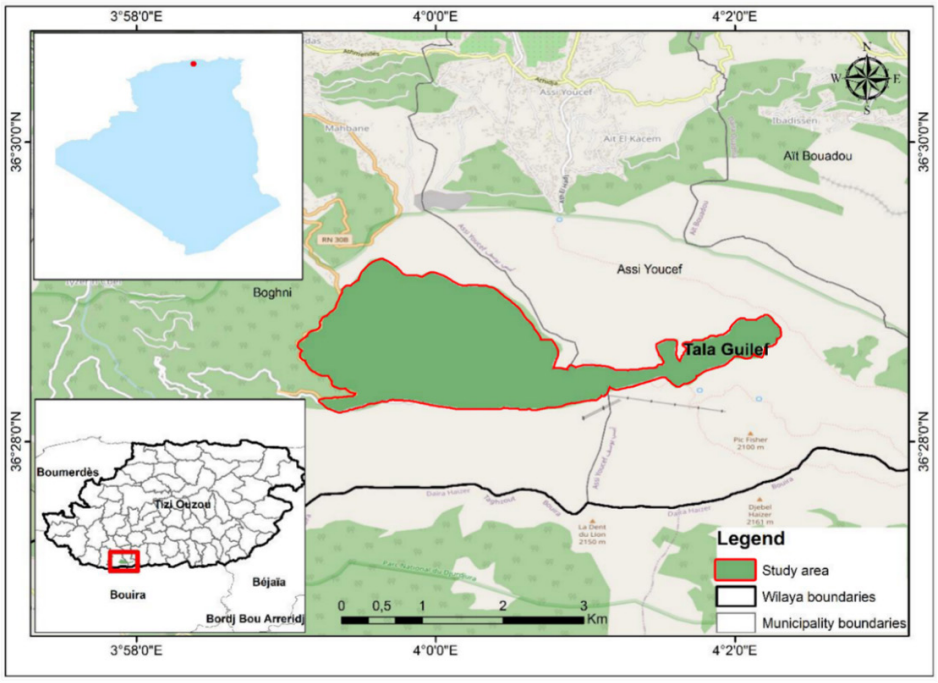

Figure 1 The location of the study area according to Davis's floristic grid system.

species with perennating buds located close to the ground surface. Species density was calculated by converting the number of individuals per plot into individuals per hectare.

Atlas Cedar Structural Attributes

Dendrometric measurements were conducted on adult *C. atlantica* individuals in each stand. Total height and crown height were measured using a Vertex IV dendrometer, while stem diameter at breast height (DBH) was recorded at 1.3 m above ground using a forestry caliper. Crown diameter was measured using a dendrometric tape and calculated as the mean of two perpendicular crown projections taken at ground level. Crown height was defined as the vertical distance between the first living branch and the apex of the tree.

Basal area and density were calculated exclusively for adult *C. atlantica* at the stand level and then expressed per hectare. For each individual, basal area was calculated using the formula . The total basal area of each stand was obtained by summing individual values and converting the result to m^2/ha. Stem density corresponded to the number of adult individuals per stand and was expressed as individuals per hectare.

Atlas Cedar Classes of Regeneration

Regeneration of *C. atlantica* was classified into four size classes based on height and diameter thresholds: seedlings ($h < 50$ cm), short saplings ($50 \text{ cm} \leq h < 130$ cm), tall saplings ($h \geq 130$ cm and DBH < 5 cm), and juveniles (5 cm ≤ DBH < 10 cm), according to Dobrowolska and Veblen (2008) and Navarro-Cerrillo et al. (2013). Seedlings and short saplings were considered early regeneration stages, whereas tall saplings and juveniles represented advanced stages.

Indicators of Atlas Cedar Fertility

Cone production was used as an indicator of reproductive potential and was assessed during the summer period (August–September), when cones are most visible in the canopy. Cones were counted visually from the ground for each mature *C. atlantica* tree within each stand. To reduce underestimation due to crown overlap, each tree was observed from multiple angles by moving around the trunk. The number of cones per tree was then aggregated at the stand level.

Indicators of Disturbance

Indicators of anthropogenic and natural disturbances were systematically recorded in each stand. These included: grazing, identified through the presence of animal droppings and browsing marks; waste left by visitors; signs of logging such as cut stumps or branches; evidence of fire, including charred wood or burnt vegetation; and erosion, indicated by visible soil loss or exposed roots. Each disturbance type was assessed through direct field observation and recorded as present or absent. The frequency of each disturbance was calculated as the percentage of the 32 stands in which the corresponding indicator was observed.

Data Processing and Statistical Analyses

Statistical analyses were performed using R software (version 4.4.1), and graphical representations were produced using Excel 2019. Species diversity was evaluated using species richness, the Shannon index, and Pielou's equitability index, calculated with the *vegan* package in R. The distribution of Atlas cedar trees by classes of structural attributes was examined. The diameter structure of *C. atlantica* was analyzed using histograms in which individuals were grouped into 18 classes, including regeneration classes (A–D) corresponding to seedlings, short saplings, tall saplings, and juveniles, and adult classes. Adult trees with DBH ≤ 140 cm were partitioned into 10 cm intervals (classes E–Q), while individuals with DBH greater than 140 cm were grouped into a single class (R), following Navarro-Cerrillo et al. (2013).

Variation in structural attributes of adult *C. atlantica* across stand factors was tested using one-way analysis of variance (ANOVA), followed by Tukey's post hoc test at a significance level of $p < 0.05$ when significant differences were detected. The occurrence and density of regeneration classes were analyzed using chi-square (χ^2) tests to assess their dependence on ecological factors. A principal component analysis (PCA) was performed using six standardized quantitative variables, namely diameter at breast height, total height, crown height, crown diameter, basal area, and density, in order to summarize the relationships among structural attributes. Ecological variables, including elevation, slope, aspect, stand composition, and vegetation cover, were included as supplementary qualitative variables to facilitate the interpretation of the PCA axes.

RESULTS

Woody Species Diversity

Across the 32 stands investigated, a total of 27 woody species belonging to 21 genera and 17 families were recorded (Table 1). Rosaceae was the most represented family, accounting for 25% of the total, followed by Aceraceae and Fagaceae, each contributing 9.4%. Fabaceae, Cupressaceae, Thymelaeaceae, and Rhamnaceae each represented 6.3%, while the remaining families each accounted for 3.1%. The most abundant woody species were *C. atlantica* and *Quercus ilex*, occurring in 100% and 70% of the stands, respectively.

Species richness ranged from 2 to 13 species per stand. Among the 32 stands, only three contained more than 10 species, fifteen included between 5 and 10 species, and the remaining stands contained fewer than five species. The stand with the highest species richness, including species such as *Prunus avium* (L.) L., *Quercus canariensis* Willd., and *Acer obtusatum* Waldst. et Kit. ex Willd., corresponded to a remnant portion of the original forest with relatively higher woody species diversity.

The Shannon diversity index ranged from 0.05 to 1.99 across stands. These low values reflect the strong dominance of *C. atlantica*, which constitutes the main structural species of this forest type, while other woody species form a secondary floristic assemblage. Pielou's equitability index was consistently low (< 0.25), confirming the limited evenness of species distribution and the dominance of a single species within the stands.

Table 1 Woody species recorded in Atlas cedar stands of the Tala Guilef Forest.

Families	Genera	Species	Biological life form (Raunkiaer 1937)
Sapindaceae	*Acer*	*Acer monspessulanum*	Mesophanerophyte
		Acer obtusatum	Mesophanerophyte
Fabaceae	*Cytisus*	*Cytisus triflorus*	Nanophanerophyte
	Genista	*Genista tricuspidata*	Nanophanerophyte
	Calicotome	*Calicotome spinosa*	Nanophanerophyte
Rosaceae	*Crataegus*	*Crataegus laciniata*	Microphanerophyte
		Crataegus monogyna	Microphanerophyte
	Prunus	*Prunus avium*	Mesophanerophyte
		Prunus prostrata	Chamaephyte
	Rosa	*Rosa canina*	Nanophanerophyte
		Rosa sicula	Nanophanerophyte
	Rubus	*Rubus ulmifolius*	Nanophanerophyte
Berberidaceae	*Berberis*	*Berberis hispanica*	Nanophanerophyte
Thymelaeaceae	*Daphne*	*Daphne gnidium*	Nanophanerophyte
		Daphne laureola	Nanophanerophyte
Araliaceae	*Hedera*	*Hedera helix*	Liana
Aquifoliaceae	*Ilex*	*Ilex aquifolium*	Mesophanerophyte
Cupressaceae	*Juniperus*	*Juniperus oxycedrus*	Microphanerophyte
Pinaceae	*Cedrus*	*Cedrus atlantica*	Megaphanerophyte
Rhamnaceae	*Rhamnus*	*Rhamnus alaternus*	Microphanerophyte
Betulaceae	*Alnus*	*Alnus glutinosa*	Mesophanerophyte
Taxaceae	*Taxus*	*Taxus baccata*	Mesophanerophyte
Caprifoliaceae	*Lonicera*	*Lonicera etrusca*	Liana
Fagaceae	*Quercus*	*Quercus ilex*	Mesophanerophyte
		Quercus canariensis	Mesophanerophyte
Salicaceae	*Salix*	*Salix pedicellata*	Microphanerophyte
Ulmaceae	*Ulmus*	*Ulmus minor*	Mesophanerophyte

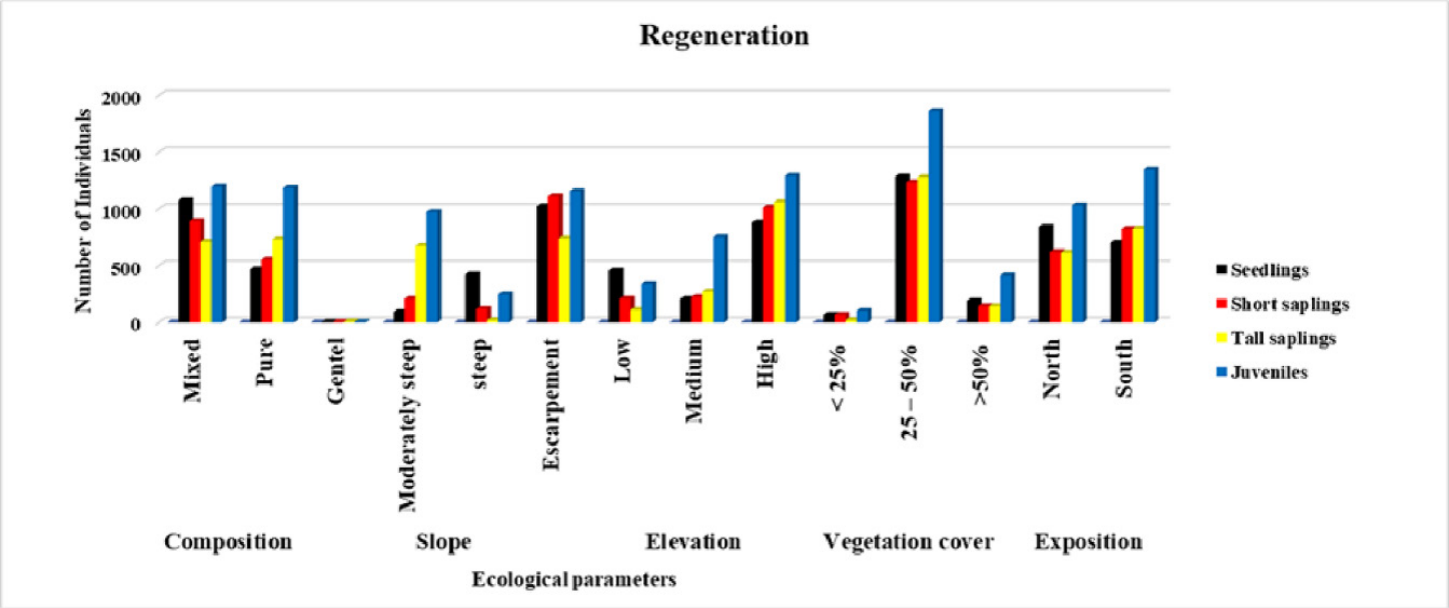

Figure 2 Atlas cedar regeneration classes according to stand ecological parameters: slope classes [gentle (15-25°), moderately steep (25-35°), steep (35-45°), and escarpment (>45°)], vegetation cover classes [R1: very light (0-25%), R2: light (25-50%), and R3: fairly light (50-75%)], and elevation classes [low (<1400 m a.s.l.), medium (1400-1600 m a.s.l.), and high (>1600 m a.s.l.)].

Stands with low species richness were observed across a wide range of environmental conditions, including both high and low elevations, pure and mixed stands, and moderately steep to escarpment slopes. Regarding biological life forms, only one species was classified as megaphanerophyte, nine as mesophanerophytes, five as microphanerophytes, nine as nanophanerophytes, two as lianas, and one as chamaephyte. At low elevations and on northern exposures, *C. atlantica* was the only species occupying the upper canopy layer in pure stands, whereas in mixed stands, *Quercus ilex* and *Acer monspessulanum* L. also contributed to this layer.

Atlas Cedar Regeneration

The presence or absence of regeneration classes was not significantly affected by stand factors, as indicated by the chi-square test ($p > 0.05$). In contrast, regeneration density showed significant dependence on ecological factors, including slope, stand composition, vegetation cover, elevation, and exposure ($p < 0.05$).

Regeneration density varied markedly with local ecological conditions (Figure 2). Slope exerted a strong influence on regeneration structure, with very high densities of early stages (seedlings and short saplings) observed on

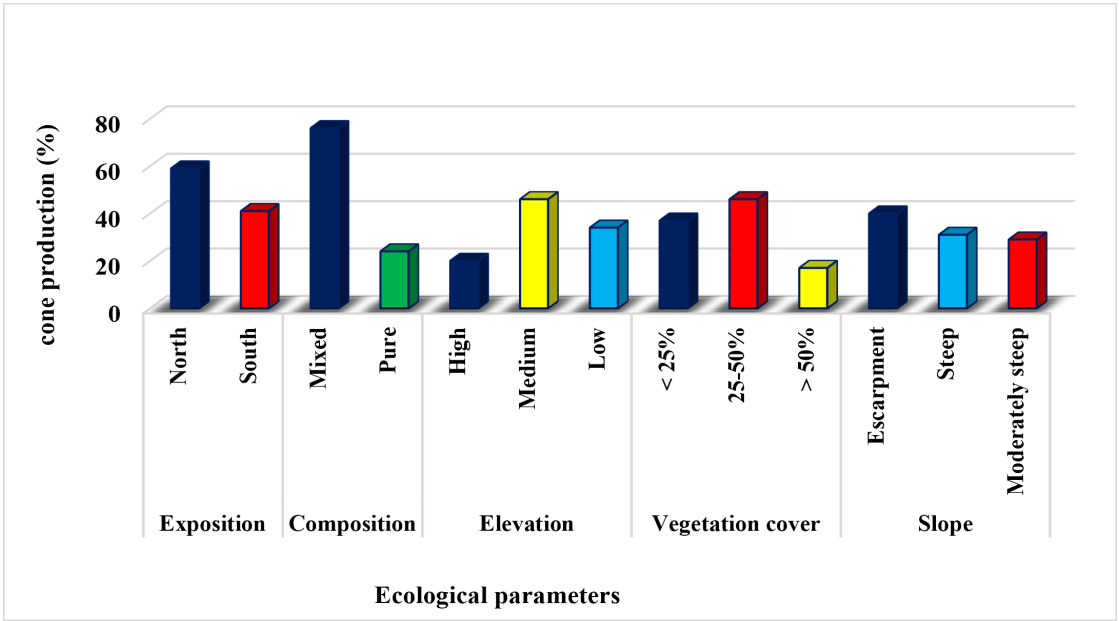

Figure 3 Contribution of stand modalities to total cone production (%): slope classes [gentle (15-25°), moderately steep (25-35°), steep (35-45°), and escarpment (>45°)], vegetation cover classes [R1: very light (0-25%), R2: light (25-50%), and R3: fairly light (50-75%)], and elevation classes [low (<1400 m a.s.l.), medium (1400-1600 m a.s.l.), and high (>1600 m a.s.l.)].

Table 2 Structural characteristics of the sampling stands in the Tala Guilef Forest according to composition, elevation, exposure, slope and vegetation cover. Values are means ± SE. Statistical differences among the categories of each studied factor were tested using one-way ANOVA and are indicated as follows: ns = non-significant, * P < 0.05, ** P < 0.01, *** P < 0.001.

	Modalities	DBH	Total height	Crown height	Crown diameter	Basal area	Density
Exposure	North	47.29 ± 2.80 **b** ***	14.94 ± 0.32 **a** *	11.36 ± 0.28 **a** ns	9.01 ± 0.21 **a** ***	5.66 ± 0.73 **a** ns	369 ± 61.20 **a** ns
	South	57.52 ± 2.47 **a** ***	13.77 ± 0.36 **b** *	11.19 ± 0.29 **a** ns	7.05 ± 0.23 **b** ***	6.72 ± 0.80 ns	363 ± 61.44 **a** ns
Composition	Pure	45.85 ± 2.13 **a** ***	14.30 ± 0.28 **a** ns	11.16 ± 0.25 **a** ns	7.92 ± 0.18 **a** *	4.58 ± 0.52 **b** *	441 ± 62.95 **a** ***
	Mixed	68.18 ± 3.51 **b** ***	14.74 ± 0.48 **a** ns	11.63 ± 0.41 **a** ns	8.71 ± 0.30 **b** *	10.37 ± 1.40 **a** *	258 ± 50.49 **b** ***
Elevation	Low	49.80 ± 4.21 **ab** **	11.29 ± 0.39 **c** ***	9.92 ± 0.41 **b** ***	7.02 ± 0.35**b** ***	4.72 ± 0.81 **b** ***	250 ± 70.18 **a** ns
	Medium	56.90 ± 2.46 **a** **	16.23 ± 0.33 **a** ***	12.69 ± 0.27 **a** ***	8.90 ± 0.21 **a** ***	7.92 ± 0.88 **a** ***	380 ± 61.51 **a** ns
	High	42.31 ± 3.65 **b** **	12.79 ± 0.46 **b** ***	9.22 ± 0.40 **b** ***	7.28 ± 0.30 **b** ***	3.27 ± 0.66 **b** ***	481 ± 113.41 **a** ns
Slope	Gentle	33.08 ± 13.94 **b** ***	9.27 ± 1.78 **c** ***	8.45 ± 1.56 **b** ***	6.53 ± 1.17 **b** ***	0.28 ± 0.07 **b** ***	40 ± 55.65 **a** ns
	Moderately steep	41.27 ± 3.38 **ab** ***	12.25 ± 0.43 **b** ***	10.10± 0.38 **ab** ***	6.41 ± 0.28 b ***	2.63 ± 0.38 **b** ***	354 ± 80.35 **a** ns
	Steep	65.23 ± 4.79 **a** ***	12.94 ± 0.61 **b** ***	9.56 ± 0.54 **b** ***	8.20 ± 0.40 **ab** ***	12.65 ± 2.31 **a** ***	296 ± 81.42 **a** ns
	Escarpment	54.53 ± 2.50 **ab** ***	16.14 ± 0.32 **a** ***	12.47 ± 0.30 **a** ***	9.09 ± 0.21 **a** ***	6.48 ± 0.72 **a b** ***	417 ± 68.32 **a** ns
Vegetation cover	<25%	46.47 ± 4.21 **a** ns	11.34 ± 0.40 **a** ***	10.07 ± 0.47 **a** ***	6.08 ± 0.34 **c** ***	2.59 ± 0.40 **b** **	171 ± 63.06 **ab** *
	25–50%	50.34 ± 2.70 **a** ns	13.57 ± 0.33 **b** ***	10.39 ± 0.30 **b** ***	7.65 ± 0.22 **b** ***	6.08 ± 0.78 **a** **	423 ± 59.21 **a** *
	>50%	56.92 ± 3.15 **a** ns	17.29 ± 0.52 **a** ***	13.18 ± 0.35 **b** ***	9.95 ± 0.30 **a** ***	8.20 ± 1.13 **a** **	419 ± 88.56 **a** *

escarpments, whereas advanced stages were more frequent on moderately steep slopes. In contrast, regeneration density across all classes remained very low on gentle slopes.

Stand composition also influenced regeneration density, which was generally higher in mixed stands than in pure stands. This difference was less pronounced for tall saplings, which were more evenly distributed between stand types. Exposure significantly affected regeneration patterns, with higher densities on southern exposures for juveniles (1624 vs 757 stems/ha), tall saplings (1056 vs 388 stems/ha), and short saplings (820 vs 626 stems/ha). In contrast, seedling density was higher on northern exposures, reaching 870 stems/ha compared to 676 stems/ha on southern slopes.

Along the elevational gradient, both early and advanced regeneration stages reached their highest densities at high elevations, while densities remained lower at low and medium elevations (Figure 2). It is important to note that this pattern applies only to regeneration and should not be confused with adult *C. atlantica* density, which did not vary significantly with elevation (Table 2).

Vegetation cover also influenced regeneration structure. Stands with low canopy cover (<25%) exhibited low densities across all regeneration classes. In contrast, stands with intermediate canopy cover (25–50%) showed the highest regeneration densities, with juveniles predominating (1729 stems/ha). Stands with higher canopy cover (50–75%) displayed low to moderate regeneration densities.

Cone Production

The total number of cones recorded on mature Atlas cedar trees, used as an indicator of fertility and regeneration potential, reached 15,260 across 32 stands (Figure 3). A total of 72% of the stands contributed to this production. Higher cone production (Figure 3) was observed in mixed stands (76%), at medium elevations (46%), on north-facing slopes (59%), under intermediate forest cover (25–50%), and on escarpments (40%).

Atlas Cedar Stand Structure and Dendrometric Attributes

Diameter Distribution

The distribution of Atlas cedar stems by diameter at breast height (DBH) exhibited a reverse J-shaped structure across all ecological stand factors, indicating a strong dominance of small-diameter classes (Figure 4). Regardless of stand orientation, composition, slope, or elevation, the 10–20 cm class was consistently the most represented. Trees with a diameter greater than 140 cm at breast height (DBH) were recorded across most slope and elevation classes, in both orientations and in both pure and mixed stands. However, they were more frequently observed in mixed stands, on south-facing slopes, on escarpments, and at medium elevations. In contrast, intermediate large-diameter classes (120–140 cm) were either absent or present in small numbers

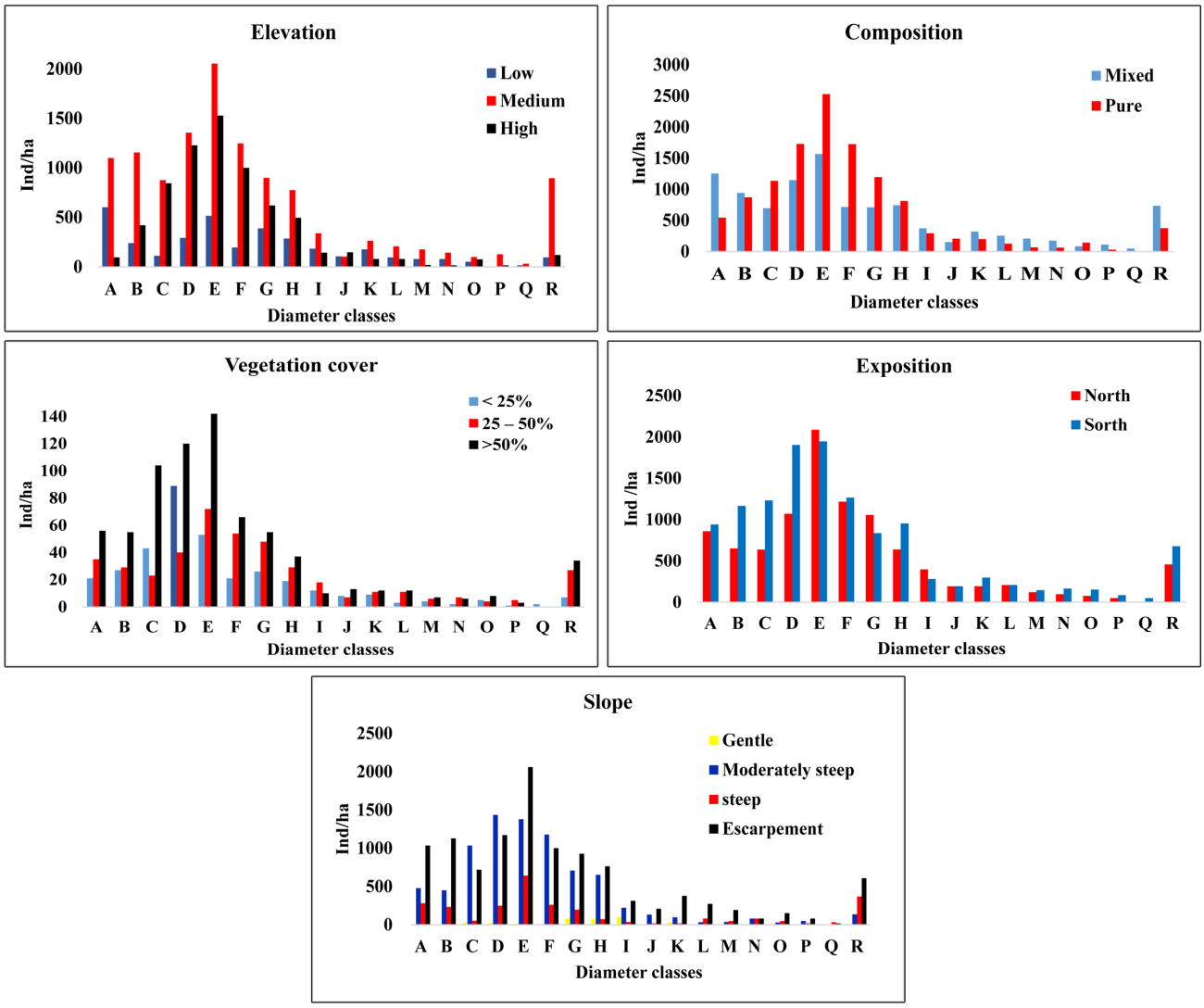

Figure 4 Diameter class distribution according to stand ecological parameters: A–D represent regeneration stages [A = seedlings (h < 50 cm), B = short saplings (50 cm ≤ h < 130 cm), C = tall saplings (h ≥130 cm and dbh < 5 cm), D = juveniles (5 cm < dbh < 10 cm)], and E–Q represent mature trees grouped into 10 cm dbh classes, while R corresponds to trees with dbh > 140 cm.

under low and high elevation conditions and on gentle slopes. Overall, the diameter structure remained heterogeneous in response to local ecological parameters while maintaining a consistent inverted J-shaped curve, indicating continuous recruitment of young individuals across a wide range of environmental conditions (Figure 4).

Basal Area and Density

The mean basal area was 6.14 m^2/ha (Table 2). This parameter did not vary significantly between north- and south-facing stands but was higher in mixed stands (10.37 m^2/ha) than in pure stands (4.58 m^2/ha). It was also higher at medium elevations (7.92 m^2/ha) than at low and high elevations, forming a single homogeneous group (3.27–4.72 m^2/ha). Regarding slope, basal area was highest on steep slopes (12.65 m^2/ha), intermediate on escarpments (6.48 m^2/ha), and lowest on moderately steep slopes (2.63 m^2/ha). This variable was significantly lower in stands with vegetation cover below 25% (2.59 m^2/ha) compared to those with vegetation cover above 25% (6.08–8.20 m^2/ha).

The density of Atlas cedar trees averaged 367 individuals per hectare. This parameter did not differ significantly between north- and south-facing stands but was higher in pure stands than in mixed stands (Table 2). Density did not vary significantly with elevation (Table 2), although the highest mean value was recorded at high elevations. It was lowest on gentle slopes (40 individuals/ha) compared to the other slope classes (296–417 individuals/ha). It was also higher in stands with vegetation cover between 25 and 50% and above, compared to stands with vegetation cover below 25%.

Tree Dimensions

Diameter at breast height averaged 51.85 cm and varied significantly across most modalities of the stand factors (Table 2). Mean values were higher on southern exposures (57.52 cm) than on northern ones (47.29 cm), in mixed stands (68.18 cm) compared to pure stands (45.85 cm), at medium elevations compared to high elevations (56.90 cm and 42.31 cm, respectively), and on steep slopes (65.23 cm) compared to gentle slopes (33.08 cm). This structural attribute did not vary significantly with vegetation cover classes.

The overall mean total height of Atlas cedar was 14.42 m. Apart from stand composition, all other stand factors had significant effect on this variable (Table 2). Mean values were higher on northern exposures (14.94 m) than on southern ones (13.77 m). Total height was also higher at medium elevations compared to low and high elevations, which formed distinct groups, with a maximum difference of nearly 5 m between medium and low elevations and 3 m between medium and high elevations. Heights were highest on escarpments (16.14 m) compared to steep and moderately steep slopes (Table 2), and lowest on gentle slopes (9.27 m). Total height also differed between stands with vegetation cover above 50% and those with lower cover.

Crown height averaged 11.28 m. It did not vary significantly with stand exposure or stand composition (Table 2). However, it varied significantly with elevation, with the mean value at medium elevation (12.69 m) differing from those at high and low elevations, which formed a single group (9.22–9.92 m). It also varied significantly with slope (Table 2), with higher values on escarpments (12.47 m) compared to gentle, steep and moderately steep slopes (respectively 8.45, 9.56 and 10.10 m), and with vegetation cover, with stands above 50% cover (13.18 m) differing from those with lower cover (10.07–10.39 m).

Crown diameter averaged 8.13 m and varied significantly across all ecological stand factors (Table 2). It was larger on northern exposures (9.01 m) than on southern ones (7.05 m), in mixed stands compared to pure stands, at medium elevations (8.90 m) compared to low and high elevations (7.02–7.28 m), on escarpments (9.09 m) compared to moderately steep and gentle slopes (6.41–6.53 m), and in stands with vegetation cover above 50% (9.95 m) compared to lower cover classes.

Principal component analysis (PCA) showed that the first two axes explained 71.4% of the total variance, with Axis 1 accounting for 46.91% and Axis 2 for 24.47% (Figures 5A and 5B). Axis 1 was positively correlated with total height, crown height, crown diameter, and diameter at breast height, reflecting variation in stand structural development. Axis 2 was mainly associated with basal area and stem density, representing a gradient in stand density and spatial occupation.

The first two PCA axes therefore provided a reliable summary of the main structural variability among the studied stands (Figure 5B). The analysis of supplementary ecological variables indicated that vegetation cover, slope, and, to a lesser extent, elevation contributed most to the ecological interpretation of the axes, whereas aspect and stand composition showed lower discriminatory power.

Projection of these variables suggested that higher elevation, greater vegetation cover, and steeper slopes were associated with more developed stands, whereas lower elevation, lower vegetation cover, and gentler slopes were associated with less developed stands. Exposure and stand composition showed limited differentiation on the factorial plane (Figure 5A).

Disturbance Indicators

Grazing was identified as the most widespread disturbance, affecting 84.38% of the stands and likely compromising natural regeneration. Waste was observed in 71.88% of the stands. Traces of logging and past fire events, of both human and natural origin (including lightning), were recorded in 37.5% and 34.32% of the stands, respectively. Signs of erosion were observed in 3.13% of the stands.

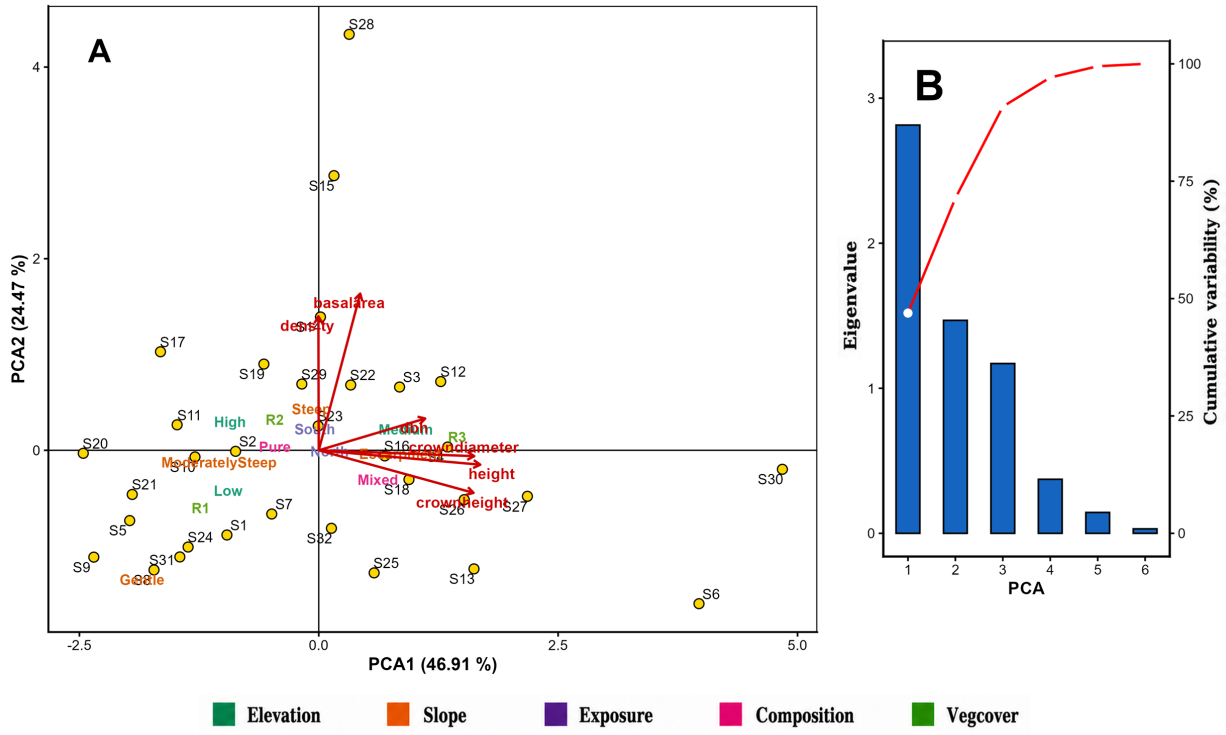

Figure 5 PCA triplot showing the first two principal component axes for the structural attributes of Atlas cedar stands, supplementary ecological factors, and stands (A); eigenvalues of the six principal components with cumulative explained variance (B).

DISCUSSION

The woody species composition of the Atlas cedar forest of Tala Guilef is typical of *C. atlantica* forests (Quézel 1965, Médail and Quézel 1997, Yahi 2007). Diversity indices showed that Atlas cedar was the most widespread species across all stands, followed by holm oak. Other woody species, such as *Acer obtusatum*, *Quercus canariensis*, and *Prunus avium*, were found in very few stands and were comparatively less abundant than in the Atlas cedar forest of Ait-Ouabane (northeastern Djurdjura). Lapie (1909) described this forest as a relic mosaic forest.

In the Tala Guilef forest, Atlas cedar showed active regeneration, as evidenced by consistent cone production and the presence of the four regeneration classes. Good fertility of Atlas cedar has previously been documented in the same forest (Derridj 1990, Krouchi 2010, Krouchi et al. 2004) and in other Atlas cedar forests, including introduction areas in France (Toth 1980), where consistent numbers of seeds per cone were reported. Local ecological factors influenced cone production (Figure 3). These factors affected regeneration dynamics by influencing density rather than presence or absence, highlighting spatial heterogeneity in recruitment success (Figure 2).

Topography appears to play a key role in regeneration dynamics. Terrain configuration influences the establishment and persistence of regeneration (Shevchenko and Geraskina 2023), with greater efficiency observed on sloping terrain. This is consistent with our results (Figure 2), which showed high regeneration density on escarpments at early stages (seedlings and short saplings) and on moderately steep slopes at advanced stages (tall saplings and juveniles). Similar effects of slope have been reported in the Aures Mountains (Nedjahi 1993), where regeneration of Atlas cedar was shown to be confined to steep, less dense, and less accessible areas, suggesting greater resource availability (Quézel and Médail 2003). However, Arar et al. (2020) reported that slopes exceeding 40% increase erosion and the export of seeds and litter, thereby degrading soils and limiting regeneration. This may explain why advanced stages are more prevalent on moderately steep slopes.

In the Tala Guilef forest, low vegetation cover (less than 25%) increases accessibility and susceptibility to disturbance. As noted by Mhirit (2006), very sparse forest cover can lead to increased temperatures and seedling desiccation. Conversely, steep slopes may act as natural barriers that promote Atlas cedar regeneration.

Exposure modulates environmental conditions, particularly light and temperature (Toth 1978). Cooler conditions on northern exposures may explain the higher abundance of seedlings, as more humid conditions favor germination and early survival.

Atlas cedar regeneration has been reported both in canopy gaps, where light and soil conditions are favorable (Barbero and Quézel 1989, Yahi 2007, Alileche et al. 2021), and along forest edges, where the species can progressively establish (Lepoutre 1964). The establishment and success of regeneration may also be facilitated by nurse plants such as *Juniperus communis* L., which promote regeneration in the Djurdjura Atlas cedar forests (Barbero and Quézel 1989, Yahi 2007, Meddour et al. 2019). Similarly, holm oak plays a comparable role in mixed stands of the Aures Atlas cedar (Belhouchet et al. 2024).

Atlas cedar stand dynamics, including regeneration, are also influenced by management practices, grazing, fire, and climate change (Navarro-Cerrillo et al. 2013). Signs of anthropogenic disturbance were observed in most of the investigated stands.

Grazing appears to be the main limiting factor for regeneration. In the studied stands, signs of intense browsing by cattle were observed on young Atlas cedar and maple individuals, with livestock remaining in the area year-round without supervision. The fencing of a perimeter in the Tala Guilef Atlas cedar forest in 1979, at an elevation of 1500 m, resulted in successful recruitment of the species, reaching densities of up to 4000 individuals/ha (Messaoudene, personal communication). This density falls within the range reported by Messaoudene et al. (2013) for several Atlas cedar forests in Algeria (2500 to 5400 individuals/ha at 30 and 10 years, respectively).

In the Chrea Atlas cedar forest, Addar et al. (2016) reported seedling survival rates of 54–76% in stands protected from grazing, compared to 9–21% in grazed stands. Furthermore, recruitment within stands and expansion into adjacent open areas may increase under controlled anthropogenic pressure. Active recruitment was observed around remnant mother trees at 2100 m on the Haizer plateau in the Tala Guilef forest, corresponding to the upper altitudinal limit of the species in this area.

Frequent fires represent a major driver of forest cover loss in Djurdjura. Messaoudene et al. (2013) reported that more than 800 hectares of Atlas cedar were destroyed by fires in the Tikjda forest between 1958 and 2012. A diachronic analysis over 37 years revealed that 24% of the forest's initial area was lost (Dib et al. 2023).

Despite its designation as a National Park in 1983, the Djurdjura Mountains continue to experience multiple forms of human pressure, including overgrazing, illegal logging, recurring fires, and increasing tourism pressure. These constraints are consistent with those reported in other Atlas cedar forests in Algeria (Derridj 1990, Addar et al. 2016, Kherchouche et al. 2021). Logging for construction was historically common in the region, as reflected in local place names (e.g. Lainser Inejaren), which refer to traditional cedar wood harvesting practices.

Atlas cedar forests are also affected by climatic constraints. Kherchouche et al. (2021) reported a significant reduction in the distribution area of Atlas cedar due to drought-induced mortality. Derridj (1990) noted that summer drought limits seedling establishment. Since 1980, drought events have been shown to reduce radial growth and increase the sensitivity of Atlas cedar (Linares et al. 2011, Rabhi et al. 2014).

The diameter distribution exhibited an inverted J-shaped structure, indicating active recruitment, with a strong representation of the 10–20 cm class across different ecological conditions. The coexistence of mature and young individuals has also been reported in other Atlas cedar forests in Djurdjura (Meddour 1995; Yahi et al. 2004). However, in Tikjda, the dominance of large stems has been attributed to the absence of silvicultural management (Rabhi et al. 2016), a practice not currently implemented in the management plans of Algerian national parks.

Adult *C. atlantica* density did not exhibit significant variation among classes of stand elevation, as shown in Table 2, although the highest mean value was recorded at high elevations. Regeneration was more abundant at high elevations (Figure 2), suggesting that these stands may currently offer more favorable conditions for recruitment. Density was also higher on escarpments (Table 2); these slopes are less dense and more difficult to access, which may allow greater resource availability (Quézel and Médail 2003). The mean density recorded across the 32 stands in the Tala Guilef forest (367 stems/ha) exceeds the values reported by Rabhi et al. (2014) for other Djurdjura Atlas cedar forests (53–78 stems/ha, depending on the forest), as well as those reported by Taleb et al. (2016) for Theniet El Had (169 stems/ha). However, it remains lower than the value reported by Sarmoum et al. (2018) for the Theniet El Had Atlas cedar forest (941 stems/ha).

Basal area also varied considerably among stands, with maximum values observed in mixed stands at medium elevations. The mean value (6.14 m^2/ha) is lower than those reported for mixed stands in Theniet El Had, namely 33.46 m^2/ha (Taleb et al. 2016) and 14.13 m^2/ha (Sarmoum et al. 2018).

The highest mean values of diameter and height were recorded in mixed stands at medium elevations, although these attributes did not respond similarly to other ecological factors (Table 2). Diameter at breast height was higher on south-facing slopes, whereas total height and crown diameter were greater on north-facing slopes (Table 2). Although north-facing slopes are generally more humid and less stressful environments (Navarro et al. 2013, Sarmoum et al. 2019), the higher diameter values observed on south-facing slopes may be explained by site-specific conditions, including stand density, age structure, competition, and disturbance history, rather than by a general ecological pattern. The mean total height (14.42 m) and diameter (51.85 cm) recorded in the Tala Guilef forest are comparable to those reported by Sarmoum et al. (2018) for pure stands in Theniet El Had Forest (14.9 m and 50 cm, respectively), but slightly higher than those reported for mixed stands (11.7 m and 37.5 cm, respectively). Rabhi et al. (2016) reported a higher mean height of 25.95 m for Atlas cedar in the Tikjda forest, likely reflecting older stand age.

According to Quézel and Médail (2003), topography influences tree morphology, while high stand density and crown overlap may intensify competition (Wang et al. 2020). The mean crown height of Atlas cedar in the Tala Guilef Forest (11.28 m) is similar to that reported by Taleb et al. (2016) for the same species in Theniet El Had forest (11.82 m).

The current structure of Atlas cedar forests reflects both past and ongoing human activities, while climate change and natural disturbances also play a significant role in shaping their dynamics (Cheddadi 2009, Bouahmed et al. 2019).

Overall, the concordance between structural attributes, the inverted J-shaped diameter distribution (Figure 4), and cone production (Figure 3) suggests good viability of the Atlas cedar population despite the constraints imposed by anthropogenic and climatic factors. Reducing anthropogenic pressure, identified as the most widespread disturbance across the 32 study sites, is essential to promote natural regeneration. Protective measures implemented in the Tala Guilef and Chrea forests have yielded satisfactory results, with significantly higher recruitment and survival rates. From a management perspective, the installation of temporary fencing in stands with high regeneration potential and productivity could be an effective approach. Priority should be given to stands at medium to high elevations, mixed stands with intermediate canopy cover, and stands located on steep slopes and escarpments (Figure 2, Figure 3, Table 2).

CONCLUSIONS

This study examined the dynamics of Atlas cedar within the natural stands of the Tala Guilef forest. Based on data collected from 32 stands, the analysis focused on stand structure, regeneration processes, cone production, and the influence of local ecological factors and disturbances. The structural attributes of Atlas cedar analyzed in this study indicate active stand dynamics and good population viability, as evidenced by consistent cone production, the presence of different regeneration classes, and an inverted J-shaped diameter distribution, reflecting continuous recruitment across a range of stand conditions.

Adult Atlas cedar density showed less variation than regeneration density, with no significant differences between exposures or along the elevation gradient, whereas regeneration density varied significantly with slope, exposure, vegetation cover, stand composition, and elevation. These findings suggest that, despite the combined effects of climate and human activity, the species retains a substantial capacity for regeneration at the local scale, although grazing remains a major constraint. Promoting the spatial recolonization of Atlas cedar and associated plant species therefore requires limiting human pressure and regulating grazing through an integrated management strategy involving local populations. Protecting areas with high regeneration potential or ongoing regeneration may represent a cost-effective alternative to reforestation programs. It is also essential that forest managers secure the support of local communities using Djurdjura as a grazing land, particularly through the implementation of temporary and rotational protection systems, which can support both species regeneration and broader ecological recovery.

The present study is limited in scope, as it focuses solely on the cedar forest of Tala Guilef. The trends identified in the study can be extrapolated to other cedar forests in Djurdjura, which are located within the same mountain range, share a similar geographical and bioclimatic context (Tellian Atlas), and are subject to comparable human pressures. Nevertheless, this assumption requires validation through comparative studies before any regional generalization can be made.

This analysis of Atlas cedar dynamics in natural stands could be complemented by similar investigations in reforested stands within the same forest area, where success rates have been lower than in naturally regenerated stands. Future research should also extend this approach to other Atlas cedar forests in the Djurdjura region in order to compare stand structure, regeneration dynamics, and disturbance effects at a broader regional scale.

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