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Population dynamics and demographic structure of *Juniperus Phoenicea L.* in Semi-Arid North African ecosystems

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Abstract: The present study aims to characterize the demographic structure of the red juniper (*Juniperus phoenicea* L.) population under a semi-arid bioclimate in the Central Saharan Atlas Mountains (North Africa) to define its dynamics and predict its future status and conservation. Based on ten selected homogeneous sites, a total of 100 temporary observation plots, each covering 400 m², were surveyed. Within each plot, dendrometric variables (Total height, density) were measured to establish demographic analysis and a static life table. Data analysis revealed that the studied *Juniperus phoenicea* populations fall into three contrasting "ecological types": expanding populations, self-sustaining populations with natural regeneration, and declining populations. The persistence of the latter is mainly due to the species' relatively long lifespan, allowing natural renewal to be maintained and ensuring that the population size remains stable at a certain point in the future.

Keywords: *Demographic structure, Dynamics, Static life table, Juniperus phoenicea, North Africa, Semi-arid ecosystems.*

1. Introduction

Juniperus phoenicea Linnaeus [1] is a shrub or small tree (1–8 meters), often mo-noecious, upright, and branching from the base, with a circumference exceeding two meters. According to Boratyński, et al. [2] its maximum height can reach 12 meters. The Phoenician Juniper thrives in extreme ecological conditions [3]. It is highly resistant to drought, soil degradation, and anthropogenic pressure, particularly in the most arid regions [3]. It plays a crucial role in the dynamics of pre-forest communities [4]. This species actively contributes to biodiversity conservation by providing both shelter and a food source. Potential frugivores in the region feed on its galbules during periods of scarcity [5-8]. The tree possesses therapeutic properties [9-13] and serves as a source of firewood [14]. Several studies have reported different potential distribution scenarios for the *Juniperus phoenicea* complex [15, 16]. These scenarios indicate a significant reduction in the species' spatial distribution by 2070 due to various environmental factors driving these changes [17-20]. Based on the literature reviewed in this section, few studies have addressed the structuring and functioning of juniper woodlands worldwide, particularly in Egypt [15, 16] Saudi Arabia [21] Libya [22, 23] and France [24, 25]. Age structure is a key characteristic of populations, and numerous researchers have used size structure analysis [26, 27] in studies on population structure and dynamics. In some cases, size may be a better predictor of reproductive output than age, particularly under similar forest growth conditions [28-30].The static life table, also known as a time-specific life table, estimates survival and mortality by age based on the structure of a population at a given moment. It is particularly useful for long-lived

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plants, where it is impractical to track cohort decline over time [31, 32]. This approach illustrates population changes in terms of birth and mortality rates and explains survival strategies [33, 34]. Although this type of vegetation formation covers a significant area in Algeria (290,000 hectares) [35] no field study has yet been conducted to characterize the demo-graphic structure and dynamics of Algerian juniper forests. However, the Saharan Atlas Mountains of Algeria represent the species' last southern refuge in North Africa. The objective of this study is to characterize the population structure of *Juniperus phoenicea* under a semi-arid bioclimate in the Central Saharan Atlas Mountains (North Africa) through demographic analysis and static life table assessment, in order to define its dynamics and predict its future status and conservation prospects.

2. Materials and Methods

2.1. Study Area

The study area is part of the Ouled Naïl Mountains, which form the central section of the Saharan Atlas. It is located in the wilaya of Djelfa, 300 km south of Algiers. This area encompasses the five (05) main mountain ranges of the Ouled Naïl Mountains, namely the notable and forested massifs of Sénalba Chergui, Sénalba Gharbi, Sahary Guebli, Sahary Dahry, and Djebel Djellel Chergui (Figure 1). The regional bioclimate is of the semi-arid Mediterranean type with a cold winter [36]. Annual precipitation fluctuates around 310 mm, while average temperatures range between 26°C in July and 5.4°C in January. The precipitation pattern follows the A.P.H.E. regime (Autumn, Spring, Winter, Summer) [37].

2.2. Sampling

A mixed sampling approach (stratified and systematic) was adopted in this study. For the stratified sampling, the study area was divided into ten (10) stations based on the mountain massif (Table 01 and Figure 01), slope orientation, and soil type. Within each station, ten (10) temporary observation plots were established (100 plots in total) using systematic sampling with fixed intervals of 100 m. These circular plots cover an area of 400 m², with a radius of 11.28 m. They were delineated using a measuring tape stretched horizontally and were geo-referenced using the geographical coordinates of their centers [38].

Table 1.
Presentation of Geographical Characteristics for each Study Station.

Station	Massif	Exposure of the slope	Place called	Substratum	Altitude (m)
ST01	Senalba Chergui	Northern	Haoues	Marl-limstone	1188
ST02		Northern - South	Nakazia	Sandstone	1208
ST03	Senalba Gharbi	Nord- South	Zabache	limstone	1342
ST04		Northern - South	Gouttaia	Marl-limstone	1520
ST05	Djellal Chargui	Northern	SaboaMokrane	limstone	1390
ST06		South	SboaMokrane	Marl-limstone	1346
ST07	Sahari Guebli	Sud	Chebeika	Sandstone	1120
ST08		Nord	Dreoua	limstone	1120
ST09		Nord-Sud	Medjedel	Marl-limstone	1055
ST10	Sahari Dahri	Nord-Sud	Gueltet Stell	Sandstone	1195

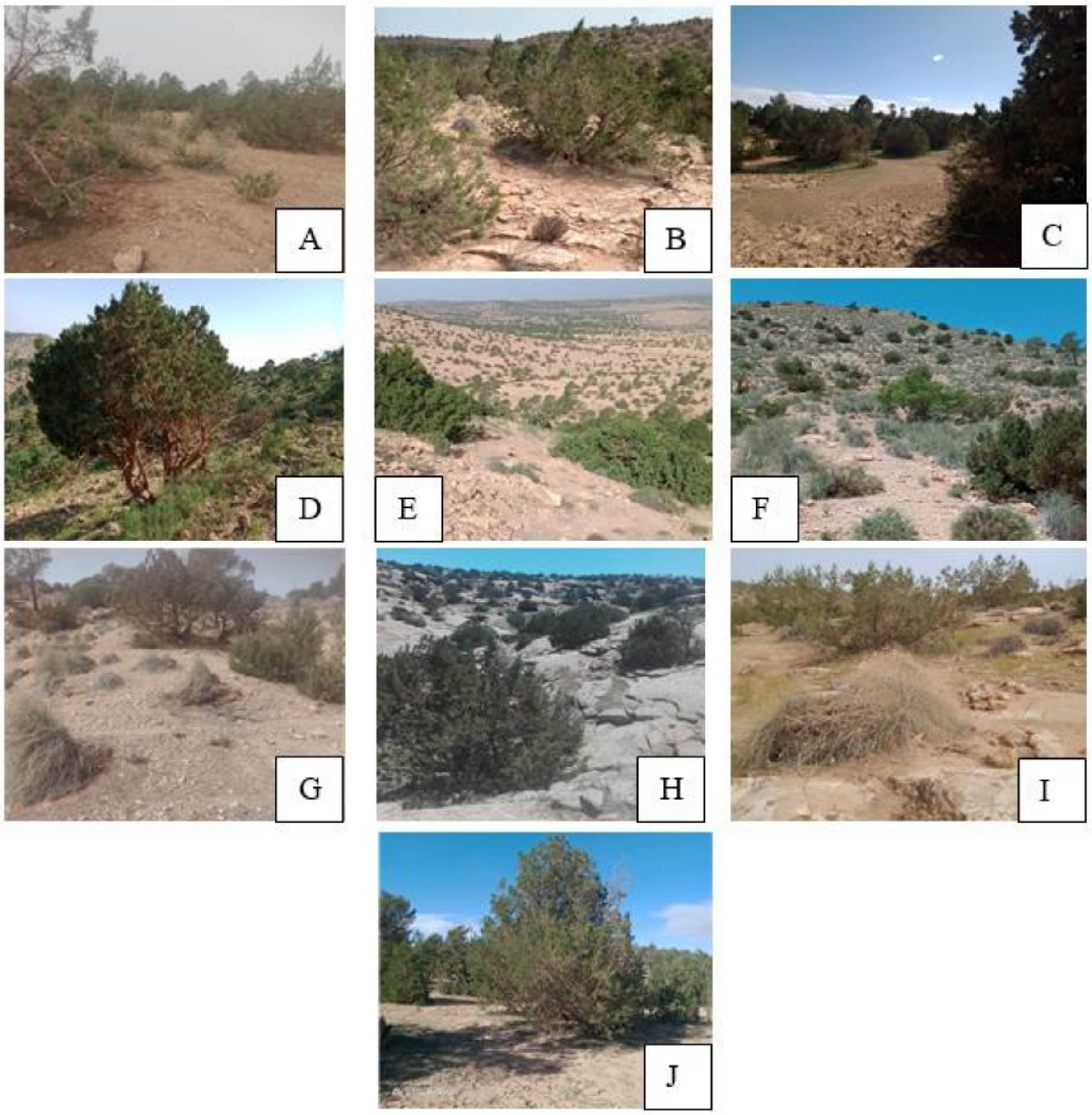

Figure 1.
Photographs of the different juniper woodlands in the study stations.
Source: Legend : (a) St01 Haoues ; (b) St02 Nakazia ; (c) St03 Zabache ; (d) St04 Gouttaia ; (e)St05 Saboa Mokrane Nord ; (f) St06 Saboa Mokrane Sud ; (g) St07 Chebeika ; (h) St08 Dreoua ; (i) St09 Medjedel ; (j) St10 Gueltet Stell.

2.3. The Static Survival Table

In each plot, a dendrometric inventory is conducted to characterize the stand (total average height; dominant height; density per hectare).

Measuring the total height of a tree involves determining the length of the straight segment connecting the base of the tree to its terminal bud. The instrument used for this measurement is the Blum-Leiss dendrometer.

Density represents the number of trees per hectare:

$$N/_{ha} = \frac{N \times 100}{S}$$

Where:
N: Number of trees,
S: Plot area in ares.

Due to the lack of data on wood analysis and the difficulty of extracting cores to determine tree age, as well as the unique morphology of *Juniperus phoenicea*, which typically has multiple trunks that are often inaccessible due to its interwoven branching system, an alternative approach was necessary. According to Frost and Rydin [39] the response of a species in terms of age and size within the same environment is characterized by consistency in age and size.

Therefore, we used height-class structure to represent the temporal sequence of woody plants and construct a static survival table [21]. The age structure was determined by assigning each individual to one of the following age classes: established seedling, juvenile, reproductive adult, and senescent [40-44]. Each age category corresponds to the following size classes:

- Seedlings: <0.25 m
- Juveniles: 0.25–1.3 m
- Adults: 1.3–5 m
- Senescent: >5 m

The static survival table was constructed for individual populations as well as for the entire grouped population, following the methods of Pielou [45]; Hegazy [46] and Zaghloul, et al. [47].

All life table functions are mathematically interdependent, meaning that any function can be derived from another. The most commonly expressed functions in the life table are those computationally significant for estimating the life expectancy of individuals at each stage or interval of the life cycle [28]. Statistical methods for the associated indicators used in the survival table are recorded in Table 02.

Table 2.
Parameters of the static life table used to estimate the survival and mortality rates of *Juniperus phoenicea* populations in the Saharan Atlas.

Symbol	Description
x	Age category considered at the time of the survey.
Nx	Number of individual trees living in age category x.
ax	Number of survivors at the beginning of age category x (number of survivors up to age x, used to plot a survival curve).
lx	Number of survivors in each category standardized to 1000.
lx = Nx / N0	Formula for calculating the standardized number of survivors.
Lx	Average number of surviving individuals (from x to x + 1).
Lx = (lx + lx+1) / 2	Formula for calculating the average number of survivors.
Tx	Total number of individuals alive at age category x and beyond.
Tx = Σ Lx - x-1	Formula for calculating the total number of individuals alive.

2.4. Statistical Analysis.

Basic statistical calculations were performed at both intra- and inter-plot sampling scales. The Fisher test at $\alpha = 5\%$ was used to analyze variance with a single variation factor, followed by the Tukey test to determine homogeneous groups.

3. Results and Discussions

3.1. Average Stand Density

A highly significant difference in the distribution of the average stand density of *Juniperus phoenicea* was recorded among the studied sites (ANOVA: $F (10; 90) = 14.344$, $p = 0.00000$) (Table 3).

Table 3.
Distribution of the average stand density of *Juniperus phoenicea* in the Djelfa region (Central Saharan Atlas).

Stations	category	Average ± standard deviation (Individus/ha)	Min.	Max.	C V (%)
St01	Juveniles	225±80.79	150	375	35.91
	Adults	102.5±27.51ab	75	150	26.84
St02	Juveniles	162.5±47.51	75	225	29.23
	Adults	165±35.75a	125	225	21.66
St03	Juveniles	322.5±81.18	225	450	25.17
	Adults	115±33.75ab	75	150	29.34
St04	Juveniles	20±15.81	0	50	79.06
	Adults	65±17.48b	50	100	26.89
St05	Juveniles	290±47.43	225	375	16.36
	Adults	177.5±51.97a	125	250	29.28
St06	Juveniles	90±24.15	75	150	26.84
	Adults	82±26.87b	50	150	31.62
St07	Juveniles	80±32.91	25	125	41.14
	Adults	137.5±27a	100	175	19.64
St08	Juveniles	417.5±100.7	300	550	24.13
	Adults	107.5±31.29ab	75	150	29.11
St09	Juveniles	190±33.75	150	250	17.76
	Adults	117.5±35.45ab	75	175	30.17
St10	Juveniles	97.5±32.17	50	150	32.99
	Adults	187.5±37.73a	150	250	20.12
All stations	Juveniles	189.5±130.86	0	550	69.05
	Adults	126±49.99	50	250	39.67

The different letters above the means indicate a highly significant difference at ($p < 0.05$) according to the Tukey test (ANOVA: F (10; 90) = 14.344, p = 0.00000); CV: coefficient of variation.

The highest average stand density values correspond to the older categories (Figure 2), which include flowering and fruiting individuals, namely adults and senescent trees. In St02, St05, St10, and St07, the density exceeds 130 trees/ha, with values of 165 ± 35.75, 177.5 ± 51.97, 187.5 ± 37.73, and 137.5 ± 27 trees/ha, respectively. Conversely, in St04 and St06, the average density is low, with only 65 ± 17.48 and 82 ± 26.87 trees/ha, respectively. St01, St03, St08, and St09 exhibit an intermediate density, ranging between 100 and 130 trees/ha.

Salvà-Catarineu, et al. [18] reported an average stand density for the same species in northern Sinai, ranging from 86.3 to 152.7 individuals per hectare. However, these values are lower than those recorded in Libya's Al-Akhdar mountains, where the J. phoenicea stand density varies from 24 to 26 trees/m² [22]. Similarly, Tsiourlis [48] reported a density of 554 trees/ha in Greece.

Sarangzai, et al. [49] reported a stand density for J. excelsa ranging between 29 and 268 trees/ha, with an average of 176 ± 77 trees/ha. In contrast, low densities have been observed in Lebanon for the same species (J. excelsa), varying between 45 and 147 trees/ha Douaihy, et al. [50]. Badri [51] recorded an average stand density of 201 trees/ha for J. thurifera in Morocco, fluctuating between 100 and 292 trees/ha.

Furthermore, the average density of the senescent category remains low across all stations, not exceeding 32 trees/ha. Despite its low density (65 trees/ha), the senescent category in St04 represents 50% of the total stand density of J. phoenicea.

It is also observed that the average stand density is higher on the northern slope of Djellal Chargui, with 177.5 trees/ha, compared to the southern slope of the same relief (82.5 trees/ha).

A significant variation in the distribution of J. phoenicea stand density is observed across age categories from one station to another. However, the older categories in St02, St04, St06, St07, and St10 exhibit higher densities compared to juvenile categories.

Conversely, the youngest categories (seedlings and juveniles) in St01, St03, St05, St08, and St09 display higher densities than the older categories.

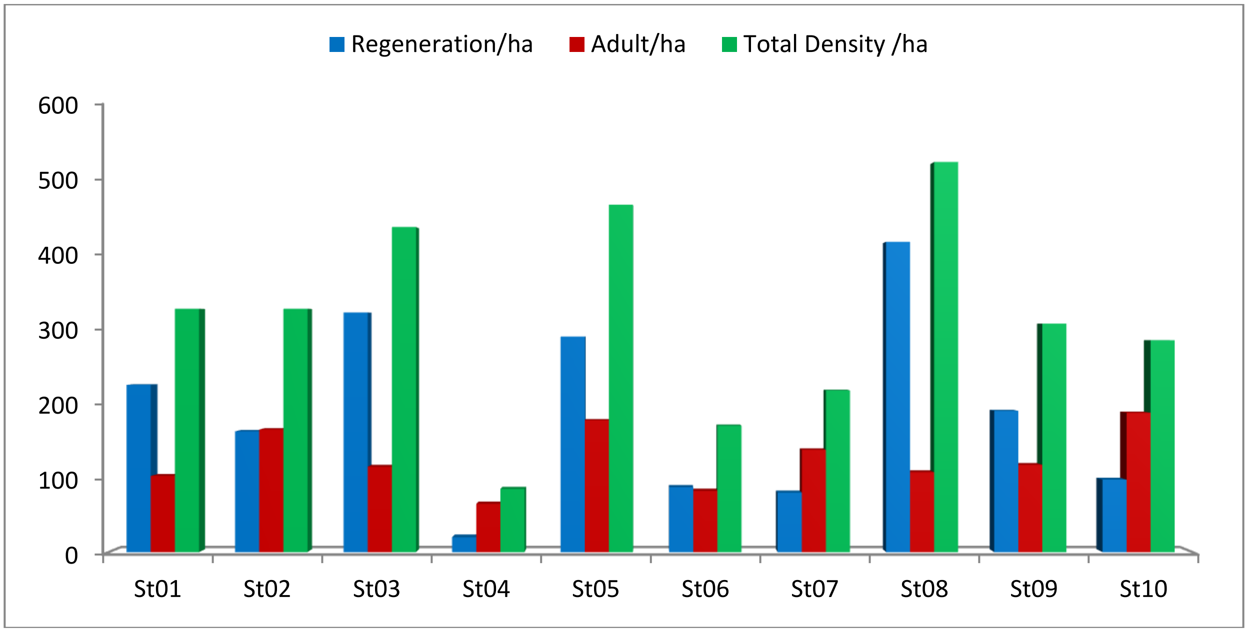

Figure 2.
Structure of *Juniperus phoenicea* stands by station.

3.2. Age Structure

The density histograms of age category distributions (Figure 3) are fair indicators of future population trends for the studied stations. However, the populations of J. phoenicea in St 01, 03, 05, 08, and 09 are characterized by the predominance of young individuals which includes both seedling and juvenile stages at 69%, 74%, 62%, 80%, and 62%, respectively. This indicates a positive skewed distribution (L-shaped curve) which is generally considered an indicator of self-replacing populations. The high regeneration rate shows a pattern similar to that of populations of J. communis in the Atlantic, Northern European, and Boreal regions [52-55]. Conversely, a negative asymmetric distribution (J-shaped curve) of J. phoenicea populations on juveniles is 50.4%, 77%, 51%, 63%, and 66%, respectively. Such distribution characterizes a declining population because it has a large proportion of individuals that are adults than the ones that are juveniles (i.e., a limited regeneration capacity). This may indicate a strong limitation of juniper regeneration in these habitats. This bot-tleneck in regeneration can be imposed by several factors that do not exclude each other. Limited regeneration in stations St02, St07, and St10 may be due to the fact that these stations reach their maximum capacity where junipers occupy the smallest gaps in the fissures of the sandstone rock that is characterized by a strong coverage by the outcrop of the parent rock. These latter outcrops can reach up to 70% in certain plots, especially in St10.

Furthermore, these three stations, on siliceous soil, are unfavorable due to their low water retention capacity and sometimes their lack of nutrients [56]. Thus, Sarmoum, et al. [57] assert that populations on sandstone substrates are more sen-sitive to hazards and climate changes than those on limestone or marl-limestone soils. Farahat [16] shows that the regeneration of populations is limited to a few habitats where the soils have a high water storage capacity. It has been observed that juniper populations decrease with the increase in drought in southern Saudi Arabia, Oman, and Egypt [58-61]. Henceforth, St06 is located on the sunny side of Djebel Djellal Chargui with a cover that does not exceed 10% and a density of 82.5 trees/ha. This slope highlights the consequences of exposure, in comparison with the shady side of the same forest massif where the density reaches 177.5 trees/ha. The harmful effects of water stress, introduced by exposure, on the establishment and persistence of J. phoenicea in these stations are rather precarious conditions.

Indeed, on what concerns the expositions, the variations are related to the radiative balance and the flow of air masses; the radiation is stronger during the day on the sunny slopes than on the shady slopes, generating updrafts of warm air. At night, the cold air accumulates in the valleys [56]. Finally, station St04 is an altitudinal station above 1450 m, has a northern exposure, and is located above the potential bioclimatic level of the Aleppo pine in the study area. The conditions necessary for the establishment of old specimens of J. phoenicea are not maintained to ensure its regeneration on site.

In this vegetal formation that is featured with the presence of high-altitude species similar to Bupleurum spinosum, Ephedra major, Artemisia atlantica, and Prunus prostrata, there exists a re-sistance to the establishment of J. phoenicea. This provides way to other more mesic species (Quer-cus ilex, Pistacia terebinthus, …).

Actually, a very high frequency of juveniles in a population can indicate intense competition among the adult individuals of the trees [62]. This is what we observed at stations St03 and St08, both of which are dominated by very young individuals. However, these two populations were located in Aleppo pine forests.

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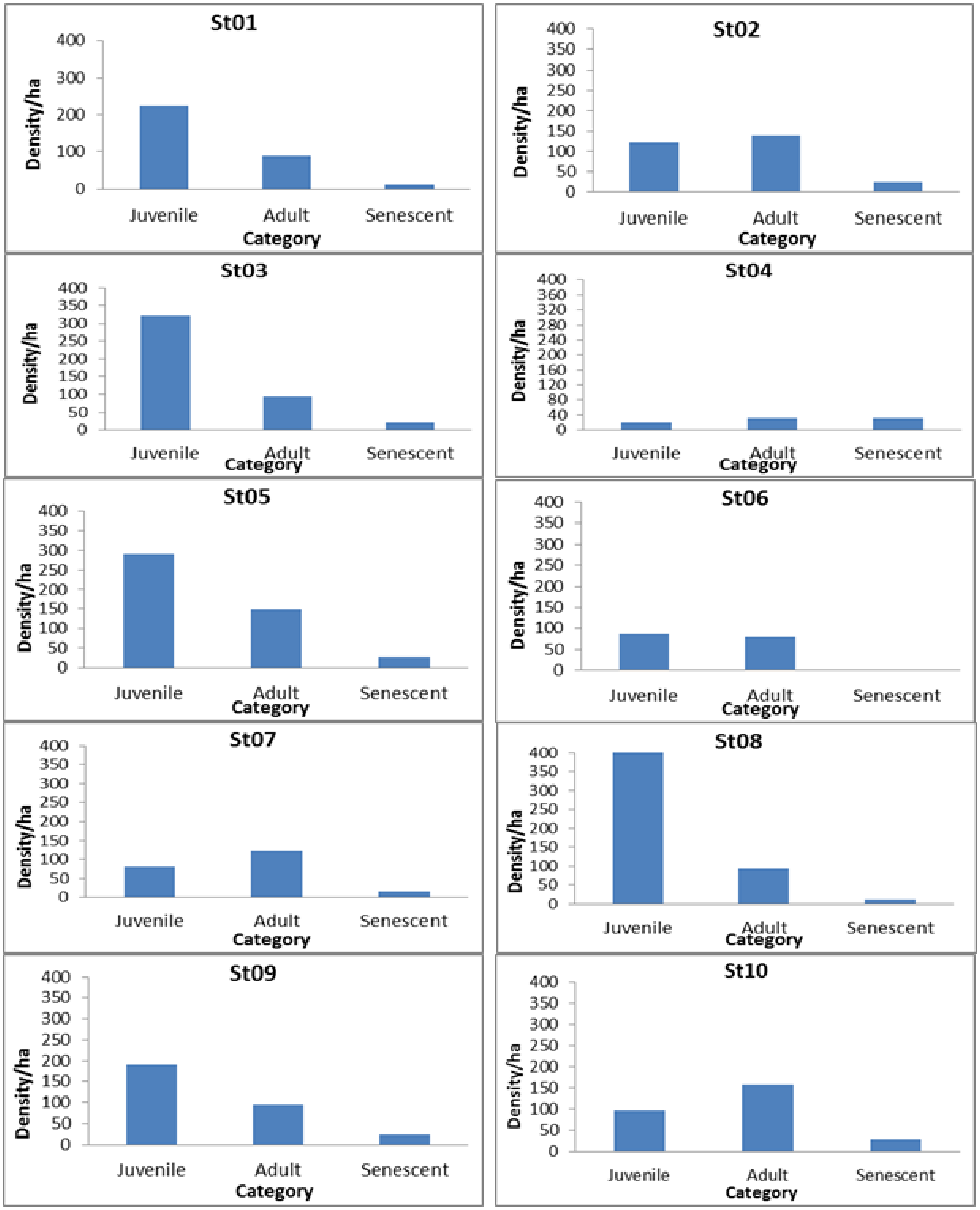

Figure 3.
Distribution of the average density of *Juniperus phoenicea* populations by age category in the Central Saharan Atlas.

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3.3. Static Mortality Table

Based on the age structure and the static mortality table of *Juniperus phoenicea* in the study area, senescent trees have a high probability of dying in the near future (qx = 1.00).

These trees represented 3.8%, 6.4%, 4.6%, 38.2%, 5.9%, 1.5%, 6.9%, 2.4%, 7.3%, and 10.5% of the sampled trees in Haouas (St01), Nakazia (St02), Zabache (St03), Goutaia (St04), Djellel Chargui North (St05), Djellel Chargui South (St06), Chebeika (St07), Dreoua (St08), Medjedel (St09), and Gueltet Stell (St10), respectively.

When combining all ten stations, senescent trees accounted for 6.2% of the total sampled trees, while seedlings and juveniles made up 20% and 40%, respectively, of the total sampled trees.

The differences in age structure among the different stations are significant (Table 04). The highest mortality rate (qx) for seedlings was observed in St03 and St08, with 38% and 43%, respectively.

The life expectancy (ex) of J. phoenicea across the ten studied stations decreases rapidly at the seedling stage, especially in St04, St07, and St10. It continues to decline progressively and signifi-cantly after seedling establishment, indicating that individuals that have established themselves have a low chance of surviving to later age categories.

Table 4.
Static mortality table of the populations in the different studied stations, as well as the combined populations of J. phoenicea.

Station 01 Haouas									
	Nx	**A**	**Lx**	**Lx**	**Tx**	**Ex**	**Dx**	**Qx**	**F**
Seedling	11.00	131.00	1000.00	958.00	1767.17	1.77	84.00	0.08	0.08
Juvenile	79.00	120.00	916.00	614.50	809.17	0.88	603.00	0.66	0.60
Adult	36.00	41.00	313.00	175.59	194.67	0.62	274.83	0.88	0.28
Senescent	5.00	5.00	38.17	19.09	19.09	0.50	38.17	1.00	0.04
Station 02 Nakazia									
Seedling	16.00	131.00	1000.00	939.00	1958.34	1.97	122.00	0.12	0.23
Juvenile	49.00	115.00	878.00	691.00	1019.34	1.16	374.00	0.43	0.34
Adult	56.00	66.00	504.00	290.17	328.34	0.65	427.66	0.85	0.36
Senescent	10.00	10.00	76.34	38.17	38.17	0.50	76.34	1.00	0.06
Station 03 Zabache									
Seedling	66.00	175.00	1000.00	811.40	1431.30	1.43	377.20	0.38	0.38
Juvenile	63.00	109.00	622.80	442.80	619.90	1.00	360.00	0.58	0.36
Adult	38.00	46.00	262.80	154.25	177.10	0.67	217.10	0.83	0.22
Senescent	8.00	8.00	45.70	22.85	22.85	0.50	45.70	1.00	0.05
Station 04 Goutaia									
Seedling	1.00	34.00	1000.00	985.00	2616.70	2.62	30.00	0.03	0.03
Juvenile	7.00	33.00	970.00	867.35	1631.70	1.68	205.30	0.21	0.21
Adult	13.00	26.00	764.70	573.35	764.35	1.00	382.70	0.50	0.38
Senescent	13.00	13.00	382.00	191.00	191.00	0.50	382.00	1.00	0.38
Station 05 Djellel Chargui Nord									
Seedling	25.00	187.00	1000.00	933.15	1804.80	1.80	133.70	0.13	0.13
Juvenile	91.00	162.00	866.30	623.00	871.65	1.01	486.60	0.56	0.49
Adult	60.00	71.00	379.70	219.25	248.65	0.65	320.90	0.85	0.32
Senescent	11.00	11.00	58.80	29.40	29.40	0.50	58.80	1.00	0.06
Station 06 Djellel Chargui Sud									
Seedling	2.00	68.00	1000.00	985.25	1970.50	1.97	29.50	0.03	0.03
Juvenile	33.00	66.00	970.50	727.90	985.25	1.02	485.20	0.50	0.49
Adult	32.00	33.00	485.30	250.00	257.35	0.53	470.60	0.97	0.47
Senescent	1.00	1.00	14.70	7.35	7.35	0.50	14.70	1.00	0.01
Station 07 Chebeika									
Seedling	1.00	87.00	1000.00	994.25	2189.70	2.19	11.50	0.01	0.01
Juvenile	31.00	86.00	988.50	810.35	1195.45	1.21	356.30	0.36	0.36
Adult	49.00	55.00	632.20	350.60	385.10	0.61	563.20	0.89	0.56

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Senescent	6.00	6.00	69.00	34.50	34.50	0.50	69.00	1.00	0.07
Station 08 Dreoua									
Seedling	92.00	210.00	1000.00	780.95	1291.46	1.29	438.10	0.44	0.44
Juvenile	75.00	118.00	561.90	383.83	510.51	0.91	356.14	0.63	0.36
Adult	38.00	43.00	205.76	114.78	126.68	0.62	181.96	0.88	0.18
Senescent	5.00	5.00	23.80	11.90	11.90	0.50	23.80	1.00	0.02
Station 09 Medjedel									
Seedling	23.00	123.00	1000.00	906.50	1768.28	1.77	187.00	0.19	0.19
Juvenile	53.00	100.00	813.00	597.56	861.78	1.06	430.89	0.53	0.43
Adult	38.00	47.00	382.11	227.64	264.23	0.69	308.94	0.81	0.31
Senescent	9.00	9.00	73.17	36.59	36.59	0.50	73.17	1.00	0.07
Station 10 Gueltet Stell									
Seedling	4.00	114.00	1000.00	982.45	2228.10	2.23	35.10	0.04	0.04
Juvenile	35.00	110.00	964.90	811.40	1245.65	1.29	307.00	0.32	0.31
Adult	63.00	75.00	657.90	381.60	434.25	0.66	552.60	0.84	0.55
Senescent	12.00	12.00	105.30	52.65	52.65	0.50	105.30	1.00	0.11
Grouped Station									
Seedling	261.00	1284.00	1000.00	898.35	1750.70	1.75	203.30	0.20	0.20
Juvenile	520.00	1023.00	796.70	594.20	852.35	1.07	405.00	0.51	0.40
Adult	423.00	503.00	391.70	227.00	258.15	0.66	329.40	0.84	0.33
Senescent	80.00	80.00	62.30	31.15	31.15	0.50	62.30	1.00	0.06

3.4. Analysis of the Survival of Juniperus Phoenicea Populations.

To explain the trend of population dynamics change in *Juniperus phoenicea*, we plotted graphs of:

- The survival function, based on the values of population survival numbers (lx) and their corresponding age categories from the static mortality table (Figure 4);
- The mortality function, based on mortality rates in age category x (qx) and their corresponding age categories from the static mortality table (Figure 5).

For stations St04, St07, and St10, the survival rate (lx) is high for individuals in younger age categories; lx=1.00 for the seedling category and lx=97%, 98.85%, and 96.49%, respectively, for the juvenile category. The mortality rate (qx) is high for individuals in later categories, i.e., adults, with 50%, 89%, and 84%, respectively, and senescent individuals (qx=100%). Conversely, the survival rate (lx) at stations St03 and St08 shows a rapid decline at the initial stage (seedling category), with 38% and 43%, respectively, and remains relatively stable afterward, indicating extremely high early-life mortality. Due to the high early mortality in these populations, life expectancy is low.

Moreover, the shape of the survival curve for station St01 shows a distortion affecting the actual form of the survival curve. This fluctuation may be due to a recruitment deficit of new individuals in recent years.Stations St02, St05, St06, and St09 show a trend of gradual decline in the number of individuals as the age category increases, indicating a consistent mortality rate throughout their lifespan.

The analysis of the 10 survival curves of our stations (Figure 4) led to the conclusion that the age structure of J. phoenicea stands in the study region follows the three survival curve types suggested by Deevey (1947), depending on the dynamics of the considered vegetation formation and the environmental conditions (both exogenous and endogenous). The survival curve of populations at sta-tions St02, St04, St10, and St07 closely correlates with Deevey's Type I curve. It is also evident that the survival curve of populations at stations St05, St06, and St09 corresponds to a significant Deevey Type II curve, which is diagonal, indicating a stable mortality rate throughout the popula-tion's developmental stages. Finally, the survival curves of stations St01, St03, and St08 correspond to Deevey's Type III curve.

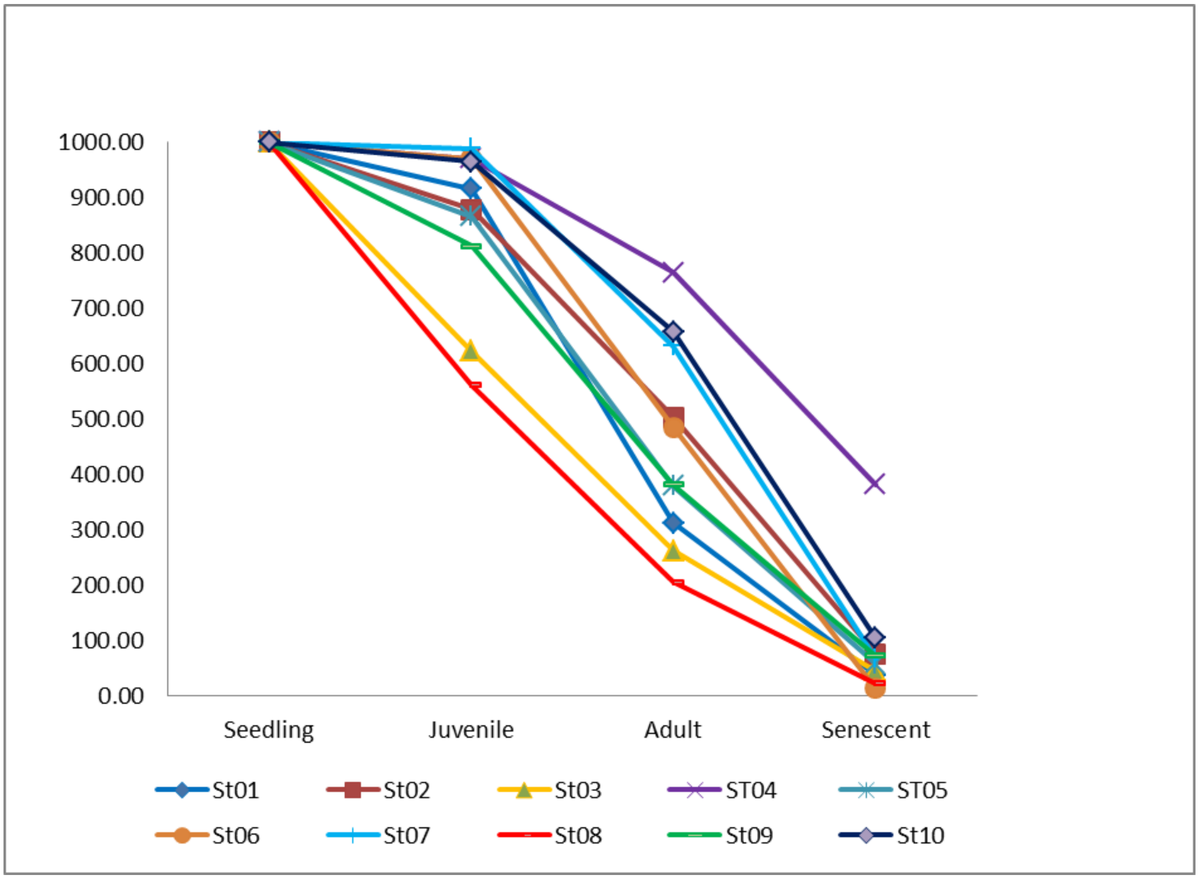

Figure 4.
Survival rate curves of *Juniperus phoenicea* populations from the studied stations in the Central Saharan Atlas.

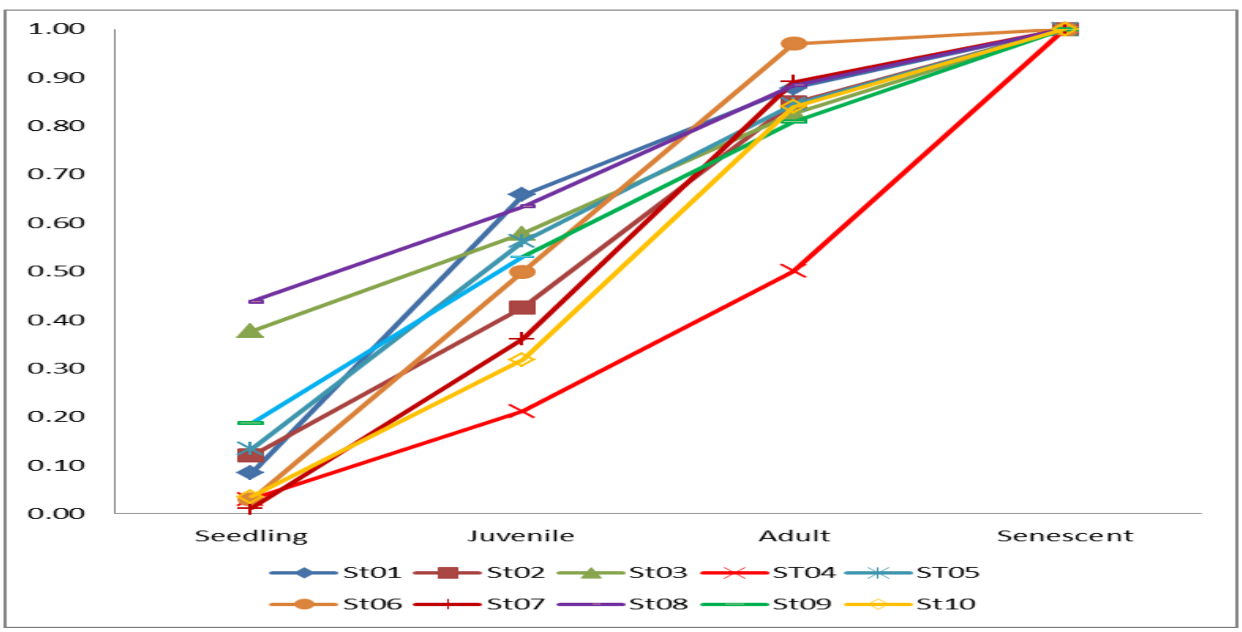

Figure 5.
Mortality rate curves of *Juniperus phoenicea* populations from the studied stations in the Central Saharan Atlas.

The highest life expectancy (ex) values appear in the youngest categories, including seedlings and juveniles, at stations St04, St07, and St10, with values of (2.62; 1.68), (2.19; 1.21), and (2.23; 1.29), respectively. In contrast, stations St01, St03, and St08 exhibit lower values in the younger catego-ries, at (1.77; 0.88), (1.43; 1.00), and (1.29; 0.91), respectively, indicating that established individu-als have a low probability of surviving into later categories. Given that the life expectancy (ex) of the adult category is nearly identical across stations, ranging between 0.53 and 0.69, it is also ob-served that the life expectancy of the senescent category is uniform across all ten stations, with in-dividuals in this category having the same survival probability (ex=0.5).

The studied *Juniperus phoenicea* populations fall into three contrasting "ecological types": expand-ing populations, self-sustaining populations, and declining populations.

- The first type consists of relatively young populations, characterized by a high re-generation density and a juvenile-to-adult ratio of 2.2 to 3.8 juveniles per adult, where Pinus halepensis is in decline, making way for *Juniperus phoenicea.*
- The second type includes mature populations with a balanced juvenile-to-adult ratio of around 1. These stable juniper woodlands, with self-sustaining natural regeneration, are found on slopes with limestone soils.
- Finally, the third type consists of old, declining populations with a juvenile-to-adult ratio not exceeding 0.5. Their persistence is primarily due to the species' relatively long lifespan, making population decline less immediately apparent. These resource-limited stands are subject to physical constraints (rocky outcrops, sandstone soils), climatic factors (southern exposure), and biotic influences (resilience and competition).

4. Conclusions

The demographic analysis of *Juniperus phoenicea* under semi-arid conditions in the Central Saharan Atlas reveals a heterogeneous population structure, comprising expanding, self-sustaining, and declining populations. Despite the regressive trends observed in some stands, the species' long lifespan supports a degree of natural regeneration, allowing for potential population stability over time. However, this persistence masks underlying ecological stress, particularly in declining populations, where limited regeneration is linked to ongoing anthropogenic pressures. These pressures contribute to a gradual transition from pine-dominated communities to aging juniper stands with reduced vitality and resilience. Understanding these dynamics is critical for developing targeted conservation strategies that address both ecological and human-driven factors affecting *Juniperus phoenicea* in arid and semi-arid ecosystems.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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