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Leaf morphological variation in common yew (*Taxus baccata* L.) at the species' southern range margin in North Africa

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Abstract. The main aim of this study was to provide the first morphometric characterization of *Taxus baccata* L. leaves in North Africa. Phenotypic variability was investigated in nine natural populations from Algeria and Morocco using 11 quantitative and qualitative traits. analysis of variance (ANOVA) followed by Fisher's post hoc test revealed significant differences at multiple hierarchical levels, including trees within populations, among populations, regions and mountain ranges for all quantitative variables. In parallel chi-square analysis indicated significant variation in qualitative traits. Hierarchical clustering classified the studied populations into two major clusters for both types of morphological traits. The Chrea population displayed the largest leaves, whereas the Saharan Atlas populations showed the smallest. Principal component analysis (PCA) clearly separated populations and geographic groups in relation to both ecological and leaf morphological factors. Overall, the observed morphological differentiation suggested that phenotypic plasticity together with possible genetic differentiation, is driven more by local ecological conditions than by latitude alone. North African yews are characterized by relatively narow leaves and region specific variation in petiole and apex morphology, reflecting high degree of ecological adaptability to various ecological and geographical conditions. These findings have important implications for conservation of southern marginal population of this relic threatened conifer.

Keywords: *Taxus baccata L.*, leaf morphology, morphometric variability, North Africa.

Introduction

The geographical range of *Taxus baccata L.* is extensive, spanning a broad latitudinal gradient from Scandinavia in the north margin to North Africa in the south, as well as a longitudinal gradient from England in the west to western Asia (Iran) in the east (Lapie and Maige, 1914; Maire, 1916; Thomas and Polwart, 2003). At the southernmost Mediterranean margin of its distribution, yew is limited to Algeria and Morocco, where it occurs in the understory of cedar and oak forests (Barbero and Quézel, 1994; M'hirt *et al*., 1999; Boudy, 1950).

Given its wide distribution range, *T. baccata* is exposed to diverse environmental conditions (Iszkuło *et al*., 2009; Cedro *et al*., 2011; Robakowski *et al*., 2018). In North Africa, the climate is characterized by hot, dry summers and humid to per-humid winters. In Algeria in particular, where *T. baccata* occupies a wide geographical range, it experiences pronounced climatic variability, from humid and per-humid bioclimates in the north to semi-arid to sub humid conditions in the south (Abdessemed, 1981; Derridj, 1990; Meddour, 2014). It can therefore be hypothesized that populations in these regions have developed specific adaptations to cope with such environmental constraints. Various plant traits, including leaf morphology and anatomy, may serve as indicators of these adaptations (Portsmuth *et al*., 2007; Wyka *et al*., 2007; Iszkuło *et al*., 2012).

Plant responses to environmental variability involve multiple biological mechanisms, including growth (Angert, 2006; Iszkuło *et al*., 2012; Perrin *et al*., 2013), survival (Schirone *et al.,* 2010; Linares *et al.,* 2013; Núñez-Cruz et al., 2018), and reproduction and dispersal (Garcia *et al*., 2000; Iszkuło *et al*., 2009; Nkosi *et al*., 2024). These processes are often associated with variations in morphology, anatomy, physiology, and phenology, which ultimately influence the adaptive capacity of individuals to specific environments (Medina et al., 1990; Schirone *et al*., 2010; Zandalinas *et al.,* 2017). Leaves are particularly sensitive organs to the environmental conditions, and their morphological variability in size and shape is considerable, providing information on plant responses to habitat conditions (Boeger *et al.,* 2004; Boratyński, 2008; Pescador *et al.,* 2015).

Numerous studies on *T. baccata* leaf morphology have been conducted in southern Asia (Spjut, 2007; Shah *et al*., 2008), Europe (Mitchell, 1998; Schirone *et al.*, 2010; Vessella *et al*., 2013), and Siberia (Stefanovic *et al.*, 2017), highlighting substantial variability in leaf traits. Previous studies in the Azores (Schirone *et al*., 2010) and Madeira (Portugal) (Vessella *et al.,* 2013) identified the presence of minor morphotypes. These findings suggest that *T. baccata* populations in Macaronesian islands may represent relict lineages, with the occurrence of smaller leaves potentially resulting from long-term geographic isolation.

Despite increasing research on *Taxus baccata* L. across Europe and the Mediterranean Basin, populations in North Africa remain largely neglected. To date, only a few studies have addressed this region: Romo et al. (2017) documented the regression of yew in Morocco, Vessella *et al*. (2010) included three Algerian samples in a broader morphometric analysis of leaf traits, and Hamidouche *et al.* (2014) carried out a preliminary assessment of geographic distribution and general morphological variation in Algerian yew. However, no comprehensive investigation has yet targeted North Africa populations. Given the wide climatic variation across North Africa, it is expected that local populations exhibit specific leaf traits reflecting adaptation to these environments. This study addresses a critical knowledge gap on the adaptive and functional significance of leaf traits in marginal yew population. Morphometric analysis was employed to characterize *yew* populations across North Africa. A total of eight Algerian populations were investigated, including six from the Tell Atlas and two from the Saharan Atlas, along with one Moroccan populations from the Middle Atlas. This study aims to address the following questions: (i) What is the extent of variation in leaf morphology among North African yew populations? and (ii) Does leaf morphology in *T. baccata* vary along a latitudinal gradient in North Africa at its southern range margins?

Materials and methods

Study sites

Taxus baccata L., commonly known as yew, reaches the southern Mediterranean margin of its distribution in North Africa, where it occurs in the understory of *Quercus canariensis* forests and mixed *Cedrus atlantica–Quercus rotundifolia* stands. Its distribution in this region has been well documented in early floristic works (cited before) and further supported by phytosociological studies (M'hirt *et al.*, 1999; Laribi, 2000; Yahi, 2007).

Given the threatened status of *Taxus baccata* L. in North Africa, the sampling strategy was designed to be exhaustive as possible as at population level to capture the widest possible range of morphological variation within each population. Adult trees were selected randomly among accessible individuals in order to ensure representative and unbiased sampling of the local population structure.

The present study included nine sites in North Africa, including eight in Algeria and one in Morocco (Fig. 1). In Algeria, sampling was conducted in mountainous areas of the Tellian and Saharan Atlas, between 1300 and 2500 m a.s.l. In the Tellian Atlas, three regions comprising six sites were investigated: Chréa (CHR), Djurdjura (Tala Guilef (TG), Tikjda (TK), Ath Ouabane (AOB), Ath Zikki (AZ)), and Akfadou (stand named Fontaine des Ifs) (AK). In the Saharan Atlas, populations were sampled in the Aurès Mountains, specifically at Djebel Chelia (CHL) and Djebel Feraoun (FER) The study also included one Moroccan site located in the Middle Atlas (Ifrane (IFR)). Figure 1 shows their geographic distribution, and Table 1 summarizes the ecological characteristics of the sites.

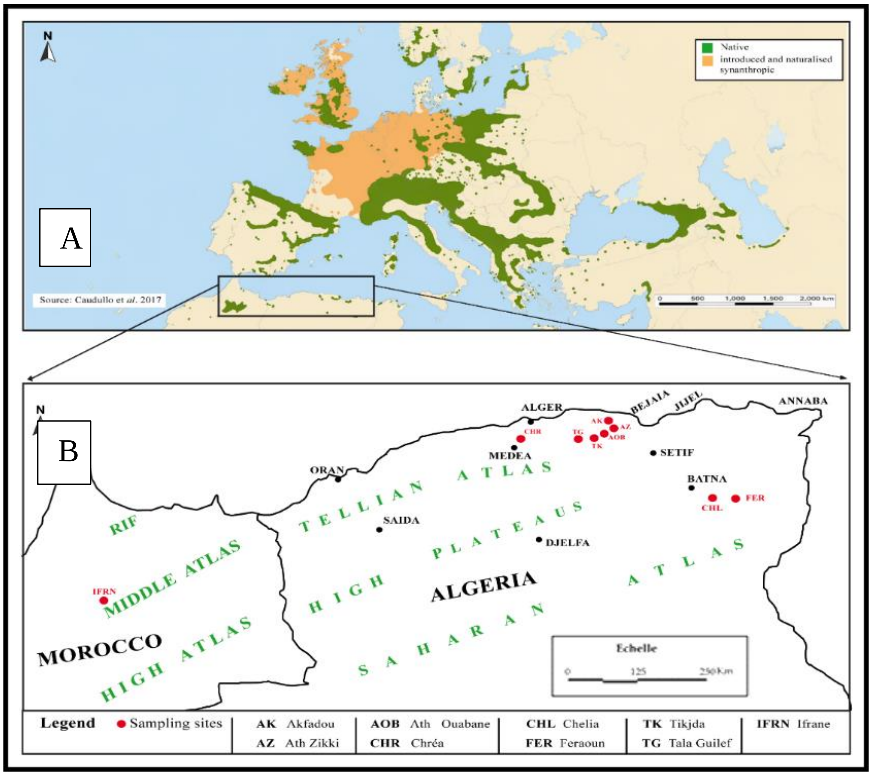


Figure 1. A-Word Geographic distribution of *Taxus baccata* L.,
B-Sampled population in North Africa (red dots).

Table 1. Geographic and ecological characteristics of the studied populations and sample size.

MOUNTAIN RANGE	**TALLIAN ATLAS**						**SAHARAN ATLAS**		**MIDLE ATLAS**
Region	**Djurdjura**				**Akfadou**	**Blidean Atlas**	**Aures**		**Morocco**
Stand name	**Tikjda (TK)**	**AthOuabane (AOB)**	**Tala Guilef (TG)**	**Ath Zikki (AZ)**	**Akfadou (AK)**	**Chrea (CHR)**	**Dj. chelia (CHL)**	**Dj. feraoun (FER)**	**Ifrane (IFR)**
Longitude	4.1263E	4.2925E	4.0007E	4.5088E	4.5739E	2.7211E	6.5647E	7.0957E	5.0972W
Latitude	36.4472N	36.4705N	36.4738N	36.5544N	36.6641N	36.3948N	35.3875N	35.3517N	33.5550N
Elevation (m)	1450	1000-1600	1300-2500	1500-1600	1130-1300	1300-1450	1983-2095	1830-1916	1400 -2080
Orientation	NW	N	N	N	N	NW	N and NW	NE	N
Slope	Low	Medum to High	High	High	Low	Low to medium	Medium to hiegh	Medium to hiegh	Medium to hiegh
Substrate	Calcareous	Calcareous	Calcareous	Calcareous	Numidian sandstone	Schist	White sandstone	Calcareous and stone	Calcareous
T (°c)	14,66	11,2	13,18	14,67	12,62	16,73	14,25	10,88	11
P (mm)	899,8	1169	939,4	900,15	987,01	676,92	363,58	483,6	647
Bioclimate	Humid	Humid	Humid	Humid	Subhumid to humid	Humid	Semiarid to subhumid	Semiarid to subhumid	Humid
Type of vegetation cover	*Cedrus atlantica, Quercus rotundifolia*	*Cedrus atlantica, Quercus rotundifolia*	*Cedrus atlantica, Quercus rotundifolia*	Remnant *Quercus rotundifolia*	*Quercus canariensis*	*Cedrus atlantica, Quercus rotundifolia*	*Cedrus atlantica*	*Cedrus atlantica*	*Cedrus atlantica*
Canopy %	60	60	70	10	80	90	65	50	
Sampled trees	8	14	13	3	10	11	10	10	10
Sampled leaves	240	560	390	90	300	330	300	300	300

Leaf morphology

Biological material was collected from adult *Taxus baccata* L. individuals, in total, 89 Taxus baccata trees were sampled, and leaves were collected from the mid-crown. for each tree, 30 to 40 undamaged leaves aged 2–3 years were collected and stored at 4 °C until measurement. Preliminary analyses were performed to test for potential variation among leaf orientations within individual trees (north, south, east, and west). As no significant differences were detected, leaf orientation was excluded from subsequent analyses in agreement with (Hamidouche et *al.,* 2014). The focus was placed on the accessible and sunny part of the crown. In total of 2810 leaves were collected, pressed and scanned with the abaxial surface facing upward using an Epson GT-15000 scanner at a resolution of 300 dpi. Size and shape were measured on image analysis using Digimizer 3.0 software. Five quantitative traits were measured (leaf area, leaf length, leaf width, petiole length, and apex length) and two derived ratios were calculated (leaf length/leaf width and leaf length/petiole length). The shape was further characterized using qualitative traits namely leaf curvature, leaf base, apex shape, and leaf apex (Fig. 2). These characters were assessed according to the previously published methodologies (Möller *et al.*, 2007; Shah *et al.,* 2008; Vessella *et al.,* 2010).

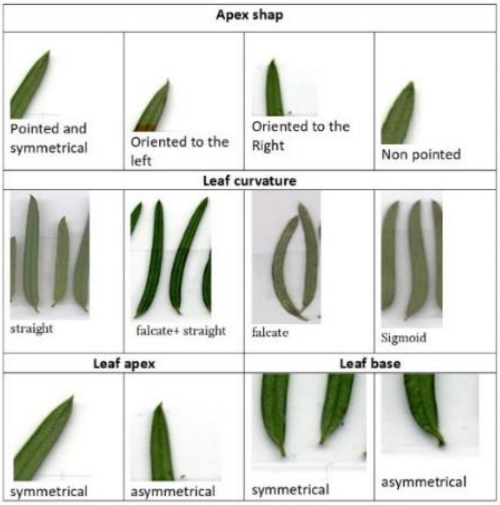


Figure 2. Assessment of qualitative traits of *Taxus baccata* L. leaves

Statistical analyses

Statistical analyses were carried out using **R** (version 4.0.3) and Excel software. The first step involved calculating descriptive statistics for each site. These statistics included the mean, the coefficient of variation and the range (from minimum to maximum).

To determine the differences between qualitative trait categories among populations, contingency tables were used. For each character a Pearson's Chi-square test (χ^2) of independence was performed

To explore the data structure, box plots were used to visualize the distribution of the measured variables.

To assess the variability between populations and among trees within the same population, across region as well as among Mountain ranges, analysis of variance (ANOVA) as normality of data and homogeneity of variances were confirmed, and Fisher's LSD post hoc test ($p< 0.05$) were performed separately for each level. Then a principal component analysis (PCA) was carried out to confirm patterns of similarity among yew populations and identify the main ecological and morphological factors likely to contribute to the convergence or divergence of populations, regions and mountain ranges.

To summarize the overall similarity among populations, Hierarchical clustering was used. For quantitative traits, based on standardized mean values, whereas qualitative variables clustering was applied to the frequency profiles of trait modalities observed withing each population, this approach provided a synthetic visualization of population affinities and completed the inferential analyses performed on individual traits

Results

Leaf shape variation

Analysis of qualitative traits related to Leaf shape variation revealed significant geographic diferences (χ^2 test, $p < 0.001$) for three traits (leaf curvature, leaf apex, and apex shape), wheras leaf base appeared relatively stable across populations (Tab. 2).

At population level, data reveal that sigmoid curvature was the rarest modality, whereas, the proportion of straight leaves ranged from 46.67% and 68.33%. The symmetrical apex was represented at rates above 58% among 05 populations. However, Tikjda and Akfadou populations were distinguished by a more balanced frequency between the two modalities. Furthermore, the apex shape indicated predominance of leaves with pointed and symmetrical apices in eight of the nine studied populations whereas, Ath Ouabane population displayed equal proportions of pointed, symmetrical apices and non-pointed apices (Tab. 2).

Table 2. Frequencies of qualitative variables of *Taxus baccata* and Khi2 test results per variable.Leaf curvature: straight (St); falcate to straight (FSt),falcate (F), sigmoid (Sg); Apex shape : symmetrical (Sy), symmetrical (Asy); leaf base: symmetrical (Sy); Asymmetrical (Asy) and leaf shape: pointed and symmetrical (PS), pointed and oriented to the left(PL), pointed and oriented to the right(PR) and non- pointed(NP). population abbreviations follow Table 1.

Population	AK	AZ	CHR	TK	TG	AOB	CHL	FER	IFR
Leaf Curvature % **(X^2_{obs} = 244,7; X^2 th = 51,18; α =1‰)**									
St	52,33	46,67	57,88	47,08	57,18	59,11	50,00	55,67	68,33
FSt	16,00	13,33	15,15	13,33	17,18	22,86	34,00	27,33	25,00
F	18,67	40,00	24,24	29,58	18,21	11,07	14,67	14,00	5,33
Sg	13,00	0,00	2,73	10,00	7,44	6,96	1,33	3,00	1,33
Leaf base % **(X^2_{obs} = 31,15; X^2 th = 51,18; α =1‰)**									
SY	30,67	46,67	32,12	34,58	35,64	37,50	41,67	39,33	25,33
SY	69,33	53,33	67,88	65,42	64,36	62,50	58,33	60,67	74,67
Leaf Apex % **(X^2_{obs} = 401,80; X^2 th = 51,18; α =1‰)**									
sy	40,00	63,33	57,88	49,17	75,13	78,57	90,00	92,33	85,67
Asy	60,00	36,67	42,12	50,83	24,87	21,43	10,00	7,67	14,33
Apex shape % **(X^2_{obs} = 449,36; X^2 th = 51,18; α =1‰)**									
PS	36,00	63,33	58,48	48,33	57,69	39,11	80,67	77,67	80,00
PL	19,33	15,56	14,85	17,50	9,74	12,50	6,00	5,33	12,00
PR	19,66	10,00	4,85	16,25	10,00	8,57	7,33	7,33	7,00
NP	26,00	11,11	21,82	17,92	22,56	39,82	6,00	9,67	1,00

Leaf size variation

The descriptive statistics of *quantitative leaf morphology* revealed variations both among the populations and within populations for the studied traits, highlighting differences among trees, as reflected by ranges between minimum and maximum values (Table 3).

Boxplot showed a clear interpopulation differenceswhile the presence of the Outliers, reflected intrapopulation variability (Fig. 3). within each populations some trees are displayed high values for all the studied traits, whereas others showed consistently lower values, this pattern was observed within all the populations, supporting the significant intra-population variability among in leaf morphology.

The overall leaf area mean registered in our study was 42,54 mm^2. The Chrea population exhibited the largest leaf areas with 90% of needles exceding 50 mm^2, whereas the Saharan Atlas populations displayed the smallest areas, with most leaves measuring less than 40 mm^2 (data non shown). Leaf length varied markedly among populations ranging from a mean of 22.59 mm in FER to 29.0 mm in CHR. In contrast, leaf width was less variable, with an overall mean of 2.15 mm and cv=12,47. Population means ranging from 1.96 mm inTK to 2.39 mm in CHR populations.

The calculated L/W ratio averaged 10.47 and ranged from 9.69 in CHL to 12.19 in CHR sites. the greatest petiole lengths were observed in TG and IFR sites (1.28 mm) and the shortest petioles were recorded in the Saharan Atlas populations (0.97-1mm). The calculated L/Pl ratio averaged 20.37, with the lowest mean in AOB and AZ and the highest in Chrea sites (25.32). Finally, apex length ranged from 0.32 mm in FER to 0.53 mm in AK .

The performed ANOVA analysis revealed highly significant differences across populations for all studied quantitative traits with distinguished homogenous groups according to Fisher s test post hoc (Fig. 4). it appeared that chrea formed the first group for all trait except petiole lenght foe whish Ath Zikki exhibited the highest values and apexe lenght for whish Akadou was ranked first.

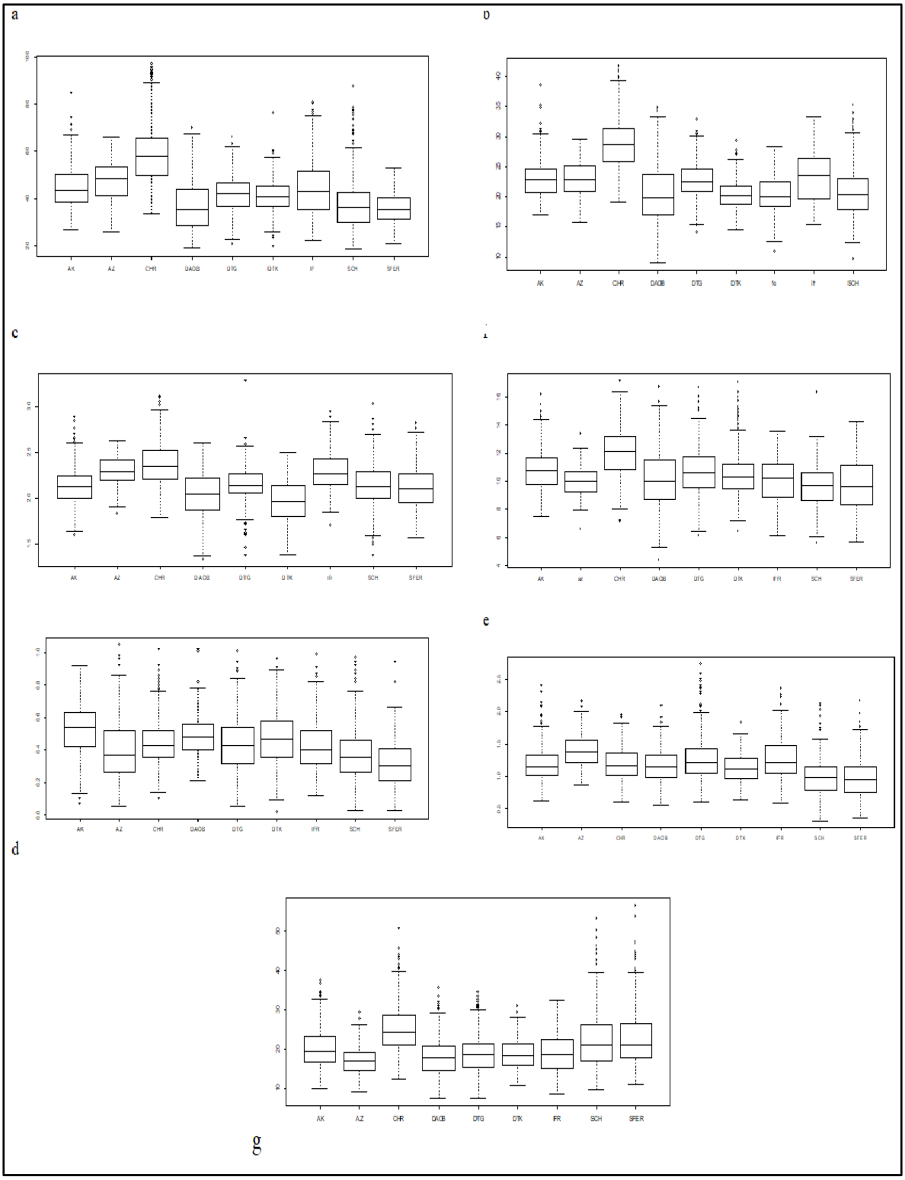
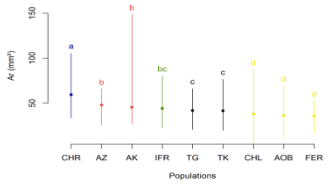
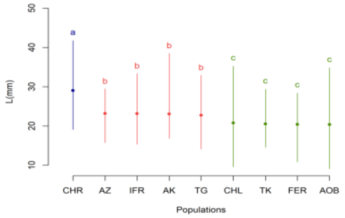


Figure3. Mean and range values distribution of *T. baccata* per site. Morphometric traits -a-leaf area; b-leaf length; c-leaf width; d- petiole length, and e-apex length; calculated ratio: f-leaf length/leaf width (L/W) and g-leaf length/petiole Length, population abbreviations follow Table 1.

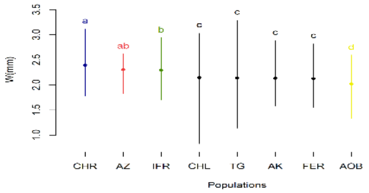
Leaf area



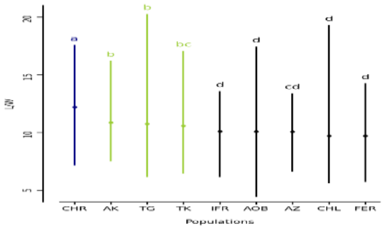
Leaf length



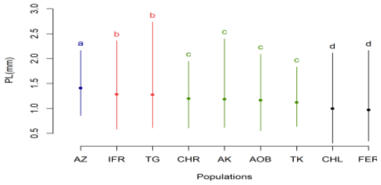
Leaf width



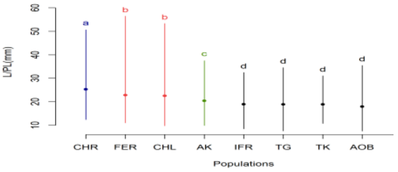
Leaf Length / Leaf Width ratio



Petiole length



Leaf length /Petiole length ratio



Apex length

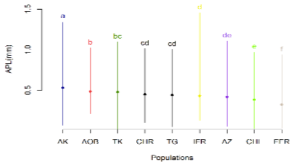


Figure 4. Leaf morphology variation among *Taxus baccata* populations and Fisher's homogeneous groups. Population abbreviations follow Table 1

Table 3. Mean values (mean ± standart errors), homogenous groups according to Fisher's LSD test ($p < 0.05$); -coefficient of variation (cv %) and Minium-Maximun values (Min-Max) of studied *T. baccata* populations population abbreviations follow Table 1.

Mountain range	***Region***	***Population***	***Tree (N)***	***Leaf (N)***	***Statistical parameters***	Leaf area ***(Ar) (mm2)***	Leaf Length ***(L) (mm)***	leaf width ***(W) (mm)***	Leaf Length/ width ***(L /W)***	petiole length ***(Pl) (mm)***	Leaf length /petiole length ***(L/Pl)***	Apex length ***(Apl) (mm)***
Tellian Atlas	**Djurdjura**	**TG**	13	390	mean ± se	41,87±0,60 c	22,74±0,19b	2,14 ±0,01 c	10,75±0,09 b	1,27±0,01 b	18,86±0,28 d	0,44±0,007 cd
					cv	18,71	13,6	10,58	16,66	27,36	24,75	34,62
					Min-Max	20,88-66,13	14,09-32,89	1,14-3,28	6,13-20,26	0,61 -2,73	7,55-34,57	0,05-1,00
		TK	8	240	mean ± se	41,47±0,67c	20,51 ±0,24 c	1,96±0,01 e	10,59±0,12bc	1,12±0,01 c	18,86±0,35 d	0,48 ±0,009 bc
					cv	18,4	12,55	10,95	17,28	19,32	19,69	36,53
					Min-Max	19,66-76,53	14,55-29,33	1,37-2,50	6,46-17,07	0,64-1,83	10,71-31,08	0,02 -1,09
		AOB	14	560	mean ± se	36,25±0,44 **d**	20,36 ±0,16 c	2,02±0,01 d	10,09±0,09d	1,16± c	17,98±0,23 d	0,48 ±0,006 b
					cv	30,61	22,47	11,57	20,06	20,07	25,08	24,4
					Min-Max	10,67 - 69,94	9,10-34,80	1,33-2,59	4,40-17,44	0,55-2,09	7,49 -35,51	0,21-1,02
		AZ	3	90	mean ± se	47,83±1,11 b	23,13±0,4 b	2,3±0,02 ab	10,06±0,12cd	1,41±0,03 a	17,06±0,58 d	0,42±0,016 de
					Cv	17,34	11,97	7,2	11,54	20,34	22,9	52,88
					Min-Max	25,75-66,21	15,74 -29,45	1,83-2,62	6,59 -13,4	0,85 -2,16	8,99 -29,32	0,05-1,11
	A.kfadou	AK	10	300	mean ± se	45,47±0,60 b	23,07±o,21 b	2,13± 0,01 c	10,85 ±0,09b	1,18 ±0,01 c	20,39 ±0,32 c	0,53 ±0,008 a
					Cv	25,32	15,12	10,56	13,72	24,38	24,44	30,04
					Min-Max	26,63-149,04	16,85-38,49	1,58-2,87	7,50 -16,21	0,62-2,39	9,83 -37,48	0,07-1,34
	Chrea	**CHR**	11	330	mean ± se	59,55±0,57 a	29±0,20 a	2,39±0,01 a	12,19±0,01 a	1,19 ±0,01 c	25,32±0,30 a	0,45 ±0,008 cd
					Cv	30,61	22,47	11,57	20,06	20,07	25,08	24,4
					Min-Max	33,71-105,52	19,08-41,70	1,77-3,11	7,15-17,56	0,61-1,94	12,42-50,66	0,11-1,02
Saharan Atlas	**Aures**	**CHL**	10	300	mean ± se	37,8±0,60 d	20,71±0,21 c	2,14 ±0,01 c	9,69±0,09d	1±0,01 d	22,54±0,32 b	0,38 0,008 e
					Cv	31,5	19,33	12,56	16,44	30,52	33,59	42,63
					Min-Max	5,57-87,71	9,60 -35,22	0,83 -3,03	5,59 -19,29	0,31-2,1 2	9,71-53,33	0,3 - 0,96
		FER	10	300	mean ± se	35,96±0,60 b	20,39±0,22 c	2,13 ±0,01c	9,7±0,11 g	0,97±0,01 d	22,8±0,32b	0,32±0,008 f
					Cv	18,37	15,02	10,79	18,76	30,37	32,87	45,14
					Min-Max	16,62-52,84	10,83 -28,36	1,55 -2,81	5,7 -14,25	0,34 -2,17	10,99 -56,48	0,03 -0,94
Middle Atlas	**Ifrane**	**IFR**	10	300	mean ± se	44,13±0,60bc	23,15±0,21b	2,29±0,01 b	10,09±0,09d	1,28±0,01 b	18,92±0,32 d	0,43±0,009 d
					Cv	25,85	17,15	9,65	14,62	24,41	25,79	41,09
					Min Max	22,53-80,98	15,33-33,30	1,69 -2,94	6,1-3,57	0,58-2,36	8,44-32,50	0,1-1,46

The same tendency was observed at regional scale, Chréa region exhibited highest values for leaf area, length, width L/W ratio, and L/Pl ratio, Ifrane showed the heighest petiole lenght followed by Djurdjura. And Akfadou desplayed the first rank for the apex lenght. On another hand Aures populations (CHL and FER) were characterized by the smallest leaf size (Fig. 5).

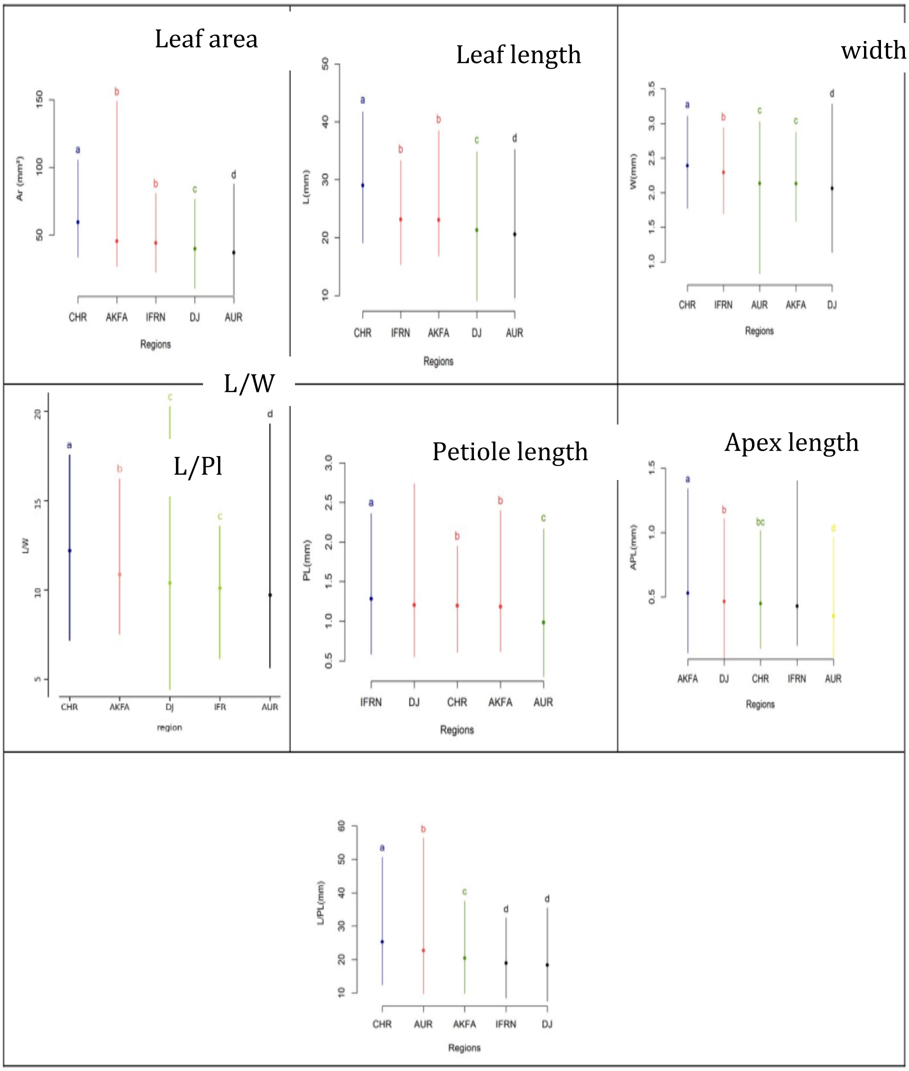


Figure 5. Leaf morphology variation among Taxus *baccata* region and Fisher's homogeneous groups. Population abbreviations follow Table 1

The comparaison of mean values among the three mountaine ranges revealed significant range variation in quantitaive leaf morphological traits. Populations from Tellian Atlas and Middle Atlas formed a homogeneous group for the leaf area and lenght, whereas they differed significatively in leaf width, petiole lenght and the two calculated ratios. By contrast populations from saharan Atlas showed the lowest values for the most traits except the apex lenght for whish the Saharan Atlas was assigned to the higher ranking group (Fig. 6).

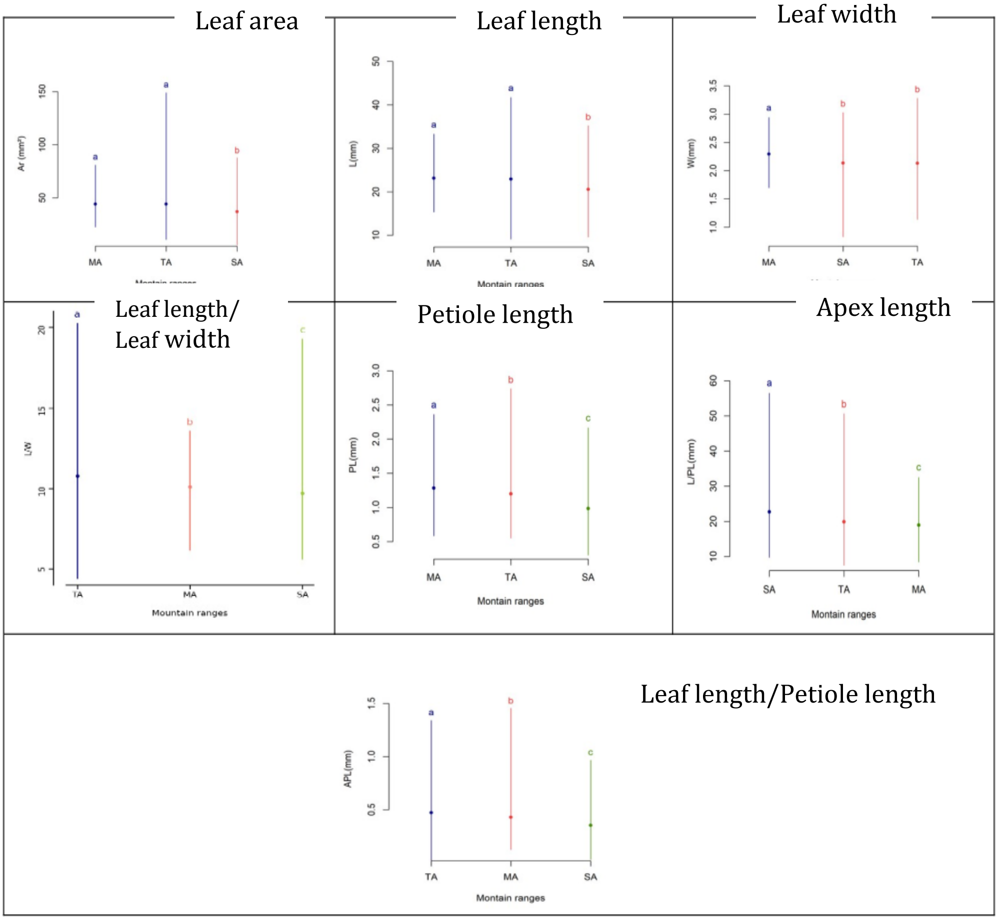


Figure 6. Leaf morphology variation among mountain ranges and Fisher's homogeneous groups.

Principal component analysis (PCA) explained 68.8% of the total variance across the first two axes (dimension 1: 42.7%; dimension 2: 26.1%). The first dimension primarily related to the bioclimate, altitude, and leaf morphological parameters, such as leaf area, leaf length, petiole length, and apex. The second dimension was associated with leaf width, annual precipitation, and leaf length (Fig. 7). The analysis clearly separated the Saharan Atlas populations from those of the Tellian Atlas, while the population of the Middle Atlas occupied an intermediate position. PCA correlation circle showed that latitude was positively associated with annual precipitation and negatively with the altitude.

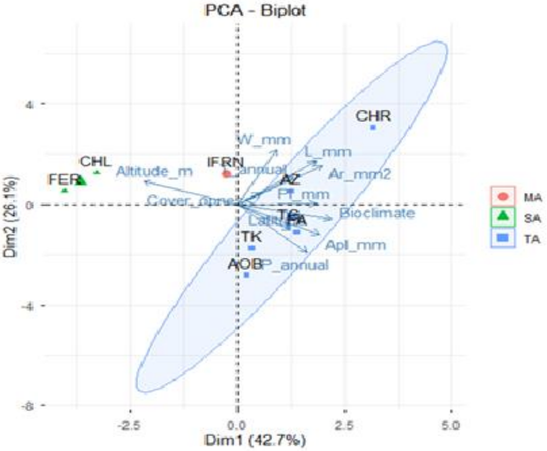
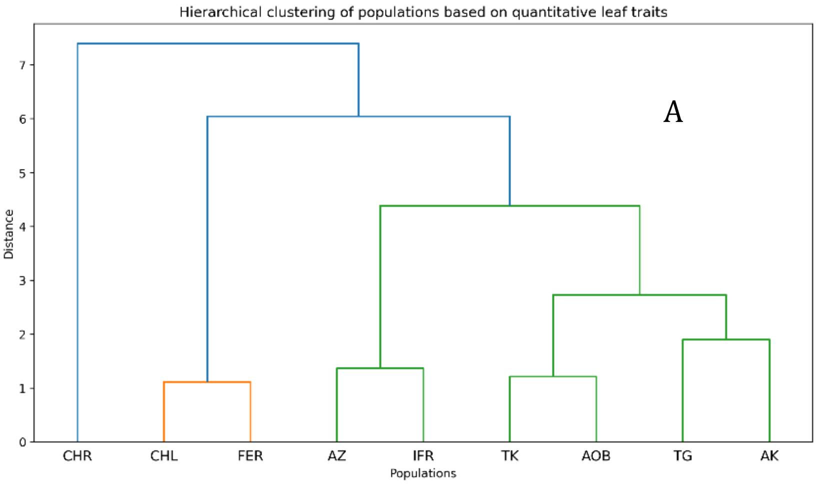


Figure 7. Principal component analysis performed for nine *Taxus baccata* L. populations based on morphometric, geographic and environmental data.

Cluster analysis revealed that North African yew populations were structured into two main groups according to leaf morphology, and corroborate with the results of ANOVA followed by Fisher's test and PCA results. for the quantitative trait and are consistent with the chi square test for the qualitative traits.

Two major groups were defined For quantitative variables. Chrea was the most divergent population being separated from the remaining populations. Within the second group, The Saharan Atlas population were closely associated, while Middle and Tell Atlas populations showed substantial similarity (Fig. 8A).

Also, two distinct groups were illustrated on the qualitative characters. Ifrane from Midlle Atlas clustered with geographically close Saharan Atlas populations, while the Tell Atlas populations showed affinities among themselves as well as AOB with TG, AK with TIK and CHR with AZ (Fig. 8B).



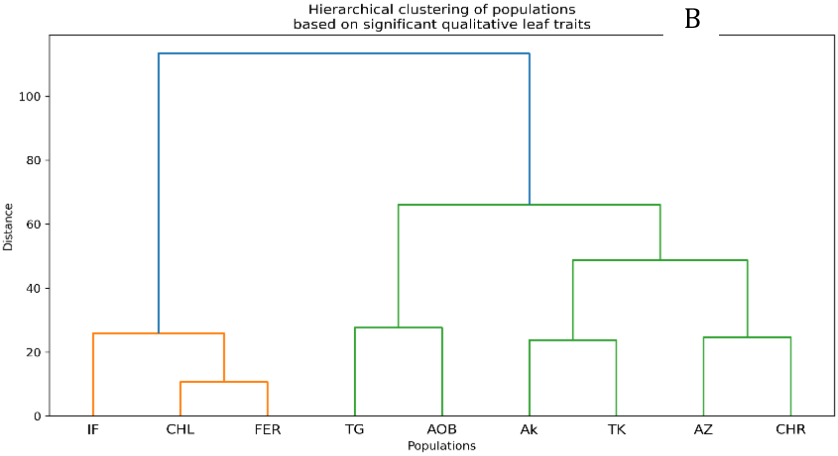


Figure 8. Hierarchical clustering based on leaf morphology characters. A-quantitative traits, B-qualitative traits.

Discussion

This study provides the first broad assessment of leaf morphological variation in *Taxus baccata* L. at its southern margin in North Africa and revealed substantial differentiation at multiple hierarchical levels. variation was recorded among populations, regions and mountain ranges and as well as among individual trees within populations, indicating that leaf morphology in North African yew was structured by both local and broader environmental factors. The relatively low standard errors associated with populations mean, together with wide coefficients of variation, indicated strong variability. Together, these results suggested that the joint influence of environmental heterogeneity and genetic differentiation.contributed to the observed morphological structure

First, an important result is the marked variation observed among individual trees within the same population. Such intra-population variability likely reflected the joint effects of intrinsic individual-tree characteristics, including age (Omarova, 2018), sex (Iszkuło et al, 2009) and vigour, together with local microenvironmental conditions related to topography, soil properties, canopy cover and light availability. Comparable tree level structuring of leaf morphology has been reported in *T. baccata* populations from the Balkans and Dagestan populations (Tumpa *et al*., 2022), in Siberian populations (Stefanovic *et al*., 2017), and in Himalayan *T. fauna* (Li *et al*., 2022), supporting the view that both phenotypic plasticity and genetic differentiation may operate at the tree level. Similar interpretations have also been advanced for other woody taxa, including *Quercus petraea* and Norway spruce, where variation among individuals has been linked to both intrinsic and local environmental conditions (Bruschi *et al.,* 2003; Metslaid et al., 2007 and Kenzo *et al.*, 2006).

At the population and regional scales, leaf morphometric traits clearly discriminated the main biogeographical groups. The Chréa population exhibited the largest leaves whereas populations from the Aurès consistently displayed the smallest one. Djurdjura and Moroccan populations were distinguished by longer petioles, while the Akfadou population showed longer apices. These differences, supported by both ANOVA and PCA analyses, indicated that leaf traits provide effective descriptors of population structure in *Taxus baccata* L. Hirarchical Clustering illustrated populations occurring at comparable environmental or morphological characteristics. More importantly, the multivariate analysis suggested that population differentiation followed an ecological gradient rather than a strictly geographical one. Higher latitude populations tended to occur under wetter climatic conditions, while lower latitude populations were associated with higher altitudes. Saharan Atlas populations were clearly separated from those of the Middle and Tell Atlas, and trait values generally decreased from the more humid northen sites toward the drier Saharan Atlas.

This, suggested that the observed variation among North African yew populations may be driven by local environmental adaptation, particularly water availability, rather than latitude alone.

The ecological contrast among sites helps explain these trends. Chréa appeared to represent the most favorable habitat, owing to its dense vegetation cover as. humid to perhumid bioclimate (Meddour, 2014) and proximity to the Mediterranean Sea, all of which contribute to cool and moist understory conditions suitable for yew persistence and growth. By contrast, the smaller leaves observed in the Aures populations were likely associated with prolonged summer drought (Beghami, 2010), more open canopies, and stronger disturbance due to anthropogenic disturbance, as well as ongoing habitat degradation linked to climatic and global changes (Abdessamed, 1990 Ramo *et al.,* 2017; Sarmoum, 2019). Such conditions increase sun exposure and reduce the maintenance of the humid microclimate required by *Taxus baccata* L., thereby imposing stronger water stress. In this context, reduced leaf size may represent a functional adjustment that limits transpirational water loss and improves drought resistance(Read et al., 2014). Ath Zikki mountain, constutures a particularly informative case:its yew individuals persist in deep, narrow roky fissures, where snow accumulates and humidity is retained over long priods (Maire, 1916 and Hamidouche *et al.* (2014).suggesting that this site functions as a local microrefugium buffering regional climatic stress.

These ecological interpretations are consistent with previous studies that describe leaf area as plastic trait closely linked to light interception and photosynthetic performance. Larger leaves are generally associated with shaded conditions, whereas smaller leaves tend to occur under high irradiance (Mitchell and Arnott, 1995; Perrin *et al.*, 2013 and Kostrakiewicz 2009). In the present study, the largest leaf areas were recorded in Chréa, Ath Zikki, Akfadou and Ifrane, which supported the hypothesis that local ecological conditions strongly influence leaf development. Under Shaded conditions in cedar and oak forests and specific habitat in Ath Zikki where the main ecological requirements for yew persistence are found, larger leaves likely enhance light capture and carbon gain. Conversely, in drier and more open habitats (Chelia and Feraoun), smaller leaves may reduce water loss .and improve stress tolerance.

More broadly, North African populations appear morphologicaly distinctive. Mean leaf area was higher than the values recorded for several Mediterranean and Atlantic European regions including Azores, Carpineto and Rossello, Madeira, Spain and Greece which reported values are 21.3, 33.99, 35.49 and 34.68 mm^2, respectively (Schirone *et al.,* 2010; Vessella et al., 2013), but lower than the values reported in Poland (57.24 mm^2) and in Serbia (47.18 mm^2) by Stefanović *et al.(*2017) and Zarek (2007). Likewise, mean leaf length was close to that reported for Siberian populations and exceeded values previously recorded from some Atlantic and Mediterranean sites. By contrast leaf width in North Africa showed relatively lower values, resulting in a comparetively high leaf length-to-width ratio and indicating that North African yew populations tend to have narrower leaves. The combination of relatively elongated and narrow leaves may represent a characteristic feature of yew at its southern range margin. Petiole length and apex length also emerged as informative traits for regional discrimination suggesting that these components of leaf architecture are especially responsive to environmental gradients. These findings are consistent with those of Roche *et al.,* (2004) and Pasini *et al*. (2006) who showed that some leaf traits are more reliable than others for ranking plant species along an environmental gradient.

The present results support the view that bioclimate and elevation may exert a stronger influence than latitude alone. Although latitude is often invoked to explain large scale trait variation. The North African case shows that local ecological compensation may create suitable conditions for persistence even at the warm and dry southern edge of the *Taxus baccata* range. This interpretation is in line with previous studies showing that leaf traits are often shaped more strongly by local drivers such as moisture, temperature and canopy structure than by broad geographic position (Alcántara *et al*., 2000). Leaf size often decreases with increasing altitude (Thomas and Polwart, 2003; Iszkuło, 2006; Stefanovic *et al.,* 2017)

Qualitative traits provided additional support for strong morphological differentiation. Leaf base shape remained relatively constant among populations, whereas leaf curvature, apex symmetry, and apex shape varied significantly among sites. The predominance of straight leaves with asymmetrical bases broadly agrees with previous descriptions of *T. baccata* needles (Elwes and Henry, 1906, cited in Dempsey and Hook, 2000; and Shah *et al.,* 2008 and Stefanovic *et al*., 2017), although other authors have emphasized falcate or recurved needles in yews (Spjut, 2007). In our material, leaf apices were predominantly pointed and symmetrical. in contrast to Shah et *al.* (2008), who noted an indistinct mucro in *T. baccata*, and to Cope (1998), who reported a short petiole and an acuminate to cuspidate apex, often angled or flattened at the tip. Taken together, this qualitative variation further reinforces the view of high phenotypic plasticity and marked geographic differentiation in *T. baccata* foliage.

Overall, the univariate and multivariate analyses converge on the conclusion that North African populations of *T. baccata* L. exhibit pronounced morphological differentiation, at both intra population and inter population levels. This variability most likely reflects the interaction between local ecological conditions and population differentiation, and it should be explicitly considered in conservation strategies for this relict and threatened conifer.

Conclusion

In this study, we quantified variation in leaf morphology of *Taxus baccata* L. across North African populations, by analysing the size and shape of 2810 leaves among 89 trees, collected from eight populations in Algeria and one in Morocco. Leaf morphometric traits proved to be powerful descriptors, revealing pronounced morphological differentiation at tree, population, region and mountain range scales. Leaf traits effectively discriminated biogeographical groups and showed clear structuring along ecological gradients. The observed variability reflected the combined influence of local ecological conditions (microclimate, canopy structure and topography) and regional to mountain climatic gradients (humidity, drought intensity, elevation and latitude) and likely underlying epigenetic differentiations.

North African *Taxus baccata* L. exhibited distinctive leaf architecture, notably narrow leaves and region -specific petiole and apex morphology. At its southern range margin, yew represents edge populations exposed to warm and frequently dry conditions where favourable local conditions compensate for otherwise limiting macroclimate. These populations therfore represent a key reservoir of morphological and potential genetic diversity. Conservation strategies should therfore adopt a population and region oriented approach, preserving population across the full altitudinal and latitudinal distributions and maintaining the adaptive potential of this relict and threatened conifer under ongoing climatic and anthropogenic pressures.

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