



Production potential and mapping of medicinal and aromatic plants in the Azilal forest (central High Atlas of Morocco)

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Research

Abstract

Background: In Morocco, a Mediterranean biodiversity hotspot, medicinal and aromatic plants (MAPs) play a key socioeconomic and cultural role, particularly in traditional healthcare and rural livelihoods. Yet, increasing anthropogenic and climatic pressures threaten their sustainability, especially in mountainous forest ecosystems where quantitative data on species distribution and productivity remain scarce.

Methods: To address this gap, a phytoecological inventory was conducted in the Azilal forest using a stratified random sampling design across nineteen plots of 400 m² each, along with aboveground phytomass assessment of dominant MAP species to assess floristic diversity and production potential.

Results: A total of 40 MAP species belonging to 22 botanical families were recorded, with Asteraceae, Fabaceae, and Lamiaceae being the most represented. Three distinct floristic facies were identified, reflecting pronounced spatial heterogeneity and areas of ecological fragility. Phytomass estimates showed substantial interspecific variability, with fresh biomass ranging from 66.84 to 998.94 kg·ha⁻¹ and dry biomass from 4.73 to 430 kg·ha⁻¹. High production potential was observed in a limited number of species, notably *Chamaerops humilis* L., *Cistus laurifolius* L., and *Asphodelus ramosus* L., whereas approximately 80% of the recorded species exhibited low cover rate and limited biomass, indicating high vulnerability to disturbance and overharvesting.

Conclusions: This study provides the first quantitative and spatially explicit evaluation of MAPs diversity and productivity in the Azilal forest. The resulting phytomass estimates and ecological facies mapping provide practical tools for identifying high-potential economic zones and prioritizing conservation areas, thereby supporting adaptive management strategies that balance local development and ecosystem preservation.

Keywords: medicinal and aromatic plants (MAPs), Azilal forest, non-timber forest products (NTFP), inventory, biomass production, sustainable management, conservation, Morocco

Background

Forests are among the fundamental pillars of global ecological balance and largely contribute to the socio-economic development of human societies. Covering approximately 31% of the Earth's land surface and housing over 80% of terrestrial biodiversity (FAO & UNEP 2020), forests provide essential ecosystem services for human well-being. Within this biological heritage, medicinal and aromatic plants (MAPs) represent a vital nexus of culture, health, and economy. According to the World Health Organization, between 70% and 95% of citizens in developing countries rely on plant-based traditional medicine for primary healthcare (WHO 2019). Indeed, this massive reliance is not only a cultural heritage; it represents a vital source of health resilience where conventional medicine is physically or financially inaccessible. Similarly, the contribution of MAPs to the modern health system remains irreplaceable. They remain an exceptional reservoir of chemical diversity and are at the basis of many essential modern medicines (Atanasov *et al.* 2015).

In recent decades, the importance of MAPs has expanded far beyond the health sector, positioning them as strategic raw materials within a rapidly growing global bio-economy. MAPs are increasingly used in cosmetics, nutraceuticals, agri-food products, and animal health (Maleš *et al.* 2022, Christaki *et al.* 2012, Godbole *et al.* 2025). This dynamic is further driven by a growing awareness among consumers who favor "natural" products. As a result, the global market of MAPs and their extracts continue to grow rapidly, which was estimated at USD 443.5 billion in 2025 and could nearly double to USD 966.5 billion by 2035, with a compound annual growth rate of approximately 8.1% (Anonymous 2025). MAPs are therefore no longer just local remedies, but global strategic raw materials on which complex value chains depend.

Morocco, thanks to its exceptional geographical and ecological diversity, stands as a major player in the global market of MAPs. Extending from coastal zones to the Rif and Atlas Mountains, and from arid steppes to Saharan regions, the country encompasses a wide range of bioclimatic zones. This diversity has fostered the development of a remarkably rich flora, making Morocco the second most floristically diverse country in the Mediterranean region and the richest in North Africa. With more than 6,552 plant species, approximately 800 of which have recognized medicinal and/or aromatic properties, Morocco ranks as the world's seventh-largest exporter of MAPs (Rankou *et al.* 2013; Fennane *et al.* 2015; Fennane & Rejdali 2016; ANPMA 2025). The MAPs sector is vital for the national economy, with export turnover estimated at around 465 million dirhams, demonstrating the strategic importance of this sector for the national economy and for the livelihoods of rural populations (Jamaledine *et al.* 2025, Jamaledine *et al.* 2017).

Despite its economic and cultural importance, the Moroccan MAPs sector faces increasing challenges linked to unsustainable harvesting practices, weak regulation, and limited domestication of wild species. Indeed, in Morocco, more than 90% of national MAPs production is based on the harvesting of spontaneous species mainly from forests (Ajebli & Eddouks 2023). Several studies have highlighted the overexploitation of emblematic species, often driven by informal collection and rising international demand, leading to population decline and habitat degradation (Teixidor-Toneu *et al.* 2021; Jamaledine *et al.* 2017). This high harvesting pressure, combined with other anthropogenic factors such as overgrazing and land clearing for agriculture, poses a serious threat to ecosystem sustainability and to the MAPs sector itself. These pressures are exacerbated by climate change, which is already altering temperature and precipitation regimes in Morocco, particularly in mountain regions, thereby affecting species distribution and productivity, and potentially altering the chemical composition of MAPs (Moukrim *et al.* 2020; Laftouhi *et al.* 2023).

The Central High Atlas, and particularly the province of Azilal, constitutes one of the most emblematic regions where ecological, socio-economic, and cultural dynamics surrounding medicinal and aromatic plants intersect. Characterized by rugged relief, strong altitudinal gradients, and a predominantly rural population, the forest landscapes of Azilal harbor a remarkable diversity of plant assemblages, including numerous medicinal and aromatic species, many of which exhibit a high degree of endemism as a result of long-term ecological isolation and environmental heterogeneity (Emberger 1939; Moujane *et al.* 2022). In this mountainous context, MAPs play a crucial socio-economic role by providing seasonal and complementary income, supporting traditional healthcare systems, and strengthening household resilience in areas where economic alternatives are limited.

Furthermore, MAPs are deeply embedded in local cultural heritage. Indeed, rural communities in Azilal have preserved rich ethnobotanical knowledge related to the use of plants for medicinal treatments, culinary enhancement, and food preservation (Ez Zoubi *et al.* 2022; Moujane *et al.* 2022). This ancestral knowledge, transmitted across generations, constitutes a cornerstone of local identity and social cohesion and contributes significantly to community empowerment, particularly for women, who are often central actors in the collection, processing, and valorization of MAPs resources (Achbah *et al.* 2025). However, despite their ecological and socio-economic importance, MAPs in the Azilal forest are

increasingly threatened by multiple anthropogenic pressures, including overgrazing, unsustainable fuelwood extraction, land-use change, and the rapid expansion of tourism infrastructure. These pressures, compounded by recurrent droughts and increasing climate variability, seriously compromise the regeneration capacity and long-term sustainability of MAP resources in the region.

Although the heritage value and local uses of MAPs are well documented in the region, there remains a critical knowledge gap regarding the actual production potential and spatial distribution of these resources. The rugged topography of the Central High Atlas and the difficult accessibility of forest areas have so far hampered the collection of reliable quantitative data, creating a gap between ethnobotanical knowledge and an objective assessment of the state of MAPs resources (Belhaj *et al.* 2020). Yet, such information is essential in a context where the socio-economic role of MAPs is increasingly recognized within national development and conservation policies. Thus, bridging this gap is essential for the effective implementation of strategic frameworks such as the “Forêts du Maroc 202-2030” strategy, which aims to promote sustainable forest management, enhance the economic valorization of forest products, and strengthen the resilience of forest ecosystems and rural livelihoods (Naggar 2020).

In this context, the present study, conducted in the Azilal forest, aims to assess the diversity and aboveground phytomass production potential of MAPs, as well as to characterize their spatial distribution within forest ecosystems. We hypothesize that the pronounced ecological heterogeneity of this mountainous region supports a high diversity of MAP species and that their production potential varies substantially according to local environmental conditions. To test this hypothesis, the study pursues three main objectives: (i) to conduct a comprehensive inventory of MAPs species, (ii) to characterize their spatial distribution through the identification of major ecological facies, and (iii) to quantify the aboveground phytomass of the dominant and economically important species. Beyond a purely floristic assessment, this work seeks to generate robust qualitative and quantitative data capable of informing evidence-based strategies for the sustainable management and valorization of MAPs resources. A rigorous methodological framework was adopted, combining phytoecological surveys, spatial mapping of MAPs distribution, and quantitative estimation of aboveground phytomass. Through this work, we aim to fill a lack of updated scientific information on the production potential of MAPs in this area, a prerequisite for the development of integrated management policies that reconcile biodiversity conservation with the improvement of rural livelihoods.

Materials and Methods

Study area

The Azilal Forest is located in the humid western sector of the Central High Atlas range and forms part of the Atlantic (oceanic) ridge. It extends around the urban center of Azilal within an approximate radius of 20 km and covers a total area of nearly 12,779 ha (ANEF 2017). Owing to the combined influence of climatic gradients, complex relief, soil heterogeneity, and long-standing anthropozoogenic pressures, this forest landscape hosts a remarkable diversity of thermophilic species, giving rise to emblematic forest and pre-forest ecosystems characteristic of the Central High Atlas. Despite its notable floristic richness, the Azilal Forest is not formally designated as a protected area, which increases its vulnerability to the intensification of human activities.

The region is characterized by a Mediterranean climate with semi-arid to subhumid bioclimatic conditions, marked by cold winters and short summers. Mean annual precipitation ranges between 490 and 515 mm, while average annual temperatures vary from 13.9 °C to 17.7 °C (ANEF 2017). From a socio-economic perspective, agriculture and livestock rearing constitute the backbone of the rural economy. These activities are predominantly traditional in nature, relying on extensive livestock systems and low-input farming practices, which place forest resources at the center of local livelihood strategies by providing grazing areas, fuelwood, and non-wood forest products.

Topographically, the forest is characterized by a rugged terrain at mid- to high-elevations (Figure 2), with more than 54% of the area exhibiting slopes steeper than 30%, locally reaching up to 60%. The predominant slope exposures are oriented toward the north, west, northwest, and northeast, and the steep gradients strongly promote erosion processes. Soils are generally shallow and highly eroded, particularly on the southern and eastern slopes, and develop over a variety of parent materials, including marl, marly-limestone formations, clays, limestone, as well as red and siliceous sandstones (ANEF 2017).

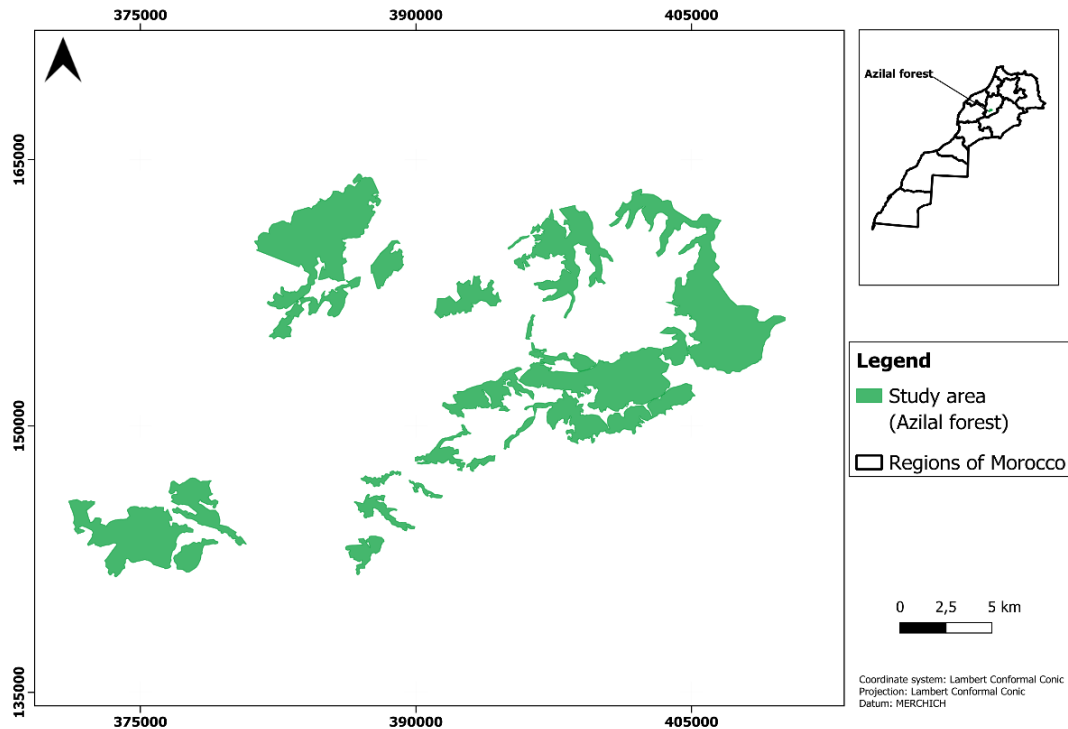


Figure 1. Map of the geographical location of the Azilal forest

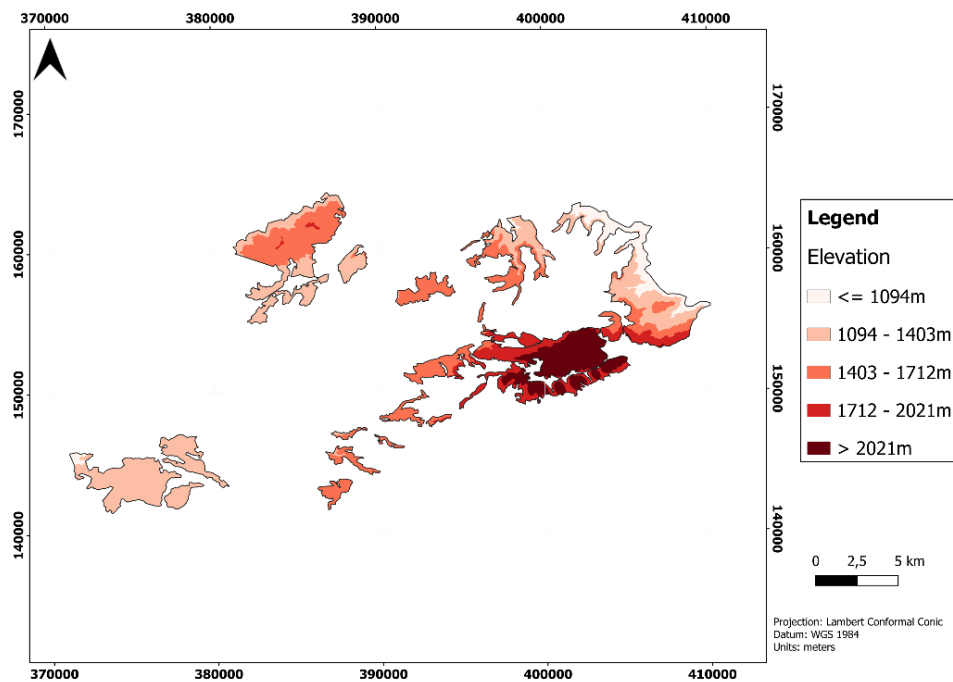


Figure 2. Elevation map of the study area

Sampling protocol

To assess the diversity and spatial distribution of medicinal and aromatic plant (MAP) species in the forest, a phytocological approach was adopted, combining field surveys, quantitative and qualitative analyses, and spatial mapping. To account for environmental heterogeneity, the study area was subdivided into relatively homogeneous forest strata based on the forest management plan (ANEF 2017). Owing to accessibility constraints and logistical limitations, full coverage of the forest was not feasible. Within the selected strata, a stratified random sampling design was implemented. A total of 19 plots (20 × 20 m) were established across the study area (Figure 3). Plot locations were randomly selected within each stratum, but only in areas where the herbaceous layer was present at the time of sampling. This criterion was necessary due to the timing of

fieldwork during a low-precipitation period, combined with strong anthropogenic pressure and complex topography, which resulted in a discontinuous and spatially heterogeneous distribution of the herbaceous layer.

As a consequence, the number of plots per stratum varied according to ecological constraints affecting species availability and detectability. This resulted in seven plots in the *Quercus rotundifolia* Lam. stratum, five plots in the *Juniperus oxycedrus* L. stratum, five plots in the coniferous reforestation stratum dominated by *Pinus halepensis* Mill., and two plots in the shrubland stratum. Figure 3 illustrates the spatial distribution of sampling plots among forest strata within the nine surveyed cantons.

Data collection and biomass estimation

Within each sampling plot, site characteristics including geographic coordinates, elevation, aspect, and slope were recorded. All plant species present were then inventoried, and their cover rate (the proportion of ground surface occupied by each species) were estimated using the Braun-Blanquet abundance-dominance scale (Braun-Blanquet, 1964). Above-ground phytomass was assessed using the reference unit technique. Within each plot, phytomass sampling was conducted at the species level. For each species exhibiting sufficiently developed and measurable aboveground phytomass, a 1 × 1 m subplot was established and all aboveground material was harvested and weighed fresh in the field. Species with very low biomass were recorded for presence-absence only and were not collected for biomass estimation, as harvesting would not have yielded reliable measurements.

As a result, the number of subplots per species and per plot varied depending on species occurrence and biomass availability. Overall, only ten species met the criteria for phytomass quantification, resulting in a total of 27 subplots distributed as follows: *Teucrium polium* L. (4), *Cistus laurifolius* L. (4), *Asphodelus ramosus* L. (5), *Thymus vulgaris* L. (3), *Urginia maritima* (L.) Stearn (2), *Beta vulgaris* L. (1), *Plantago afra* L. (1), *Scolymus hispanicus* L. (1), *Alyssum alyssoides* (L.) L. (1), and *Chamaerops humilis* L. (5). Fresh-to-dry biomass conversion factors were calculated separately for each species by oven-drying representative subsamples to constant weight, thereby accounting for interspecific differences in water content. Subplot-level phytomass values (kg m^{-2}) were subsequently extrapolated to a hectare basis (kg ha^{-1}) by multiplying by 10,000.

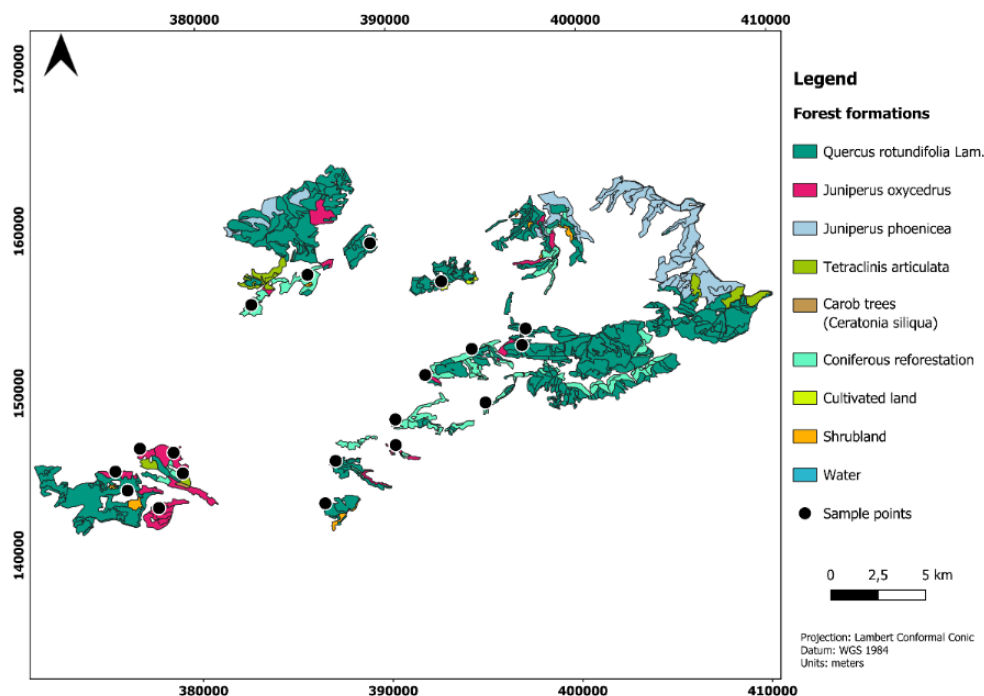


Figure 3. Distribution of sampling plots between the different strata

Data Analysis

Species identification and classification of MAPs into exploitation classes

Plant species were identified using the Practical Flora of Morocco, with taxonomic validation conducted by a specialized botanist. Medicinal and aromatic plant (MAP) species were subsequently extracted from the complete floristic inventory based on specialized bibliographic sources and local ethnobotanical studies.

The assessment of potentially exploitable MAP species was based on predefined exploitability thresholds, considering the relative importance of each species' cover rate. This classification approach is consistent with national-scale studies. As reported by the Agence pour la Promotion et le Développement du Nord (APDN 2010), MAP species' cover rates are a key criterion for evaluating their exploitation potential. Accordingly, species exhibiting cover rates greater than 50% were considered to have a high exploitation potential, whereas species with lower cover rates were classified as having limited or moderate potential. Based on these criteria, two exploitation classes were distinguished:

Class 1: Significant exploitation potential, corresponding to species with a cover rate > 50%, considered potentially valuable.
Class 2: Moderate exploitation potential, corresponding to species with a cover rate < 50%, considered priorities for conservation.

Identification of MAPs floristic facies and diversity patterns

To identify and map floristic facies dominated by medicinal and aromatic plants (MAPs), a combination of multivariate, diversity, and spatial analyses was conducted. For facies identification, the floristic data were organized into a plots × species matrix, where abundance-dominance indexes of every species were converted into the percentage of coverage following (Canullo *et al.* 2012). Hierarchical clustering was then performed using the Bray-Curtis dissimilarity index and Ward's agglomeration method, as implemented in the vegan package in R, in order to delineate distinct MAPs facies.

To characterize and compare diversity patterns among plots and facies, several diversity metrics, including species richness, Shannon diversity index, and Pielou's evenness, were calculated. Differences in species composition among facies (beta diversity) were assessed using Bray-Curtis dissimilarity. Statistical differences in community composition were tested using a permutational multivariate analysis of variance (PERMANOVA) with the *adonis2* function in *vegan*, treating facies as a categorical factor. To account for potential differences in within-facies variability, the homogeneity of multivariate dispersions was evaluated using the *betadisper* function, and statistical significance was assessed through ANOVA. This procedure allowed discrimination between true compositional differences and effects driven by unequal dispersion among facies. The Bray-Curtis index was selected because of its suitability for species cover data, as it incorporates differences in relative abundances while excluding joint absences, thereby providing ecologically meaningful dissimilarity estimates (Bray & Curtis 1957). All statistical analyses were conducted in R version 4.5.0 (2025-04-11 ucrt). The resulting facies classification was subsequently integrated into ArcGIS to produce a spatial map of MAPs facies based on the distribution of plots among identified clusters. This spatialization enabled the delineation of representative floristic facies and supported ecological interpretation.

Ultimately, in this study, MAPs facies are defined as continuous or discontinuous vegetation units exhibiting relatively homogeneous characteristics in terms of species composition, spatial distribution, and ecological importance. Facies classification was based on two main criteria: species composition and cover (abundance-dominance index). Species composition reflects the floristic assemblage defining each facies, whereas cover provides an estimate of production potential and ecological dominance.

Results

Identified Medicinal and Aromatic Plant Species in the Azilal Forest

Our Phytoecological surveys conducted across 19 plots (20 m × 20 m) distributed among nine cantons of the Azilal forest resulted in the identification of 40 medicinal and aromatic plant (MAP) species belonging to 22 botanical families (Table 1). This level of taxonomic richness highlights the considerable ecological potential of the study area. Nevertheless, it is important to note that the survey didn't cover the entire forest, which could lead to an underestimation of the true potential of MAPs. Among the recorded families, Asteraceae was the most represented, with seven species, followed by Fabaceae (five species) and Lamiaceae (three species). Several families, namely Brassicaceae, Plantaginaceae, Cistaceae, Geraniaceae, Euphorbiaceae, and Asparagaceae, were each represented by two species, while the remaining families were represented by a single species (Table 1). All 40 recorded species are used for medicinal purposes, and eight also possess aromatic uses, as detailed in Table 1.

Identified MAPs floristic facies

The hierarchical cluster analysis based on Bray-Curtis dissimilarity confirmed a clear compositional separation between the plots and allowed us to identify three main facies (Figure 4). Facies 2 appeared as the most distinct community, branching off at the highest level of dissimilarity, while Facies 1 and 3 showed a closer relationship but remained as two independent

clusters. These results imply that each facies represent a discrete ecological entity, suggesting the potential variability both in facies composition and MAPs availability within them.

Table 1. List of the main spontaneous MAPs identified in the Azilal forest.

Scientific Name	Vernacular name	Family	Medicinal	Aromatic
<i>Beta vulgaris</i> L.	-	Amaranthaceae	+	+
<i>Pistacia lentiscus</i> L.	drou, fadis, tithakth	Anacardiaceae	+	
<i>Eryngium tricuspdatum</i> L.	kharzizwa, hessika, keff d-dib	Apiaceae	+	
<i>Chamaerops humilis</i> L.	doum, tighazdamte	Arecaceae,	+	
<i>Aristolochia paucinervis</i> Pomel	barreztem	Aristolochiaceae	+	
<i>Dipcadi serotinum</i> (L.) Medik.	-	Asparagaceae	+	
<i>Muscari comosum</i> (L.) Mill.	bsyla	Asparagaceae	+	+
<i>Asphodelus ramosus</i> L.	berwag, ingri, berwiga	Asphodelaceae	+	
<i>Scolymus hispanicus</i> L.	kchach, garnina	Asteraceae	+	+
<i>Micropus supinus</i> L.	-	Asteraceae	+	
<i>Phagnalon saxatile</i> (L.) Cass.	alfaghnaloun	Asteraceae	+	
<i>Hypochaeris glabra</i> L.	-	Asteraceae	+	
<i>Atractylis cancellata</i> L.	najma, asnnan wado	Asteraceae	+	
<i>Anacyclus clavatus</i> (Desf.) Pers.	tagendest	Asteraceae	+	
<i>Echinops spinosissimus</i> Turra	tasekra, taskra	Asteraceae	+	
<i>Alyssum alyssoides</i> (L.) L.	-	Brassicaceae	+	
<i>Diplotaxis sp</i> DC.	l-kerkaz, l-harra, asheryad	Brassicaceae	+	
<i>Arenaria serpyllifolia</i> L.	hdaq n'ghilane	Caryophyllaceae	+	
<i>Cistus laurifolius</i> L.	amziwet	Cistaceae	+	+
<i>Cistus creticus</i> L.	ibourch	Cistaceae	+	
<i>Convolvulus althaeoides</i> L.	aya, tamnaye, mesran eddib, tanesfalt	Convolvulaceae	+	
<i>Euphorbia nicaeensis</i> All.	tezzi urturya, tanagut	Euphorbiaceae	+	
<i>Euphorbia resinifera</i> O.Berg	tikiwt	Euphorbiaceae	+	
<i>Crotalaria uguenensis</i> Taub.	-	Fabaceae	+	
<i>Genista tricuspdata</i> Desf.	-	Fabaceae	+	
<i>Ononis spinosa</i> L.	afezzaz, saboun laâzara	Fabaceae	+	
<i>Vicia benghalensis</i> L.	jelbanet lehnouch	Fabaceae	+	+
<i>Coronilla minima</i> L.	-	Fabaceae	+	
<i>Erodium cicutarium</i> (L.) L'Hér. Ex Aiton	abou machgha, aghanbou	Geraniaceae	+	
<i>Geranium rotundifolium</i> L.	-	Geraniaceae	+	
<i>Teucrium polium</i> L.	jâydiya, jaâda, ayrar	Lamiaceae	+	
<i>Salvia verbenaca</i> L..	khiyyata, keff-jmel	Lamiaceae	+	
<i>Thymus vulgaris</i> L.	meslah l-endar, aberdud yizem	Lamiaceae	+	+
<i>Urginia maritima</i> (L.) Stearn	ansal	Liliaceae	+	
<i>Phillyrea angustifolia</i> L.	metwâl, imtutel, qtom	Oleaceae	+	+
<i>Fumaria parviflora</i> Lam.	dbayba, ijujer, qlila	Papaveraceae	+	
<i>Plantago afra</i> L.	zentet l-khrouf	Plantaginaceae	+	
<i>Veronica arvensis</i> L.	-	Plantaginaceae	+	
<i>Crataegus laciniata</i> Ucria	admam, buzorulu	Rosaceae	+	
<i>Galium lucidum</i> All.	-	Rubiaceae	+	+

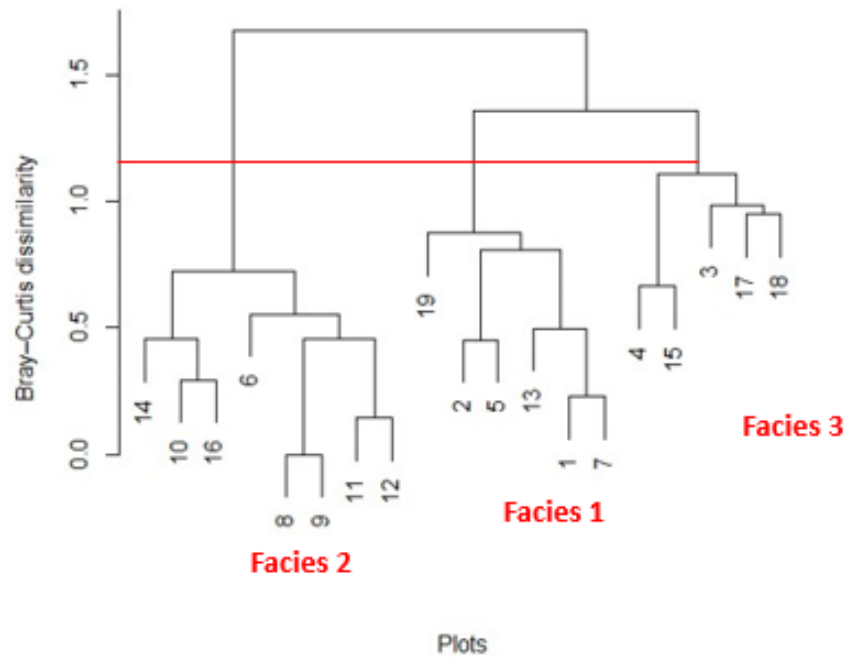


Figure 4. Result of the hierarchical clustering of plots showing three main floristic facies

Species diversity patterns among plots and facies

Species richness and diversity varied markedly among the 19 plots and across facies (Table 2). At the plot level, species richness ranged from 2 to 11 species, with the lowest value observed in Plot 12 and the highest in Plot 19, while most plots exhibited intermediate richness (5-9 species). Shannon diversity index values varied between 0.54 and 2.13, reflecting differences in both species' richness and relative cover distribution, with lower values associated with plots showing strong dominance patterns and higher values corresponding to more diverse and balanced communities. Pielou's evenness ranged from 0.33 to 1.00, indicating contrasting dominance structures among plots, with some low-richness plots exhibiting high evenness, suggesting equitable species cover distribution despite limited species numbers. At the facies level, considering the pooled species composition across plots within each facies, Facies 3 showed the highest species richness ($S = 25$), Shannon diversity ($H' = 2.58$), and evenness ($J = 0.81$), followed by Facies 1 ($S = 23$, $H' = 2.28$, $J = 0.73$), whereas Facies 2 exhibited markedly lower diversity ($S = 15$, $H' = 1.72$) and evenness ($J = 0.63$), indicating a floristic assemblage characterized by reduced richness and stronger dominance effects. Overall, these results highlight pronounced spatial heterogeneity in diversity at both plot and facies scales.

Beta diversity analysis based on Bray-Curtis dissimilarities revealed that the composition of plant communities differed significantly among the three facies (PERMANOVA, $F = 5.44$, $R^2 = 0.41$, $p = 0.001$), indicating that approximately 41% of the total variation in species composition was associated with facies. However, the test for homogeneity of multivariate dispersions showed significant differences in within-facies variability (ANOVA on distances to centroids, $F = 11.26$, $p < 0.001$), suggesting that some of the observed differences among facies may be influenced by unequal dispersions within groups. Consequently, while the results clearly demonstrate that facies have an impact on structuring plant community composition, part of the observed differentiation may also reflect differences in within-facies variability rather than solely shifts in community centroids. These results should thus be interpreted with caution, considering both compositional turnover and dispersion effects. Additional details on the statistical analyses are provided in the Appendix.

Facies characteristics and implications for MAPs production and management

Analysis of facies composition revealed clear differences in diversity, dominant species, and environmental conditions, which have direct implications for MAPs production potential and management. Facies 3, the most diverse, is dominated by *Asphodelus ramosus*, *Chamaerops humilis*, *Anacyclus clavatus* (Desf.) Pers., and *Alyssum alyssoides*. This facies occurs at high elevations (>1400 m) on relatively steep slopes (30-60%), and most plots within it have southeast and southwest exposures. Such environmental conditions likely influence microclimatic conditions, soil moisture, and sunlight availability, favoring the growth of a diverse assemblage of MAPs. Consequently, Facies 3 presents the highest potential for sustainable MAPs harvesting, providing valuable resources for local communities while requiring careful management to prevent erosion, as

this facies may be ecologically fragile. Facies 1, the second most diverse and ecologically similar to Facies 3, is dominated by *Cistus laurifolius*, *Chamaerops humilis*, *Thymus vulgaris* L., and *Euphorbia resinifera* O.Berg. It occurs at moderately high elevations (1200-1500 m) with relatively gentle slopes (10-40%) and predominantly north- and northeast-facing exposures. These conditions support a slightly lower overall diversity than Facies 3, but this facies remains highly valuable due to the presence of species with significant socio-economic importance, including *Thymus vulgaris*, *Euphorbia nicaeensis* All., *Teucrium polium* L., and *Cistus creticus* L. This composition highlights the considerable potential of Facies 1 to provide local communities with important MAP resources. However, given the economic value of these species, sustainable management is essential to prevent overexploitation and ensure the long-term conservation, especially within facies 1.

Table 2. Species diversity metrics across plots and facies.

Plot	Richness	Shannon Index	Pielou's evenness	Facies
Plot 1	10	1.62	0.71	1
Plot 2	4	0.79	0.57	1
Plot 3	5	0.54	0.33	3
Plot 4	8	1.52	0.73	3
Plot 5	3	0.76	0.69	1
Plot 6	4	1.32	0.95	2
Plot 7	7	1.34	0.70	1
Plot 8	9	1.65	0.75	2
Plot 9	9	1.65	0.75	2
Plot 10	5	0.88	0.55	2
Plot 11	5	0.98	0.61	2
Plot 12	2	0.69	1	2
Plot 13	6	1.22	0.68	1
Plot 14	3	0.77	0.70	2
Plot 15	6	1.20	0.66	3
Plot 16	9	1.57	0.71	2
Plot 17	5	1.58	0.98	3
Plot 18	7	1.94	1	3
Plot 19	11	2.13	0.88	1
At Facies level				
Facies	Richness	Shannon Index	Pielou's evenness	
3	25	2.58	0.81	
1	23	2.28	0.72	
2	15	1.71	0.63	

In contrast to the previous two facies, Facies 2 is the least diverse and is dominated by *Pistacia lentiscus* L., *Chamaerops humilis*, *Phillyrea angustifolia* L., and *Asphodelus ramosus*. It occurs at lower elevations (1100-1300 m) with gentle slopes (5-30%). The relatively homogeneous environmental conditions, coupled with the dominance of shrub species, likely limit the availability and diversity of MAPs within this facies, suggesting a lower production potential. The spatial delineation of all facies (Figure 5) highlights areas with high MAPs diversity and production potential, providing a basis for evidence-based management and conservation strategies. Areas of the forest that were not surveyed in this study were classified as undetermined facies, indicating regions that require further field assessment.

Potentially exploitable MAPs and species requiring conservation

Based on species cover rates and availability, they were classified into two main management categories: (i) species with high production potential (cover rate > 50%), considered suitable for sustainable exploitation, and (ii) species with medium to low production potential (cover rate < 50%), for which harvesting should be limited to maintain population viability and preserve floristic diversity (Table 3). Species such as *Cistus laurifolius*, *Chamaerops humilis*, *Asphodelus ramosus*, *Phillyrea angustifolia* L., and *Anacyclus clavatus* (Desf.) Pers., which are characterized by high biomass and cover rates, emerge as priority candidates for regulated harvesting schemes, provided that extraction rates remain below their natural regeneration capacity. In contrast, approximately 80% of the identified species exhibited low cover rates and limited phytomass, requiring targeted conservation measures to prevent population decline and local rarefaction.

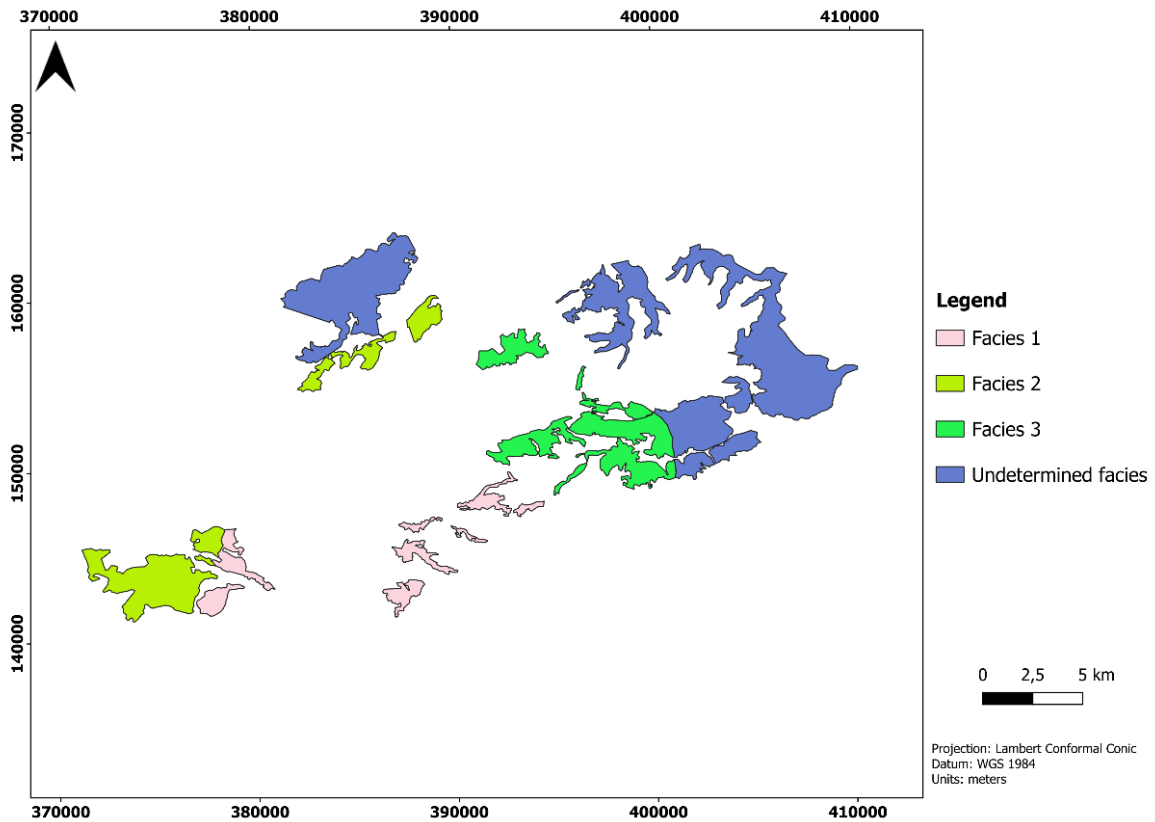


Figure 5. Spatial distribution of MAPs floristic facies in the Azilal forest

Table 3. List of potentially exploitable MAPs and those to be preserved according to their cover rates.

Scientific name	Cover rate (%)	Facies
Potentially valuable		
<i>Euphorbia resinifera</i> O.Berg	75%	2
<i>Cistus laurifolius</i> L.	75%	1 and 3
<i>Asphodelus ramosus</i> L.	75%	1, 2, and 3
<i>Chamaerops humilis</i> L.	75%	1, 2, and 3
<i>Pistacia lentiscus</i> L.	75%	2
<i>Anacyclus clavatus</i> (Desf.) Pers.	50%	3
<i>Crataegus laciniata</i> Ucria	50%	3
<i>Phillyrea angustifolia</i> L.	50%	2
To be conserved		
<i>Scolymus hispanicus</i> L.	25%	2 and 3
<i>Eryngium tricuspdatum</i> L.	25%	1 and 3
<i>Coronilla minima</i> L.	5%	3
<i>Micropus supinus</i> L.	5%	3
<i>Alyssum alyssoides</i> (L.) L.	25%	1, 2, and 3
<i>Plantago afra</i> L.	25%	1 and 3
<i>Convolvulus althaeoides</i> L.	5%	1 and 3
<i>Phagnalon saxatile</i> (L.) Cass.	5%	1, 2, and 3
<i>Hypochaeris glabra</i> L.	5%	1, 2, and 3
<i>Fumaria parviflora</i> Lam	5%	1
<i>Muscari comosum</i> (L.) Mill	5%	1
<i>Salvia verbenaca</i> L.	5%	1
<i>Aristolochia paucinervis</i> Pomel	5%	1
<i>Erodium cicutarium</i> (L.) L'Hér. Ex Aiton	25%	3 and 2
<i>Diploxaxis</i> sp DC.	5%	1, 2, and 3

<i>Urginia maritima</i> (L.) Stearn	5%	3 and 2
<i>Dipcadi serotinum</i> (L.) Medik.	5%	3
<i>Geranium rotundifolium</i> L.	5%	1
<i>Veronica Arvensis</i> L.	5%	3
<i>Cistus creticus</i> L.	25%	1
<i>Atractylis cancellata</i> L.	25%	1 and 3
<i>Crotalaria uguenensis</i> Taub	5%	1
<i>Euphorbia nicaeensis</i> All.	25%	1
<i>Genista ticuspidata</i> Desf.	25%	1
<i>Ononis spinosa</i> L.	25%	1
<i>Echinops spinosissimus</i> Turra	25%	3
<i>Galium lucidum</i> All.	5%	3
<i>Vicia benghalensis</i> L.	5%	3
<i>Arenaria serpyllifolia</i> L.	25%	2
<i>Thymus vulgaris</i> L.	25%	1, 2, and 3
<i>Teucrium polium</i> L.	25%	1 and 2
<i>Beta vulgaris</i> L.	25%	3

Biomass production potential of MAPs

The phytomass assessment included ten dominant MAPs species that, at the time of observation (April 2025), exhibited a measurable aboveground phytomass, allowing for a reliable estimation of their production potential. Figure 6 below illustrates the variation in dry biomass across facies at both community (a) and species (b) levels. At the community level, mean dry biomass shows only modest differences among facies, with values ranging approximately from 65.78 to 78.195 kg·ha⁻¹. Facies 3 exhibits the highest mean dry biomass, followed by facies 1 and facies 2. However, the large standard deviations indicate substantial variability within facies due to high biomass variation among species. At the species level, contrasting response patterns across facies are evident. *Asphodelus ramosus* shows a strong increase in dry biomass from facies 1 (15,78 kg·ha⁻¹) to facies 2 (185,26 kg·ha⁻¹) and facies 3 (238,94 kg·ha⁻¹), indicating a clear variation depending on facies. In contrast, *Chamaerops humilis* displays a marked decrease from facies 1 (198.94 kg·ha⁻¹) to facies 2 (≈ 55 kg·ha⁻¹), followed by a moderate increase in facies 3 (71,05 kg·ha⁻¹). *Cistus laurifolius* maintains relatively stable dry biomass across facies, with values consistently around 160-170 kg·ha⁻¹. The Other species exhibited low dry biomass values (generally < 30 kg·ha⁻¹) across all facies, with only minor variations. Overall, while facies effects on mean dry biomass at the community level are not striking, species-specific responses reveal pronounced and contrasting patterns, highlighting strong variability in species biomass production depending on facies.

At the forest scale, total biomass per species was calculated by aggregating fresh and dry biomass values across all facies. Biomass varied substantially among species, with fresh biomass ranging from 66.84 to 998.94 kg·ha⁻¹ and dry biomass from 4.73 kg·ha⁻¹ to 430 kg·ha⁻¹ (Figure 7). *Chamaerops humilis* exhibited the highest biomass, with 998.94 kg·ha⁻¹ fresh and 325.79 kg·ha⁻¹ dry, accompanied by relatively large standard deviations, reflecting considerable variability across facies. Similarly, *Cistus laurifolius* displayed high biomass (985.26 kg·ha⁻¹ fresh; 328.94 kg·ha⁻¹ dry), though with lower variability compared to *C. humilis*. *Asphodelus ramosus* also contributed substantially, with 760.52 kg·ha⁻¹ fresh biomass and the highest dry biomass (430 kg·ha⁻¹) but showed one of the largest standard deviations among species, indicating strong heterogeneity in biomass distribution across facies. The high dry matter yields of these species reflect both their structural dominance and their high potential for sustainable utilization, provided appropriate harvesting guidelines are implemented.

In contrast, species such as *Urginea maritima*, *Scolymus hispanicus*, *Beta vulgaris*, and *Plantago afra* consistently exhibited low biomass, with fresh biomass <105 kg·ha⁻¹ and dry biomass <30 kg·ha⁻¹, highlighting limited production potential and high vulnerability to overharvesting. Overall, these results demonstrate pronounced interspecific differences in biomass accumulation, with a few dominant species accounting for the majority of total biomass. These quantitative estimates provide an essential foundation for defining preliminary harvesting thresholds, enabling species to be prioritized for either regulated exploitation or conservation-focused management.

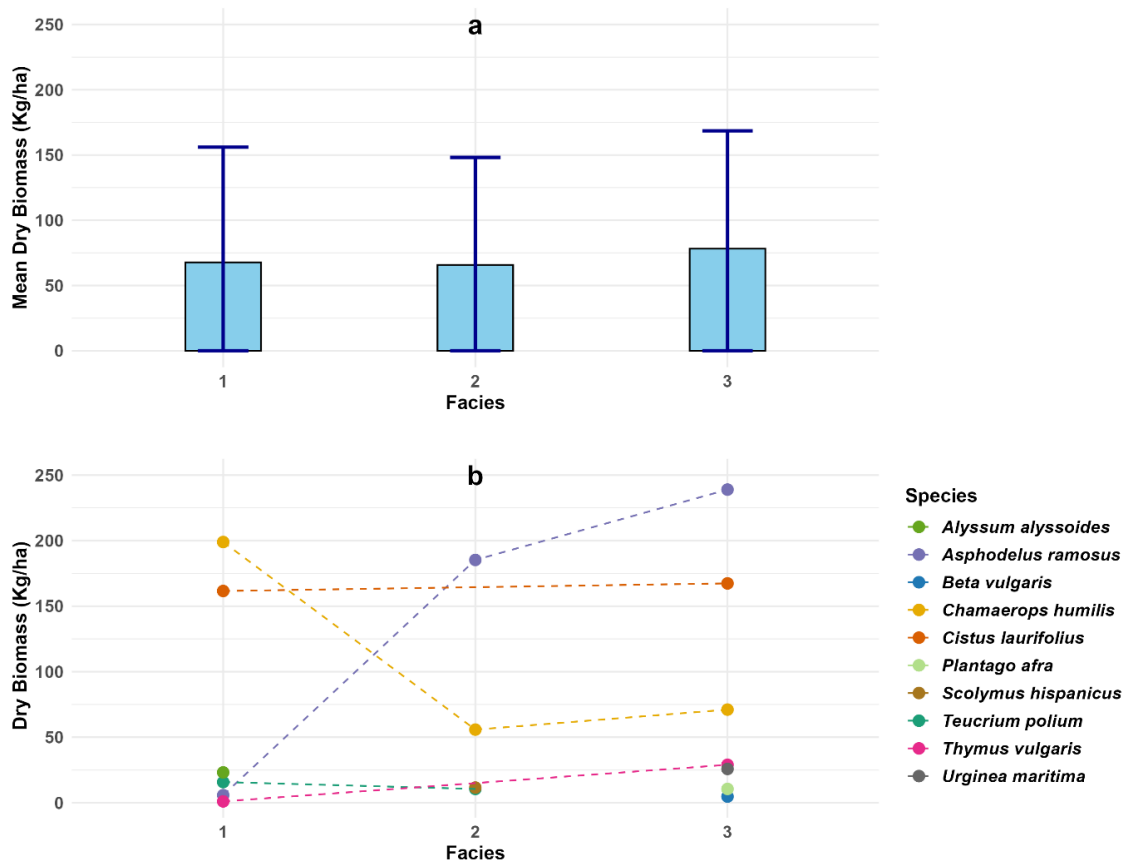


Figure 6. Dry Biomass variation across facies at both community (a) and species (b) levels for the measured species

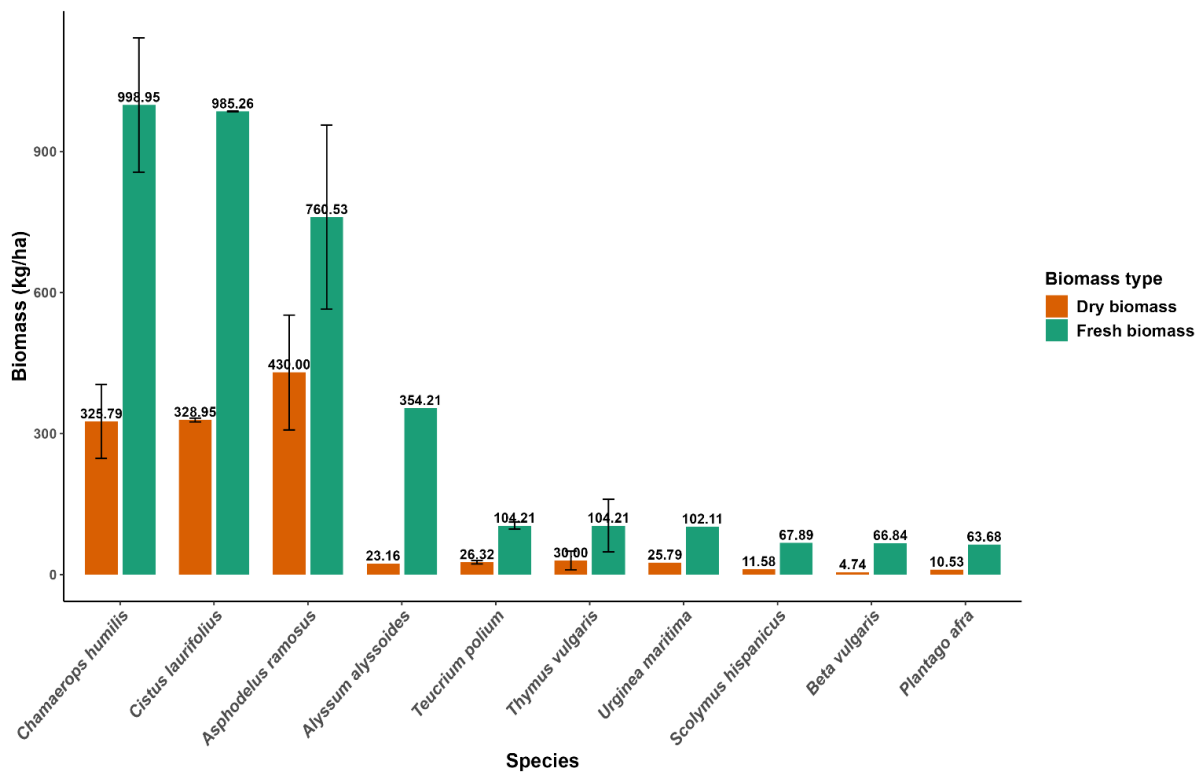


Figure 7. Total biomass estimates for the measured MAPs species

Discussion

Diversity of MAPs in the Azilal forest

Our floristic inventory has identified 40 species of MAPs, representing 22 botanical families. Among these, Asteraceae, Fabaceae, and Lamiaceae were the most dominant, confirming their structuring role in the Moroccan flora and their importance in terms of therapeutic and socioeconomic uses. This finding aligns with other previous ethnobotanical studies in Morocco, which reported a strong representation of these three botanical families within medicinal and aromatic floras (Bellakhdar 1997; El Alami & Chait 2017; Belhaj *et al.* 2020; Moujane *et al.* 2022). The observed diversity in terms of MAPs can be attributed to the ecological heterogeneity of the study area, characterized by high altitudinal variability and diverse microclimates. These factors favor the coexistence of diverse species and may explain the dominance of certain families well adapted to semi-arid Mediterranean conditions. Furthermore, the significant compositional differences among facies further confirm that MAP diversity in the Azilal forest is strongly structured by ecological facies, a pattern already documented in Morocco along altitudinal and ecological gradients (Benabid & Fennane 1994).

Beyond the ecological dimension, MAPs play a crucial role in the daily lives of local populations. They constitute a source of additional income and make a major contribution to local livelihood, through the commercialization of dried or processed plants, while ensuring direct access to primary healthcare. Indeed, several studies have demonstrated the importance of MAPs for rural communities (El Azzouzi and Zidane 2015, Jamaledine *et al.* 2017; Naggar & Iharchine 2016), but, unlike purely ethnobotanical works, the present study provides a quantitative dimension by evaluating both floristic diversity and MAPs phytomass production. Thus, the identified MAPs diversity confirms that the Azilal forest is not only an ecological reservoir, but also a strategic resource for local socio-economic development.

Phytomass production and Spatial distribution of MAPs

The quantitative assessment of phytomass provides valuable insights into the relative production potential of some key MAP species. The strong interspecific variability observed in both total fresh mass (TFM) and total dry mass (TDM) reflects the pronounced ecological heterogeneity of the Central High Atlas, demonstrating how microclimatic gradients, edaphic constraints, and disturbance regimes strongly shape plant growth and regeneration capacity (Emberger 1939; Benabid 2000). Species such as *Cistus laurifolius*, *Chamaerops humilis*, and *Asphodelus ramosus* displayed comparatively high phytomass values, suggesting a greater capacity to accumulate harvestable biomass under current conditions, and thus could be targeted for sustainable harvesting. Similar patterns have been reported in other Mediterranean ecosystems, where perennial shrubs and hemicryptophytes dominate biomass production due to their morphological plasticity and resilience to water stress (Simões *et al.* 2012; De Dato *et al.* 2008).

The clustering analysis allowed us to distinguish three main MAPs ecological facies, each characterized by a specific floristic composition and level of productivity. This spatial differentiation of MAPs according to ecological facies highlights the strong coupling between species distribution, environmental conditions, and disturbance intensity. Therefore, mapping dominant and low-density MAP facies represents a significant step toward spatially explicit management, as recommended by the National Agency for Water and Forests. In this context, spatialized phytomass information allows forest managers to identify areas where controlled harvesting could be done, as well as areas where conservation or restoration efforts should be prioritized.

Implications for local communities

Beyond their ecological functions, MAPs in the Azilal region are deeply integrated into local livelihood systems and cultural practices. Ethnobotanical research conducted in the High Atlas and neighboring regions consistently documents the use of species such as *Thymus vulgaris*, *Teucrium polium*, *Plantago afra*, *Asphodelus ramosus*, *Salvia verbenaca* L., *Phagnalon saxatile* (L.) Cass., *Scolymus hispanicus*, *Urginea maritima*, *Diplotaxis sp* DC., in traditional medicine, food preservation, and household health care (Bellakhdar 1997; El Alami & Chait 2017; Ez Zoubi *et al.* 2022; Moujane *et al.* 2022; Benali *et al.* 2021; Yaagoubi *et al.* 2021; Kachmar *et al.* 2021). These uses represent more than symbolic or cultural traditions; they constitute a fundamental component of household resilience, particularly in remote rural areas where access to formal healthcare systems and diversified income sources remains limited.

Several species identified in this study as having relatively high biomass production also exhibit significant potential for economic valorization, provided that harvesting practices are adequately regulated. Species such as *Cistus laurifolius* and *Chamaerops humilis*, traditionally harvested for medicinal and domestic uses, are increasingly exploited in the perfumery and cosmetics industries due to their documented antioxidant, antimicrobial, and anti-inflammatory properties (Belhaoues *et al.* 2017; Lachkar *et al.* 2020; Ledrhem *et al.* 2022; Kielar *et al.* 2025). Similarly, *Pistacia lentiscus* and *Phillyrea angustifolia*,

widely used in local medicine for digestive, dermatological, and inflammatory conditions, have attracted growing interest for their bioactive compounds, supporting their potential applications in cosmetic and nutraceutical sectors (Ouahabi *et al.* 2023; Boufissiou *et al.* 2024; Bouchfara *et al.* 2025).

Herbaceous species also play a central role in local pharmacopoeia and resource use. *Anacyclus clavatus* is widely employed in Moroccan traditional medicine for its analgesic, anti-inflammatory, and antimicrobial properties, and constitutes a locally accessible alternative to the more intensively harvested *Anacyclus pyrethrum* (L.) Lag. (Bellakhdar 1997; Elazzouzi *et al.* 2014). Likewise, *Salvia verbenaca* is commonly used in herbal teas and traditional remedies for digestive and respiratory ailments and has demonstrated notable antioxidant and antimicrobial activities (Bellakhdar 1997; Belkhiri *et al.* 2017). In addition, species of the genus *Euphorbia* hold particular cultural and economic significance. *Euphorbia resinifera*, an emblematic Moroccan species, is traditionally exploited for its latex and has attracted increasing pharmacological interest, especially for analgesic applications, although its known toxicity requires strict regulation of harvesting practices (Hammad *et al.* 2025).

Given the diversity of uses and valorization pathways of these species, local communities, particularly through existing forestry cooperatives, could substantially benefit from a more diversified and sustainable integration of MAPs into local value chains. Such diversification is critical, as many cooperatives currently rely on a limited number of species, a situation that can exacerbate harvesting pressure on specific resources. Species with relatively high phytomass productivity, such as *Pistacia lentiscus*, *Chamaerops humilis*, *Euphorbia resinifera*, *Phillyrea angustifolia*, and *Cistus laurifolius*, could be more systematically incorporated into cooperative activities. This process could be facilitated through strengthened public-private partnerships, particularly between local cooperatives and the National Agency of Water and Forest (ANEF). This approach, strongly recommended in the national “Forêts du Maroc 2020-2030” strategy (Naggar 2020), would contribute to the promotion of certified sustainable MAP products and their integration into broader territorial development strategies, thereby enhancing economic benefits while preserving ecological functions and long-term resource sustainability.

Need for sustainable management of MAPs in the Azilal forest

The quantitative and spatial patterns revealed by this study highlight both the production potential and the pronounced vulnerability of MAP resources in the Azilal forest. Although some species exhibited local abundance and relatively high phytomass, nearly 80% of the recorded species were classified as non-exploitable due to their low spatial coverage. This imbalance reflects the strong anthropogenic pressures affecting this ecosystem, which are further amplified by increasing climatic stress. As observed in many Moroccan forest ecosystems, MAP resources in this region are exposed to multiple, interacting stressors, including overgrazing, unregulated fuelwood extraction, land-use change, and growing market-driven harvesting pressure (Dougan 2024). Moreover, rising demand for certain high-value species can intensify exploitation in the absence of collective rules or technical support, as previously documented for some Moroccan MAPs such as *Origanum compactum* and *Anacyclus pyrethrum* (Jamila & Mostafa 2014; Ouarghidi & Abbad 2019).

Ensuring the long-term sustainability of MAP resources, therefore, requires the implementation of integrated management strategies. On the one hand, targeted regulatory frameworks are needed to govern harvesting practices based on species-specific production potential and regeneration capacity. On the other hand, awareness-raising among local populations regarding sustainable harvesting techniques remains essential, particularly because some economically important MAP species may experience rapid population decline when harvesting intensity exceeds natural regeneration rates. Importantly, reliance on spatial coverage alone entails ecological risks, as some species with low apparent abundance may be subject to disproportionately high harvesting pressure due to strong cultural or medicinal value, while others with high coverage may still be vulnerable if harvesting targets reproductive organs or occurs repeatedly during sensitive phenological stages (Ticktin 2004). These considerations underscore the need to integrate spatial indicators with biological traits and harvesting modalities in management decision-making, such as regeneration capacity, life-history traits, harvesting intensity, and socio-economic demand.

Beyond ecological considerations, the sustainable management of MAPs in the Azilal forest is closely linked to the structuring of local value chains. Indeed, as demonstrated in other studies, the absence of organized value chains, collective governance mechanisms, and technical guidance often leads to resource depletion with limited long-term economic benefits for local communities (Achbah *et al.* 2025; Labrighli *et al.* 2025). In this respect, the spatially explicit data generated by this study provide a valuable foundation for developing integrated management approaches that combine regulated harvesting, community-based cooperatives, and continuous resource monitoring. Such approaches are essential to reconcile economic

valorization with ecosystem conservation, ensuring that the production potential of MAPs contributes to sustainable rural development rather than to the progressive degradation of already vulnerable mountain ecosystems.

Limitations and future research perspectives

Despite the robustness of the results, several limitations of the present study must be acknowledged. The sampling effort, based on 19 plots, remains limited in relation to the overall extent and ecological heterogeneity of the Azilal forest and may not fully capture its altitudinal, edaphic, and microclimatic gradients. In addition, accessibility constraints imposed by steep topography inevitably influenced the sampling design, potentially leading to the underrepresentation of some discrete, localized, or rare species. The phytoecological survey was conducted during a single season (spring), which may not adequately reflect interannual and seasonal variability in MAP productivity, nor allow for the detection of species with specific phenological windows or short life cycles. Furthermore, although the classification of species into “potentially exploitable” and “to be conserved” categories based on a 50% recovery or coverage threshold represents a pragmatic management-oriented approach, reliance on coverage alone entails ecological risks. Indeed, some species with low spatial abundance may nonetheless be subject to intense harvesting pressure due to high cultural or economic value, while others with high coverage may remain vulnerable if harvesting targets reproductive organs or occurs repeatedly during sensitive phenological stages.

These methodological constraints imply that the findings should be interpreted with caution, as they do not provide an exhaustive assessment of MAP across the Azilal forest but rather provide a first quantitative snapshot obtained under specific ecological and seasonal conditions. Consequently, the findings should be regarded as indicative rather than definitive, serving as a baseline for future investigations. Future research should aim to address these limitations by integrating multi-seasonal and multi-year biomass monitoring, demographic and regeneration studies, and participatory ethnobotanical surveys that document harvesting practices and local ecological knowledge. Combining ecological, social, and institutional dimensions would enable the refinement of sustainability thresholds and support the development of adaptive and context-specific management strategies.

Conclusion

In a context of increasing anthropogenic pressures on Moroccan natural ecosystems, exacerbated by climate change, the sustainable management of medicinal and aromatic plants (MAPs) has become a major challenge. This study aimed to fill a critical knowledge gap by assessing the diversity, spatial distribution, and phytomass production of MAPs in the Azilal forest. A total of 40 MAP species were recorded and structured into three distinct floristic facies that differed in species composition, diversity, and biomass production. Phytomass estimates highlighted a limited number of species with high production potential, notably *Chamaerops humilis*, *Cistus laurifolius*, and *Asphodelus ramosus*, while approximately 80% of recorded species exhibited low cover rate and biomass, indicating high vulnerability to overharvesting. Facies-level analysis showed that Facies 3 and Facies 1 concentrate both the highest diversity and the greatest production potential, whereas Facies 2 presents lower productivity and should be prioritized for conservation.

These findings provide a robust basis for differentiated and spatially targeted management strategies. Harvesting activities should be restricted to high-biomass species and concentrated in facies with demonstrated production capacity, while low-cover species should be subject to strict conservation or restoration measures. The spatial mapping of MAPs facies offers a practical decision-support tool for zoning the forest into areas dedicated to sustainable use, ecological protection, and long-term monitoring. Integrating these results into local forest management plans would help reduce pressure on vulnerable species while maintaining ecosystem integrity.

Beyond ecological management, the identified production potential of MAPs has direct implications for local livelihoods in the Azilal region. By clearly identifying exploitable species and suitable harvesting zones, this study highlights opportunities to diversify and secure rural incomes through regulated harvesting, local processing, and cooperative-based valorization of MAPs. Focusing on high-biomass species while limiting exploitation of vulnerable taxa can enhance economic returns without compromising resource sustainability. Finally, expanding phytomass monitoring across seasons and climatic conditions is recommended to refine sustainable harvesting thresholds and support adaptive management under increasing climatic and anthropogenic pressures.

Declarations

List of abbreviations: MAPs -Medicinal and Aromatic Plants; ANEF- Agence Nationale des Eaux et Forêts; ANPMA- Agence Nationale des Plantes Médicinales et Aromatiques

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials: The data featured in this manuscript can be obtained from the corresponding author

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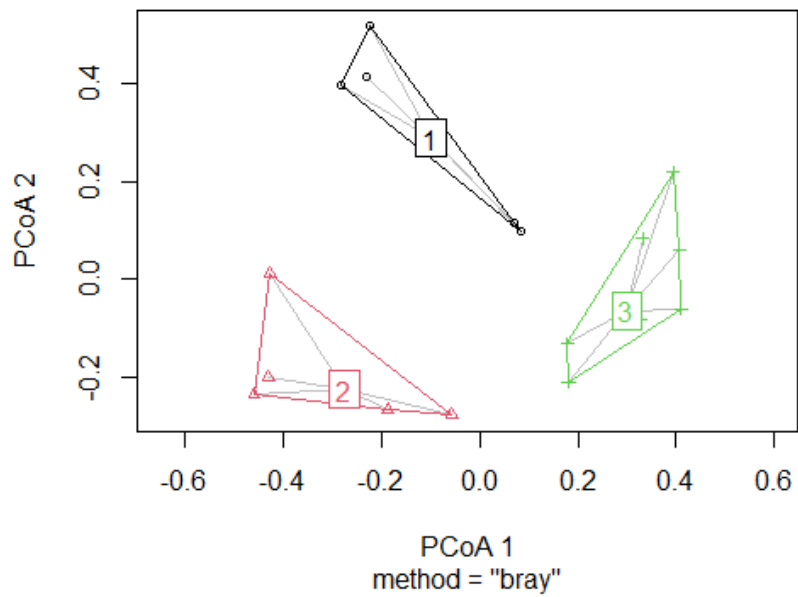
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Appendix

Appendix A: dispersion analysis across the three floristic facies



Appendix B: Results of the beta-diversity analysis among facies

PERMANOVA RESULTS					
TERM	Df	SumOfSqs	R2	F	Pr(>F)
MODEL	2	2.31841585	0.40479395	5.44072355	0.001
RESIDUAL	16	3.40898166	0.59520605		
TOTAL	18	5.72739751	1		
BETA DISPERSION (ANOVA)					
TERM	Df	Sum Sq	Mean Sq	F value	Pr(>F)
GROUPS	2	0.29988166	0.14994083	11.26088	0.00088575
RESIDUALS	16	0.21304315	0.0133152		