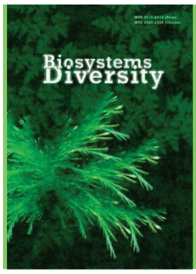

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Contribution to the evaluation of the biomass of medicinal and aromatic plants in Morocco: Case of *Globularia alypum*

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Morocco is distinguished by the richness of its flora, including medicinal and aromatic plants (MAPs) which play an important role, particularly in rural populations. Due to pressures often associated with overexploitation, monitoring of MAPs is essential to ensure their sustainability. This study looked to explore the status of *Globularia alypum* in the Amsittene site of biological and ecological interest (SBEI) in Morocco. A destructive technique was adopted to quantify biomass and productivity of *G. alypum* at six sites with different ecological characteristics in the Amsittene SBEI. Linear regression was used to model *G. alypum* biomass as a function of the normalized difference vegetation index (NDVI). Tree cover had the greatest influence on *G. alypum* dynamics, showing a significant effect on shrub height, leaf productivity, and total productivity, as did the cutting method, with the highest biomass estimated based on pair matching of similar individuals. NDVI was found to be an adequate indicator of *G. alypum* biomass, given their high correlation (0.84) with the selected model having an R^2 of 0.7. The yield of extracted essential oils ranged from 3.19 to 113.43 L, from which 10 chemical compounds were identified, with ethylvanillin being the most prominent.

Keywords: biomass estimation; medicinal plants; aromatic plants; Amsittene; Morocco.

Introduction

Medicinal and aromatic plants (MAP) have been instrumental in providing ecological, economic, and socio-cultural benefits for human well-being since ancient times. These plants have been widely used for traditional healing practices across diverse cultures (Rao et al., 2004; Hasan et al., 2016; El Cadi et al., 2020; Petrakou et al., 2020). As per the World Health Organization, around 80% of the global population depends on traditional medicine as their primary healthcare, and plant extracts or their active components constitute a significant portion of such therapy (Sardesai, 2002; Ghanmi et al., 2014). In fact, in many developing countries and regions, the collection of MAP for personal use or trade is a primary source of income (Mir et al., 2021; Shafi et al., 2021). However, the increasing demand for MAP has led to their overexploitation, destruction of natural habitats, and unsustainable harvesting practices. This has put the very existence of these species at risk and caused genetic erosion (Ciftcioglu, 2015; van Andel et al., 2015; Wani et al., 2021). The uncontrolled and unsustainable harvest of medicinal plants can lead to the extinction of some species or to the degradation of their populations (Ciftcioglu, 2015). It is thus imperative to establish regulations and standards for the sustainable harvesting of MAP to protect these valuable resources and ensure their availability for future generations (van Andel et al., 2015).

Morocco's economy heavily relies on the exploitation of medicinal and aromatic plants (MAP), particularly in rural areas (Ghanmi et al., 2011). From a socio-economic perspective, the cultivation and development of MAP offer a promising avenue for diversifying agricultural production and generating additional income for local communities (Montanari & Bergh, 2019). Among members of agricultural cooperatives, 55.5% expressed willingness to start a business related to the cultivation of MAP, indicating the growing recognition of the opportunities provided by this industry (Bouichou et al., 2021). The sector of medicinal and aromatic plants (MAP) contributes around 33,000 tons per year and generates 500,000 working days, equivalent to 25 million Moroccan dirhams (MAD), according to Ghanmi et al. (Ghanmi et al., 2014). Meanwhile, Morocco's exports of essential oils (EO) and aromatic extracts have been volatile from year to year, but in 2008, they totaled 725 tons, which amounted to 248 million MAD (Ghanmi et al., 2014). Among the more than 4,200 plant species in Morocco, 800 are MAP, and 80 are actively exploited, including argan (*Argania spinosa*), rosemary (*Rosmarinus* sp.), white wormwood (*Artemisia herba-alba*), thyme (*Thymus* sp.), wild chamomile (*Cladanthus mixtus*), carob tree (*Ceratonia siliqua*), oregano (*Origanum* sp.), lavender (*Lavandula* sp.), mastic tree (*Pistacia* sp.), myrtle (*Myrtus* sp.), and rockrose (*Cistus* sp.), among others (Zrira, 2017). Despite the proven value of MAP in Morocco, they remain subject to degradation, which is often attributed to anthropogenic pressure manifested through overgrazing or excessive harvesting, and/or poor technique.

Several studies have been dedicated to the preservation and sustainable utilization MAP. To conserve these plants, it is essential to establish species inventory and monitoring systems, as well as to adopt integrated conservation practices both onsite and offsite, as highlighted in previous studies (Joshi & Joshi, 2014; Pangriya, 2015). A crucial step in the sustainable management of MAP is the assessment of the status of plant species through biomass estimation. Methods for estimating biomass can be classified into two groups: non-destructive and destructive methods (Pasalodos-Tato et al., 2015; Yao et al., 2021). Non-destructive methods are associated with lower labor costs and less damage to the ecological environment, as they avoid activities such as cutting down and weighing plants (Rojo et al., 2017; Bohlman et al., 2018). On the other hand, although they are usually more costly and time-consuming, destructive techniques tend to yield more precise outcomes (Shi & Liu, 2017). The choice of method depends on several factors, such as the study objectives and the availability of resources. Ultimately, the selection of the most suitable method should ensure the accurate assessment of the status of the species while minimizing the impact of the assessment on the environment.

This study aims to contribute to the monitoring and management of MAP in Morocco, particularly the *G. alypum* species in the Amsittene

SBEI. The goal is to identify the current status of *G. alypum* and explore opportunities for its sustainable and rational exploitation in the region. Specifically, this study aims to achieve three objectives: first, to estimate the biomass and productivity of *G. alypum*, second, to assess the factors affecting its distribution and map its distribution in the study area and lastly, this study aims to assess the potential of *G. alypum* for essential oil production and to provide significant insights into the sustainable management and conservation of this plant species. Such information is vital for the long-term sustainability of the medicinal and aromatic plants (MAP) industry in Morocco.

Materials and methods

Study area. The study area, as illustrated in Figure 1, encompasses the Amsittene Site of Biological and Ecological Interest (SBEI), which is a protected area in Morocco (Arrad et al., 2020). It covers 3,500 hectares, which is one-third of the total area of Amsittene Forest. The SBEI extends 20 km east-west in length and 10 km north-south in width. It is located in Southern Morocco, between the cities of Essaouira (45 km to the north) and Tamanar (20 km to the south). The area's climate is influenced by its proximity to the Atlantic Ocean and the High Atlas Mountains. The precipitation is irregular, occurring mainly during the first three months of the year, and ranges from 270 to 340 mm/year. The mean monthly temperatures vary from 17.2 °C in Essaouira to 19.8 °C in Tamanar. The mean maximum temperature during the hottest month is 22 °C in Essaouira and 36 °C in Tamanar, while the mean minimum temperature during the coldest month is 9.7 °C in Essaouira and 6.6 °C in Tamanar. The dominant bioclimate is the upper semi-arid, which is characterized by a drought that can last up to 7 months, significantly impeding the growth and development of vegetation.

The dominant geology in the study area comprises formations dating back to the Jurassic period, consisting primarily of limestone cliffs on the southern slopes, and dolomitic clay and sandstone formations on the rest of the slopes, which are more conducive to forest vegetation. Soil types in the study area include loose clay, silty clay, and silty clay-sand soils. These soils are generally shallower on the southern slopes than on the northern slopes and include fersialitic red soils, brown soils with crusts, terra rossa truncated red soils, colluvial red soils, sandy soils, lithosols, and regosols (Benabid, 1976). The woody vegetation in the study area is mainly composed of Barbary thuja (*Tetraclinis articulata*: TA) and argan (*Argania spinosa*: AS) tree stands, with some areas also featuring holm oak (*Quercus rotundifolia*: QR) and carob tree (*Ceratonia siliqua*). This species' composition is greatly influenced by altitudinal variation, aspect, substrate, and continentality. The shrub and herbaceous layers, although rich in perennial and annual species, many of which are medicinal and aromatic plants (MAP), have suffered significant degradation.

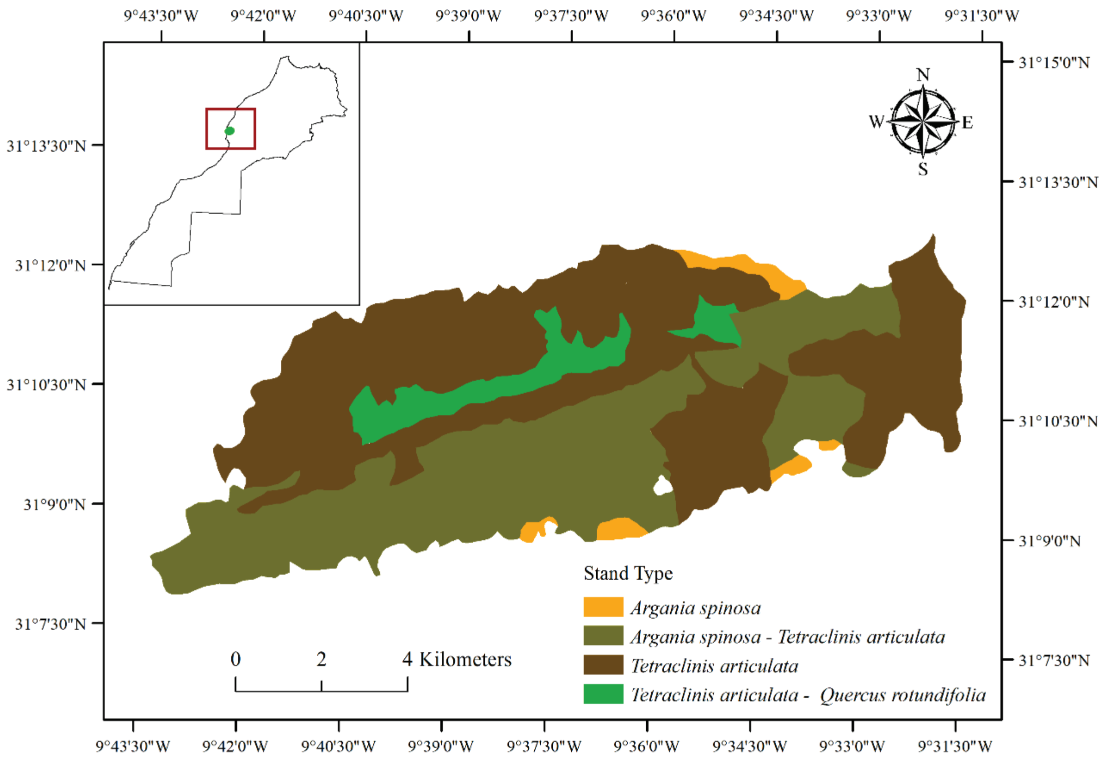

Fig. 1. Geographic location of the Amsittene SBEI with the dominant forest stands

Methodology. In order to evaluate the morphometric parameters, the dry biomass, and the productivity of the different aboveground parts of *G. alypum*, a destructive sampling was carried out in late autumn (November) and early spring (March) of the following year. This consisted of (i) identification of north and south-facing slopes; (ii) selection of sampling sites in the upper, middle, and lower sections of each slope; and (iii) collection of *G. alypum* samples of three size classes (small, medium, large) at each of the six sites, with three replicates for each site (3 × 6 × 3) based on the area-species curve method. Thus, a total of 54 *G. alypum* samples were collected for biomass assessment in this study.

Table 1 presents the characteristics of the six sites from which samples were collected. Elevations ranged from 566 to 854 m, while the slope was moderate to steep, ranging from 8% to 28%. The substrate was predominantly rocky throughout the study area. *G. alypum* density ranged from 1 600 to 2 800 plants/ha, while most of the sampled sites were characterized by the no-cover tree type.

To assess the growth and development of *G. alypum* plants, the evaluation of morphometric parameters such as maximum crown height, large crown diameter, and small crown diameter (perpendicular to the large diameter) is crucial. These parameters provide valuable insights into the ecological and physiological characteristics of the plant (Kramer et al., 1979). In addition to morphometric parameters, the dry biomass of the aboveground parts of the *G. alypum* samples was also analyzed. The initial and final dry biomasses were determined through a three-step process: (i) drying the samples for 24 hours in an oven at 104 °C, (ii) separating the different parts of the *G. alypum* samples, and (iii) measuring the leaf dry biomass, stem dry biomass, and total dry biomass.

To determine the biomass of *G. alypum*, allometric equations based on regression models were developed using easily measurable parameters, such as large crown diameter (D), small crown diameter (d), and density (den) of the plant in the field. The stepwise multiple linear regression approach was adopted for modeling. This approach allows the development of a model that is based on the most significant variables, which can improve the accuracy of biomass estimation (Usó et al., 1997; Gibbs et al., 2007). Furthermore, Landsat 8 satellite imagery was utilized to extract the Normalized Difference Vegetation Index (NDVI) for the area. NDVI is a widely used vegetation index that can provide valuable information about vegetation cover and biomass (Rouse et al., 1974). NDVI was then used in the dry biomass modeling of *G. alypum*, which can improve the accuracy of biomass estimation and provide more comprehensive information on plant growth and development.

Table 1
Topographical parameters and site characteristics of the sampled areas

Site	Coordinates	Altitude, m	Slope, %	Aspect	Nature of substrate	Density, plants/ha	Tree cover
1	31.16176°N ; 9.69285°W	566	12	north	rocky	2 200	no cover
2	31.15768°N ; 9.69019°W	700	28	north	rocky	1 600	mixed
3	31.16178°N ; 9.67720°W	826	22	north	rocky	2 400	no cover
4	31.9009° N ; 9.57907°W	750	19	south	rocky	1 600	no cover
5	31.18908°N ; 9.59189°W	854	8	south	non-rocky	1 600	mixed
6	31.16071°N ; 9.67603°W	840	20	south	mixed	2 800	no cover

The productivity of *G. alypum* was determined using two methods: (i) the method based on the matching of pairs of similar individuals; and (ii) the direct method. The first method involves selecting three pairs of *G. alypum* individuals at each site and size class. The initial dry biomass of one individual from each pair is determined by taking a first cut of the sample in late autumn, while the final dry biomass is determined by taking a second cut in early spring of the following year. The difference in biomass between the initial and final biomass of each pair represents the increase in biomass and productivity. This method provides a comparative approach to determine the productivity of *G. alypum* individuals. In contrast, the direct method involves assessing the biomass growth of a single individual from each size class after the late autumn cut. This method provides an individual approach to determining the productivity of *G. alypum*.

Hydro-distillation was the method used in this study to extract essential oils from *G. alypum*. This variant of steam distillation is commonly used to extract and separate essential oils from plants for use in natural products (Xavier et al., 2011). Its popularity stems from the minimal impact on oil yield and quality during the distillation process (Li et al., 2013; Božović et al., 2017; Golmohammadi et al., 2018). The plant material is in direct contact with boiling water, and the evaporation of water can be achieved by direct heating (open fire flask) or injection of superheated steam. In this study, 150 g of crushed dry leaves were mixed with 750 mL of water in a one-liter flask topped with a 60 cm column and connected to a refrigerator. The flask was heated to boiling point, and the essential oil extracts were collected at one-hour intervals until they were fully exhausted. The chemical composition of the essential oils was determined by chromatographic analysis using the gas chromatography-mass spectrometry (GC-MS) technique. GC-MS is an instrumental technique that combines a gas chromatograph with a mass spectrometer to separate, identify, and quantify complex chemical mixtures (Palmer, 2006; Medeiros, 2018). The analyses were conducted using an HP 6890 Hewlett Packard gas chromatograph equipped with an HP-5 capillary column (30 m x 0.25 mm). The Kovats retention index (RI) was used to indicate the elution order of *G. alypum* compounds in the chromatogram (van Den Dool & Dec. Kratz, 1963; Eiceman & Gardea-Torresdey, 2006; Aćimović et al., 2021). In this study, where the temperature was programmed, the RI was calculated using the equation (1).

$$RI = 100 * \frac{T_n - T_x}{T_{n+1} - T_n} + 100n \quad (1)$$

where T_x represents the retention time of compound x; T_n and T_{n+1} are the retention times of straight-chain alkanes with carbon numbers n and n+1 respectively.

In this study, statistical analyses were conducted using different approaches. Firstly, the correlation matrix was used to investigate the pairwise relationships between *G. alypum* morphometric parameters and to explore the correlations between *G. alypum* parameters and different site characteristics. Secondly, the effect of site characteristics on different *G. alypum* parameters was analyzed using one-way ANOVA. This approach allowed for the comparison of means between different groups of parameters, followed by the Newman-Keuls post-hoc test to identify distinct groups among these parameters. The significance level for statistical tests was set at a P-value less than 0.05, indicating a significant difference between the groups.

Results

Relationship between site- and G. alypum specific parameters. The results of the evaluation of the pairwise relationship between *G. alypum* parameters as well as the relationship between site characteristics and *G. alypum* parameters are presented in Table 2. Pairwise relationships between *G. alypum* parameters. The results reveal strong correlations between the various *G. alypum* parameters, particularly the morphometric parameters, dry biomass, and productivity. This highlights their significance in estimating the overall production of *G. alypum* in the study area's ecological conditions. However, among the diameter variables, large crown diameter displayed stronger correlations with biomass and productivity than height.

Table 2
Correlation matrix of simple linear regressions between dendrometric parameters, site characteristics, and biomass

Parameters		*G. alypum*									Site					
		H	D	d	BSF	BSTg	BST	PrF	PrTg	PrT	Asp	Alt	Den	Slp	Subs	Cov
G. alypum	H	1.00	0.69**	0.46**	0.59**	0.73**	0.72**	0.58**	0.63**	0.70**	0.09	0.19	–0.25	–0.31*	0.27*	0.50**
	D	–	1.00	0.80**	0.82**	0.86**	0.87**	0.69**	0.57**	0.70**	0.04	0.06	–0.04	–0.22	0.09	0.27*
	d	–	–	1.00	0.81**	0.79**	0.81**	0.58**	0.42**	0.54**	–0.09	–0.11	–0.20	–0.07	–0.01	0.24
	BSF	–	–	–	1.00	0.88**	0.92**	0.56**	0.50**	0.60**	0.13	0.08	–0.24	–0.06	0.00	0.27*
	BSTg	–	–	–	–	1.00	0.99**	0.64**	0.56**	0.68**	–0.01	0.05	–0.14	–0.11	0.02	0.35*
	BST	–	–	–	–	–	1.00	0.64**	0.56**	0.67**	0.01	0.06	–0.16	–0.10	0.01	0.34*
	PrF	–	–	–	–	–	–	1.00	0.46**	0.74**	–0.16	0.09	0.12	0.04	0.04	0.46**
	PrTg	–	–	–	–	–	–	–	1.00	0.94**	0.31*	0.29*	–0.00	–0.17	0.27	0.43**
	PrT	–	–	–	–	–	–	–	–	1.00	0.18	0.25	0.05	–0.11	0.22	0.51**
Site	Asp	–	–	–	–	–	–	–	–	–	1.00	0.58**	–0.07	–0.38**	0.48**	–0.06
	Alt	–	–	–	–	–	–	–	–	–	–	1.00	0.15	0.01	0.47**	–0.04
	Den	–	–	–	–	–	–	–	–	–	–	–	1.00	0.09	–0.11	–0.29*
	Slo	–	–	–	–	–	–	–	–	–	–	–	–	1.00	–0.47**	–0.06
	Sub	–	–	–	–	–	–	–	–	–	–	–	–	–	1.00	0.04
	Cov	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.00

Note: H: maximum height of crown; D: greater crown diameter; d: smaller crown diameter (perpendicular to D); BSF: leaf dry biomass; BSTg: stem dry biomass; BST: total dry biomass; PrF: leaf productivity; PrTg: stem productivity; PrT: total productivity; Asp: aspect; Alt: altitude; Den: density; Sub: substrate; Cov: nature of tree cover; * and ** indicate significant correlations at P < 0.05 and P < 0.01, respectively.

The correlation coefficients between height and biomass and productivity parameters ranged from 0.58 (leaf productivity) to 0.72 (total dry biomass), while the coefficients for the relationship between large crown diameter and the same parameters ranged from 0.57 (stem productivity) to 0.87 (total dry biomass).

Relationship between G. alypum parameters and site characteristics. Upon observation, site characteristics displayed mostly weak relationships with *G. alypum* dynamics. The aspect was found to be very weakly correlated with *G. alypum* parameters, with the highest correlation coefficient obtained with stem productivity at 0.31. Negative correlations were observed for small crown diameter, stem dry biomass, and leaf productivity, with coefficients of –0.01, –0.09, and –0.16, respectively. Similarly, altitude exhibited weak relationships with *G. alypum* parameters, with the highest correlation coefficient observed with stem productivity at 0.29. Slope and stand density exhibited the weakest relationships with *G. alypum* parameters, with slope showing negative correlations with all parameters except leaf productivity (0.04), while only leaf productivity, stem productivity, and total productivity had non-negative correlation coefficients with density. On the other hand, tree cover showed the strongest relationship with *G. alypum* parameters among the site variables. However, the correlations were mostly weak to moderate, with coefficients ranging from 0.24 to 0.51, corresponding to small crown diameter and maximum height, respectively.

Effect of site characteristics on G. alypum parameters. Table 3 displays the results of the one-way ANOVA conducted to investigate the influence of site characteristics on *G. alypum* parameters. Upon initial observation, it appears that site characteristics have limited effects on *G. alypum* parameters. Specifically, stand aspect and density did not have significant effects on any of the *G. alypum* parameters, while altitude and slope had significant effects ($P < 0.05$) only on maximum *G. alypum* height. Substrate type was also found to have a significant effect ($P < 0.05$) on both height and stem productivity. The presence or absence of tree cover, however, was found to have the greatest influence on *G. alypum* parameters. It had a very highly significant effect ($P < 0.001$) on height, leaf productivity, and total productivity, as well as a highly significant effect ($P < 0.01$) on stem productivity.

Table 3
One-way ANOVA results on the effect of site parameters on morphometric parameters and biomass of *G. alypum*

Parameter	F_{obs}					
	aspect	altitude	slope	density	substrate	tree cover
H	0.38	3.43*	3.43*	1.88	4.09*	16.85***
D	0.09	0.72	0.72	0.24	0.48	4.13*
d	0.40	0.64	0.64	1.10	0.00	3.30*
BSF	0.85	0.88	0.88	1.19	0.00	4.24*
BSTg	0.01	0.56	0.66	0.46	0.01	7.13*
BST	0.01	0.53	0.53	0.55	0.01	6.82*
PrF	1.38	1.11	1.11	0.72	0.07	14.10***
PrTg	5.67	1.89	1.89	1.54	4.03*	11.76**
PrT	1.67	1.27	1.27	0.72	2.60	17.95***

Note: *, ** and *** indicate significant effects at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Tables 4 and 5 present the homogeneous groups identified by the Newman-Keuls test for the respective *G. alypum* parameters. In relation to tree cover type (Table 4), the Newman-Keuls test revealed that *G. alypum* crown height was highest for shrubs with tree cover compared to shrubs without cover. On the other hand, large and small crown diameters were highest (78 ± 36 and 57 ± 25 cm, respectively) in the group of *G. alypum* under tree cover compared to shrubs without cover (58 ± 23 and 42 ± 20 cm, respectively). Consistent with the morphometric parameters, *G. alypum* biomass and productivity were highest for shrubs with tree cover. The distinct groups corresponding to leaf dry biomass, stem dry biomass, and total dry biomass parameters as a function of tree cover revealed that the highest values (58 ± 30, 270 ± 181, and 329 ± 208 g, respectively) were observed for shrubs under cover, while the lowest values were obtained for *G. alypum* shrubs without cover. Similarly, the highest values for leaf productivity, stem productivity, and total productivity recorded at 34 ± 17, 59, and 92 ± 39 g, respectively, were observed for the group shrubs under cover, highlighting the significant role of tree cover in their development.

Table 4
Classification of morphometric parameters of *G. alypum* based on tree cover type

Morphometric parameters	Parameter value	Tree cover	F_{obs}	P-value
Height, cm	42.4 ± 10.5	NC	16.85	<0.001
	67.6 ± 33.8	C		
Large crown diameter, cm	57.9 ± 22.8	NC	4.13	0.047
	78.1 ± 35.5	C		
Small crown diameter, cm	41.7 ± 19.5	NC	3.29	0.075
	56.6 ± 24.9	C		
Leaf dry biomass, g	36.0 ± 26.4	NC	4.24	0.045
	58.4 ± 30.1	C		
Stem dry biomass, g	130.4 ± 120.8	NC	7.13	0.010
	270.2 ± 181.1	C		
Total dry biomass, g	166.7 ± 144.6	NC	6.82	0.012
	329.0 ± 208.2	C		
Leaf productivity, g	14.5 ± 12.0	NC	14.09	<0.001
	33.7 ± 16.7	C		
Stem productivity, g	23.5 ± 22.8	NC	11.76	0.001
	58.5 ± 39.0	C		
Total productivity, g	38.0 ± 28.7	NC	17.95	<0.001
	92.2 ± 48.2	C		

Notes: C: with cover; NC: without cover.

Table 5 presents the classification of *G. alypum* crown height by elevation, based on the Newman-Keuls test, which reveals two distinct groups of crown height. The first group consists of the highest crown height (63 ± 31 cm), corresponding to the site with the highest elevation (854 m), while the second group consists of the remaining sites and their corresponding observed *G. alypum* crown height values. Similarly, two distinct groups are observed in the *G. alypum* crown height classification by slope (Table 5), with the highest maximum crown height obtained on the lowest slope (8%) for one group, and the other group including the remaining slope classes and corresponding crown height values. Regarding the substrate, the non-rocky substrate group exhibited the highest crown height (54 cm), whereas the lowest crown height (48 cm) was observed in the rocky substrate group.

Table 5
Classification of the maximum crown height based on altitude and slope

Altitude, m	Slope, %	Height, cm
840	20	34.9 ± 10.5^{a}
700	28	40.9 ± 10.7^{a}
566	12	42.2 ± 8.2^{a}
750	19	43.7 ± 8.6^{a}
826	22	49.4 ± 11.5^{ab}
854	8	62.8 ± 31.0^{b}

Effect of cut method on leaf productivity of G. alypum. The analysis of variance (ANOVA) conducted to investigate the effect of the cut method on leaf productivity of *G. alypum* revealed a highly significant effect ($P < 0.001$) of the cut type on productivity ($F = 9.35$). This indicates that the specific method used for cutting *G. alypum* significantly impacts leaf productivity. Furthermore, the analysis highlighted the importance of choosing the appropriate technique for estimating productivity. When using the direct method, the estimated leaf productivity was very low, around 5 grams per shrub. In contrast, the method based on pairs of similar individuals estimated an average productivity of 17 grams for each individual shrub. These findings underscore the need to carefully consider the choice of cutting method when assessing leaf productivity in *G. alypum*. The selection of technique can have a substantial impact on the estimated productivity levels.

Modeling of the dry and total biomass of G. alypum. Table 6 shows that for modeling and estimating leaf biomass, the D*d estimator accounted for 68% of the variation in the model. Introducing the inverse of density to this model (Model 2) resulted in a 5% increase in explained variance, with 73% of the variation accounted for. The polynomial form (Model 3) accounted for 75% of the variation, resulting in a gain of 2.4%. This model also presented a Durbin-Watson statistic of 1.90, indicating that it was suitable for the estimation of leaf-dry biomass. Conversely, Dd*1/den was a reliable estimator of total plant biomass, accounting for 77% of the variance in total biomass. Moreover, the Durbin-Watson statistic corresponding to this model was estimated to be 1.80, indicating that Model 2 under total biomass was chosen to estimate the total plant biomass of *G. alypum*.

Table 6
Linear regression models for leaf biomass and total biomass of *G. alypum*

Biomass	Variant	Model	R^2, %	S_{yx}	DW
Leaf Biomass	1	BF = 10.915 + 0.009 Dd	68	15.7	2.16
	2	BF = 11.361 + 17.196 (Dd*1/den)	73	14.5	1.90
	3	BF = -4.221 + 0.021 Dd - 0.000001 Dd²	75	13.8	1.95
Total Biomass	1	BT = 15.509 + 0.056 Dd	75	80.4	1.80
	2	BT = 21.941 + 103.392 (Dd*1/den)	77	77.3	1.80
	3	BT = - 31.752 + 0.093 Dd - 4.110E - 006 Dd²	77.2	77.5	1.70

Notes: R2: coefficient of determination; $S_{yx} = \Sigma(x - \bar{x})(y - \bar{y})$; DW: Durbin Watson statistic; BF: Leaf Biomass; BT: Total Biomass D: greater crown diameter; d: smaller crown diameter; Den: density.

Relationship between NDVI and biomass of G. alypum. To further investigate the dynamics of *G. alypum*, modeling based on NDVI was performed, and the resulting NDVI map is presented in Figure 2. The correlation between NDVI, altitude, and *G. alypum* is shown in Table 7, revealing a close and statistically significant ($P < 0.05$) relationship between NDVI and *G. alypum*, with a correlation coefficient of 0.84.

Linear regression analysis showed the applicability of NDVI in modeling *G. alypum* biomass in the study area, with the results presented in Table 7. The model was found to be sufficiently accurate in predicting the dry biomass of *G. alypum*, with an R^2 value of 0.70. Therefore, the selected model is presented in equation (2).

$$\text{Total dry biomass (g)} = -953.86 + 9201.56 * \text{NDVI} \quad (2)$$

Evaluation of yield of essential oils derived from G. alypum and corresponding chemical compounds. The evaluation of *G. alypum* potential at the Amsittene SBEI for essential oil production revealed a relatively low yield (0.05%) of extracted essential oils, ranging from 11.6 to 65.0 mL/ha, with an average of 35.6 ± 15.8 mL/ha. The estimated total yield in the Amsittene SBEI ranged from 3.2 to 113.4 L, with an average of 36.4 ± 37.9 L. Chromatographic analysis of the essential oils derived from *G. alypum* identified 10 chemical compounds (Table 8). The major content of the oils was ethylvanillin, with an average content of about 24.2%, while trans-methyl isoeugenol presented the lowest content at 3.2%. The other two most common compounds in the oils were β-endesmol and trans-farnesyl acetate, with average contents of 19.3% and 13.2%, respectively. The respective contents of the other components were lower than 8.7%.

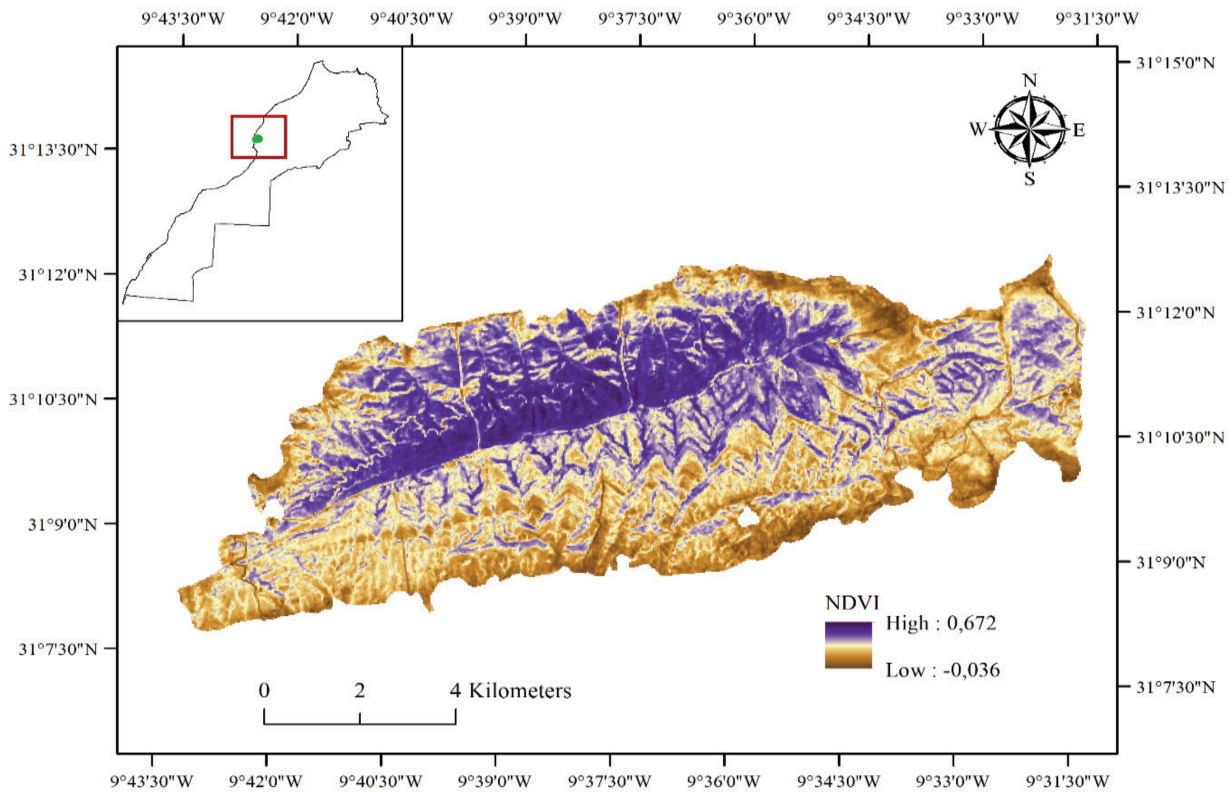

Fig. 2. NDVI distribution across the Amsittene SBEI

Table 7
Linear regression modeling of biomass of *G. alypum* based on NDVI

Linear regression	Coefficients	Standard error	t-stat	P-value
Intercept	–953.9	860.9	-1.11	0.33
NDVI	9201.6	2980.4	3.09	0.04

Discussion

Morocco boasts a diverse flora, thanks to its unique geographical and climatic conditions. This diversity includes a significant number of medicinal and aromatic plants (MAP), which are valuable resources for the rural population and have major implications for the economy. However, MAP are often under pressure from a variety of natural and anthropogenic factors, which can threaten their sustainability (Bouayyadi et al., 2015; Chaachouay et al., 2020). Therefore, it is important to assess the current status of these species and analyze their potential for rational exploitation that ensures the sustainability of the resource and continued use by local populations.

The main objective of this study was to assess the potential of *G. alypum* as a medicinal and aromatic plant (MAP) in the ecologically significant Amsittene site in Morocco. To achieve this, a destructive biomass estimation of *G. alypum* was conducted, analyzing both leaf biomass and total biomass. Additionally, the study evaluated the potential of *G. alypum* in producing essential oils, providing insight into the factors influencing its distribution and productivity in the region.

Table 8
Chemical compounds of the essential oils extracted from *G. alypum*

Compound	RI	Percentage, %
Cinnamic acid	1439.5	3.92
Ethylvanillin	1452.2	24.20
Trans-methyl isoeugenol	1495.3	3.21
Elemicin	1557.2	5.91
Hexadecane	1592.1	6.47
β-Endesmol	1636.8	19.30
Patchouli alcohol	1661.5	6.59
Trans-farnesyl acetate	1841.8	13.24
Beyerene	1917.5	8.50
Isophyllocladene	1966.7	8.66

Note: RI: Kovats retention index.

Results revealed that tree cover played a significant role in the development of understory shrubs, with the greatest influence on the morphometric parameters, biomass, and productivity of *G. alypum*. The study's findings that the density and biomass of *G. alypum* were highest in areas with tree cover, compared to those without cover, were consistent with previous studies in the literature (Caccia & Ballaré, 1998; Akpo et al., 2001; Augusto et al., 2003; Goudiaby et al., 2017). This tree cover effect could be attributed to the buffering role of the canopy on environmental conditions, which accentuates the heterogeneity of the environment and affects the distribution of understory vegetation. In sub-humid to semi-arid bioclimates, the favorable effect of trees is frequently linked to the attenuation of the evaporative demand of the air and the increase in soil fertility (Akpo et al., 2001). It is important to note that while tree cover and canopy effect are significant factors in promoting understory growth, they may not always have a positive impact. In this study, degraded Barbary thuja stands were found to have the highest *G. alypum* biomass compared to dense stands. This outcome is due to competition for resources, including light and understory resources like soil nutrients (Harrington, 2006). The analysis of biomass morphometric parameters revealed that crown diameter played a significant role in determining the biomass of *G. alypum*. Specifically, both large and small crown diameters were found to have the highest correlations with *G. alypum* biomass and productivity, making them the most reliable variables for estimating the latter. These findings are consistent with the results of previous studies by Northup et al. (2005) and Conti et al. (2013), which found crown area to be the most effective variable for both species-specific and multi-species shrub models. Similarly, Škėma et al. (2018) demonstrated that diameter was the best predictor for estimating both aboveground and total biomass of underbrush vegetation.

The essential oil yield observed in the study area was relatively low compared to other species in the region, typically ranging between 5–15% (Ghanmi et al., 2010). This suggests that *G. alypum* may be underdeveloped not only in the study area but throughout Morocco, as indicated by the MAP inventory in the Agoundis Valley, which revealed limited exploitation of *G. alypum* in the region (Montanari, 2012). Despite this, the potential use of *G. alypum* has been demonstrated, with the extracted oils containing ethylvanillin and β-endesmol as the most common compounds. Ethylvanillin is widely used in fragrances and, more importantly, in the food industry for flavoring chocolate, baked goods, and ice cream. On the other hand, β-endesmol is commonly used in the pharmaceutical industry as an antimigraine agent (O'Neil, 2013; Panten & Surburg, 2015; Lewis, 2016).

The study sheds light on the potential socioeconomic and ecological roles of *G. alypum* as a MAP in the Amsittene region. However, to gain a more comprehensive understanding of the species, continued monitoring is recommended through in-depth studies that compare biomass estimation methods, including those that incorporate advanced technologies such as remote sensing. This would provide a basis for the management and development of not only *G. alypum* but also other MAP species in the region.

Conclusion

This study provides insights into the current status and potential of *G. alypum* as a medicinal and aromatic plant (MAP) at Amsittene SBEI in Morocco. The research results highlight the significant role of shrub cover in the biomass constitution and productivity of the species, with highly productive sites characterized by abundant shrub cover. The study further reveals that the nature and type of forest stands, including their level of degradation, play a crucial role in limiting the distribution of *G. alypum*. Specifically, higher densities of *G. alypum* are found in degraded Barbary thuja stands due to the availability of space and resources to support growth, while low densities are observed under dense young stands. The potential of *G. alypum* to thrive in degraded areas presents an interesting opportunity for conservation and management strategies in the region, particularly in the production of essential oils. However, further efforts are needed to develop the local industry in the area, focusing not only on *G. alypum* but also on other MAP, and adopting practices that promote the development of the respective species. Additionally, policies such as the creation of management plans and regulations for the exploitation of MAP should be implemented to ensure their sustainability in the region.

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