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A new proposal for a statistically-derived biogeographical regionalization of Algeria, North Africa

Djilali Tahri
Département des sciences naturelles, École Normale Supérieure de Laghouat, BP 4033, Route de Ghardaïa, 03000, Laghouat, Algérie.
Corresponding author

Rachid Meddour
Département des sciences agronomiques, Faculté des sciences biologiques et des sciences agronomiques, BP 17 RP, Hasnaoua 2, 15000 Tizi Ouzou, Algérie.

Cyrille Chatelain
Conservatoire et Jardin botaniques de Genève, ch. de l'Impératrice 1, C.P. 71, 1292 Chambésy, Switzerland.

Frédéric Médail
Aix Marseille University, Avignon University, CNRS, IRD, IMBE. Campus Aix, Technopôle de l'Environnement Arbois-Méditerranée, F-13545 Aix-en-Provence cedex 4, France.

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Abstract. Most proposals relating to the biogeographic regionalization of Algeria have been made by traditional qualitative method (geography, geology, climatology, vascular flora), on the basis of expert's opinions. A new biogeographic regionalization of Algeria is herein proposed, based on quantitative approach and using objective multivariate methods. Bio-geoclimatic datasets were analysed using cluster analysis techniques to define biogeographical units. A georeferenced floristic database for Algerian strict-endemic plants was compiled, including distribution information from different sources, to characterise the indicator species of these units. Our new proposal for Algeria encompasses 28 biogeographical units recognised within the country that reflect specific regional topography and ecoclimatic conditions. Eight distinct and spatially coherent sectors were identified, and 20 nested districts were detected, based on biogeographical features. All of these biogeographical units are listed and their position and boundaries are mapped. The main predictive environmental descriptors of the sectors were Thornthwaite aridity index, elevation, Min Temperature of Coldest Month (Bio6), Precipitation of Warmest Quarter (Bio18), Coefficient of variation of Enhanced Vegetation Index (EVI), Evenness of EVI, and soil organic carbon. We highlighted the endemic plants that define the districts, using the indicator species criterium. The use of a large dataset of environmental factors and endemic plant species, coupled with numerical analyses, makes this study novel and allows an enhanced bioregionalization system for Algeria. We provide a reliable sectorisation for use in conservation planning, biodiversity assessment, or climate change studies.
Keywords: districts, endemic plant species, environmental variables, IndVal, *k*-mean clustering, Mediterranean, Sahara, sectors.

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1. Introduction

The hierarchical system in which biogeography categorises geographical areas, based on their biotas, is defined as 'biogeographical regionalization' (Morrone, 2018). The delineation of biogeographic regions represents a useful tool to better understand the organization of biodiversity on earth and for conservation planning and management, as recognised by several authors (Heikinheimo *et al.*, 2007; Rueda *et al.*, 2010; Whittaker *et al.*, 2013) and this is particularly useful in the development of conservation biogeography (Ladle & Whittaker, 2011). In plant biogeography, regions are classified into floristic zones, each characterized by a broadly similar composition of native plant species (Kaplan, 2017; Takhtajan, 1986), in terms of endemic taxa and/or plant communities (e.g., Fattorini, 2017; Morrone, 2015; Rueda *et al.*, 2010; Vilhena & Antonelli, 2015). They are identified especially by the cooccurrence of a large number of endemic taxa (Escalante, 2009; González-Orozco *et al.*, 2014). This conjunction of taxa in the same area must be linked to a causal invariance at the level of ecological requirements, the history of the flora, geographic constraints and/or evolutionary processes (Lomolino *et al.*, 2010), in response to past or current physical and biological forces (Kreft & Jetz, 2010).

In many regions of the world, biogeographic sectorization is not carried out or is based on old data. This is the case of Algeria in North Africa which belongs to the Holarctic Kingdom (Tethyan or Mesogean Subkingdom) and more precisely to the Mediterranean Region (West-Mediterranean Subregion) and the Saharo-Arabian Region (Saharan Subregion) (Loidi & Vynokurov, 2024; Quézel, 1978; Takhtajan, 1986). In this large country, Quézel (1978) recognised the following domains: 1. Mediterranean North-African, 2. Steppic North-African, 3. North-Western Saharan, 4. Northern Saharan, 5. Saharan High Mountains, 6. Central Saharan, 7. Western Saharan, 8. Southern Saharan. These areas are further subdivided into biogeographical sectors and districts.

The first attempt at a bioregionalization of Algeria up to the district level was by Lapie (1909), using vegetation types, mainly the forest formations. Then, the domains, sectors and districts, have been described successively, using expert knowledge (Maire, 1926; Meddour, 2012; Quézel & Santa, 1962). All these works have been made mostly on descriptive and empirical bases, via the information provided by several sciences (geography, geology, edaphology, climatology, etc.), as well as on the distribution of plant taxa and communities. Algeria was entirely divided biogeographically, based mainly on the distribution of endemic plant taxa, by Quézel & Santa (1962), into 20 biogeographic sectors and subsectors, including 5 for the Sahara. These subdivisions are established and have been consecrated by practice for 60 years, and this regionalization is still widely accepted as the most consistent one.

However, apart from a nomenclatural description, a biogeographical hierarchy, and the map of the district units, Quézel & Santa (1962) do not give any diagnosis or ecologic-floristic description of the proposed biogeographical subdivisions, which have been later provided by Meddour (2012), along with a new nomenclature. Then, Meddour *et al*. (2019) described the floristic affinities between the biogeographic units of Northern Algeria, by using numerical analyses and several datasets comprising 219 endemic species, 137 woody taxa, and 98 forest plant communities. These authors highlighted a major north-south and a secondary east-west ecological gradients structuring the relationships between biogeographic regions. They used the district subdivision instead of subsector which constitutes an intermediate unit.

However, these biogeographical sectorization based on expert's knowledge are non-replicable, and this directly or indirectly influenced the relevance of these biogeographical regionalizations (Gao & Kupfer, 2018). Thus, the lack of transparency and quantitative support has set constraints on their utility (Kreft & Jetz, 2010). Moreover, detecting boundaries between different biogeographical units is not upfront and some recent tests using biodiversity data question the validity of traditionally-established regionalizations (Chiarucci *et al*., 2019; Ficetola *et al*., 2017; Holt *et al*., 2013; Kreft & Jetz, 2010; Morrone, 2018).

Thus, the availability of novel multivariate techniques now enables a quantitative analysis and a more robust extension of biogeographical regionalization that will facilitate more rigorous uses (Kreft & Jetz, 2010). Indeed, the development of clustering procedures, together with the availability of extensive environmental datasets and accurate species distribution, raised the interest of biogeographers to release and assess the biogeographical unit boundaries by the use of replicable methods (Hattab *et al*., 2015; Kreft & Jetz, 2010). Some noteworthy cases are to be cited, for example, Italy (Abbate *et al.*, 2016), Sardinia (Fenu *et al*., 2014), Iberian Peninsula (Buira *et al*., 2017; Moreno Saiz *et al*., 2013), French Mediterranean region (Lenormand *et al*., 2019), Egypt (Abdelaal *et al.*, 2020), Maghreb (Walas & Taib, 2022), Atlantic Sahara (Chatelain *et al*., 2024), and sub-Saharan Africa (Linder *et al*., 2012). However, while big data has improved our ability to delineate biogeographical regions for many parts of the world (e.g., Edler *et al*., 2017; Holt *et al*., 2013; Morrone, 2018), some regions remain highly data-deficient (Farooq *et al*., 2021). Algeria, and especially its Sahara Desert, is one such region marked by deep biogeographical ignorance (Chatelain *et al*., 2024; Médail & Quézel, 2018), despite the first sectorisations proposed by Quézel (1978) and Le Houeron (1995). According to (Linder *et al*., 2012), species distribution data and modern cluster analysis techniques can be used now to define biogeographical regions in Africa that reflect the patterns of plant distribution.

Based on these shortfalls, we argue that the "historical" biogeographical units provided by Quézel & Santa (1962), does not reflect correctly the present biogeographical structure of Algeria, and this should be re-examinated on quantitative bases. Therefore, the aim of this study is to lay out a comprehensive biogeographical system for the vascular flora of Algeria, based on environmental features, together with the distribution of endemic plants. We present there in a statistically-derived biogeographic regionalization, identifying the most driven environmental variables (climate, topography, habitat and soil parameters), the indicator species and the relationships between the various biogeographical units.

2. Material and methods

2.1. Study area

Algeria is a North African and Maghreb country, bounded by coordinates 8.67°W-11.9°E and 18.9°N-37.1°N, with an area of 2,381,741 km^2. The topography of Algeria is characterised by two main mountain ranges: the Tell Atlas and the Saharan Atlas, dividing the country into three major natural regions: the Tell, which includes the coastline and the Tellian Atlas (4% of the total area of the country), the High Plateaus (Steppic), between the two mountain ranges (9%), and the Sahara south of the Steppic (87%). The major mountains include Tahat (2918 m asl) in the Ahaggar range, the Tassilin'Ajjer (2158 m asl), Djebel Chelia (2328 m asl) in the Aurès, Lalla Khedidja (2308 m asl) in the Djurdjura range, and Djebel Babor (2004 m asl) in the Babors range (Figure 1). From a climatic viewpoint, in the entire northern fringe of Algeria, the climate is exclusively of the Mediterranean type, with a high thermal and pluviometry variability (Despois & Raynal, 1975). On the contrary, the major characteristic of the Sahara region is its general aridity, which becomes extreme in the Tanezrouft, a region located across Algeria and Mali, in the western and southern part of the Sahara. Areas of the territory which receive more than 400 mm of rain per year are limited to a band of a maximum of 150 km deep from the coast (MEER, 2019). The Sahara's northern most strip receives limited rainfall in winter,while the southern areas experience rainfall primarily in the summer (Despois & Raynal, 1975; Loidi & Vynokurov, 2024). The mean annual precipitation and the average annual temperature in these three regions areas follow: 703.9±238.1 mm and 17.7±0.7 °C for the Tell, 328.7±59.4 mm and 15.9±0.8 °C for the High Plateaus, and 53.45±38.7 mm and 23.8±2.3 °C in the Sahara. From North to South, the climate of Algeria changes significantly. It goes from a humid Mediterranean type to a dry desert climate, passing through a semi-arid climate (MEER, 2019). Algeria's climate can be classified, according to the aridity index, into four categories: hyper-arid (89% of the total surface area of Algeria), arid (4.78%), semi-arid (4.12%), and dry subhumid (1.82%) (Zomer *et al*., 2022). The diversity of the geological bedrock (Hamimi *et al*., 2024), the wide variety of bioclimatic types (from hyper-arid to humid), the diverse origin of the flora, and the long-lasting isolation of mountains have generated a high diversity of habitats (Meddour, 2012), a great number of plants (4449 native and naturalised taxa) and endemic species in Algeria, representing 6.51% (Dobignard & Chatelain, 2013). Knowing that the Kabylies-Numidia-Kroumirie region constitutes a significant biodiversity hotspot, characterized by a mosaic of forests, mountainous terrain, and rich coastal ecosystems (Véla and Benhouhou, 2007).

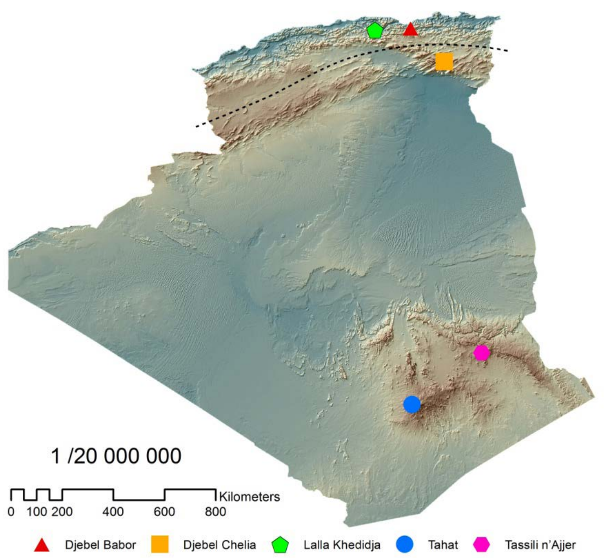

Figure 1. Geographic map highlighting the major mountain ranges in Algeria. Dotted line separates the Tell Mountain range from the Saharan mountain range.

2.2. Datasets of environmental features and endemic species

The environmental clustering in this study was based on 34 variables describing climate, topography, habitat heterogeneity, and soil (Appendix S1). A great part of the 27 climate variables were obtained from WorldClim version 2 with a spatial resolution of 30 arc seconds (~ 1 km), or 19 bioclimatic variables (Bio1 to Bio19) derived from the monthly temperature and rainfall values from the period 1970-2000 (worldclim.org/data/index.html) (Fick & Hijmans, 2017). The other 8 variables were downloaded from ENVIronmental Rasters for Ecological Modeling (ENVIREM), which provides data at the same resolution as WorldClim. These data include annual potential evapotranspiration, the Thornthwaite aridity index, the climatic moisture index, the continentality index, the Emberger's pluviothermic quotient, growing degree days at 0 °C, growing degree days at 5 °C, and the maximum temperature of the coldest month (envirem.github.io/) (Title & Bemmels, 2018). Topography was represented by elevation data obtained from ALOS World 3D (earth.jaxa.jp/en/data/2552/index.html) (Courty *et al.*, 2019). Four habitat heterogeneity metrics based on the textural features of the enhanced vegetation index (EVI) imagery namely, the coefficient of variation (normalised dispersion of EVI), evenness of EVI, range of EVI, and Shannon diversity of EVI were downloaded from EarthEnv version 1.0, available at 30 arc-second (~1 km) (earthenv.org/texture) (Tuanmu & Jetz, 2015). Finally, two soil data layers, soil pH (water) and organic carbon content at a depth interval of 0–30 cm, were downloaded from SoilGrids 2.0 (soilgrids.org/) (Poggio *et al*., 2021).

The list of strictly Algerian endemic species (defined by the borders of the country) was obtained from (Meddour *et al*., 2023), and the search for distribution data was conducted for a total of 249 endemic species and subspecies. Species occurrence points were primarily gathered from the GBIF database (gbif.org/fr/country/DZ), digitised herbaria, such as the Royal Botanic Gardens (Kew), the National Museum of Natural History of Paris (MNHN), and the University of Montpellier (MPU), published articles describing these species, or research-grade observations from iNaturalist (inaturalist.org/places/algeria). As a result, 641 occurrence points were collected. This low number of occurrences is explained by the fact that a high percentage of Algerian endemic plants have a narrow distribution range in Algeria and are often known from only one floristic region or even one site (Meddour *et al*., 2023).

2.3. Data analyses and clustering

All the environmental datasets were clipped and resampled to the same resolution (1969x1680 pixels, of approximately 1 km^2 each), then aligned using ArcGIS 10.5 (ESRI, 2021) and QGIS 2.18.0 (QGIS Development Team, 2019). To detect multicollinearity and identify the predictive variables, the *r.covar* module of GRASS GIS 7.0.5 (Grass Development Team, 2019) was used to calculate the covariance/correlation matrix. Variables with values greater than 0.5 were excluded from the next clustering step (Abdelaal *et al*., 2020; Walas & Taib, 2022), in order to exclude independent variables that are highly correlated.

Clustering analyses, based on environmental datasets and distribution of endemic species, have been widely applied to define statistically-derived biogeographic regionalization (Abbate *et al*., 2016;

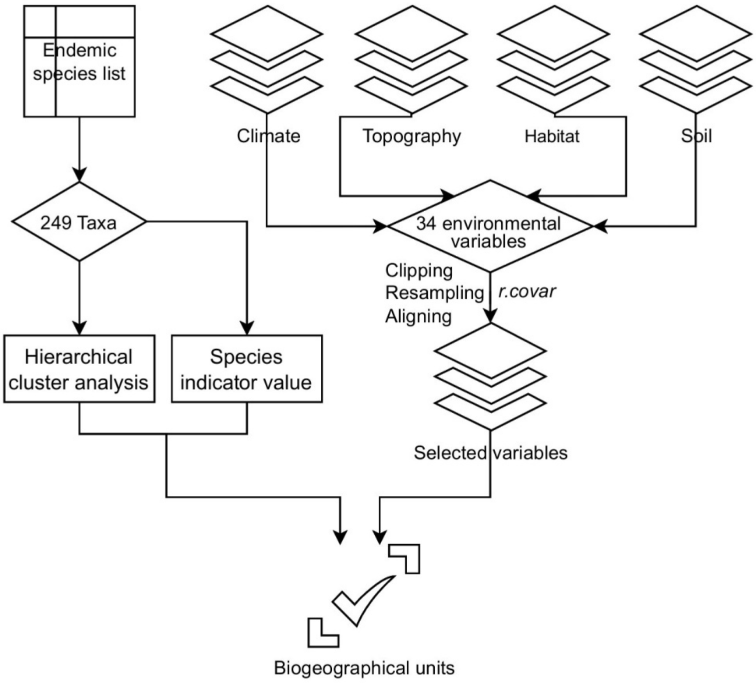

Figure 2. Conceptual diagram describing the methodology used to delineate biogeographical units.

Abdelaal *et al*., 2020; Bradshaw *et al*., 2015; Buira *et al.*, 2017; Kreft & Jetz, 2010; Linder *et al.*, 2012; Moreno Saiz *et al*., 2013; Rueda *et al*., 2010). In particular, the partitioning techniques, such as *k*-mean clustering have usually been employed for clustering grid cells in biogeographic analysis (e.g., Heikinheimo *et al*., 2007; Linder *et al*., 2012; Rueda *et al*., 2010; Valdés *et al*., 2006). The *k*-mean clustering aims to provide a classification of objects (grid cells) into *k* clusters in which each grid cell belongs to the cluster with the nearest centroid, serving as a prototype of the cluster (Buira *et al*., 2017). The value of *k* is decided by the user after an iterative procedure of object reallocation (Dufrêne & Legendre, 1997). The decision about how many clusters to recognize is necessarily subjective within the range of divisions (Kreft & Jetz, 2010). Therefore, the clustering process of selected environmental variables was based on the *k*-mean clustering for grids, using a combined iterative minimum distance and Hill-climbing method in SAGA 7.9.0 (Conrad *et al*., 2015), with a maximum of 10 iterations and normalizing grids by standard deviation before clustering. Generated rasters were filtered with the SAGA Majority filter for grids tool to minimise noise caused by isolated pixels in a cluster belonging to another cluster (Walas & Taib, 2022). The importance of a variable in a resulting cluster was estimated according to (Abdelaal *et al*., 2020), by the smallest shared value, calculated from the ratio of the range of a variable within a cluster to its overall range within the whole country, multiplied by 100. Thus, the shared value ranges between 0 and 100%, and variables with less than 30% were considered significant in the clustering process of that cluster.

After identifying the clusters, designated as sectors, a further subdivision was conducted using the same methodology to define biogeographical districts within each sector. Environmental datasets for each sector were clipped and resampled to a uniform resolution based on their boundaries. The tool *r.covar* was utilised to select variables for each cluster, with the corresponding covariance matrices provided in Appendix S2. The analysis process was based on *k*-mean clustering for grids, incorporating a combined iterative minimum distance and Hill-climbing method in SAGA 7.9.0.

However, it is important to highlight that there is no known procedure to decide which biogeographic unit should be assigned to a given area (Morrone, 2018). In the present study, we will follow (Loidi & Vynokurov, 2024) for lower-ranking units (i.e., sectors, districts); these units were named in relation to their current local toponymy in Algeria, with customized qualifiers.

Hierarchical cluster analysis (HCA) was based on the presence/absence data of the strict-endemic species (Algerian in our case) among the districts resulted from the *k*-mean clustering analysis, using the Unweighted Paired Group Mean Arithmetic (UPGMA) algorithm, as an agglomeration method, and the Euclidean distance to calculate the similarity index. This analysis is performed using Past 4.13 (Hammer *et al*., 2001), which is a software for scientific data analysis. Hierarchical methods construct a hierarchy of clusters. This is particularly useful for biogeographical purposes, because biogeographical regions are hierarchically arranged (Escalante, 2009) and the relative relationships between regions can be highly informative about underlying biogeographical connections and processes (Kreft & Jetz, 2010). According to Bradshaw *et al*. (2015), UPGMA was the consistently best performing clustering algorithm in biogeographic analysis.

To identify diagnostic species of a given cluster, the indicator value (IndVal) of species (Dufrêne & Legendre, 1997; MacCune & Mefford, 1999) was calculated for each sector and district using Past 4.13, with the statistical significance of these values estimated by 9,999 random permutations of sites across groups

(Hammer *et al*., 2001). We will therefore indicate for each biogeographic unit, the list of endemic species (or subspecies), and those which are “indicator species”. A species is considered as an indicator of a given cluster if it is faithful to it, that is to say absent or relatively less frequent in the other clusters, i.e., when its IndVal≥0.50 for $p \leq 0.05$ (Abdelaal *et al*., 2020).

The non-parametric ANOSIM (ANalysis Of Similarities) test was conducted using Past 4.13 to detect significant differences between clusters. This test compares the distances between groups to the distances within groups to assess similarity (Clarke, 1993). The significance level was determined through a one-tailed permutation test, with 9,999 replicates to ensure robust results.

Finally, we compared the spatial congruence of our biogeographical regionalization with the sectors and subsectors defined by Quézel & Santa (1962), and with the Ecoregions 2017 (Dinerstein *et al*., 2017); ecoregions.appspot.com). The conceptual diagram illustrating the methodology employed in this study is displayed in Figure 2.

3. Results

3.1. Environmental clusters

Applying the *k*-mean clustering method to environmental grid cells generates geographically compact clusters that are hierarchically nested and exhibit longitudinally elongated, sector-like shapes. This result suggests pronounced regional gradients within the environmental dataset analysed. By default, SAGA gives the number of 10 clusters, we did several tests with different values of *k* (between 8 and 20 clusters), and finally, we opted for the value of *k* which gives a model with the least noise and for which the boundaries between clusters are clearer.

From the ANOSIM test, with a probability of 0.05, comparing Algerian sectors, the similarity within sectors to similarity between sectors is higher in our regionalization (Appendix S3). There are thus statistically significant differences between these eight sectors and the number retained is therefore supported. However, environmental changes are less marked for the Steppic and Wahranian sectors.

Eight biogeographical clusters were thus identified in Algeria, mostly well defined by the environmental features, named from north to south: Algero-Kabylo-Annabian, Wahranian, Naïli-Constantinian, Steppic, Northern Saharan, Central Saharan, Tanezrouftian, and In Guezzamian. These clusters were distinguished by seven predictive environmental variables (3 bioclimatic, 1 topographic, 2 vegetational and 1 edaphic) (Table 1).

Table 1. Covariance matrix of the predictive variables for biogeographical clustering. Abbreviations are: AI, Thornthwaite aridity index; Elev, Elevation; Bio6, Min Temperature of Coldest Month; Bio18, Precipitation of Warmest Quarter; CV-EVI, Coefficient of variation of Enhanced Vegetation Index; Even-EVI, Evenness of Enhanced Vegetation Index; SOC, Soil organic carbon at a depth of 0-30 cm.

	AI	Elev (m)	Bio6 (°C)	Bio18 (mm)	CV-EVI	Even-EVI	SOC (dg/kg)
AI	1	-0.48	0.41	0.26	0.20	0.29	0.28
Elev (m)		1	-0.23	-0.10	-0.08	-0.12	-0.11
Bio6 (°C)			1	-0.02	-0.19	-0.16	-0.26
Bio18 (mm)				1	0.42	0.37	0.62
CV-EVI					1	0.58	0.50
Even-EVI						1	0.47
SOC (dg/kg)							1

The importance of the predictive variables in each environmental cluster is described by the shared values in Table 2. The coefficient of variation of EVI is the most important variable in distinguishing these clusters, except for the Wahranian and Northern Saharan sectors. Additionally, the Thornthwaite Aridity Index is significant in all sectors, except for Algero-Kabylo-Annabian and Wahranian sectors. However, the Precipitation of the Warmest Quarter (Bio18) is important for the Northern Saharan and Tanezrouftian sectors. In contrast, the elevation, the minimum temperature of the coldest month (Bio6), and the soil organic carbon are significant for the In Guezzamian sector.

Table 2. Importance of the predictive variables in environmental clusters as indicated by shared values (values below 30% are highlighted in bold). Abbreviations are: AI, Thornthwaite aridity index; Elev, Elevation (m asl); Bio6, Min Temperature of Coldest Month (°C); Bio18, Precipitation of Warmest Quarter (mm); CV-EVI, Coefficient of variation of Enhanced Vegetation Index; Even-EVI, Evenness of Enhanced Vegetation Index; SOC, Soil organic carbon at a depth of 0-30 cm (dg/kg).

	Algero-Kabylo-Annabian	Naïli-Constantinian	Wahranian	Steppic	Northern Saharan	Central Saharan	Tanezrouftian	In Guezzamian
AI	99.8	**0.2**	99.8	**0.3**	**0.2**	**0.1**	**0.0**	**0.0**
Elev	74.0	80.7	66.3	70.1	69.5	91.6	64.5	**20.9**
Bio6	67.0	63.7	58.2	48.9	50.5	50.0	33.0	**24.2**
Bio18	100	63.3	51.1	51.1	**24.4**	43.3	**27.8**	43.3
CV-EVI	**24.2**	**23.9**	35.9	**24.1**	100	**26.0**	**25.7**	**14.0**
Even-EVI	100	100	100	100	100	100	100	100
SOC	100	82.5	86.0	44.6	72.1	38.6	32.8	**6.3**

The second environmental-based clustering identified subclusters within the previously defined clusters, assigned to district units. Consequently, 20 subclusters were distinguished and are represented in Figure 3. The results indicate the presence of three districts in the Algero-Kabylo-Annabian, three districts in the Wahranian sector, four districts in the Naïli-Constantinian sector, four districts in the Steppic sector, three districts in the Northern Saharan sector, and two districts in the Central Saharan sector. The Tanezrouftian and In Guezzamian clusters were not sub-clustered, due to no predictive variables.

The significance of the predictive variables in environmental subclusters is described in Appendix S2. 13 climatic-related variables, mainly the Thornthwaite aridity index (AI) and the Precipitation Seasonality (coefficient of variation) (Bio15), elevation, soil organic carbon, pH_{water} and EVI (coefficient of variation and evenness) were the most important determining factor for the environmental sub-clustering (Table 3). The main inferred gradients of these variables are underlying the sectorisation of the districts.

The main climatic features and the elevation of the biogeographical sectors and districts of Algeria are presented in Table 4 (a web-map displaying these variables is available for consultation at: dtahri.github.io/bioclimatic_variables/).

First of all, the annual rainfall decreases across sectors from north to south in Algeria, contrary to the annual potential evapotranspiration, suggesting relatively strong latitudinal changes in these variables and their correlates. The Algero-Kabylo-Annabian sector stands out from the others due to its high rainfall (Bio12 = 843 mm/year), while the four Saharan sectors, with an annual rainfall less than 100 mm, are subject to the highest potential evapotranspiration. Furthermore, the Tanezrouftian sector can be considered the most hostile due to its negligible rainfall, sometimes ranging from 6 to 9 mm per year (16.4 mm in average), high mean annual temperature (26.33 °C), significant temperature annual range (35.9 °C), and high potential evapotranspiration of 3711.6 mm (Table 4). The Central Saharan sector exhibits mountainous ranges with a weaker mean annual temperature (23.7 °C) than its surrounding sectors (more than 26 °C). The Naïli-Constantinian sector is characterised by a low average of annual temperature (14.9 °C), high temperature range (31.9 °C), and a significant altitude (918 m asl).

3.2. Endemism in the biogeographical units and their indicator species

Twenty districts, along with the Tanezrouftian and In Guezzamian sectors, are represented by the Hierarchical Cluster Analysis dendrogram in Figure 4, depicting the biogeographic similarity between districts, based on the occurrence of 249 Algerian endemic species.

Eight biogeographical sectors can be classified into five main groups based on a decreasing rate of endemism, starting from the Eastern coastal zone (Algero-Kabylo-Annabian sector), the Western coastal zone (Wahranian sector), the Eastern inland zone (Naïli-Constantinian sector), the Steppic and Atlas Saharan zone (Steppic sector), and finally the Saharan zone (Northern Saharan, Central Saharan, Tanezrouftian, and In Guezzamian sectors). Conversely, the geographical area increases in this order, with 0.95%, 1.36%, 3.84%, 6.73% and 87.12% for the five groups, respectively (Table 5). The Algero-Kabylo-Annabian sector owns the highest number of endemic species (102, or 41%) and indicator species (90). This sector shows the maximum floristic distinctiveness, across all its districts, as indicated by the dendrogram. Then, the Naïli-Constantinian sector contains 79 endemic species (31.7%), with 56 indicator species, the Wahranian sector has 55 endemic species (22%), with 48 indicator species, and the Steppic sector has 47 endemics (18.9%) and 35 indicator species. Then, the endemism rate notably decreases in the Saharan sectors, with 17 endemic species (6.8%) and 11 indicator species, in the Northern Saharan sector, and 15 endemics (6%), almost all of which are indicator species, in the Central Saharan sector. The Tanezrouftian and In Guezzamian sectors have the fewest endemic species, 2 and 1, respectively. The lists of endemic and indicator species for each sector are indicated in Appendix S4.

Indicator Species Analysis results showed that almost all the districts have a noticeable number of endemic and indicator species (Figure 5). The Jijelo-Annabian (J), Kabylian (K), Wahranian littoral (W), Algiers littoral (A), Constantinian (C), Saïdian (S) districts have the highest number of endemic and indicator species (10 or more indicator species with a significant *p*-value). Each district is clearly distinguishable by at least four indicator species, with the exception of the Tindoufian district, which is characterized by only one known indicator species to date. In particular, the results highlighted the special richness of Jijelo-Annabian district (J), with 57 endemic species of which 43 had an indicator value. Besides, the Kabylian district (K) has a high number of endemic and indicator species (38 and 31, respectively) despite its smallest area in Algeria (5300 km^2). On the contrary, subsectors with larger areas (between 110000 and 680000 km^2) have a low number of endemics (and indicator species), as Becharo-Mzabian (BM): 13 (8), Tassilian (TA): 9 (8), Ahaggarian (AH): 7 (6), Tadmaïto-Golean (TG): 6 (4), and Tindoufian (TI): 1 (0). The districts with higher levels of endemicity are of particular interest, as they host indicator species that serve as markers for these unique biogeographic regions, highlighting their ecological significance and distinctiveness. These species are specifically indicative of the environmental conditions of their districts. The lists of endemic and indicator species for each district are presented in Appendix S5. Endemic species belonging to the Asteraceae family make it the most represented across all sectors, accounting for 14%, followed by the Fabaceae (13%), Lamiaceae (10%), Caryophyllaceae (8%), and the Brassicaceae, Poaceae, and Papaveraceae families, each representing 7%.

Table 3. Predictive variables used in environmental subclustering of the sectors. Abbreviations are: Elev, Elevation (m asl); AI, Thornthwaite aridity index; CV-EVI, Coefficient of variation of Enhanced Vegetation Index; Even-EVI, Evenness of Enhanced Vegetation Index; SOC, Soil organic carbon at a depth of 0-30 cm (dg/kg); Bio2, Mean Diurnal Range (Mean of monthly (max temp - min temp) (°C); Bio3, Isothermality (Bio2/Bio7) (×100); Bio4, Temperature Seasonality (standard deviation ×100); Bio6, Min Temperature of Coldest Month (°C); Bio7, Temperature Annual Range (°C); Bio8, Mean Temperature of Wettest Quarter (°C); Bio14, Precipitation of Driest Month (mm); Bio15, Precipitation Seasonality (Coefficient of Variation); Bio16, Precipitation of Wettest Quarter (mm); Bio18, Precipitation of Warmest Quarter (mm); pH_{water}, Soil pH (water), Moist, Climatic Moisture Index: a metric of relative wetness and aridity; Cont, Continentality: average temp. of warmest month-average temp. of coldest month (°C).

	Algero-Kabylo-Annabian	Naïli-Constantinian	Wahranian	Steppic	Northern Saharan	Central Saharan
Elev	+	+	+	+	+	
AI	+	+	+	+	+	
Bio2				+		
Bio3						+
Bio4					+	
Bio6						+
Bio7	+		+			
Bio8		+			+	+
Bio14	+	+		+		
Bio15			+	+	+	+
Bio16			+			
Bio18	+		+			+
CV-EVI	+		+	+	+	+
Even-EVI	+	+	+	+	+	+
SOC	+	+	+	+	+	+
pH_{water}		+	+	+	+	
Moist		+				
Cont		+				

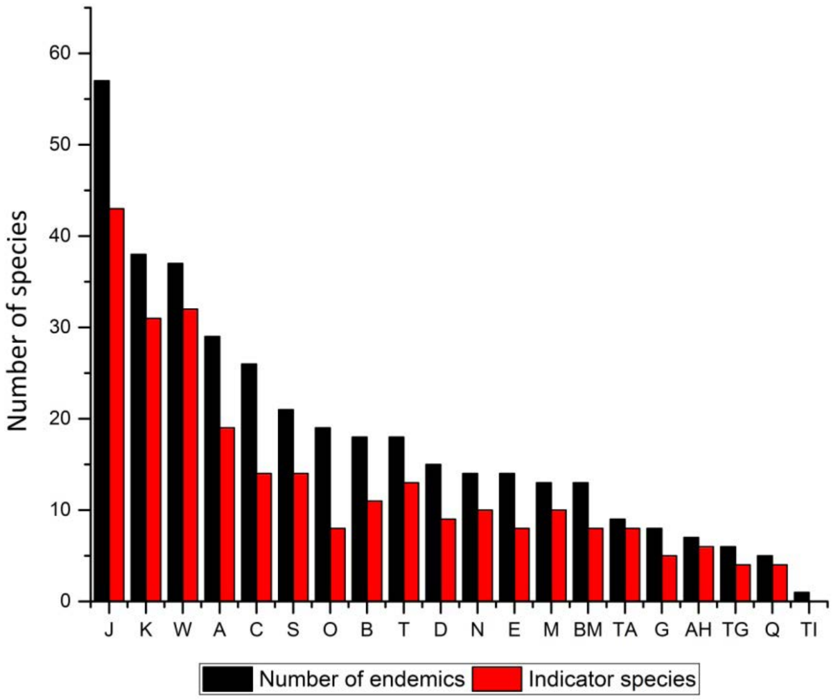

Figure 5. Numbers of endemic and indicator species of each biogeographic district in Algeria (linear correlation coefficient between the two variables is 0.975, indicating a strong positive relationship between them). See Figure 3 for the full denomination and the geographical location of each district.

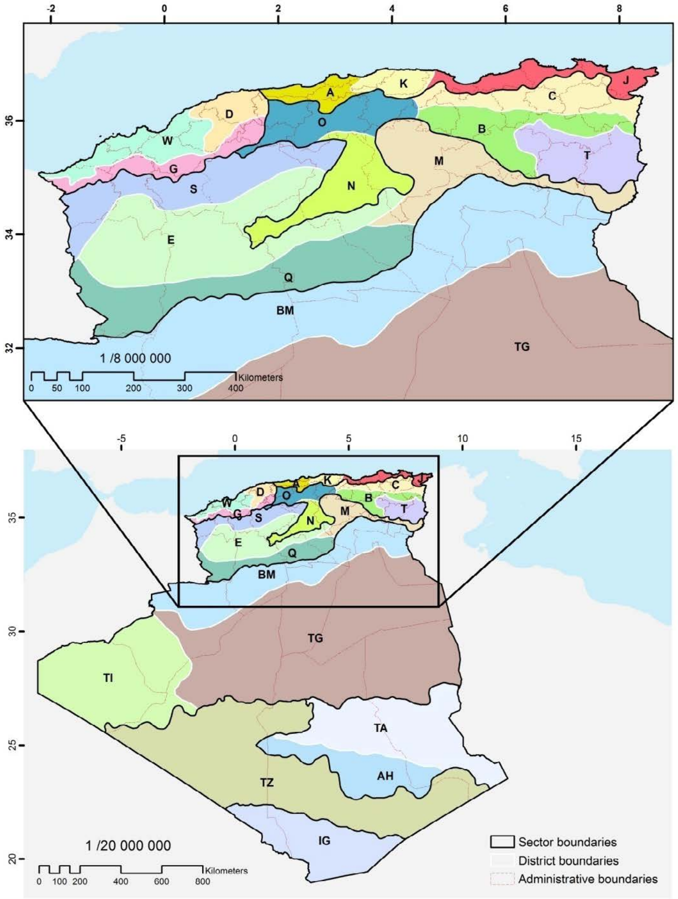

Figure 3. Biogeographical map of the sectors and districts of Algeria, resulted from the *k*-mean clustering analysis, along with their new nomenclature, abbreviations and boundaries. Biogeographic typology: Holarctic Kingdom: I, Mediterranean Region: A1, Mediterranean North African Province, Algero-Kabylo-Annabian sector (A, Algiers littoral district; K, Kabylian district; J, Jijelo-Annabian district), Wahranian sector (W, Wahranian littoral district; D, Dahran district; G, Ghrissian district), Naili-Constantinian sector (O, Ouarsenian district; C, Constantinian district; B, Belezmo-Auresian district; T, Tebessian district; N, Naïlian district). A2, Steppic North African Province, Steppic sector (S, Saïdian district; E, El-Bayadhian district; Q, Qsourian district; M: Msilian district). II, Saharo-Arabian Region B, Mediterranean Saharan province, Northern Saharan sector (BM, Becharo-Mzabian district; TG, Tadmaïto-Golean district; TI, Tindoufian district), Central Saharan sector (TA, Tassilian district; AH, Ahaggarian district); TZ, Tanezrouftian sector; IG, InGuezzamian sector.

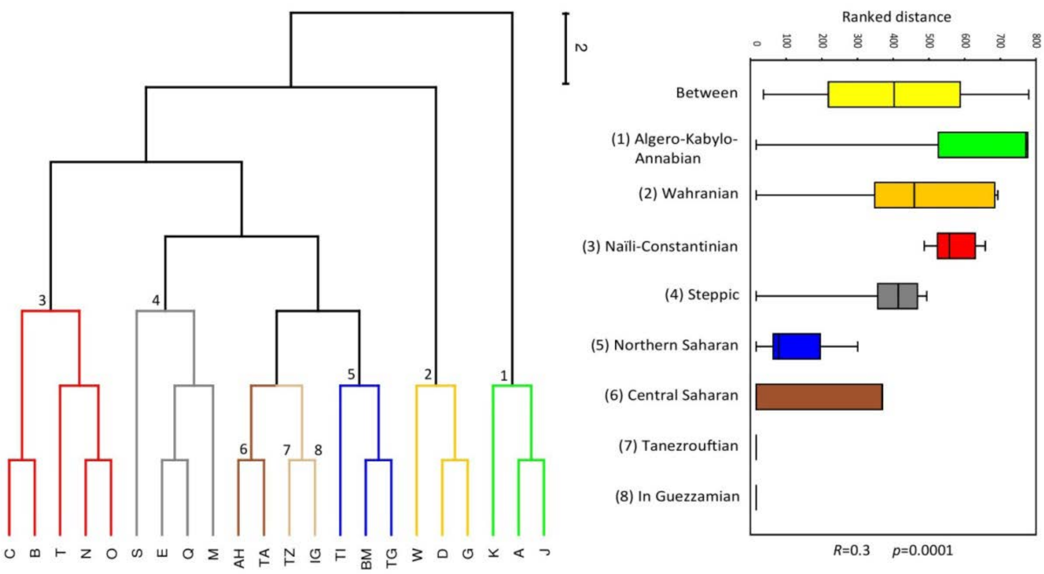

Figure 4. Dendrogram of Hierarchical Cluster Analysis (UPGMA method/Euclidean distance) depicting the biogeographic similarity between districts of Algeria, based on the occurrence of strict-endemic species in the clusters of the *k*-mean clustering analysis. The eight distinct floristic sectors are highlighted in the dendrogram with different colours. Biogeographic typology: A, Algiers littoral district; K, Kabylian district; J, Jijelo-Annabian district; W, Wahranian littoral district; D, Dahran district; G, Ghrissian district; O, Ouarsenian district; C, Constantinian district; B, Belezmo-Auresian district, T: Tebessian district, N: Naïlian district, S: Saïdian district; E, El-Bayadhian district; Q, Qsourian district; M, Msilian district; BM, Becharo-Mzabian district; TG, Tadmaïto-Golean district; TI, Tindoufian district; TA, Tassilian district; AH, Ahaggarian district; TZ, Tanezrouftian sector; IG, InGuezzamian sector.

Table 4. Bioclimatic features and elevation of biogeographical sectors and districts in Algeria. Abbreviations are: Bio1, Annual Mean Temperature (°C); Bio7, Temperature Annual Range (°C); Bio12, Annual Precipitation (mm); PET, Potential Evapotranspiration (millimeters per year); Elev, Elevation (m asl); Biogeographic typology: A, Algiers littoral district; K, Kabylian district; J, Jijelo-Annabian district; W, Wahranian littoral district; D, Dahran district; G; Ghrissian district; O, Ouarsenian district; C; Constantinian district; B, Belezmo-Auresian district; T, Tebessian district; N, Naïlian district; S, Saïdian district; E, El-Bayadhian district; Q, Qsourian district; M, Msilian district; BM, Becharo-Mzabian district; TG, Tadmaïto-Golean district; TI, Tindoufian district; TA, Tassilian district; AH, Ahaggarian district; TZ, Tanezrouftian sector; IG, InGuezzamian sector.

Sectors	Bio1	Bio7	Bio12	PET	Elev
Algero-Kabylo-Annabian	16.34 ± 1.48	26.03 ± 1.75	843.05 ± 155.44	1613.68 ± 66.55	430.2 ± 353.91
Naïli-Constantinian	14.95 ± 1.33	31.96 ± 1.9	453.15 ± 147.26	1784.67 ± 124.69	918.6 ± 302.9
Wahranian	17.6 ± 0.78	29.19 ± 1.98	423.69 ± 58.01	1785.54 ± 73.03	319.54 ± 207.9
Steppic	16.06 ± 1.33	34.21 ± 1.44	260.54 ± 78.96	2112.81 ± 190.73	1019.81 ± 232.77
Northern Saharan	22.82 ± 1.935	38.33 ± 1.6	49.55 ± 33.85	3222.34 ± 390.36	443.9 ± 214.08
Central Saharan	23.71 ± 1.86	34.83 ± 2.14	28.55 ± 10.94	3473.52 ± 208.33	910.1 ± 365.55
Tanezrouftian	26.33 ± 1.11	35.92 ± 2.67	16.41 ± 6.84	3711.56 ± 149.58	468.27 ± 227.78
In Guezzamian	26.8 ± 0.68	32.66 ± 1.85	40.12 ± 11.05	3663.65 ± 89.27	520.75 ± 96.29

Sector	District	Bio1	Bio7	Bio12	PET	Elev
Algero-Kabylo-Annabian	A	16.66 ± 1.4	26.53 ± 1.31	711.59 ± 64.11	1649.47 ± 61.45	411.48 ± 362.71
	K	16.22 ± 1.63	26.73 ± 1.71	913.3 ± 104.72	1624.13 ± 54.15	499.27 ± 368.6
	J	16.13 ± 1.4	25.05 ± 1.71	921.3 ± 162.9	1571.8 ± 55.2	400.16 ± 328.5
Naïli-Constantinian	O	15.74 ± 1.19	31.3 ± 1.47	522.32 ± 103.31	1767.14 ± 79.22	755.28 ± 235.72
	C	15.59 ± 1.37	29.82 ± 1.58	678.51 ± 92.54	1670.62 ± 58.18	634.71 ± 313.95
	B	14.29 ± 1.39	31.96 ± 1.37	431.97 ± 74.37	1727.05 ± 90.1	1008.15 ± 265.04
	T	14.9 ± 1.04	32.84 ± 1.56	365.43 ± 52.6	1866.17 ± 100.46	1041.6 ± 196.95
	N	14.97 ± 0.9	33.7 ± 1.03	301.9 ± 28.3	1928.96 ± 70.01	1043.1 ± 227.36
Wahranian	W	17.91 ± 0.61	28.16 ± 1.77	384.64 ± 39.7	1751.9 ± 78.7	206.6 ± 159.2
	D	17.61 ± 0.7	29.94 ± 1.7	464.46 ± 52.6	1812.95 ± 53.1	346.19 ± 166.45
	G	16.62 ± 0.71	30.3 ± 1.68	431 ± 35.14	1812.93 ± 58.12	589.85 ± 162.9
Steppic	S	15.1 ± 0.81	32.71 ± 1.32	379.5 ± 69.2	1864.5 ± 87.63	996.6 ± 196.04
	E	15.7 ± 0.8	34.4 ± 0.85	254.8 ± 36.11	2116.2 ± 117.91	1118.95 ± 134.26
	Q	17.5 ± 1.1	36.06 ± 0.7	158.98 ± 31.9	2417.54 ± 103.45	1002.41 ± 241.62
	M	17.67 ± 1.53	33.8 ± 1.76	214.5 ± 53.86	2160.68 ± 151.9	642.53 ± 204.62
Northern Saharan	BM	20.72 ± 1.11	36.9 ± 1.44	89.5 ± 24.91	2794.8 ± 211.7	550.58 ± 288.72
	TG	23.43 ± 1.16	38.81 ± 1.07	31.28 ± 14.24	3360.6 ± 263.51	363.66 ± 146.1
	TI	24.75 ± 1.27	39.49 ± 1.21	28.11 ± 19.44	3579.34 ± 223.52	456.99 ± 99.73
Central Saharan	TA	23.81 ± 1.64	35.36 ± 1.94	26.9 ± 8.72	3479.2 ± 199.61	854.28 ± 328.5
	AH	23.5 ± 2.27	33.6 ± 2.1	32.2 ± 14.3	3460.2 ± 227.49	1040.44 ± 412.7

4. Discussion

4.1. A strong environmental determinism and latitudinal gradient

The bioregionalization with the *k*-mean clustering reveals a strong latitudinal division of Algeria between a Mediterranean northern region and a Saharan southern region, based on differences in their bioclimatic, topographic, edaphic, and floristic aspects. We identified the environmental predictors with the highest explanatory value for the partitioning of the sectors: Thornthwaite aridity index (AI), elevation, Min Temperature of Coldest Month (Bio6), Precipitation of Warmest Quarter (Bio18), Coefficient of variation of Enhanced Vegetation Index (EVI), Evenness of EVI, and soil organic carbon (SOC). Justly, four out of these seven environmental variables were also mentioned as significant for the biogeographical clustering of the entire Maghreb by Walas & Taib (2022).

However, the most important factors were climatic variables, such as the Thornthwaite aridity index (AI), which is a quantitative indicator of the degree of water deficiency present at a given location, based on P/PET ratio (Le Houeron, 1995). It's not surprising for a large country that embraces three major climatic regions across a latitudinal gradient: Mediterranean, Steppic, and Saharan (from north to south). There is a strong latitudinal gradient in the aridity index, which ranges from humid in the northern areas close to the Atlas Mountain chain to hyper-arid close to the Tassili N'Ajjer mountain (Zomer *et al*., 2022). The same trend is observed in other desertic regions of North Africa (Abdelaal et al., 2020; Chatelain *et al*., 2024). For instance, potential evapotranspiration in the Central Sahara, combined with low precipitation, is very high and constitutes a major environmental constraint (Walas & Taib, 2022).

Table 5. Number of endemics and indicator species for each sector and district in Algeria. For abbreviations see Figure 3.

Sector	Area (km²)	Number of endemics	Indicator species	District	Area (km²)	Number of endemics	Indicator species
Algero-Kabylo-Annabian	22000	102	90	A	5900	29	19
				K	5300	38	31
				J	10800	57	43
Naïli-Constantinian	89000	79	56	O	16400	19	8
				C	16500	26	14
				B	19100	18	11
				T	18300	18	13
				N	18700	14	10
Wahranian	32000	55	48	W	13000	37	32
				D	7800	15	9
				G	11200	8	5
Steppic	160300	47	35	S	31500	21	14
				E	62600	14	8
				Q	41000	5	4
				M	25200	13	10
Northern Saharan	1110100	17	11	BM	160100	13	8
				TG	680000	6	4
				TI	270000	1	0
Central Saharan	330200	15	14	TA	220200	9	8
				AH	110000	7	6
Tanezrouftian	487100	2	2				
In Guezzamian	151000	1	1				

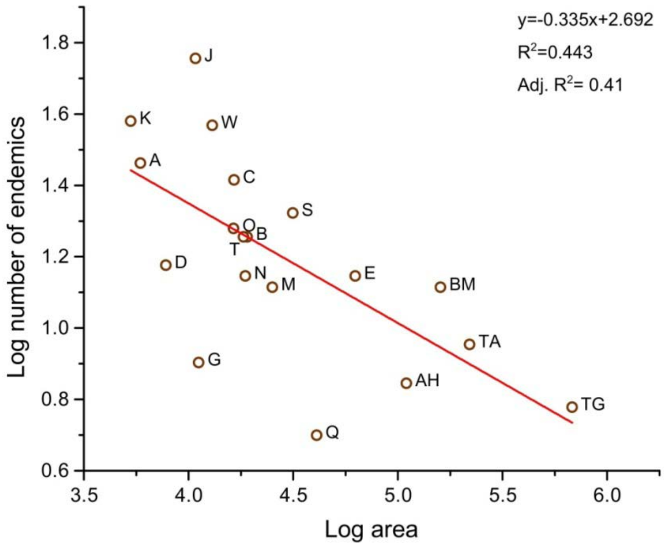

Figure 6. Endemics-area relationships for the biogeographical units (see definition and location in Figure 3) resulted from the *k*-mean clustering analysis: correlation between the number of endemic species and the district area (km²).

Besides, the distribution of endemic plant species is structured by multiple parameters, notably the level of aridity (Chatelain *et al*., 2024). Thus, Algeria is well compartmentalized, with a strong north-to-south rainfall/evapotranspiration/aridity gradient. The strong climatic determinism in biogeographic regionalization, and a major north–south gradient defining the relationships between biogeographical areas in Algeria were already established by Meddour *et al*. (2019).

4.2. Endemism richness and distribution patterns

The distribution patterns of the endemic flora have often been used for classifying biogeographical areas (e.g., Abdelaal *et al*., 2020; Bradshaw *et al*., 2015; Buira *et al*., 2017; Fenu *et al*., 2014; Walas & Taib, 2022). Since the existence of endemic taxa and their distribution are related to geographic areas, they are key elements in biogeographical regionalization (Crisp *et al*., 2001). An advantage of defining biogeographic areas using endemic taxa is that they are more likely to be indicative of the interaction between local historical processes and contemporary factors (Bradshaw *et al*., 2015; Chiapella & Demaio, 2015). Each of the biogeographical area of Algeria has a unique flora, which have diagnostic value (Kaplan, 2017). Indeed, we found a high indicator and differential value of the endemic flora in the partitioning and arrangement of various districts, sectors and areas of Algeria, as previously shown by Meddour *et al*. (2019). Each identified biogeographic district meets environmental and topographic conditions that have allowed the differentiation in its species composition. Endemic richness was strongly correlated with the area's orography, with mountains being the most important orographic feature. For example, districts with high elevation presents a particular endemism: *Juniperus thurifera* subsp. *aurasiaca* (Véla & P. Schäf.) Véla (Belezmo-Auresian district), *Cupressus dupreziana* A. Camus (Tassilian district), etc.

Moreover, according to Vavrek (2016), a higher endemicity creates more highly differentiated clusters. In our case, the Jijelo-Annabian (J), Kabylian (K), Wahranian (W) districts were highly distinguished from the other districts due to their higher richness in endemics, a similar finding was previously reported by Véla and Benhouhou (2007). According to Meddour *et al*. (2023), a large percentage of the Algerian endemic flora is constituted by range-restricted taxa, which greatly individualise these coastal Mediterranean areas biogeographically, as they constitute indicator species.

4.3. Endemics-area relationship (EAR), correlation between the number of endemic species and the district area

The species-area relationship (SAR) describes the very general tendency for species number to increase with habitat area (Lomolino, 2001), as for the endemics-area relationship (EAR). However, SAR is not necessarily linear, and the number of endemics does not necessarily increase linearly with area, when the compared regions have very different areas (Fattorini, 2017). As shown in Iberian and Balearic regions, Buira *et al*. (2017) observe that surface does not directly affect the number of endemics. Indeed, the correlation between the number of endemic species and the district area in Algeria is moderate (R^2 = 0.44), yet it helps to explain the non-linear relationship observed between these two variables (Figure 6).

Buira *et al*. (2017) specified that the areas with compact reliefs, i.e., with a high density of mountains, plains, valleys and plateaus, usually have a high rate of endemics plants (and a larger proportion of diagnostic species). Specifically, the Tell districts with compact reliefs are characterised by smaller surface areas, but a high number of endemic species, whilst there is a stark contrast with the Saharan districts, where large and open areas correspond to a much lower number of endemics. This suggests that while the overall correlation may be moderate, the geographic context plays a significant role in shaping the distribution of endemic species across different regions. The case of the Saharan districts could be useful to test whether the desertic areas deviate from the common pattern of species/endemics-area relationship.

4.4. The extent of congruence of the new biogeographical sectors with Ecoregions 2017

According to Dinerstein *et al*. (2017), ten ecoregions can be identified in Algeria stretching from north to south (see ecoregions.appspot.com). Mediterranean conifer and mixed forests (0.6% of the total area), Mediterranean woodlands and forests (5.7%), and Mediterranean dry woodlands and steppe (7.5%) cover the Northern Algeria (i.e., 13.8% of the area). North Saharan Xeric Steppe and Woodland (22.2%), Saharan halophytics (0.6%), West Sahara Desert (29.7%), South Sahara Desert (22.4%), West Saharan Montane Xeric Woodlands (8.3%), East Sahara Desert (2%), and Sahelian Acacia Savanna (1%) are covering the overall Algerian Sahara (86.2%). A detailed description of the seven ecoregions of the Sahara is provided by Naia & Brito (2021).

When compared to our results, the Mediterranean woodlands and forests Mediterranean conifer and mixed forests ecoregions encompass the Algero-Kabylo-Annabian, the Wahranian and the Naïli-Constantinian sectors. The Mediterranean dry woodlands and steppe overlaps more or less the Steppic sector (with the entire Saharan Atlas). Notably, the boundaries between the Steppic and the Northern Saharan sectors coincide with the transition from Mediterranean dry woodlands and steppe to North Saharan Xeric Steppe and Woodlands ecoregions. This pattern is also evident in the boundaries of the Northern Saharan sector with the Tanezrouftian and Central Saharan sectors, where they align with the divisions between the West Sahara Desert, South Sahara Desert, and North Saharan Xeric Steppe and Woodlands. Furthermore, it is important to highlight that the Central Saharan sector, specifically the Tassilian and Ahaggarian districts corresponding to the high Saharan mountains of Quézel (1978) or the altimontane Sahara of Le Houeron (1995), is distinctly representative of the West Saharan Montane Xeric Woodlands ecoregion, while the In Guezzamian sector is congruent with the Sahelian Acacia savanna ecoregion (Dinerstein *et al*., 2017; Naia & Brito, 2021). The comparative map of Algeria's ecoregions alongside the districts identified in this study is available in Figure 7 and for online consultation (dtahri.github.io/ecoregions_algeria/).

4.5. Comparison and congruence between the new biogeographical sectors and the traditional biogeographic map of Algeria

Recent comparative studies on historical climate suggest that geographic isolation plays a more significant role in dividing the Saharo-Arabian and Holarctic realms. However, future projections (2040–2100) predict a decrease in phylogenetic beta diversity, potentially leading to greater homogenization of biogeographic regions. Despite this trend, certain regions, such as the Circumboreal, Afrotropics, Saharo-Arabian, Malesian, and Indian-Indochinese areas, are expected to remain similar to present-day floristic regions (Liu *et al*., 2023;

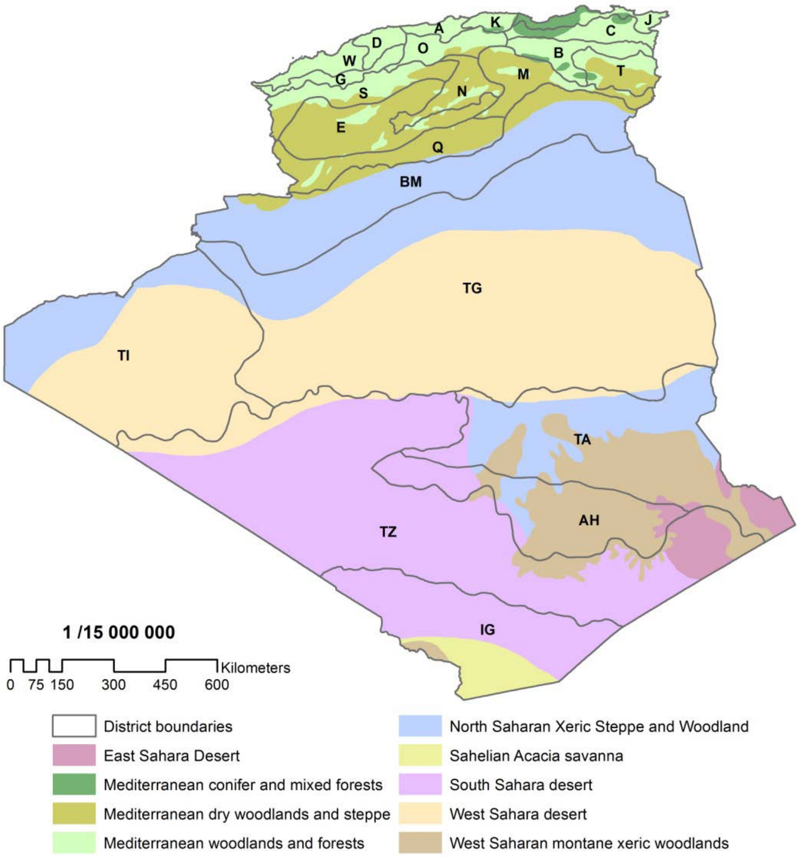

Figure 7. Comparison of the new proposed biogeographical sectorisation with Ecoregions 2017 (Dinerstein *et al.*, 2017). Biogeographic typology: A, Algiers littoral district; K, Kabylian district; J, Jijelo-Annabian district; W, Wahranian littoral district, D, Dahran district; G, Ghrissian district; O, Ouarsenian district; C, Constantinian district; B, Belezmo-Auresian district; T, Tebessian district; N, Naïlian district; S, Saïdian district; E, El-Bayadhian district; Q: Qsourian district; M, Msilian district; BM, Becharo-Mzabian district; TG, Tadmaïto-Golean district; TI, Tindoufian district; TA, Tassilian district; AH, Ahaggarian district; TZ, Tanezrouftian sector; IG, InGuezzamian sector.

Table 6. Correspondence of the biogeographic units from this study with those established by Quézel & Santa (1962).

Present study		Quézel & Santa (1962)	
Sector	District	Sub-sector	Sector
Wahranian	W	O1	Oranian
	D	O2	
	G	O3	
Algero-Kabylo-Annabian	K	K1	Kabyle and Numidian
	J	K2	
		K3	
	A	A1	Algiers
Naïli-Constantinian	O	A2	
	C	C1	Tell Constantinois
	B	H2	High Plateaus
	T		
	N	H1	
Steppic	S		
	E		
		AS2	Saharan Atlas
	Q	AS1	
	M	AS3	
		Hd	Northern Sahara
Northern Saharan	BM	SS1+SS2 (North part)	
	TG	SS1+SS2 (South part)	
	TI	SO	Western Sahara
Tanezrouftian	TZ	SS1 (South part)	Northern Sahara
Central Saharan	TA	SC	Central Sahara
	AH		
In Guezzamian	IG	SM	Southern Sahara

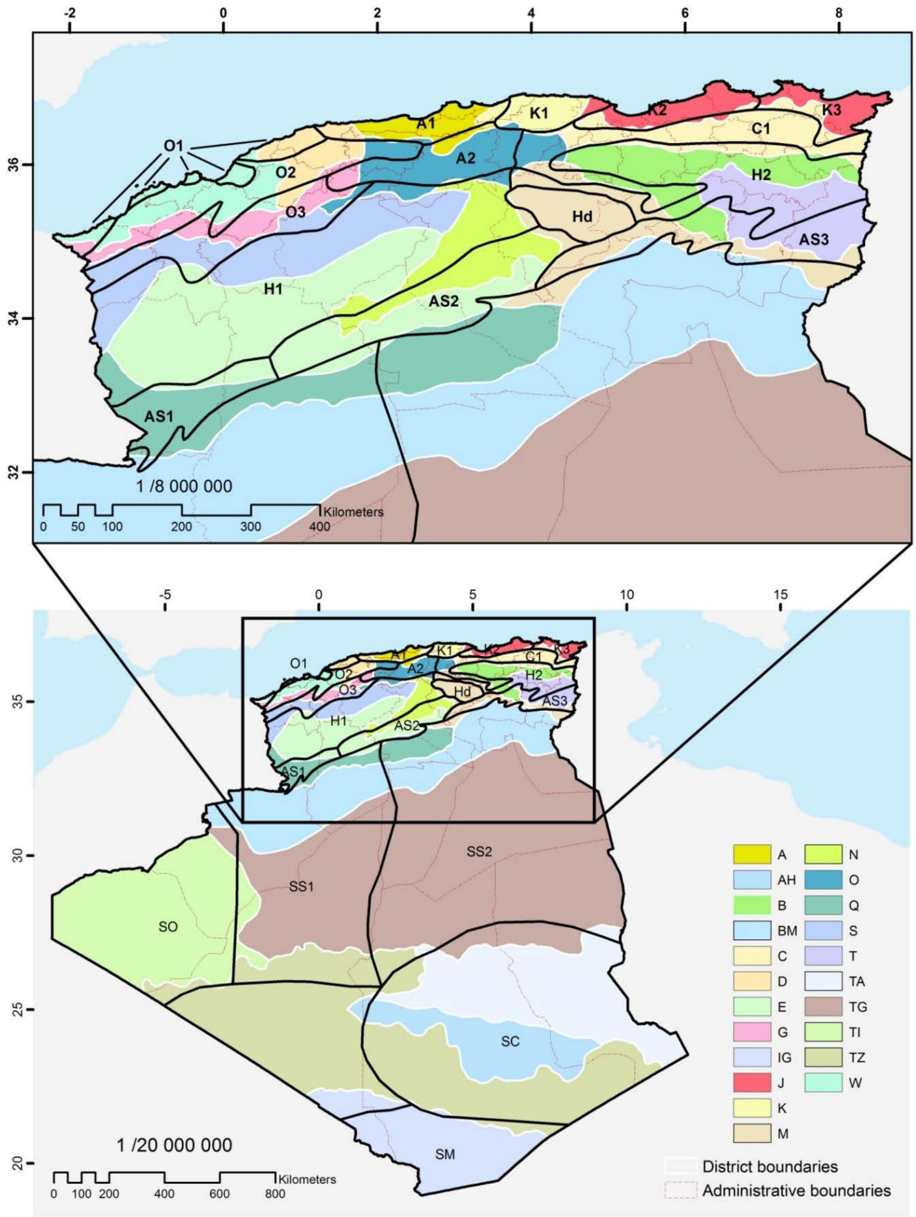

Figure 8. Comparison of the previous biogeographical divisions of Algeria by Quézel & Santa (1962) with the new proposed biogeographical sectorisation. Biogeographic typology, A1; Coastal subsector; A2, Tell Atlas subsector; K1, Greater Kabylia; K2, Lesser Kabylia; K3, Numidia; C1, Constantine Tell sector; O1, Coastal Sahels subsector; O2, Coastal plains subsector; O3, Tell Atlas subsector; H1, Algiers and Oran High Plains subsector; H2, Constantine High Plains subsector; AS1, Oran Saharan Atlas subsector; AS2, Algiers Saharan Atlas subsector; AS3, Constantine Saharan Atlas subsector; Hd, Hodna subsector; SS1, Western Northern Sahara subsector; SS2, Eastern Northern Sahara subsector; SC, Central Sahara sector; SO, Western Sahara sector; and SM, Southern Sahara sector; A, Algiers littoral district; K, Kabylian district; J, Jijelo-Annabian district; W, Wahranian littoral district; D, Dahran district; G; Ghrissian district; O, Ouarsenian district; C; Constantinian district; B, Belezmo-Auresian district; T, Tebessian district; N, Naïlian district; S, Saïdian district; E, El-Bayadhian district; Q, Qsourian district; M, Msilian district; BM, Becharo-Mzabian district; TG, Tadmaïto-Golean district; TI, Tindoufian district; TA, Tassilian district; AH, Ahaggarian district; TZ, Tanezrouftian sector; IG, InGuezzamian sector.

Minev-Benzecry and Daru, 2024). As an independent evaluation of the bioregionalization by *k*-mean clustering, we compare the new map proposed in this study with the previous biogeographical map of Algeria (Quézel & Santa, 1962). Our numerical clustering determined eight sectors and twenty districts for Algeria, whereas ten sectors and the same number of districts were previously proposed based on empirical expert knowledge. The Figure 8 offers a comprehensive visual representation of these correspondences.

However, the eight sectors are in general congruent with the recent findings of Walas & Taib (2022) in the Maghreb, except for the Tanezrouftian and In Guezzamian sectors covering the extreme south of Algeria, which are also indicated by Médail & Quézel (2018) and Naia & Brito (2021). Besides, the nomenclature used to describe the biogeography of Algeria has changed (Table 6), and our sectorisation is moderately coincident at the district level with the ancient biogeographic map of Quézel & Santa (1962).

The 20 districts are partially overlapping the previous subsectors, and there are clear similarities in some districts, particularly A, K and J (corresponding to A1, K1, K2 and K3). In the Naïli-Constantinian sector, the Constantinian (C), the Tebessian (T) and Belezmo-Auresian (B) districts altogether correspond to the districts H2 and AS3 as defined by Quézel & Santa (1962). It's important to note that the boundaries of the districts of the Constantine Tell region in this study are further validated by the subdivision into two distinct districts, C1 and C2, as proposed by Meddour *et al*. (2019). On the other hand, the In Guezzamian district corresponds to the Southern Saharan (SM) sector and belongs to the Paleotropical Kingdom according to Quézel (1978), and would correspond to the Sahelian Acacia savanna ecoregion (Dinerstein *et al*., 2017; Naia & Brito, 2021). Though, our results do not allow us to confirm it. A recent review on the biogeographical position of the southern Sahara, provided by Médail & Quézel (2018), pleads in this direction.

Despite some rough similitudes, significant differences become apparent in other districts, notably within the North Algerian sectors and districts, where the delineations diverge considerably. Moreover, in the Northern Saharan sector, the subdivision into two districts occurs according to the latitude and the annual rainfall (Becharo-Mzabian district, 50-100 mm/year; Tadmaïto-Golean district, <50 mm/year), and not according to longitude (SS1, West-Northern Sahara; SS2, East-Northern Sahara). Accordingly, *Stipa tenacissima* L., a major indicator species over most of its distribution area in the Mediterranean steppe, penetrates deep into the Chebka of M'Zab, but also into the reliefs around Bechar, that is to say in regions generally considered to be part of the Sahara (Médail & Quézel, 2018). It could correspond to a Saharo-Steppe transition zone, with rainfall of 50 to 100 mm/year. In North Africa and even more so in the Sahara, it is appropriate to define transition zones, and not just clearly delimited units (Chatelain *et al*., 2024), and thus, these discrepancies are not surprising. For a more detailed comparison, the sectorisation map is available online (dtahri.github.io/biogeographical_divisions/).

6. Conclusion

We proposed a new biogeographical delineation of Algeria based on a quantitative method of the environmental data and endemism of vascular plants. The use of environmental predictors and representative plant taxa improved the definition of the biogeographical regions of Algeria. Indeed, our results show a hierarchical partition between areas, some partitions being more important than others, corresponding to the sectors and districts. It was possible to establish in Algeria a total of 20 homogeneous areas (districts), included in larger areas (8 sectors), which constitute the current biogeographical typology of the territory. The definition of homogeneous regions (to a district level) generated from environmental features allowed the identification of the predictive factors that influence the distribution of the endemic plant species. However, Saharan formations, such as Ergs, Regs, Hamadas, and plateaus, despite their significant ecological roles, are not fully reflected within the biogeographic Saharan sectors of the new biogeographical system. This gap highlights the need for more detailed studies that integrate the specific characteristics of these Saharan landscapes. The recognition of homogeneous biogeographical territories is an essential tool for the management of the biodiversity of Algeria, since the identification of smaller biotic areas, such as districts, constitutes a more efficient level for biodiversity conservation, particularly of endemic or rare plants.

Authorship

D.T.: Data, Analysis, Writing Original Draft. R.M.: Conceptualization, Interpretation, Writing. C.Ch. & F.M.: Conceptualization, Methodology, Review & Editing.

Conflict of interest

None.

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Supplementary Material

Appendix S1. List of bioclimatic variables used in the environmental clustering.
Appendix S2. Covariance matrices of selected variables for the different studied sectors.
Appendix S3. Matrices of p-values and R^2 values from ANOSIM comparing Algerian sectors.
Appendix S4. Lists of endemic species for the different sectors.
Appendix S5. Lists of endemic species for the different districts.