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VEGETATION SURVEY

Phytosociological survey of the desert vegetation of Sinai, Egypt

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Abstract

Aims: Although Sinai is a global hotspot for desert vegetation, there is no well-documented overview of the Sinai vegetation. We aim to provide a phytosociological overview of Sinai desert vegetation based on an extensive database and formal classification. We further aim to describe the vegetation communities and provide information on their distribution.

Location: Sinai, Egypt.

Methods: We built a comprehensive database utilizing all available vegetation plot data of the study area from published literature and our field surveys. We determined the database clustering tendency (Hopkins' test analysis) and estimated its optimal number of clusters (Elbow method). We performed a cluster analysis (modified TWINSPAN) and improved the validity of the resulting groups by approximating natural clustering using the Silhouette algorithm. We visualized the results by calculating Non-metric Multidimensional Scaling and drawing distribution maps for the observed vegetation communities.

Results: We distinguished nine classes representing Sinai desert vegetation: *Salicornietea fruticosae*, *Retametea raetam*, *Haloxylonetea salicornici*, *Retamo-Tamaricetea fluviatilis*, *Acacietea tortilis*, *Artemisietea herbae-albae*, *Anabasietea articulatae*, *Chiliadenetea iphionoidis*, and *Stellarietea mediae*. We distinguished 25 vegetation groups, of which seven are new findings, representing four main vegetation groups: salt desert, lowland desert, mountain desert, and ruderal desert. We observed a high diversity in life forms, chorotypes, and alpha-diversity of the vegetation among the main groups. Therophytes, chamaephytes, hemicryptophytes, and phanerophytes are the dominant life forms. Prevailing chorotypes are Saharo-Arabian, Mediterranean, Mediterranean-Irano-Turanian and Irano-Turanian-Saharo-Arabian. The salt desert and lowland desert vegetation are species-poor, whereas the mountain desert vegetation is relatively species-rich. The ruderal desert vegetation is the most species-rich.

Conclusion: We present a common classification of Sinai desert vegetation based on cutting-edge methods and provide an updated description of the desert vegetation groups of Sinai. Our study forms an important basis for decision-making in nature conservation, global change issues, and further in-depth studies on Sinai vegetation.

KEYWORDS
classification, desert, desert vegetation, modified TWINSPAN, NMDS, plant community distribution, silhouette, Sinai, syntaxonomy, vegetation database

1 | INTRODUCTION

The ability of plants to survive harsh desert conditions of deserts has long fascinated botanists. Because it is a central region for biodiversity in the Middle East, its geographic location at the meeting of three continents, and climatic changes happening in recent times (Ayyad et al., 2000), Sinai is one of the most important desert regions globally. Sinai has attracted the attention of geographers and botanists since the 17th century (Batanouny, 1985), who have contributed important insights into the flora of Sinai (Delile, 1813; Forsskål, 1775; Fresenius, 1834; Täckholm, 1932). In 1935, for the very first time, Zohary addressed the phytogeographical classification of Sinai flora, which served as a basis for further local and regional studies of the Sinai flora and vegetation (Ahmed, 1983; Danin, 1983; Fayed et al., 2004; Hatim et al., 2016; Migahid et al., 1959; Shaltout et al., 2004).

Although Zohary (1973) and Danin (1983) made notable attempts to provide an overview of syntaxonomical classification, no study has provided a convincing classification scheme of the desert vegetation of Sinai. However, despite being highly comprehensive and providing detailed community descriptions, their proposed classification schemes can hardly be reconciled with the widely recognized International Code of Phytosociological Nomenclature (Theurillat et al., 2021). Furthermore, the scientific reference material (vegetation relevés or equivalents) is missing in the work of Zohary (1973), which means that most of Zohary's syntaxa need to be considered *nomina nuda*, according to the Code (Theurillat et al., 2021).

In the current period of large-scale decline in biodiversity, excessive land use and exploitation, and climate change, we urgently need an overview of the current status and diversity of ecosystems. Based on an extensive vegetation plot database comprising 1,421 relevés to which we apply approved, cutting-edge methods in vegetation science, our study updates earlier studies, including the work of Hatim et al. (2016; 816 relevés). More precisely, we answer the following questions: (a) what are the vegetation communities of the Sinai desert vegetation; (b) where do they occur; (c) which diversity and ecological patterns, plant-life forms, and geological features characterize the observed vegetation communities; and (d) can we develop a syntaxonomical scheme summarizing previous and current research? The results of our study may serve as an improved basis for decision-making in Sinai nature conservation and environmental policy, and further in-depth studies on Sinai vegetation.

1.1 | Study area

The Sinai Peninsula is a triangular plateau in the northeast of Egypt. Bordered by the Mediterranean Sea in the north, it extends south to Ras Muhammad, where the eastern coast of the Gulf of Suez meets

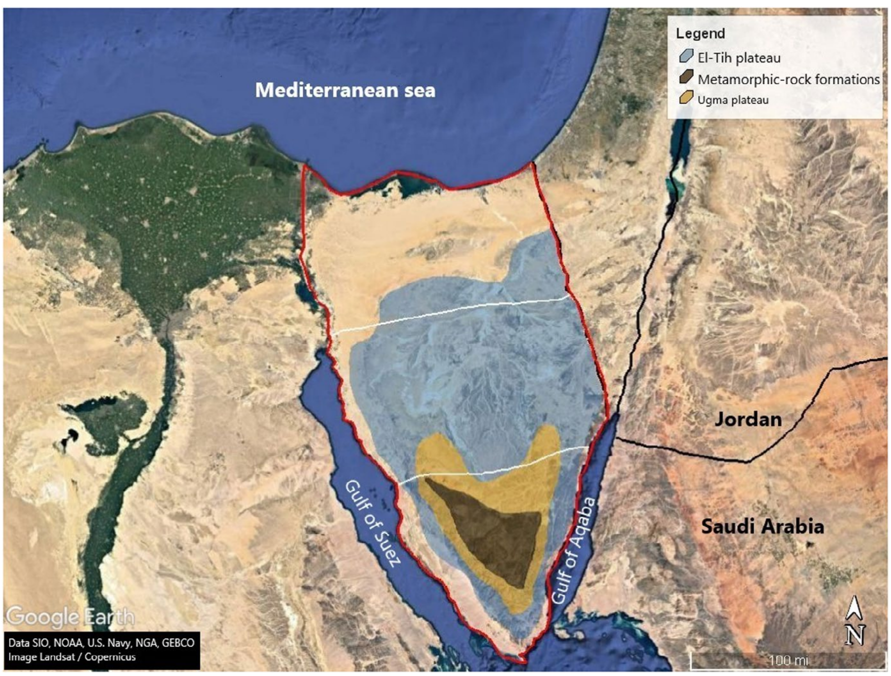

FIGURE 1 Map of Sinai showing features of the study area. The Sinai region is surrounded by a red line and divided by two white lines into three regions, southern, central and northern Sinai, from the south to the north (prepared from Google Earth)

the western coast of the Gulf of Aqaba. The area of the Sinai Peninsula (61,000 km^2) comprises approximately 6% of Egypt. The core of the peninsula is situated near its southern end and consists of high and very rugged igneous and metamorphic rock formations (Figure 1). The northern two-thirds of the peninsula are characterized by a tremendous northward-draining limestone plateau (El-Tih and Ugma Plateau), which rises from the Mediterranean coast, extends southwards, and terminates in a high escarpment on the northern flanks of the igneous core (Said, 1962). The Sinai Peninsula can be divided into three regions based on their geomorphological features: northern, central, and southern (Figure 1). The elevation ranges from 0 m to 2,641 m at the highest peak of Mount Catherine (Zahran & Willis, 2009).

The Sinai Peninsula lies at the junction of three floristic regions: the Saharo-Sindian, which corresponds to Zohary's (1966) Saharo-Arabian; the Irano-Turanian; and the Mediterranean (Zahran & Willis, 2009). Unlike the Saharo-Arabian chorotype, Danin and Plitmann (1987) stated that the Mediterranean chorotype declines from north to south in Sinai. While the Irano-Turanian chorotype is common in the highlands of the Sinai desert, the Sudanian chorotype is common in the lowlands of southern Sinai (Danin & Plitmann, 1987).

According to Ayyad et al. (1986), the Sinai Peninsula climatically belongs to the Saharo-Arabian region. It is distinguished by an arid zone in northern Sinai and a hyperarid zone in central and southern Sinai. The arid zone is characterized by hot summers, mild winters, and rainfall during winter. According to Emberger (1963), this zone is further distinguished into two provinces: (a) the coastal belt province, which is under the maritime influence of the Mediterranean Sea and has a relatively short dry period with annual rainfall ranging from 100 to 200 mm; and (b) the inland province, with a relatively long dry period and annual rainfall of 20–100 mm. The hyperarid zone includes the central and southern regions of Sinai. It is further divided into two provinces: (a) the hyperarid province with hot summers, mild winters, and winter rainfall, which includes central Sinai or the El-Tih Plateau, together with the western and eastern coasts of the gulfs of Aqaba and Suez; and (b) the hyperarid province with cold winters and hot summers, which occurs around the Sinai mountains (Zahran & Willis, 2009).

Air temperature in Sinai is subject to significant spatial variations. The mean maximum summer temperature ranges from 20°C at Mount Catherine (southern Sinai) to more than 50°C at El-Kuntilla (central Sinai; Zahran & Willis, 2009). The mean minimum winter temperature ranges from 0°C at Mount Catherine (southern Sinai) to 9°C at Nekhel (central Sinai), 14°C at El-Arish (northern Sinai), 15°C at El-Tor (southern Sinai) and 19°C at Sharm El-Sheikh (southern Sinai). Because of its distinct landscape and pronounced climatic characteristics, Sinai has diverse ecological regions: salt desert, lowland desert, and mountain desert (Figure 2).

Land in Sinai is predominantly used for farming, especially in southern Sinai. According to Shaltout et al. (2019), edaphic and moisture conditions in the Mount Catherine region (southern Sinai) create habitats where farmland can occur. Farmland vegetation can be found in the catchment areas of the surrounding mountains or near Bedouin settlements where groundwater is available (El-Hadidi & Hosny, 2000). Sufficient groundwater, together with the locality's natural protection against wind, provides suitable conditions for cultivation in many wadis in southern Sinai (Shaltout et al., 2019). Farms are mainly cultivated with fruit trees and crops (Shaltout et al., 2019). Norfolk et al. (2013) estimated there to be about 600 farms in the Mount Catherine region (southern Sinai). Bedouins run their farms on the principles of agroforestry, where smaller orchard trees are widely spaced to allow light to reach cultivated vegetables, thus giving room for the growth of native desert plant species (Norfolk et al., 2013).

2 | METHODS

2.1 | Data compilation

We compiled an extensive data set of all available plot-based vegetation records of Sinai, comprising 1,462 relevés. We omitted single-species relevés with low abundances because it is doubtful that such records represent well-developed plant communities. The resulting data set comprised 1,421 vegetation records, including 555 taxa (species and subspecies), collected from three main sources: (a) 927 relevés retrieved from the Vegetation database of Sinai in Egypt (Hatim, 2012), stored in the sPlot repository (Bruelheide et al., 2019); (b) 345 relevés from the published literature (Abd El-Wahab, 1995, 2003; Moustafa et al., 2008; Salem & Kamal, 2003; Shaltout et al., 2015); and (c) 149 relevés recorded by the first author (MZH) in 2017 and 2019. All relevés were made according to the Braun-Blanquet approach (Braun-Blanquet, 1928; Westhoff & van der Maarel, 1973) and included information on species abundance. The compiled data reflect the geomorphological variance and habitat diversity of the Sinai desert region to a great extent (Appendix S3). The temporal range of the relevés is from 1959 to 2019, and their altitudes range from 23 to 2,450 m a.s.l.

We stored and managed our data in the Turboveg 3 program (Hennekens & Schaminée, 2001). We updated each plant species taxonomy according to World Flora Online (2021). We compiled information on plant life forms (Raunkiaer, 1934; retrieved from Täckholm, 1974; Boulos, 1999, 2000, 2002, 2005; Danin & Fragman-Sapir, 2016) and chorotypes (retrieved from Danin, 1986; Danin & Fragman-Sapir, 2016; Takhtajan et al., 1986).

2.2 | Data analysis

We conducted the classification by: (a) calculating the clustering tendency to determine if and to what level the data set has meaningful clusters; (b) approximating the optimal number of clusters; and (c) computing the final cluster analysis.

2.2.1 | Clustering tendency

To measure to what degree clusters exist in the data, we performed a Hopkins' test (Python, version 3.7.6, Python Software Foundation, Wilmington, DE, USA; Appendix S1), which is a statistical hypothesis

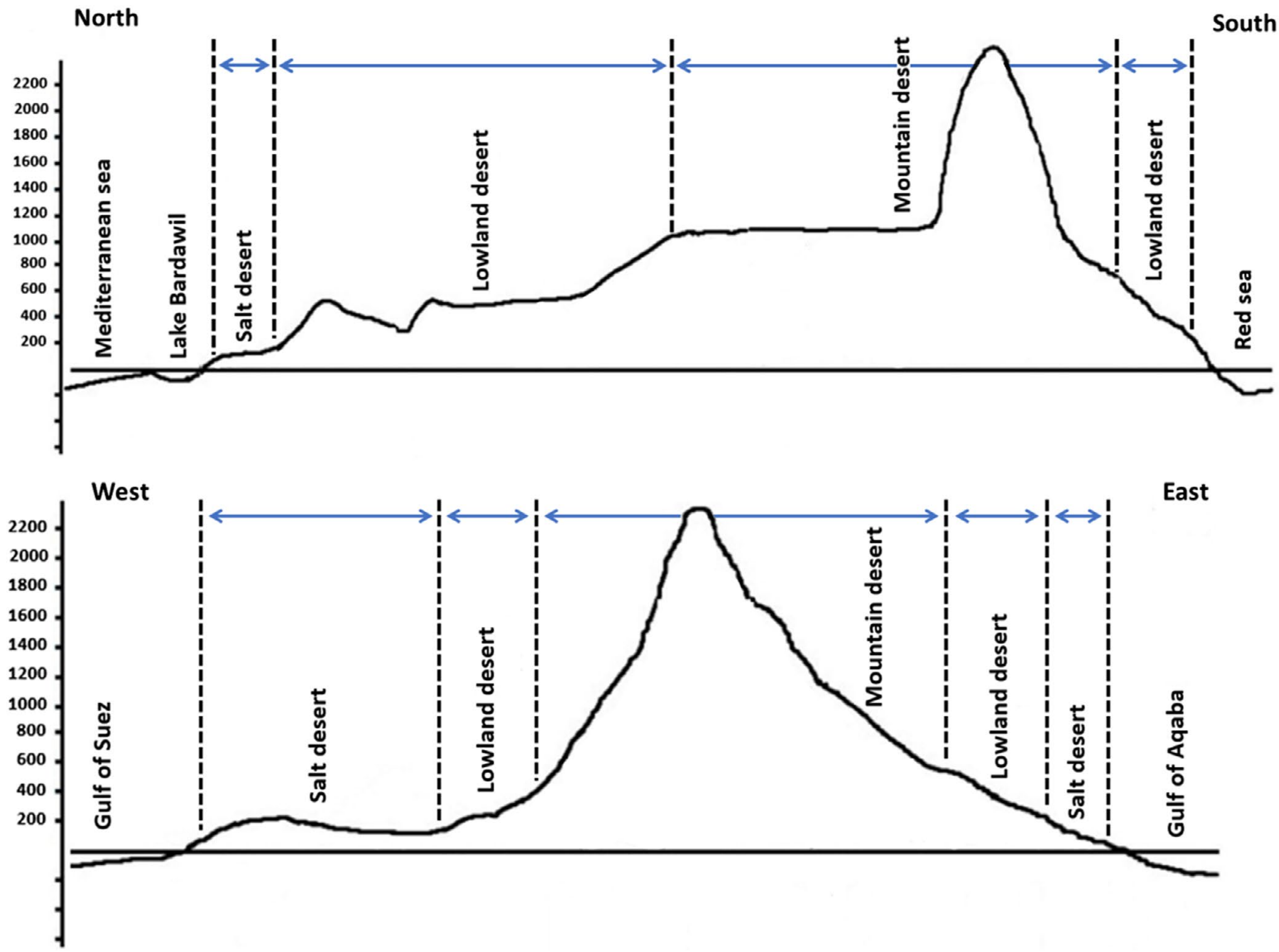

FIGURE 2 Sectors showing the main ecological regions and altitude (m a.s.l.) along the north–south and west–east directions in Sinai (modified after Hatim et al., 2016)

test to measure the probability (*H*) that a given data set is generated by a uniform or continuous data distribution (Hopkins & Skellam, 1954). The null hypothesis (H_0) states that data follow a continuous distribution (implying no meaningful clusters), whereas the alternate hypothesis (H_1) states that data are not uniformly distributed (i.e., the presence of clusters). If $H > 0.5$, the null hypothesis can be rejected (Hopkins & Skellam, 1954).

2.2.2 | The optimal number of clusters

We used the Elbow method to estimate the optimal number of clusters (Ketchen & Shook, 1996; Python, version 3.7.6, Python Software Foundation, United State Appendix S2) by performing multiple cluster analyses with varying, predefined cluster numbers (*k*). In each analysis, we also calculated the sum of within-cluster variance (*W*) as the sum of squared Euclidean distances between the plots and the corresponding centroid. Subsequently, we plotted *k* values against their opposite *W* values to find the approximate optimal number of clusters indicated by the elbow (breakpoint) of the plotted curve. This breakpoint represents the *k* value opposite to the lowest *W* value before the curve becomes almost straight, where the *W* value approaches zero as the *k* value comes close to the total number of plots.

2.2.3 | Classification and related analyses

We classified the data using a hierarchical modified TWINSPAN algorithm (Roleček et al., 2009), with, based on the given data structure, pseudo-species cut levels of 0, 5, 25, 50 (JUICE, version 7.1, Masaryk University, Brno, Czech Republic; Tichý, 2002). We refrained from further hierarchical subdivision when modified TWINSPAN did not result in groups with ecologically meaningful differential species (Tsiripidis et al., 2009). Subsequently, to improve the validity of the groups, we reallocated 194 relevés. We made reallocations only if: (a) the constancy values of the differential species of the groups were improved after reallocation; and (b) the average silhouette values (JUICE, Silhouette function) of relevant groups remained consistent or were enhanced. To visualize the relationship between the clusters, we calculated Non-metric Multidimensional Scaling (NMDS), using the Bray–Curtis distance (CANOCO 5, Microcomputer Power, Ithaca, NY, USA; ter Braak, 1989).

To develop a syntaxonomical overview, we adopted the names of syntaxa proposed in the literature, updating them in accordance with the latest version of the International Code of Phytosociological Nomenclature (Theurillat et al., 2021) where needed. Based on vegetation structure and differential, dominant and accompanying species, we allocated each group to a syntaxonomical class and, if possible, further down to the level of orders, alliances, and associations. For some syntaxa, indicated by question marks in the syntaxonomy scheme, we refrained from further allocation towards lower or upper syntaxonomical levels due to a shortage of data about the broader context of the Sinai desert vegetation and its position in the Saharo-Arabian region.

3 | RESULTS AND DISCUSSION

3.1 | Clustering tendency and the optimal number of clusters

Clustering methods produce clusters by default, even if the data show hardly any variation (dis-continuum). In this case, calculated clusters (groups) would be meaningless (Cross & Jain, 1982). For this reason and to present a mathematically approved approach, we calculated the clustering tendency using Hopkins' statistical hypothesis method. Because the result was $H = 0.96$, we rejected the null hypothesis, meaning the database very likely contains clusters.

The approximated optimal number of clusters based on the Elbow method was 24 (Figure 3). Because this value (24) is heuristic, we can accept the actual number of clusters (25). The deviation between the actual number of clusters (25) (Figure 4) and the expected number (24) resulted from reallocation of the relevés among the groups.

3.2 | Classification

After trying different approaches to classify the desert vegetation of Sinai, we found that modified TWINSPAN generated the best results. However, the low species numbers of some plots and substantial differences among the species-abundance values make our data set challenging to classify. We overcame these limitations by manually reallocating several relevés based on mathematical Silhouette values analysis and our expert knowledge. The classification resulted in four main groups (M1–M4), representing salt desert (M1), lowland desert (M2), mountain desert (M3), and ruderal desert (M4) vegetation. M1–M3 were divided into 3, 15, and 6 groups (**G**), respectively, whereas M4 remained undivided. The total number of groups was, as mentioned previously, 25. Their hierarchical relationships are shown in Figure 4.

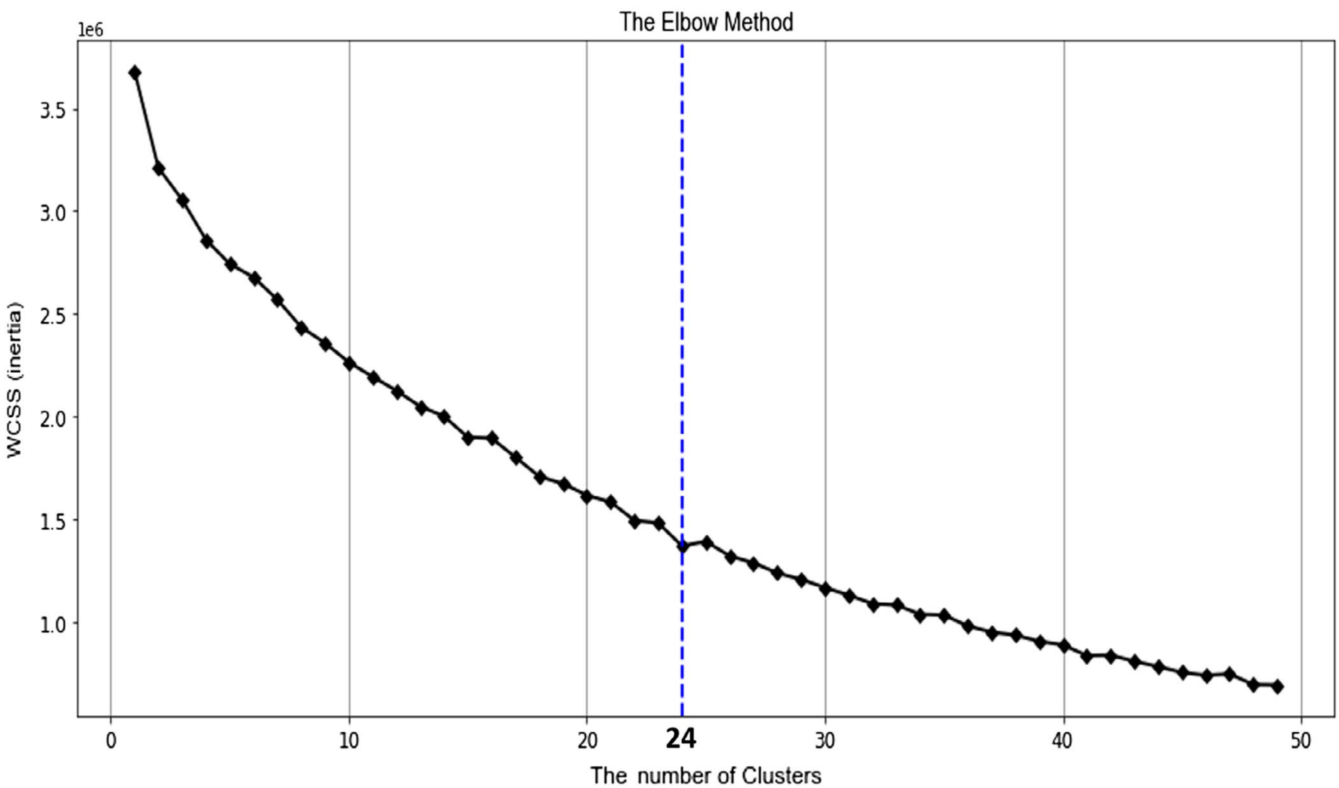

FIGURE 3 Diagram of the Elbow method showing the expected optimal number of clusters. Within Cluster Sum of Squares (WCSS) values represent the sum of squared Euclidean distances between the plots and the centroid. The lower the value of W, the more meaningful the clusters, and the better the correspondence to an optimal number of clusters. The Elbow is the last breaking point, seen before the flattening of the curve and corresponding to a low WCSS value. In our case, the Elbow corresponds to the number of clusters, 24

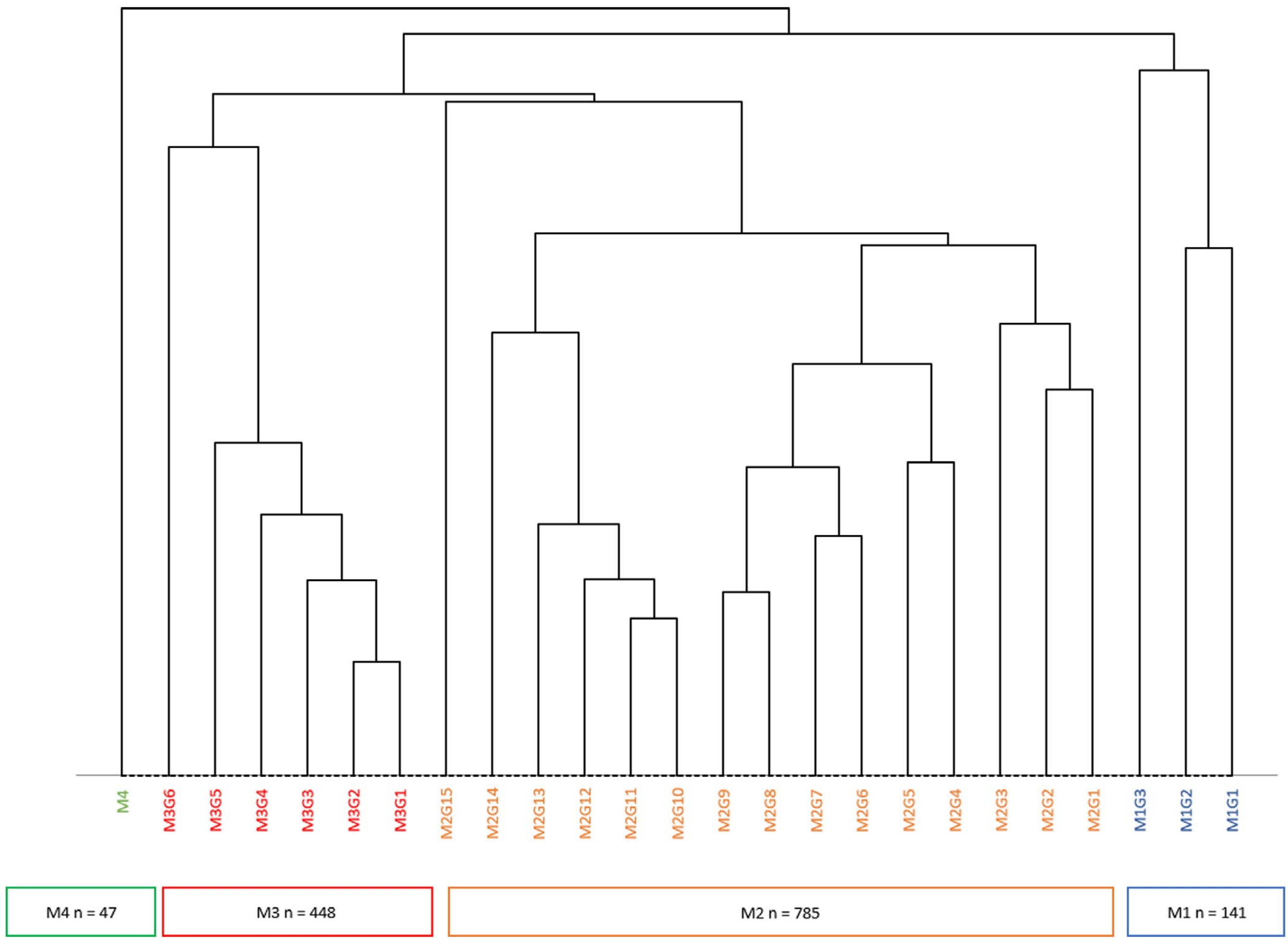

FIGURE 4 Dendrogram of the final classification based on the agglomerative clustering using Bray–Curtis analysis among the 25 groups. Different colours represent the main groups M1–M4 (blue: salt desert, M1; orange: lowland desert, M2; red: mountain desert, M3; green: ruderal desert, M4). *n* is the number of relevés in each group

Climate inconstancy, geographic isolation, edaphic variation, and the high spatial and temporal variability of further abiotic factors substantially impact the distribution of desert vegetation communities and cause greater-than-expected plant diversity (Sandquist, 2014). Our study reflected this in the high diversity of vegetation communities among the different regions and habitats in Sinai.

3.2.1 | Ordination

NMDS was calculated on three axes because the stress value was close to 0.1 (Figure 5, axes 1 and 3, length of axes 1:2, 3:1.5; stress value of axes 1:0.53, 3:0.17). We chose axes 1 and 3 because they clearly visualize the classification (Figure 4). M1–M4 are well separated by their species composition; yet M1, which is prevailed by salt desert vegetation, and M2, which is dominated by lowland desert vegetation, slightly overlap. M4, dominated by ruderal vegetation, is clearly separated from all other groups (Figures 4 and 5).

3.2.2 | Vegetation groups description and classification

Frequency values for the characteristic species of the four main groups (M1–M4) and the 25 groups are given in Tables 1–4. The differential species of the four main groups and the 25 groups are shaded in gray (for a complete synoptic table, see Appendix S4).

The main life forms of Sinai desert vegetation are therophytes, chamaephytes, hemicryptophytes, and phanerophyte shrubs (Figure 6). The dominant chorotypes are Saharo-Arabian, Mediterranean, Mediterranean-Irano-Turanian, and Irano-Turanian-Saharo-Arabian (Figure 7). We described each main group and the 25 groups below, indicating plant life forms, habitats (ecology), chorotypes, differential species, and geographical distribution.

Main groups (M1–M4) are differentiated from each other. With *Tetraena alba* as a dominant species, M1 is characterized by *Stipagrostis scoparia*, *Panicum turgidum*, *Nitraria retusa*, and *Cornulaca monacantha*. The communities of M1 mainly represent salt desert vegetation and belong to the classes *Salicornietea fruticosae* and *Retametea raetam*. They have the lowest species numbers (mean

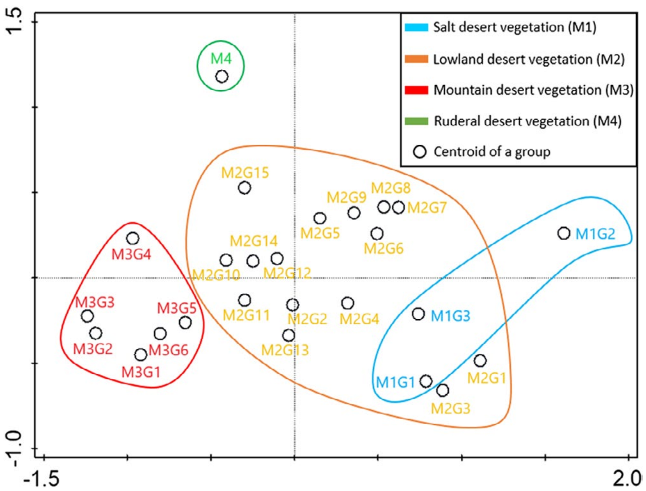

FIGURE 5 Axes 1 and 3 of the Non-metric Multidimensional Scaling ordination, using Bray–Curtis-based analysis, of the 25 vegetation groups (small black circles represent centroids of the groups) in the Sinai region, based on their floristic composition (length of axes 1:2, 3:1.5; stress values of axes 1:0.53, 3:0.17). The four main groups (M1–4) are indicated in blue (salt desert, M1), orange (lowland desert, M2), red (mountain desert, M3) and green (ruderal desert, M4)

species number = 5) compared with other main groups. M1 was divided into three groups (M1G1–M1G3) that predominantly occur in coastal and inland salt deserts. The vegetation largely consists of chamaephytes and therophytes, but is dominated by the former (Figure 6). The chorotypes are mainly Saharo-Arabian, followed by Mediterranean and Mediterranean-Irano-Turanian (Figure 7). The groups of M1 are primarily distributed in the northern and central Sinai, but rarely occur in southern Sinai (Figure 8).

M2 is characterized by *Zilla spinosa* (dominant species), *Fagonia mollis*, *Zygophyllum coccineum*, *Artemisia judaica*, *Haloxylon salicornicum*, *Retama raetam*, *Acacia tortilis*, *Fagonia arabica*, and *Iphiona scabra*. Although *Zilla spinosa* is present in all the main groups, it occurs with the highest frequencies in M2. The groups of M2 predominantly represent the diverse lowland desert vegetation that can be found in ergs (sandy plains, dunes, and wadis) and regs (gravelly plains and wadis). They belong to the classes *Retametea raetam*, *Haloxylonetea salicornici*, *Retamo-Tamaricetea fluviatilis*, and *Acacietea tortilis*. They are relatively species-poor (mean species number = 9) compared with groups of M3 and M4, but richer than the groups of M1. M2 was divided into 15 groups (M2G1–M2G15), which mainly occur in sandy plains and dunes, sandy wadis, gravelly wadis, and gravelly plains. The vegetation consists mainly of therophytes, chamaephytes, and hemicryptophytes (Figure 6). The prevailing chorotype is Saharo-Arabian, followed by Mediterranean (Figure 7). M2 groups predominantly occur in the northern, central, and southern regions of Sinai (Figure 8).

M3 is dominated by differential species *Artemisia herba-alba*. Further differential species are *Alkanna orientalis*, *Teucrium polium*, *Stachys aegyptiaca*, *Phlomis aurea*, *Tanacetum sinaicum*, *Ballota undulata*, *Achillea fragrantissima*, *Chiliadenus montanus*, *Echinops spinosissimus*, *Origanum syriacum* subsp. *sinaicum*, and *Matthiola arabica*. The

TABLE 1 Shortened synoptic table of the classified vegetation relevés of the four main groups (M1–4)

Main group	M1	M2	M3	M4
Number of relevés	141	785	448	47
Mean species number	5	9	12	17
Tetraena alba	50	2	0	0
Zilla spinosa	8	49	38	4
Fagonia mollis	2	35	35	15
Zygophyllum coccineum	14	32	1	0
Artemisia judaica	1	32	17	9
Haloxylon salicornicum	4	30	1	6
Artemisia herba-alba	1	7	54	0
Alkanna orientalis	0	1	48	0
Teucrium polium	0	5	47	0
Stachys aegyptiaca	0	2	44	0
Phlomis aurea	0	1	42	0
Tanacetum sinaicum	0	1	42	0
Ballota undulata	0	2	32	0
Achillea fragrantissima	0	7	31	2
Chiliadenus montanus	0	1	30	0
Convolvulus arvensis	0	1	1	81
Euphorbia peplus	0	1	4	79
Chenopodium murale	0	1	1	51
Cynodon dactylon	2	2	3	51
Polypogon monspeliensis	0	0	1	47
Malva parviflora	0	2	2	43
Hordeum marinum	0	1	1	43
Oxalis corniculata	0	0	0	38
Tetraena simplex	7	16	0	32
Alhagi graecorum	0	2	1	30

Note: The table shows the number of relevés, mean number of species, the list of plant species and their percent frequencies for each main group. Only differential species (with frequencies ≥30%) are included, and their value cells are shaded. The dominant species of each main group is also shaded.

TABLE 2 Shortened synoptic table of the first main group (M1), showing the resulted three groups (M1G1–3)

Group	M1G1	M1G2	M1G3
Number of relevés	79	14	48
Mean species number	4	5	6
Tetraena alba	81	36	4
Nitraria retusa	42	21	0
Salvadora persica	0	100	0
Panicum turgidum	11	0	67
Stipagrostis scoparia	13	0	65
Cornulaca monacantha	11	0	54
Convolvulus lanatus	4	0	46
Artemisia monosperma	9	0	40

Note: The table shows the number of relevés, mean number of species, the list of plant species and their percent frequencies for each group. Only differential species (with frequencies ≥30%) are included, and their values cells are shaded. The dominant species of each group is also shaded.

TABLE 3 Shortened synoptic table of the second main group (M2), showing the resulting 15 groups (M2G1–15)

Group	M2G1	M2G2	M2G3	M2G4	M2G5	M2G6	M2G7	M2G8	M2G9	M2G10	M2G11	M2G12	M2G13	M2G14	M2G15
Number of relevés	67	73	20	44	64	58	29	24	31	77	59	91	106	19	23
Mean species number	3	11	4	6	12	11	16	15	18	9	9	12	5	7	20
Zygophyllum coccineum	100	33	20	16	61	69	14	42	94	1	3	15	5	5	26
Haloxylon salicornicum	24	100	35	39	9	2	3	46	77	10	8	29	41	0	4
Asphodelus fistulosus	0	0	55	2	0	0	0	0	0	0	0	1	0	0	0
Ephedra alata	1	11	30	2	2	0	0	0	0	1	2	3	3	5	0
Acacia tortilis	3	8	5	95	61	34	76	46	68	12	7	3	9	21	13
Cleome droserifolia	4	1	30	9	53	33	17	29	10	5	2	4	0	11	0
Aerva javanica	1	16	15	25	50	10	10	42	26	10	2	29	8	32	0
Capparis aegyptia	0	4	0	0	41	0	0	0	0	6	0	9	1	5	0
Chrozophora oblongifolia	0	3	0	5	34	3	0	0	0	4	0	3	0	11	0
Echinops hussonii	0	1	0	0	30	7	21	0	0	6	2	0	2	5	0
Tetraena simplex	7	5	0	2	9	84	55	54	48	1	0	13	1	0	0
Stipagrostis plumosa	0	5	0	2	5	57	55	8	6	3	12	23	1	0	0
Pulicaria undulata subsp. *undulata*	3	3	0	11	14	52	3	0	39	10	3	24	3	5	22
Citrullus colocynthis	1	10	0	9	25	40	28	29	10	14	12	34	8	5	13
Forsskaolea tenacissima	0	8	0	11	22	50	93	75	39	12	3	30	0	11	0
Indigofera arabica	1	0	0	0	0	3	83	4	0	0	0	0	0	0	0
Aphonia scabra	15	11	0	16	50	48	69	38	45	10	3	13	4	11	0
Fagonia indica var. *indica*	1	0	0	0	0	17	52	25	26	0	0	0	0	0	0
Lotus polyphyllos	0	0	0	0	8	28	52	25	10	0	2	0	0	0	0
Aerva lanata	3	0	0	2	2	24	48	4	3	0	0	0	0	0	0
Diplotaxis harra	0	8	0	2	2	9	45	25	29	4	22	27	3	0	35
Cucumis prophetarum	0	3	0	11	19	12	45	29	13	1	0	8	0	0	0
Erodium oxyrhynchum	0	0	0	0	0	5	41	0	3	0	5	5	0	0	4
Trichodesma africanum	0	4	0	0	16	34	41	17	13	12	3	9	1	11	0
Blepharis edulis	1	0	0	0	11	12	41	0	0	4	2	8	1	5	0
Fagonia glutinosa	7	3	10	2	0	16	31	21	10	1	0	5	3	5	26
Hyoscyamus muticus	0	4	0	11	0	2	7	54	19	3	2	2	6	0	13
Tephrosia purpurea	0	1	0	0	13	7	3	46	13	3	2	1	0	11	0
Lavandula pubescens	0	3	0	5	20	0	14	42	13	4	2	0	0	11	9
Capparis cartilaginea	0	1	0	9	13	16	21	42	35	0	0	0	0	0	0

TABLE 3 (Continued)

Group	M2G1	M2G2	M2G3	M2G4	M2G5	M2G6	M2G7	M2G8	M2G9	M2G10	M2G11	M2G12	M2G13	M2G14	M2G15
Fagonia scabra	0	1	0	0	0	29	83	71	100	5	5	1	0	0	0
Atriplex halimus	0	0	5	2	3	2	0	8	58	0	0	4	1	0	0
Caylusea hexagyna	0	11	0	2	6	10	0	46	58	26	22	19	5	5	4
Ochradenus baccatus	4	12	10	20	20	9	17	25	45	17	24	31	17	0	13
Kickxia floribunda	0	0	0	0	0	7	7	13	32	0	0	0	0	0	4
Artemisia judaica	0	19	0	14	25	2	0	0	0	100	73	53	42	21	9
Zilla spinosa	19	21	15	27	39	34	83	67	87	49	93	76	48	37	35
Fagonia mollis	12	34	45	25	28	10	0	4	0	52	86	53	44	37	4
Cleome amblyocarpa	0	0	0	2	3	2	0	0	0	5	44	7	6	0	9
Fagonia arabica	10	18	5	18	3	10	10	17	6	9	37	66	12	11	30
Reseda pruinosa	0	0	0	0	20	9	0	0	0	1	15	37	1	5	0
Retama raetam	3	4	5	14	2	2	0	0	26	26	47	27	94	0	13
Lycium shawii	0	4	0	9	22	0	38	38	32	10	8	14	8	74	9
Tamarix senegalensis	7	0	0	0	9	0	0	4	13	0	3	2	6	0	65
Launaea nudicaulis	0	0	0	0	0	2	10	4	19	4	2	1	3	0	35
Filago desertorum	0	0	0	0	0	0	0	0	0	4	3	1	0	0	35
Anacyclus monanthos subsp. *monanthos*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
Ifloga spicata subsp. *spicata*	0	1	0	0	2	0	0	0	0	3	0	1	0	0	30
Trigonella stellata	0	5	0	0	0	0	0	0	0	8	3	7	3	0	30

Note: The table shows the number of relevés, mean number of species, the list of plant species, and their percent frequencies for each group. Only differential species (with frequencies ≥30%) are included, and their values cells are shaded. The dominant species of each group is also shaded.

TABLE 4 Shortened synoptic table of the third main group (M3), showing the resulted six groups (M3G1-6)

Group	M3G1	M3G2	M3G3	M3G4	M3G5	M3G6
Number of relevés	60	107	62	75	89	55
Mean species number	10	13	10	22	7	11
Stachys aegyptiaca	73	59	31	49	20	31
Ballota undulata	60	39	16	32	10	40
Galium sinaicum	42	26	6	3	3	0
Phlomis aurea	28	93	68	36	6	0
Teucrium polium	65	79	47	49	22	0
Echinops spinosissimus	13	58	29	23	13	0
Origanum syriacum subsp. *sinaicum*	23	48	37	24	1	0
Chiliadenus montanus	40	47	29	31	16	11
Tanacetum sinaicum	48	60	89	29	22	0
Crataegus × sinaica	0	13	50	8	2	0
Nepeta septemcrenata	22	35	37	8	3	0
Mentha longifolia subsp. *typhoides*	2	9	31	19	0	7
Alkanna orientalis	62	75	45	85	6	0
Peganum harmala	2	2	3	57	8	9
Achillea fragrantissima	37	49	8	55	17	5
Launaea spinosa	10	7	3	37	12	0
Matthiola arabica	32	34	10	35	13	0
Artemisia herba-alba	45	43	69	36	82	49
Anabasis articulata	0	0	0	3	11	58
Moricandia sinaica	0	0	0	1	0	53
Deverra tortuosa	7	3	0	17	2	49
Juniperus phoenicea	0	0	0	0	0	49
Gymnocarpos decandrus	3	6	2	29	17	47
Asparagus horridus	0	0	0	0	0	47
Reaumuria hirtella	0	0	0	0	2	45
Zygophyllum dumosum	0	0	0	0	0	40
Noaea mucronata	0	1	2	7	1	33

Note: The table shows the number of relevés, mean number of species, the list of plant species, and their percent frequencies for each group. Only differential species (with frequencies ≥30%) are included, and their values cells are shaded. The dominant species of each group is also shaded.

groups of M3 mainly represent the mountain desert vegetation and belong to the classes *Artemisietea herbae-albae*, *Anabasietea articulatae*, and *Chiliadenetea iphionoidis*. They have a higher mean species number (12) than M2 and M1, but lower than M4. M3 was divided into six groups (M3G1–M3G6), the main habitats of which are hamadas (rocky hillsides), rocky wadis, and outcrops. The majority of species life forms are therophytes, followed by chamaephytes (Figure 6). The common chorotypes are Saharo-Arabian, Mediterranean, and Irano-Turanian (Figure 7). The majority of groups of M3 can be found in southern Sinai, with very few occurrences in northern Sinai (Figure 8).

Convolvulus arvensis dominates M4, although other characteristic species are *Euphorbia peplus*, *Chenopodium murale*, *Cynodon dactylon*, *Polypogon monspeliensis*, *Malva parviflora*, *Hordeum murinum*, *Oxalis corniculata*, and *Tetraena simplex*. M4 represents ruderal vegetation and provides the highest mean species number (17). M4 consists of only one group (M4G1) and belongs to the class *Stellarietea mediae*. The supporting habitats are bound to nutrient-rich soils and ruderal places (Danin, 1983; Hatim et al., 2016), commonly found in areas with human activity (e.g., farms). The main life forms are hemicryptophytes and geophytes (Figure 6), while the chorotypes are mainly Mediterranean-Irano-Turanian and Cosmopolitan (Figure 7). The M4 community is restricted to southern Sinai due to intensive farming (Figure 8).

In line with the variation in climate and soil types (Danin, 1983), and partly defined by historical factors, the interaction of elements from four plant geographical regions (Saharo-Arabian, Irano-Turanian, Sudanian, Mediterranean) in the Sinai region adds to the high diversity of the vegetation. The chorotypes of the main four groups found in our study are similar to those described by Danin (1983) and Zahran and Willis (2009).

Moreover, the ruderal desert vegetation (M4) includes elements belonging to Cosmopolitan, Euro-Siberian, Tropical, and Subtropical

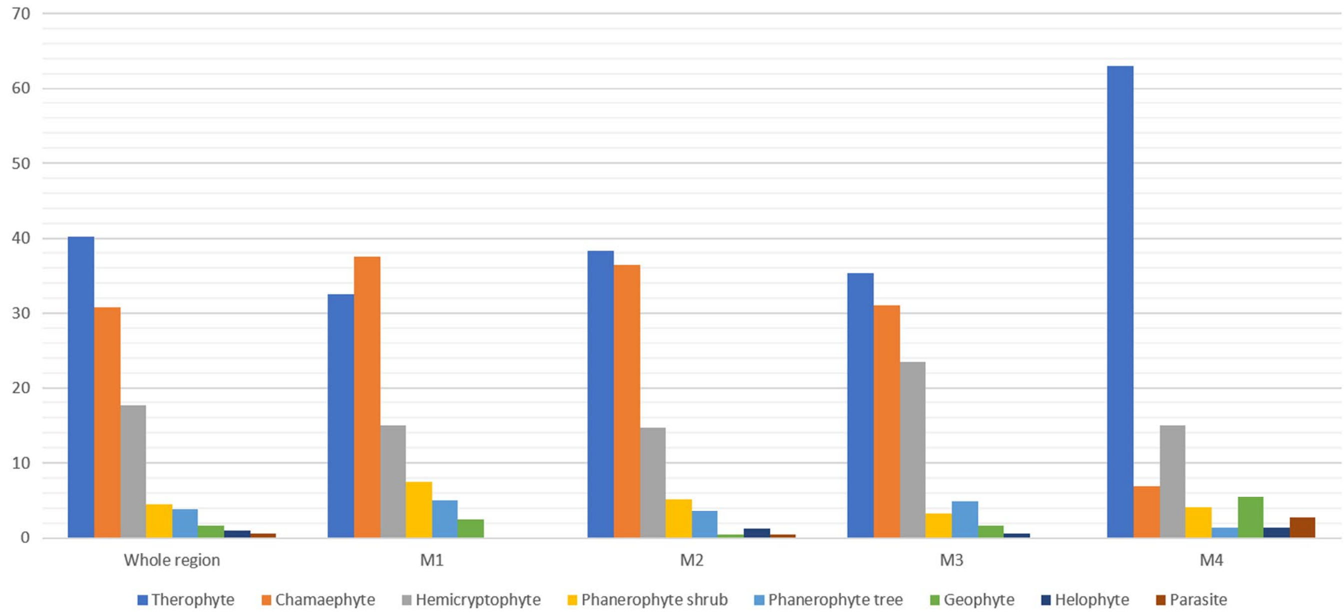

FIGURE 6 Proportions of plant life forms of the desert vegetation of Sinai, shown for the entire data set and separately for main groups M1 (40 species), M2 (253 species), M3 (187 species) and M4 (73 species)

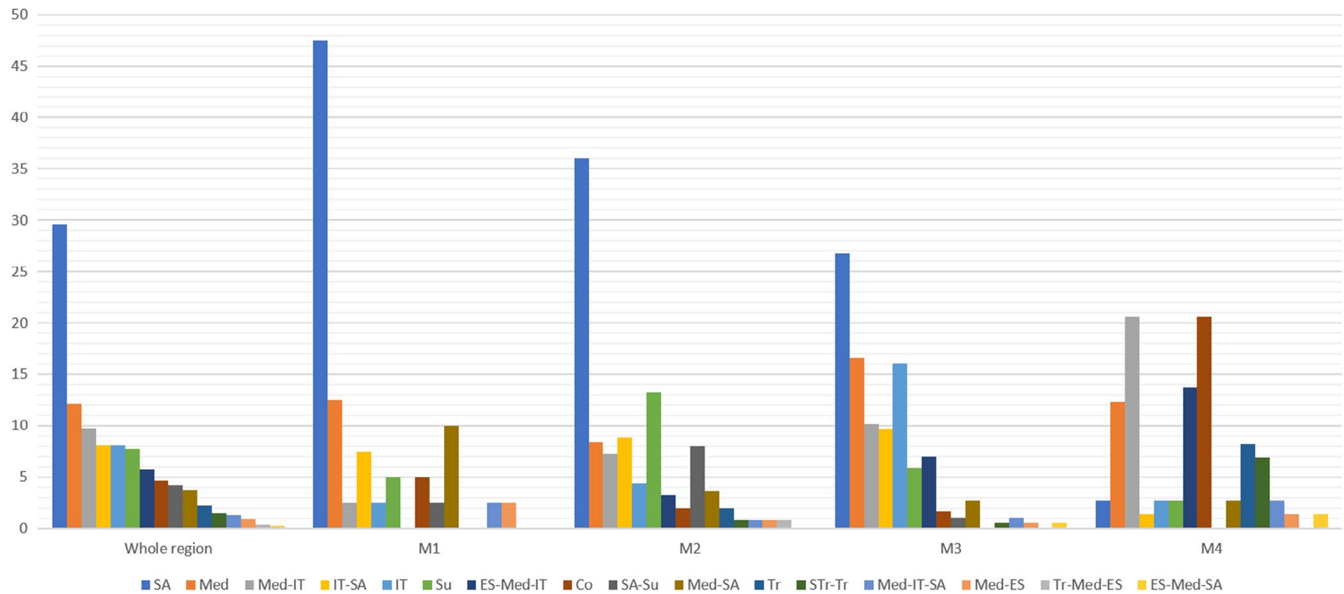

FIGURE 7 Proportions of chorotypes of the desert vegetation of Sinai, shown for the entire data set and separately for main groups M1, M2, M3 and M4. SA: Saharo-Arabian; Med: Mediterranean; Med-IT: Mediterranean-Irano-Turnian; IT-SA: Irano-Turanian-Saharo-Arabian; IT: Irano-Turanian; Su: Sudanian; ESMed-IT: Euro-Siberian-Mediterranean-Irano-Turanian; Co: Cosmopolitan; SA-Su: Saharo-Arabian-Sudanian; Med-SA: Mediterranean-Saharo-Arabian; Tr: Tropical; STr-Tr: Subtropical-Tropical; Med-IT-SA: Mediterranean-Irano-Turanian-Saharo-Arabian; Med-ES: Mediterranean-Euro-Siberian; Tr-Med-ES: Tropical-Mediterranean-Euro-Siberian; ES-Med-SA: Euro-Siberian-Mediterranean-Saharo-Arabian

chorotypes, which are not characteristic of the Sinai desert vegetation. The occasional appearances of these species in M4 and main groups M1–M3 indicate the presence of farms within their distribution range. Farms in mountainous and some desert regions have been part of the Sinai landscape for the past 1,000 years (Zalat & Gilbert, 2008), whereas the farms at Mount Catherine (aouthern Sinai) represent a recent anthropogenic change within the past 50 years (Gilbert, 2011). Farms in the mountainous region in southern Sinai are suitable for the cultivation of many wild medicinal plants (Shaltout et al., 2019). Nevertheless, we think that farms may adversely impact natural vegetation due to land-use practices like grazing, cutting, and introducing cultivated plants patterns. Regulations for land management in Sinai may become necessary, assuming this impact increases continuously. Shaltout et al. (2004, 2021) found that cessation of grazing and cutting in many enclosures in south Sinai for six years improved vegetation diversity, density, and cover.

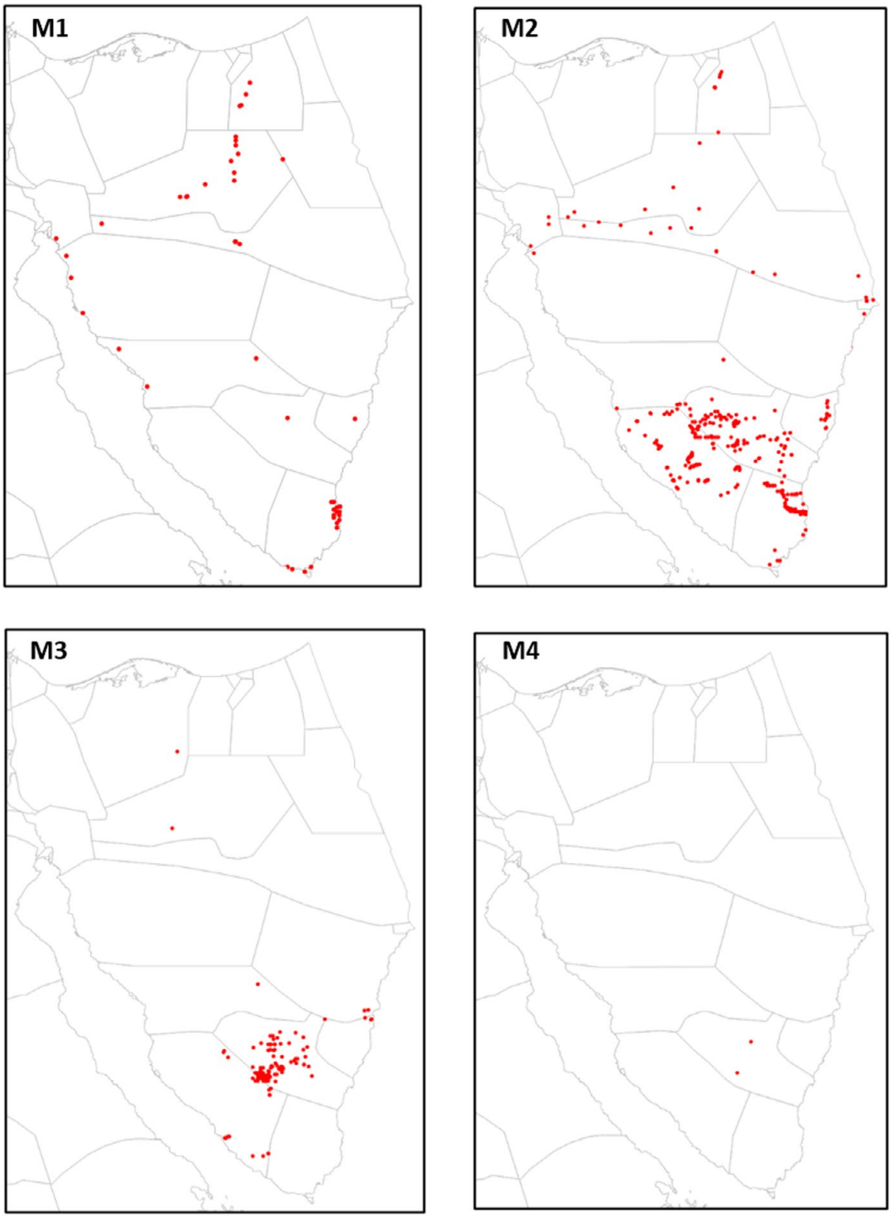

FIGURE 8 Geographic distribution of main clusters (M1–M4), showing the relevés as red dots

3.2.3 | Description of the individual communities

Main group 1: Salt desert vegetation (three groups)

The *Tetraena alba* group (M1G1) is characterized by *Tetraena alba* (the dominant species) and *Nitraria retusa*. It includes 79 relevés; its plant species mainly inhabit coastal and inland salt deserts. This vegetation occurs in the northern, central, and southern regions of Sinai (Appendix S7). Similar vegetation types in Sinai were reported by Danin (1983), Migahid et al. (1959), Hussein (1988), Gibali (1988), El-Demerdash et al. (1996), Marie (2000), El-Ghani and Amer (2003), and Hatim et al. (2016). We assigned this group to the association *Zygophylletum albi* (Danin, 1983), which belongs to the class *Salicornietea fruticosae*. This class comprises vegetation communities on saline soils where low shrubs with succulent leaves dominate (Guinochet, 1951).

In the *Salvadora persica* group (M1G2), *Salvadora persica* is the dominant species. Characteristic species are *Salvadora persica* and *Cyperus conglomeratus*. The M1G2 community consists of 14 relevés. Unlike the mother group M1, the predominant life forms are phanerophytes, mainly trees (Appendix S5). The species belong mainly to Sudanian and Saharo-Arabian chorotypes (Appendix S6), different from the M1 main chorotypes. The communities are found in the coastal desert of southern Sinai (Appendix S7). This group is similar to vegetation communities found in Sinai by Helmy et al. (1996), El-Demerdash et al. (1996), and Hatim et al. (2016). M1G2 represents the association *Salvadoretum persicae*, which we—preliminarily—group in the class *Salicornietea fruticosae*.

Panicum turgidum dominates the *Panicum turgidum* group (M1G3). Additional differential species are *Stipagrostis scoparia*, *Cornulaca monacantha*, *Convolvulus lanatus*, and *Artemisia monosperma*. This community includes 48 relevés. The plant species of this group can be found on sandy plains and dunes (ergs) in the northern and southern regions of Sinai (Appendix S7). This group is similar to communities reported in Sinai by Danin (1983), Danin and Orshan (1999), El-Demerdash et al. (1996), and Hatim et al. (2016). It reflects the association *Panicetum turgidi* (Danin, 1983). This association belongs to the class *Retametea raetam*, which includes desert plant communities on sandy soils (Zohary, 1973).

Main group 2: Lowland desert vegetation (15 groups)

Zygophyllum coccineum group (M2G1) is characterized by *Zygophyllum coccineum* only. It contains 67 relevés. The predominant life forms are chamaephytes (Appendix S5), different from the main life forms in mother group M2. This community inhabits sandy wadis, plains, and dunes (ergs) in southern Sinai (Appendix S7). This group is similar to a community found in Sinai by El-Demerdash et al. (1996), Abd EL-Wahab et al. (2006), and Hatim et al. (2016). M2G1 represents the association *Zygophylletum coccinei*, which we assign to the class *Haloxylonetea salicornici*. Similar to the class *Retametea raetam*, this class occurs in sandy deserts. However, the class *Haloxylonetea salicornici* is confined to the most extreme, hyperarid deserts, which is reflected in the low species diversity and absence of relatively high shrubs.

The only characteristic and dominant species of the *Haloxylon salicornicum* group (M2G2) is *Haloxylon salicornicum*. This group includes 73 relevés with a relatively high mean species number (11) compared with that of the mother group M2 (9). It is dominated by chamaephytes (Appendix S5). It is found on sandy plains and dunes (ergs) in the northern and southern regions of Sinai (Appendix S7). This group is similar to vegetation communities described in Sinai by Migahid et al. (1959), Zohary (1973), El-Kady et al. (1998), Abd EL-Wahab et al. (2006), Morsy et al. (2010), and Hatim et al. (2016). M2G2 belongs to the association *Haloxylonetum salicornicae* (Zohary, 1973), which is part of the class *Haloxylonetea salicornici*.

Asphodelus fistulosus group (M2G3) is characterized by *Asphodelus fistulosus* (the dominant species) and *Ephedra alata*. It consists of 20 relevés. In contrast to the mother group M2, the primary life forms are hemicryptophytes (Appendix S5). The community inhabits sandy plains and dunes (ergs) in central and southern Sinai (Appendix S7). The group most likely fits in the association *Ephedretum alatae*, as described by Zohary (1973). We preliminary group M2G3 in the class *Haloxylonetea salicornici*.

Relevés of *Acacia tortilis* group (M2G4) are dominated by *Acacia tortilis*. It has 44 relevés and is dominated by phanerophytes, mainly trees (Appendix S5). This group occurs in sandy and gravelly wadis (ergs and regs) in the central and southern regions of Sinai (Appendix S7). This group is similar to those reported in Sinai by Danin (1983), El-Demerdash et al. (1996), Helmy et al. (1996), and Morsy et al. (2010). It reflects the association *Acacietum tortilis* of the class *Acacietea tortilis*. This class was described by Knapp (1968) for relatively dry lowlands in Sudan, Ethiopia, Eritrea, and Somalia. The *Acacia tortilis* communities in the Saharo-Arabian region represent outliers of this subtropical class, bound to desert sites with relatively good water availability.

Cleome droserifolia group (M2G5) is dominated by *Cleome droserifolia*. Other characteristic species are *Aerva javanica* and *Capparis aegyptia*, while *Acacia tortilis* is abundant in most sites. The community includes 64 relevés with a relatively high mean species number (12) in comparison with the mother group M2. Its vegetation mainly consists of chamaephytes (Appendix S5) and occurs in sandy and gravelly wadis. The communities are found primarily in the central and southern regions of Sinai (Appendix S7). Its species reflect Sudanian and Mediterranean chorotypes (Appendix S6). For M2G5, no corresponding association has been described in the literature. However, based on the high cover of *Acacia tortilis* and its species composition, we provisionally assign this community to the class *Acacietea tortilis*.

Tetraena simplex group M2G6 is characterized by *Tetraena simplex* (dominant), *Stipagrostis plumosa*, *Pulicaria undulata* subsp. *undulata* and *Citrullus colocynthis*. It includes 58 relevés with a relatively high mean number of species (11). The dominant life forms are hemicryptophytes (Appendix S5). This group occurs in sandy plains and sandy and gravelly wadis (ergs and regs) in the central and southern regions of Sinai (Appendix S7). This group is similar to communities reported in Sinai by El-Demerdash et al. (1996). Although we are uncertain about the appropriate corresponding association for M2G6, we found that the species composition indicates the class *Retametea raetam*.

Forsskaolea tenacissima group (M2G7) has *Forsskaolea tenacissima* as a dominant species. Further differential species are *Indigofera arabica*, *Iphiona scabra*, *Fagonia indica* var. *indica*, and *Lotus polyphyllos*. The group includes 58 relevés and has a higher mean species number (16) than the main group M2. Its plant species are mainly chamaephytes (Appendix S5), and the supporting habitats are sandy plains and dunes (ergs) in southern Sinai (Appendix S7). We allocated M2G7 in the class *Retametea raetam* without finding a suitable corresponding association.

Hyoscyamus muticus group (M2G8) is characterized by *Hyoscyamus muticus*, followed by *Tephrosia purpurea* and *Lavandula pubescens*. It includes 24 relevés with a relatively high species number (15). Unlike M2, the dominant life forms of M2G8 are chamaephytes (Appendix S5). Relevés of M2G8 occur in sandy and gravelly plains and dunes (ergs and regs) in all regions of Sinai (Appendix S7). The prevailing chorotypes are the Sudanian and Saharo-Arabian (Appendix S6). We suggested allocating this group to the class *Retametea raetam*. However, we refrained from further allocation on the level of association.

Fagonia scabra group (M2G9) differential species are *Fagonia scabra* (dominant), *Atriplex halimus*, *Caylusea hexagyna*, and *Ochradenus baccatus*. It includes 31 relevés with a relatively high species number compared with other groups (18). The primary life forms of the vegetation are chamaephytes (Appendix S5), and the supporting habitats are sandy plains and dunes and gravelly wadis (ergs and regs). This group occurs in the central and southern regions of Sinai (Appendix S7). M2G9 is similar to communities reported in Sinai by Zohary (1973), El-Demerdash et al. (1996), and Hatim et al. (2016). The species composition of M2G9 did not allow an allocation to any known association. Nevertheless, we can assign this group to the class *Retametea raetam*.

Artemisia judaica group (M2G10) is dominated by *Artemisia judaica*. It includes 77 relevés. In contrast to the main group M2, this group is dominated by chamaephytes (Appendix S5). It inhabits sandy and gravelly plains (ergs and regs) and is represented in the central and southern regions of Sinai (Appendix S7). M2G10 is similar to communities described in Sinai by Danin (1983), Abd EL-Wahab et al. (2006), and Hatim et al. (2016) and represents the association *Artemisietum judaicae* of the class *Retametea raetam*.

Zilla spinosa group (M2G11) is characterized by *Zilla spinosa* (dominant), *Fagonia mollis*, and *Cleome amblyocarpa*. It includes 59 relevés. The dominant life forms are chamaephytes (Appendix S5). The supporting habitats are sandy and gravelly plains and wadis (ergs and regs) in the central and, more frequently, the southern regions of Sinai (Appendix S7). This group is similar to those reported in Sinai by Danin (1983), who described it as the association *Retamo raetam-Zilletum spinosae*, El-Demerdash et al. (1996), and Ayyad et al. (2000). It also resembles the *Zilletum spinosae*, as described by Kassas (1954). M2G11 fits in the class *Retametea raetam*.

Fagonia arabica, followed by *Reseda pruinosa*, dominates *Fagonia arabica* group (M2G12). This group includes 91 relevés with a relatively high mean species number (12) in comparison with that of the main group M2. This group is dominated by chamaephytes (Appendix S5), and its relevés occur in sandy and gravelly plains (ergs and regs) in all regions of Sinai (Appendix S7). The group has many species in common with M2G11; therefore, we consider it a variety of the association *Retamo raetam-Zilletum spinosae* of the class *Retametea raetam*.

Retama raetam group (M2G13) is dominated by *Retama raetam*. It includes 106 relevés. Unlike the main group M2, the dominant life forms are phanerophytes, mainly shrubs (Appendix S5), and the supporting habitats are gravelly plains and sandy and gravelly wadis (regs and ergs). This group is represented in all regions of Sinai (Appendix S7). A similar vegetation community was reported in Sinai by Migahid et al. (1959), Danin (1983), Helmy et al. (1996), Marie (2000), Abd EL-Wahab et al. (2006), Morsy et al. (2010), and Hatim et al. (2016). Nevertheless, Danin (1983) stated that this community is restricted to the northern Sinai limestone hills, whereas Hatim et al. (2016) noted that it occurs on hummocks and wadi beds. It reflects the association *Retametum raetam* (Danin, 1983) of the class *Retametea raetam*.

Lycium shawii group (M2G14) is dominated by *Lycium shawii* and includes 19 relevés. The predominant life forms are phanerophytes, mainly shrubs (Appendix S5). Relevés of M2G14 occur in gravelly plains and wadis (regs). This group is widely distributed, with a focus in southern Sinai (Appendix S7). No corresponding association for this group was found, but the species composition suggests assigning it to the class *Retametea raetam*.

Tamarix senegalensis is the dominant species in *Tamarix senegalensis* group (M2G15). Further characteristic species are *Launaea nudicaulis* and *Filago desertorum*. It includes 23 relevés with the highest mean species number (20) compared with the other groups of the main group M2. Relevés of M2G15 occur on ergs (sandy wadis, plains, and dunes), and inland salt deserts. This group is represented in the northern, central, and southern regions of Sinai (Appendix S7). This group is similar to those reported in Sinai by Migahid et al. (1959), Danin (1983), El-Kady and El-Shourbagy (1994), Marie (2000), El-Ghani and Amer (2003), and Hatim et al. (2016). M2G15 represents the association *Tamaricetum niloticae* of the class *Retamo-Tamaricetea fluviatilis*, as Zohary (1973) described.

Main group 3: Mountain desert vegetation (six groups)

Stachys aegyptiaca group (M3G1) is characterized by dominant *Stachys aegyptiaca*, *Ballota undulata*, and *Galium sinaicum*. It consists of 60 relevés. The vegetation mainly consists of chamaephytes (Appendix S5) and inhabits rocky hillsides (hamadas), wadis, and outcrops. It can be found at rocky wadi slopes and beds in the Sinai mountains. M3G1 occurs in southern Sinai (Appendix S7), and its species belong to the Mediterranean and Irano-Turanian chorotypes (Appendix S6), which are different from the main group M3 chorotypes. This group is similar to communities found in Sinai by Danin (1983), Ayyad et al. (2000), Abd EL-Wahab et al. (2006), and Hatim et al. (2016). However, Danin (1983) stated that this group is restricted to limestone outcrops in northern Sinai. M3G1 represents the association *Stachydetum aegyptiacae* (Zohary, 1973) of the class *Chiliadenetea iphionoidis* (= *Varthemietea iphionoidis* in Zohary, 1973), representing rocky vegetation as described by Danin and Oshran (1999).

In *Phlomis aurea* group (M3G2), *Phlomis aurea* occurs as a dominant species. Further differential species are *Teucrium polium*, *Echinops spinosissimus*, and *Chiliadenus montanus*. M3G2 includes 107 relevés. Unlike the main group M3, the main life forms are hemicryptophytes (Appendix S5). Relevés of this group occur in rocky wadis and outcrops in the mountains of southern Sinai (Appendix S7). Its main chorotypes are the Irano-Turanian and the Saharo-Arabian (Appendix S6). It is similar to vegetation communities reported in Sinai by Danin (1983), Helmy et al. (1996), Ayyad et al. (2000), Abd EL-Wahab et al. (2006), Shaltout et al. (2015), and Hatim et al. (2016). We assigned M3G2 to the association *Tanaceto sinaici-Phlomitetum aureae* (Danin, 1983) of the class *Chiliadenetea iphionoidis*.

Characteristic species of *Tanacetum sinaicum* group (M3G3) are *Tanacetum sinaicum*, *Crataegus × sinaica*, and *Nepeta septemcrenata*. This group includes 62 relevés, and the primary life forms are chamaephytes (Appendix S5), inhabiting rocky outcrops. This group is represented in southern Sinai (Appendix S7). Its plant species mainly belong to the Mediterranean, followed by the Mediterranean-Irano-Turanian and Saharo-Arabian chorotypes (Appendix S6). It is similar to communities found in Sinai by Danin (1983), Moustafa and Zaghloul (1996), Ayyad et al. (2000), Abd EL-Wahab et al. (2006), and Hatim et al. (2016). We allocated this group to the association *Artemisio herbae-albae-Tanacetetum sinaici* (Danin, 1983) of the class *Chiliadenetea iphionoidis*.

Alkanna orientalis group (M3G4) is dominated by *Alkanna orientalis*; the other characteristic species are *Peganum harmala*, *Achillea fragrantissima*, *Launaea spinosa*, and *Matthiola arabica*. M3G4 includes 75 relevés with the highest mean species number of all groups (22) occurring in rocky wadis in southern Sinai (Appendix S7). The dominant life forms of this group are hemicryptophytes (Appendix S5). No corresponding association for this group was found, but the total species composition allocates this community to the class *Chiliadenetea iphionoidis*.

Artemisia herba-alba is the dominant species of *Artemisia herba-alba* group (M3G5). This group includes 89 relevés with a relatively low mean species number (7) compared with that of the main group M3. The life forms are mainly chamaephytes (Appendix S5). This group inhabits rocky wadis, predominantly represented in the southern and, to a lesser extent, central regions of Sinai (Appendix S7).

Most of the plant species belong to the Irano-Turanian and Saharo-Arabian chorotypes (Appendix S6). This group is similar to those reported in Sinai by Danin (1983), Ayyad et al. (2000), and Abd EL-Wahab et al. (2006). It reflects the association *Artemisietum herbae-albae* (Zohary, 1973). It is the only group that belongs to the class *Artemisietea sieberi*, which comprises steppe communities, in most cases dominated by low wormwood shrubs (Danin & Orshan, 1999). The class is concentrated in the cooler climate of the Irano-Turanian and Mediterranean regions (Zohary, 1973), but in Sinai, similar communities are found in places where edaphic conditions are suitable.

Anabasis articulata group (M3G6) is dominated by *Anabasis articulata*. Further differential species are *Moricandia sinaica*, *Deverra tortuosa*, *Juniperus phoenicea*, *Gymnocarpos decandrus*, and *Asparagus horridus*. M3G6 includes 55 relevés. Unlike the main group M3, the main life forms are chamaephytes (Appendix S5). The supporting habitats are rocky and gravelly wadis. This group is represented in northern and southern Sinai (Appendix S7). It is similar to a community reported in Sinai by Danin (1983) under the association *Anabasetum articulatae*, which is the only group of the class *Anabasietea articulatae*, being described for extreme arid and hot, stony and gravelly deserts in Zohary (1973) and Danin and Oshran (1999). It is an hyperthermic vicariant of the class *Artemisietea sieberi*.

Main group 4: Ruderal desert vegetation (one group)

Characteristic species of *Convolvulus arvensis* group (M4G1) are *Convolvulus arvensis* (dominant), *Euphorbia peplus*, *Chenopodium murale*, and *Cynodon dactylon*. This group includes 47 relevés with relatively high mean species numbers (17). The vegetation is dominated by therophytes (Appendix S5). This group represents the ruderal deserts and occurs mainly close to arable fields. This group is similar to communities reported in Sinai by Ahmed (1983), Gibali (1988), Marie (2000), and Hatim et al. (2016). M4G1 is similar to the association *Chenopodio albi-Solanetum villosi* (Zohary, 1973), and we placed it in the broadly defined class of weed communities, *Stellarietea mediae*.

Although the first three main groups are well separated, there is a floristic link between M1 and M2, indicating the transitional state of main group M1 from salt desert to lowland desert vegetation. This interference is apparent between M1G1 and M1G3 and groups M2G3, M2G5, and M2G6 as the characteristic species (*Tetraena alba* and *Panicum turgidum*) of the former groups appear in the latter with relatively high abundance values.

Many groups have a similar distribution within each main group (M) and occur in similar habitats. Thus, we think it likely that small ecological differences cause pronounced differences in species composition. In addition to the plant diversity found on the regional level, these findings reflect the diversity of desert vegetation on a more local scale, with its mosaic of rather diffuse but delimited vegetation communities (Danin, 1983). However, M4 is inarguably segregated from M1–M3 indicating its character of ruderal vegetation. Its species composition is predominantly driven by farming activities.

In Sinai, habitat type and altitude, which affect soil moisture, are the most critical factors controlling the distribution of vegetation groups and their related plant life forms (Ayyad, 1973; Danin, 1983; Hatim et al., 2016; Helmy et al., 1996; Kassas & Batanouny, 1984; Kassas & Girgis, 1965; Moustafa, 1990; Moustafa & Zaghloul, 1993; Zohary, 1973). The observed vegetation groups of salt and lowland deserts (M1 and M2 main groups) occur at lower altitudes and have the lowest mean species numbers. This may be related to a weak water-storing capacity and the scarcity of rainfall, resulting in very open and scarce vegetation (Hatim et al., 2016). By contrast, vegetation groups at higher altitudes (mountain deserts, M3) have higher mean species numbers. Such habitats have an increased water availability related to wadi-filling materials, sediments, and high proportions of gravels and fine grains in the soil pockets, giving them the ability to retain water efficiently (Ayyad et al., 2000). M4 has the highest mean species number because it occurs on nutrient-rich soils with high water availability in ruderal desert places. However, many of its species (e.g., *Convolvulus arvensis*, *Chenopodium murale*, *Cynodon dactylon*, *Malva parviflora*, *Hordeum murinum*, *Sonchus oleraceus*, and *Solanum nigrum*) are widespread, and their occurrences are the result of human disturbance. This finding, again, indicates the negative impact of farms by introducing such species to the area and the need to adapt regulations for land management.

Our findings show that the study area is inhabited by many plant life forms strongly adapted to the prevailing conditions in the Sinai desert region. Among them, therophytes are the most common (40%), followed by chamaephytes (30.7%) and hemicryptophytes (17.7%). Hemicryptophytes grow in arid places when they experience large amounts of rainfall or flooding. By contrast, therophytes and geophytes flourish in areas with nutrient-rich soils and high water availability (represented in M4 and M3 main groups).

Of the described 25 vegetation communities, many are similar to communities mentioned by Migahid et al. (1959), Danin (1983), Hussein (1988), Gibali (1988), El-Demerdash et al. (1996), Helmy et al. (1996), Marie (2000), and Hatim et al. (2016). Most of the groups could be assigned to associations described in the literature. However, seven of them do not correspond to any of the previously described associations. The distinction of these groups in our study can be related to the higher comprehensiveness of our data compared with those used in previous studies. It might also be possible that changes in species composition have occurred. However, this is not easy to test on the available data.

We set up a preliminary scheme, shown below, based on the 25 found vegetation groups, including four syntaxonomical levels (class, order, alliance, association). However, many questions can only be answered by analyzing data sets of desert relevés for much larger regions, including the Middle East and Sahara. For instance, it is unclear whether the *Acacia*-dominated desert savannahs should be split into different classes or not. The exact floristic differences between the sandy desert classes *Retametea raetam* and *Haloxylonetea salicornici*, and between the gravelly desert classes *Anabasietea articulatae* and *Artemisietea sieberi* are also not clear. Such uncertainties also remain at some lower levels of the current syntaxonomical scheme. The names of the syntaxa were adapted according to the latest taxonomy of the species, in line with the International Code of Phytosociological Nomenclature (Theurillat et al., 2021).

Salicornietea fruticosae **Br.-Bl. et Tx. ex A. Bolòs y Vayreda et O. de Bolòs in A. Bolòs y Vayreda 1950**
Limoniastretalia guyoniani Guinochet 1951
Zygophyllion albae Géhu, Costa & Uslu 1990
Zygophylletum albi Zohary 1973
Tetraena alba community (M1G1)
? Salvadoretum persicae Kassas et Zahran 1965
Salvadora persica community (M1G2)

Retametea raetam **Eig 1939**
Stipagrosto-Retametalia raetam Zohary 1973
Alliance ?
Panicetum turgidi Zohary 1973
Panicum turgidum community (M1G3)
Haloxylo-Retametalia raetam Zohary 1973
Alliance ?
Tetraena simplex community (M2G6)
Forsskaolea tenacissima community (M2G7)
Hyoscyamus muticus community (M2G8)
Fagonia scabra community (M2G9)
Artemisietum judaicae Zohary 1973 (M2G10)
Retamo raetam-Zilletum spinosae Danin 1983 (M2G11 and M2G12)
Retametum raetam Zohary 1973 (M2G13)
Lycium shawii community (M2G14)

Haloxylonetea salicornici **Zohary 1955**
Order ?
? *Zygophyllion coccinei* El Sharkawy et Fayed 1982
Zygophylletum coccinei Zohary 1973
Zygophyllum coccineum community (M2G1)
Haloxylonetum salicornicae Zohary 1973
Haloxylon salicornicum community (M2G2)
Ephedretum alatae Zohary 1973
Asphodelus fistulosus community (M2G3)

? Retamo-Tamaricetea fluviatilis **Zohary 1973**
? *Tamaricetalia africanae* Braun-Blanquet et Bolòs 1957
? *Tamaricion africanae* Braun-Blanquet et Bolòs 1957
Tamaricetum niloticae Zohary 1973
Tamarix senegalensis community (M2G15)

Acacietea tortilis **Knapp 1968**
? *Acacietalia tortillis* Knapp 1968
? *Acacion tortilis* Eig 1946
Acacietum tortilis Eig 1946
Acacia tortilis community (M2G4)
Cleome droserifolia community (M2G5)

Artemisietea herbae-albae **Zohary 1952**
Artemisietalia herbae-albae Zohary 1973
Artemision herbae-albae Eig 1946
Artemisietum herbae-albae Zohary 1973
Artemisia herba-alba community (M3G5)

Anabasietea articulatae **Zohary 1952 ex Danin et Solomeshch 1999**
Anabasietalia articulatae Zohary 1955 ex Danin et Solomeshch 1999
Agathophoro-Anabasion articulatae Danin, Orshan et Zohary 1975 ex Danin & Solomeshch 1999
Anabasietum articulatae Zohary 1973
Anabasis articulata community (M3G6)

Chiliadenetea iphionoidis **Zohary 1955 ex Danin et Solomeshch 1999**
Artemisio sieberi-Chiliadenetalia iphionoidis Danin, Orshan et Zohary 1975 ex Danin et Solomeshch 1999
Tanaceto-Artemision herbae-albae Zohary 1973
Stachydetum aegyptiacae Zohary 1973
Stachys aegyptiaca community (M3G1)
Tanaceto sinaici-Phlomitetum aureae Danin 1983
Phlomis aurea community (M3G2)
Artemisio herbae-albae-Tanacetetum sinaici Danin 1983
Tanacetum sinaicum community (M3G3)
Alkanna orientalis community (M3G4)

Stellarietea mediae **Tüxen et al. ex Von Rochow 1951**
Order ?
Alliance ?
Chenopodio albi-Solanetum villosi Zohary 1973
Convolvulus arvensis community (M4G1)

Based on our expert knowledge, the resulting classification satisfactorily represents vegetation communities of the Sinai desert region. It is worth mentioning that two main factors may have impacted the outcomes of this study. First, strongly restricted access to northern Sinai due to security issues resulted in a lower representation of its vegetation in the database compared with other Sinai regions. And second, the high representation of the vegetation from southern Sinai due to its importance as a center of medicinal and endemic plants. However, we think that the data on the vegetation of northern Sinai collected from literature could have decreased that impact.

4 | CONCLUSIONS

The high diversity of vegetation, plant life forms, chorotypes, the relatively low species numbers, and the strongly overlapping regions and habitats are challenging for the numerical classification of Sinai desert vegetation. Nevertheless, our study presents a sound and ecologically convincing classification of the Sinai desert vegetation. Yet, there is still a need for more detailed studies revealing the ecological and historical factors that determine the different vegetation communities and studies on the broader context of the Sinai desert vegetation and its position in the Saharo-Arabian region.

Besides using a more comprehensive data set (1,421 relevés), our work differs significantly from previous studies in applying different, up-to-date analyses of vegetation science, as well as providing enhanced, updated descriptions, distribution maps, and assignments to a syntaxonomical scheme of many vegetation communities, including seven new plant communities.

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AUTHORS CONTRIBUTIONS

Study concept: MZH, JAMJ and JHJS. *Methodology*: MZH, JAMJ, RP and JHJS. *Script coding, validation, formal analysis, data curation, writing the original draft and visualization*: MZH. *Study validation*: JAMJ, RP and JHJS. *Reviewing and editing the manuscript*: MZH, JAMJ, RP, KS and JHJS. *Study supervision*: JAMJ and JHJS. *Project administration*: JHJS.

DATA AVAILABILITY STATEMENT

The database consists of 927 plots stored in the sPlot project repository and 494 plots provided by the first author upon request. The Python scripts used to perform Hopkins' Test and Elbow method are available at https://github.com/mhatim99/Hopkins-Test and https://github.com/mhatim99/Optimal_number_of_clusters/blob/main/Optimal%20cluster%20number%20using%20Elbow%20Method%20-%20Final.ipynb, respectively.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Appendix S1. The Python script we used to calculate Hopkins' statistical hypothesis value

Appendix S2. The Python script we used to calculate the optimal number of clusters using the Elbow method

Appendix S3. Table of the data sources used in the study

Appendix S4. Synoptic table of the 25 vegetation groups resulted from the application of modified TWINSPAN

Appendix S5. Proportions of the life forms of the plant species of the 25 vegetation groups

Appendix S6. Proportions of the chorotypes of the plant species of the 25 vegetation groups

Appendix S7. Geographic distribution of the 25 vegetation groups (G) belonging to the main clusters (M1–4)

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