Rendiconti Lincei. Scienze Fisiche e Naturali
https://doi.org/10.1007/s12210-024-01239-8

RESEARCH PAPER

The vegetation around the foothills of the Hijaz Mountains, Saudi Arabia

Nick Hofland[1] · Mohamed Z. Hatim[2,3] · Jacob Thomas[4] · John A. M. Janssen[5] · Awad S. Alharti[4] · Ahmed H. Alfarhan[4] · Abdulrahman A. Alatar[4] · Joop H. J. Schaminée[2,5,6] · Mohamed A. El-Sheikh[4]

Received: 12 December 2023 / Accepted: 9 March 2024

Abstract

Despite Saudi Arabia being an interesting area from a floristic perspective, its vegetation is still relatively poorly studied. This certainly applies to the Hijaz Mountains and adjacent coastal zones. We aim to describe the flora and vegetation of the foothills of the Hijaz Mountains regarding the environmental conditions. Hijaz Mountains and adjacent coastal zones, Saudi Arabia. We studied the vegetation at the Hijaz Mountains' foothills along two transects of vegetation surveys, one along the coast and one more inland. In addition, soil samples were taken and analyzed for soil texture, pH, electrical conductivity, organic matter, calcium carbonate and the concentration of the elements N, Na, K, Ca, Mg, Fe and Mn were determined. We calculated the data clustering tendency (Hopkins' test analysis) and its optimal number of clusters (Elbow method). We used modified TWINSPAN to cluster the data and validated the resulting communities using the Silhouette algorithm. Seven plant communities resulted, each one dominated by a different plant species, namely: *Haloxylon salicornicum*, *Lycium shawii*, *Senegalia hamulosa*, *Vachellia tortilis*, *Zygophyllum coccineum*, *Vachellia flava*and *Stipagrostis plumosa*, and were described based on their floristic composition and could be further grouped into three vegetation clusters. The communities had varying ranges of occurrence in the study area, some dominating certain sections, with latitude and altitude being the biggest distinguishing environmental variables between the communities. We present a description of the vegetation of the Hijaz Mountains foothills. Our study is considered an important basis for decision-making of nature conservation and in-depth surveys of the area.

Keywords Desert vegetation · Vegetation communities · Saudi Arabia · Foothills · Hijaz Mountains · Modified Twinspan

✉ Mohamed Z. Hatim
mohamed.hatim@wur.nl

[1] Department of Animal Ecology and Physiology, Radboud University Nijmegen, P.O. Box 9100, 6500 GL Nijmegen, The Netherlands

[2] Plant Ecology and Nature Conversation Group, Environmental Sciences Department, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands

[3] Botany and Microbiology Department, Faculty of Science, Tanta University, Tanta, Egypt

[4] Botany and Microbiology Department, College of Science, King Saud University, P.O. Box 2455, 11451 Riyadh, Saudi Arabia

[5] Wageningen Environmental Research, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands

[6] Department of Experimental Plant Ecology, Radboud University Nijmegen, P.O. Box 9100, 6500 GL Nijmegen, The Netherlands

1 Introduction

The Arabian Peninsula is an interesting area from a floristic perspective as it lies in the transition zone of several phytogeographical regions (Al-Nafie 2008). The Mediterranean, Irano-Turanian, Saharo-Arabian and Sudano-Zambezian regions all meet on the Arabian Peninsula (Takhtajan et al. 1986; Zohary 1973). However, the common impression of this desert region as a barren wasteland has led to little interest in studying this region's floristic and phytosociological diversity. Fortunately, the last decades have marked an increase in our knowledge of the flora and vegetation of the Arabian Peninsula in general and that of Saudi Arabia in particular, resulting in several publications. See, for example, Kürschner and Neef (2011), Al-Sodany et al. (2011), Al-Khamis et al. (2012), El-Demerdash et al. (1994), Alyemeni (2000) and Al-Fredan (2008).

Published online: 04 May 2024

Despite this, there are still vast areas that are uncharted in this regard. Even though the vegetation of the Asir mountain range has received some attention from botanists, as demonstrated by the studies of Fayed and Zayed (1989), El-Demerash et al. (1994), El-Karemy and Zayed (1996), Al Wadie (2002) and El-Deen (2005), the vegetation of the more northerly located Hijaz Mountains and the adjacent coastal plains have received only little attention. In 1957, Vesey-Fitzgerald (1957) presented a rough description of the vegetation along the coast up to the inland side of the mountains, whereas Mahmoud et al. (1982) paid attention to the coastal area near Rabigh, and Abd El-Ghani (1996) studied the vegetation in the southernmost part of the mountain range along the road connecting the two holy cities Makkah and Medina.

Extensive knowledge of floristic composition and phytosociology is vital not only for phytogeographical and ecological studies but also for adequate protection and management of ecosystems and their biodiversity in a world with rapidly changing climate and land use. Therefore, the current study aims to improve the ecological knowledge of the foothills of the Hijaz Mountains by giving an account of its flora and vegetation concerning the environmental conditions.

2 Materials and methods

2.1 Study area

The Hijaz Mountains, located at the western edge of the Arabian Shield, comprise a mountain range in the northwestern part of Saudi Arabia stretching out along the Red Sea coast. To the west, the mountain range is bordered by the Tihamah (the Red Sea coastal region), which consists mostly of gently sloping, sandy and gravelly plains with varying soil depths and salt concentrations (Mahmoud et al. 1982; Alsherif et al. 2013; Guba and Glennie 1998). The Hijaz Mountains start from the Red Sea coastal area, where the terrain rises gradually from flat sandy plains to the foothills of mountains and further into slopes; these slopes rise to the top of the mountains at approximately 2000 m high. Eastwards, the Hijaz Mountains flow out into the Central Plateau, harboring the vast Arabian desert. The Hijaz mountains largely consist of a variety of Precambrian, hard bedrock, mainly granite, metamorphic (gneiss) and volcanic rocks, with sedimentary rocks (schists) at the base (Guba and Glennie 1998). The areas where these Precambrian rocks are overlain by young volcanic (basaltic) rocks are known as *harrah*.

The area, unlike the Asir Mountains which extend from the Hijaz Mountains southwards, is located within the Nubo-Sindian local centre of endemism of the Saharo-Sindian regional zone (Kürschner 1998; Alfarhan 1999) but also contains elements of neighbouring floristic regions, including the Mediterranean and Somali-Masai regional centres of endemism (Woldewahid et al. 2007). The area consists of many different habitats, such as wadis, runnels, sand sheets, gravels, rock deserts, and hillocks. These habitats all have their specific floristic elements and different plant formations. The diversity is further enhanced by the relatively high rainfall in the higher parts of the mountains. Because of these gradients and diversity, the Hijaz Mountains are considered one of the floristically richest regions of Saudi Arabia (Collenette 1998).

In general, the climate of the study area is influenced by maritime and tropical continental air masses (Fisher and Membery 1998). The upper sectors of the mountains represent a transitional zone between the monsoon and Mediterranean climates, which is influenced by the proximity to the Red Sea and the relatively high altitude (Abd El-Ghani 1996). In the lowlands, the climate is relatively dry, with rainfall not exceeding 100 mm each year, leading to the development of scarcer vegetation (Abd El-Ghani 1996), except for the wadis (Kassas and Imam 1954).

2.2 Vegetation survey

Field surveying was performed during the spring of 2015 when most species were expected to grow after increased rainfall. The total surveyed area was 36,812 km^2. Two transects were set up: one between the Hijaz Mountains and the coast and one on the eastern side of the Hijaz Mountains (Fig. 1). The coastal transect was positioned along Saudi Arabian Highway 5 between Jeddah and Haql (1015 km Length, 15,581 km^2 Area). The inland transect followed highways 15 and 328, starting at Jeddah and ending at Sulailah (498 km Length, 21,231 km^2 Area). 110 plots (10×10 m^2) were selected subjectively to cover most of the observed variation in vegetation and habitats. Plant cover was visually quantitatively estimated as a cover percentage for each species in each plot and then transformed into Braun-Blanquet scale. Plants were identified using Collenette (1985, 1999), Miller et al. (1996) and Chaudhary (1999, 2000a, 2000b, c, 2001). Herbarium specimens were deposited in the Herbarium of Botany and Microbiology Department at the King Saud University. In addition, the GPS coordinates of every sample location were recorded. Using these coordinates, the elevation of each sample location was determined using Google Earth Pro 7.3.3.7786.

2.3 Soil sample analysis

In addition to the vegetation surveys, a sample of surface soil (0–15 cm) was taken from most of the plots. Samples were air-dried and sieved with a 2 mm sieve to remove gravel and other coarse materials. In these soil samples, the following parameters were measured: texture, pH, electrical

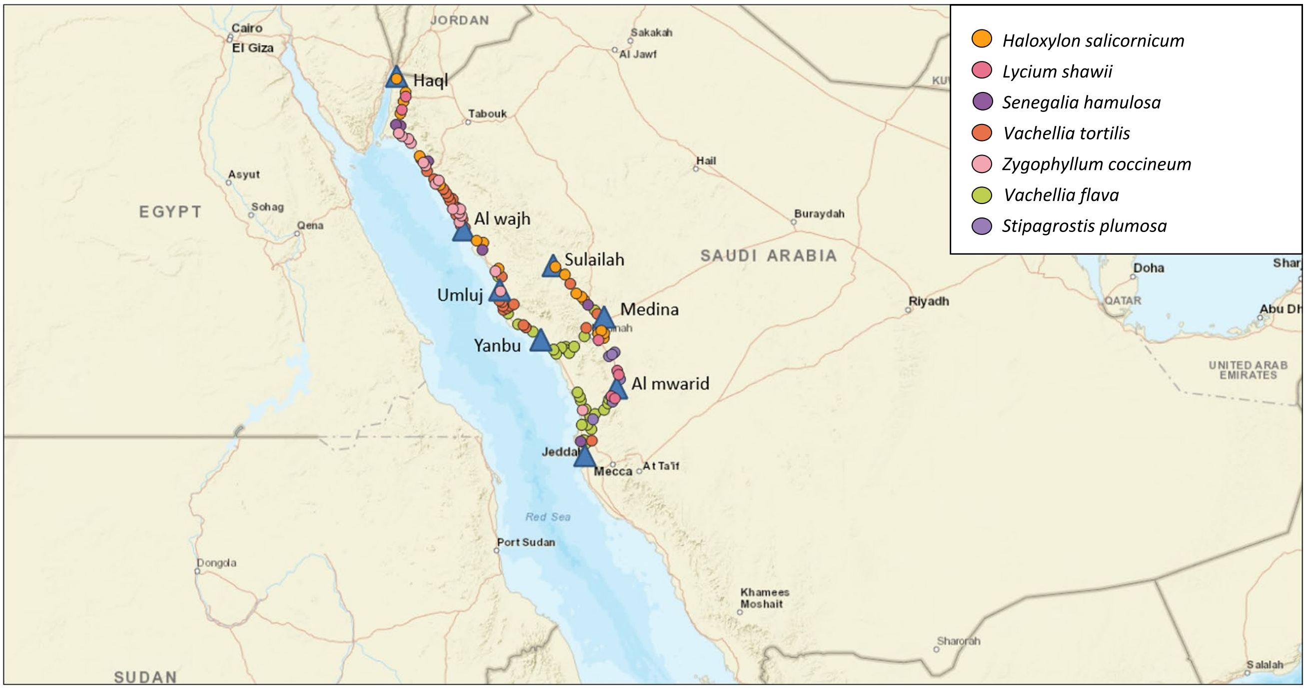

Fig. 1 Map of the study area showing the approximate locations of the vegetation plots. The color of each dot indicates the community the plot belongs to

conductivity, organic matter, calcium carbonate and the concentration of the elements N, Na, K, Ca, Mg, Fe and Mn. Soil structure was determined using the Bouyoucos (1962) hydrometer method. Soil–water extracts (1:5) were prepared to determine pH and electrical conductivity (EC) using pH and conductivity meters, respectively. Calcium carbonate content was determined by rapid titration after Sparks (1996). Organic matter content was determined by loss-on-ignition (Schumacher 2002). Soil samples were prepared for measurements of nutrient content using a TMC digestion after Sparks (1996). The total inorganic nitrogen content was determined by applying a spectrophotometric approach (Lindner 1944). The concentration of Na and K in the samples was measured by flame spectrophotometry and the concentration of Ca, Mg, Fe and Mn by atomic absorption spectrophotometry.

2.4 Data analysis

Plant species were allocated to life-forms according to Raunkiaer (1934) and to chorological units based on Zohary (1973) and Wickens (1978). The vegetation data were stored and organized using Turboveg 2.99 (Hennekens and Schaminée 2001). To determine if there are meaningful clusters (groups) in the data, the Hopkins' test (Python, version 3.7.6, Appendix A1) was used. This is a statistical hypothesis test that calculates the Hopkins' statistic (H) (Hopkins and Skellam 1954). The null hypothesis (H_0) states that the data follow a uniform distribution (implying no meaningful clusters), whereas the alternate hypothesis (H_1) states that the data are not uniformly distributed (presence of clusters). If the Hopkins' statistic outcome is larger than 0.5, the alternate hypothesis can be accepted and the data can be organized into meaningful clusters (Hopkins and Skellam 1954).

To calculate the approximate optimal number of clusters, the Elbow method (Ketchen and Shook 1996); Python, version 3.7.6 (Appendix A2) was used. In the Elbow method, a cluster analysis for the data is performed and the sum of within-cluster variance (WCSS) for different cluster numbers is calculated. The values of clusters numbers are plotted against their opposite WCSS values to find the optimal number of clusters, which is the last breaking point (elbow) of the plotted curve.

Using JUICE 7.1 (Tichý 2002), the vegetation plots were classified using a hierarchical modified TWINSPAN algorithm (Roleček et al. 2009) with pseudo-species cut levels 0, 5, 25, and 50. Hierarchical subdivision was stopped when it did not result in vegetation types with ecologically meaningful characteristic species. To improve the classification, nine vegetation plots were reallocated among the resulting groups. Reallocations only took place if (i) the segregation of the cluster by differential species constancy values was improved and (ii) the silhouette values (JUICE, Silhouette function) of the clusters remained unchanged or were increased. Ordination of the vegetation plots with the environmental data was done using a Detrended Correspondence

Analysis (DCA), using R 4.0.2 (R Core Team 2015) and the package vegan 2.5–6 (Oksanen et al. 2019).

The differences between the environmental variables of the different clusters were tested using Kruskal Wallis tests. Pairwise Wilcoxon rank sum tests with p-values adjusted using a Bonferroni correction were used as post hoc tests to determine differences between individual groups in case the Kruskal–Wallis tests showed the presence of significant differences. All these tests were done using R 4.0.2 (R Core Team 2015).

3 Results

3.1 Floristic diversity

In total, 110 plots were sampled, containing 214 plant species belonging to 42 families. The families *Asteraceae* and *Fabaceae* had the highest numbers of species, each accounting for 11.2% of the observed species. The *Poaceae* and *Amaranthaceae* each represented 7.9% of the recorded species, and the *Brassicaceae* and *Zygophyllaceae* 6.0%. Furthermore, 19 families were monotypic, whereas four families were represented by two species each.

The life-form spectrum was dominated mainly by therophytes, which accounted for 41.8% of the recorded species (Fig. 2). Chamaephytes, phanerophytes and hemicryptophytes constituted 28.8, 15.9 and 12.0% of the total number of species, respectively. Geophytes were by far the least represented life-form containing only 1.4% of the total species (Fig. 2).

The recorded plant species belonged to 16 different chorotypes, of which seven were uniregional, six were biregional and three were pluriregional (Fig. 3). The three most common chorotypes were the Saharo-Arabian, Sahel-Sudano-Zambezian and Tropical African chorotypes with 72 (33.6%), 42 (22.4%), and 21 (9.8%) species belonging to these types, respectively. The Mediterranean chorotype was represented by only five species (2.3%) and species with bi- and pluriregional chorotypes with a Mediterranean origin, such as Mediterranean-Saharo-Arabian, were just as rare or even more so. The influence of non-native species (mainly from the American Continents) is small in the study area, with only three species (1.4%).

3.2 Vegetation classification

The outcome of Hopkins' statistical analysis of the vegetation data was 0.9; thus, the alternate hypothesis, implying that the database contains clusters, was accepted. The expected optimal number of clusters based on the Elbow method was seven (Fig. 4). The hierarchical modified TWINSPAN analysis of the 110 vegetation plots resulted in the formation of seven vegetation communities grouped into three clusters (C1–C3) (Fig. 5, Table 1). C1 consisted of three communities mainly associated with wadis and runnels and mainly occurred in the inland transect. C2 also contained three communities, but these vegetation types were mainly associated with the coastal plains. C3 contained only one community, the *Stipagrostis plumosa* community, which had a low number of associated species and occurred on coarse sandy plains. Cluster C1 occurred at higher altitudes than cluster C2 ($p = 3.1e^{-8}$). In addition, the soils of the plots of C1 contained more Ca than those of C2 ($p = 0.0087$). Furthermore, the plots of C1 contained more species than C3 ($p = 0.022$).

All reported communities grew on sandy substrates with relatively low amounts of silt and clay (Table 1). The differences in soil pH were small, with all communities having high pH values, ranging between 8 and 9.2. The differences in electrical conductivity were much bigger. When plotted on the first two DCA axes, the communities cluster to some extent, although there is still considerable overlap (Fig. 6). The vegetation plots from the *Senegalia hamulosa*

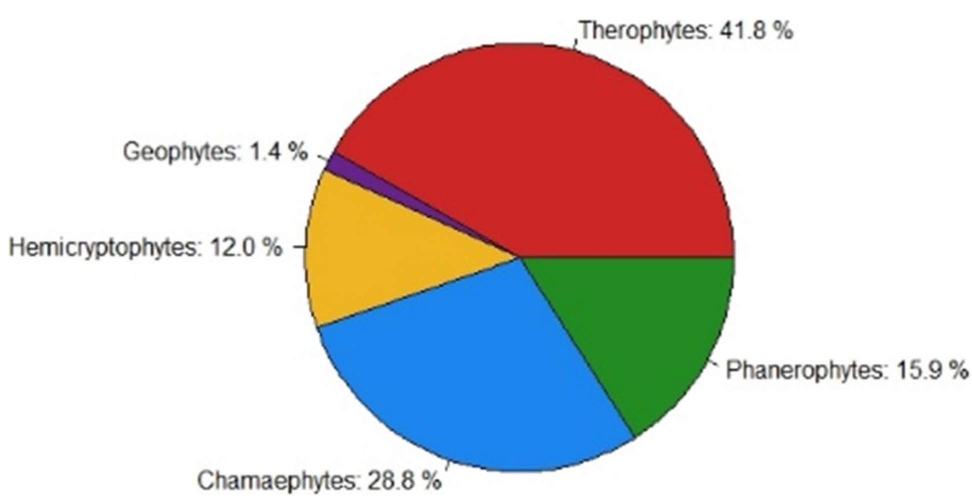

Fig. 2 The life-form spectrum of the transects vegetation

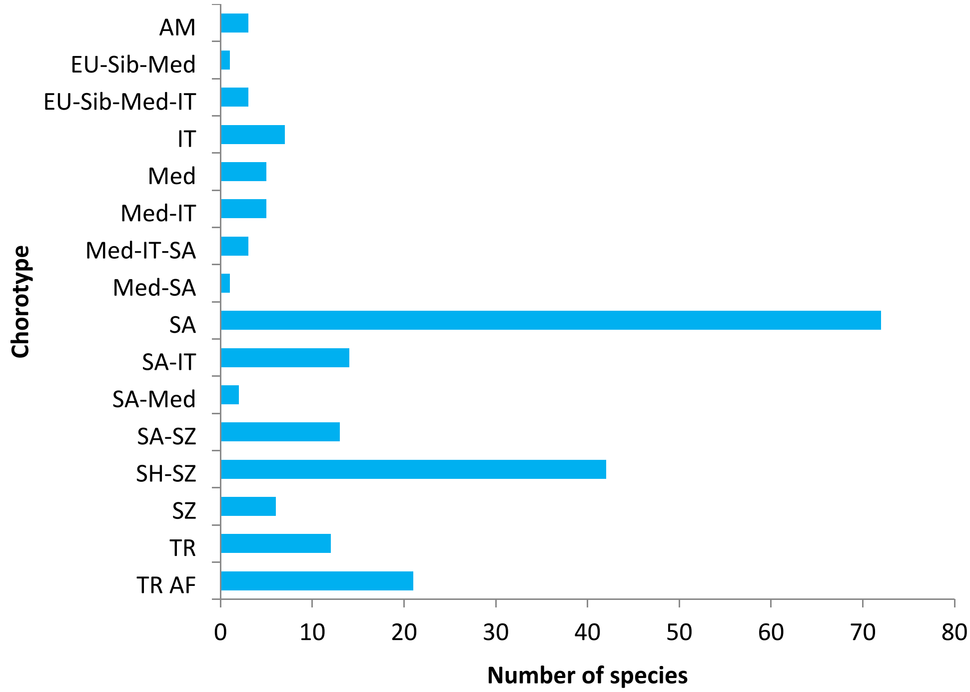

Fig. 3 The chorotype spectrum of the transects vegetation. AM-American, Eu-Sib-Med-Euro-Siberian-Mediterranean, EU-Sib-Med-IT-Euro Siberian-Mediterranean-Irano Turanian, IT-Irano Turanian, Med-Mediterranean, Med-IT-Mediterranean-Irano Turanian, Med-IT-SA-Mediterranean-Irano Turanian-Saharo Arabian, Med-SA-Mediterranean-Saharo Arabian, SA-Saharo Arabian, SA-IT-Saharo Arabian-Irano Turanian, SA-Med, Saharo Arabian-Mediterranean, SA-SZ-Saharo Arabian-Sudano-Zambezian, SH-SZ-Sahel-Sudano-Zambezian, SZ-Sudano-Zambezian, TR-Tropical, TR AF-Tropical African

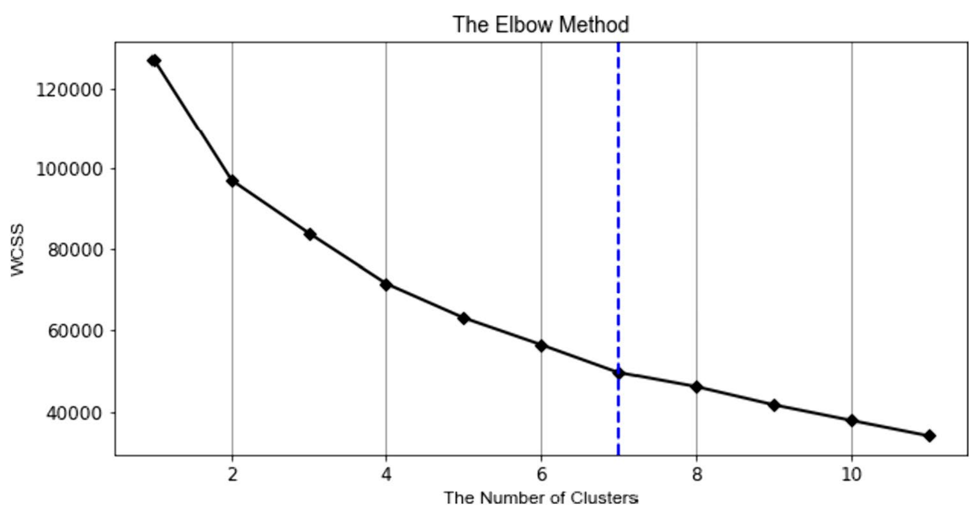

Fig. 4 The plot of the Elbow method showing the expected optimal number of clusters. The WCSS values (Within Cluster Sum of Squared distances) represent the mean distances between the plots of a group and its centroid. The lowest the value of WCSS, the more meaningful the clusters are, and the better to correspond to an optimal number of clusters. In our case, the Elbow corresponds to the number of clusters, 7

community are the most strongly clustered together on the positive side of the first DCA axis and the negative side of the second. Most of the different nutrients seem to be positively correlated with each other, as well as the silt and clay content and elevation. The exceptions to this are the nitrogen and iron concentration, which are negatively correlated to the other variables but positively correlated to each other and the sand content and latitude.

3.2.1 *Haloxylon salicornicum* community

The first shrubland community is dominated by the dwarf shrub *Haloxylon salicornicum*. *Haloxylon salicornicum* is a xeromorphic chamaephyte that is widely distributed within the Irano-Turanian and Saharo-Arabian bioprovinces. With 19 plots, this vegetation type is the most abundant shrubland community in the study area. This type of shrubland occurs in the northernmost part of both the coastal and inland transects. It occurs more north than the *Senegalia hamulosa* ($p=0.0067$) and *Vachellia flava* ($p=2.1e^{-7}$) communities. In the inland transect, it appears just south of Medina and stays prevalent, sometimes even dominating the vegetation, all the way up to the northern end of the transect. In the coastal transect, it is found north of the town of Umluj, persisting up to the Jordanian border. At the northern part of the coastal transect in the mountains along the Gulf of Aqaba,

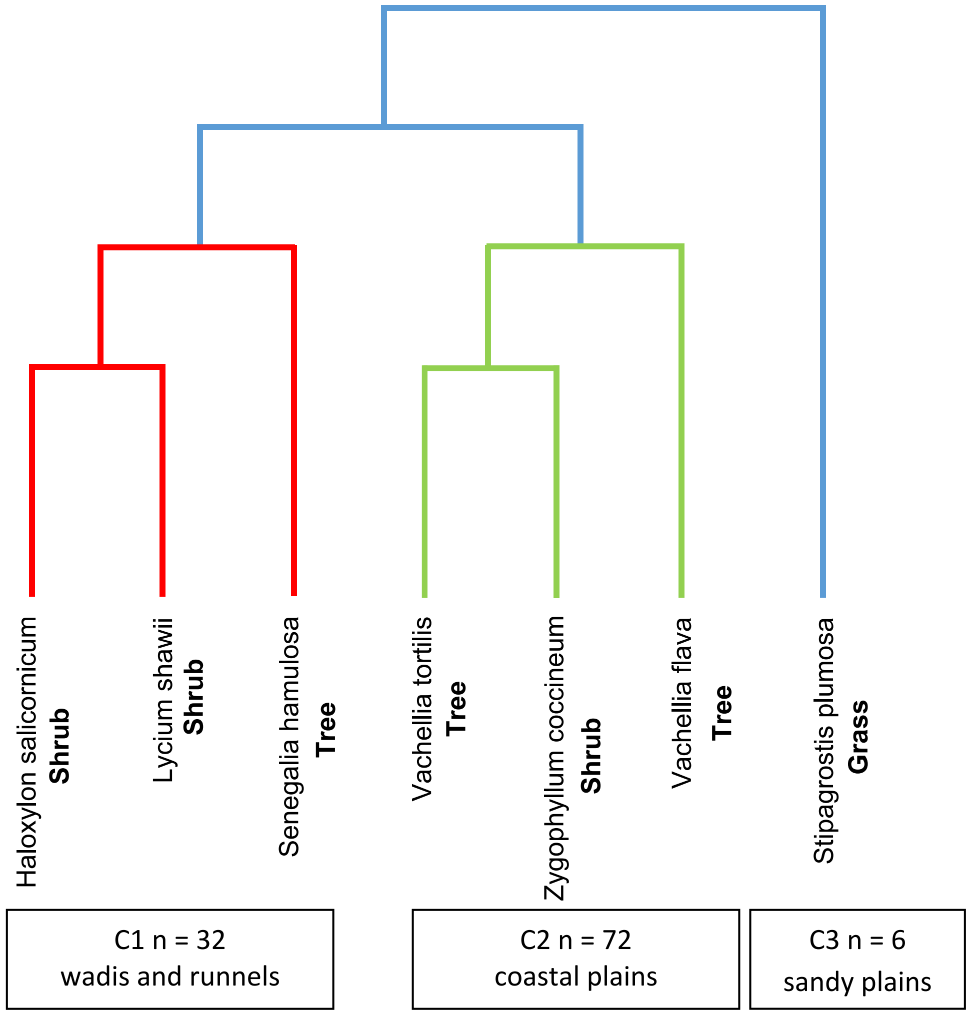

Fig. 5 The dendrogram resulting from the hierarchical modified TWINSPAN analysis, containing seven vegetation communities organized into three clusters (C1–C3) with their ecological types indicated. *n*: the total number of vegetation plots in each cluster

this vegetation type becomes dominant once again. Due to its occurrence in the inland and coastal transects, this community occurs on a lower average elevation than the *Lycium shawii* and *Senegalia hamulosa* communities. The only community of lower elevations is the *Zygophyllum coccineum* ($p = 0.0024$) community. This community was characterized by shallow runnels and plains where the soil has a coarse texture. Its most common associates are the dwarf shrub *Zygophylum simplex*, the shrub *Calotropis procera* and the perennial herb *Citrullus colosynthis*.

3.2.2 *Lycium shawii* community

The second vegetation community is dominated by the perennial shrub *Lycium shawii*. This community is very species-rich. Though it is only represented by seven plots in the current study, it still comprises the largest species list out of all communities described in this study. The average number of species per plot is higher than that of the *Haloxylon salicornicum* ($p = 0.0156$), *Vachellia tortilis* ($p = 0.0109$), *Zygophyllum coccineum* ($p = 0.0081$) and *Vachellia flava* ($p = 0{,}0057$) communities. This community is mainly recorded on mountain slopes and in wadis with sandy soils. Of all communities, it is found at the highest average altitude, mainly occurring between 700 and 1000 m above sea level. This causes it to occur at higher elevations than all communities from the C2 and C3 clusters, namely: the *Vachellia flava* ($p = 0.0024$), *Vachellia tortilis* ($p = 0.0040$), *Zygophyllum coccineum* ($p = 0.0044$) and *Stipagrostis plumosa* ($p = 0.0490$) communities. Like the *Senegalia hamulosa* community it occurs in the southern part of the inland transect, between Jeddah and Medina. However, unlike the *Senegalia hamulosa* community, it recurs in the northern part of the transect, in the mountains along the Gulf of Aqaba. Its soil has the highest average silt and organic matter (OM) contents, indicating relatively good water availability. It is a well-structured community consisting of different layers of vegetation. The shrub layer is dominated by *Lycium shawii*, sometimes accompanied by the shrub *Ochradenus baccatus* or by different species of Acacia trees (*A. ehrenbergiana*, *A. origena*, *A. johnwoodii* and *A. gerrardii*). The herb layer frequently contains the dwarf shrub *Haloxylon*

Table 1 Shortened synoptic table with the percentage frequency of occurrence and the number of plant species within each of the seven vegetation communities

Group No	1	2	3	4	5	6	7
No. of vegetation plots	19	7	6	28	16	28	6
No. of species	79	99	34	85	48	88	23
Haloxylon salicornicum	100	43	17	14	44	4	0
Calotropis procera	37	14	0	7	6	25	33
Citrullus colocynthis	37	14	0	25	13	18	17
Lycium shawii	5	86	17	39	25	14	0
Centaurea pseudosinaica	5	71	17	0	0	0	0
Aizoon canariense	21	71	17	11	0	11	0
Sisymbrium erysimoides	0	71	0	0	0	0	0
Asphodelus tenuifolius	26	71	33	7	0	0	0
Ochradenus baccatus	16	57	0	25	0	14	17
Malva parviflora	0	57	17	0	0	0	0
Trichodesma africanum	0	43	17	7	0	0	0
Zilla spinosa	11	43	0	0	0	0	0
Cuscuta planiflora	0	43	0	0	0	0	0
Rumex vesicarius	5	43	17	0	0	0	0
Echium horridum	0	43	0	0	0	0	0
Solanum glabratum	0	43	0	0	0	0	0
Otostegia fruticosa	0	43	0	0	0	0	0
Senegalia hamulosa	0	0	83	0	0	7	0
Aristida adscensionis	16	0	50	21	6	7	0
Indigofera spinosa	0	43	50	4	0	4	0
Sclerocephalus arabicus	0	43	50	0	0	0	0
Maerua crassifolia	26	14	33	25	0	7	0
Vachellia tortilis	21	29	33	96	75	36	17
Panicum turgidum	11	0	0	46	19	25	17
Blepharis ciliaris	11	14	17	43	13	4	0
Fagonia indica	11	14	17	32	6	11	17
Zygophyllum coccineum	5	0	0	18	94	29	17
Zygophyllum simplex	42	14	33	54	69	54	33
Hyphaene thebaica	11	0	0	0	31	0	0
Vachellia flava	11	43	17	4	19	86	0
Leptadenia pyrotechnica	5	14	0	4	0	36	0
Senna italica	32	14	0	18	6	36	17
Dipterygium glaucum	0	0	0	4	0	32	0
Stipagrostis plumosa	26	0	0	25	0	14	83
Capparis decidua	0	14	0	7	6	7	50

Only differential species (with frequencies ≥ 30%) are included, and their cells are shaded. The dominant species of each community is shaded

salicornicum as well as various herbs, the most common of which are the annuals *Asphodelus tenuifolius*, *Centaurea pseudosinaica*, *Malva parviflora*, *Sisymbrium erysimoides*. Patches of the creeping annual herb *Aizoon canariense* are a characteristic feature of this community.

3.2.3 *Senegalia hamulosa* community

This vegetation type is dominated by *Senegalia hamulosa*. With only six plots, this vegetation type is the rarest of the three *Acacia* communities in the study area. *Senegalia hamulosa* is a phanerophyte taking the form of a small tree or shrub. It is distributed within the Sudano-Zambezian and Saharo-Arabian floristic regions. This community has been found on slopes and wadis on loamy soils in the southern part of the inland transect, between Jeddah and Medina. Along with the *Lycium shawii* community, it is one of the most southerly occurring communities, distributed at lower latitudes than the *Haloxylon salicornicum* ($p = 0.0067$, as mentioned previously), *Vachellia tortilis* ($p = 0.0097$) and

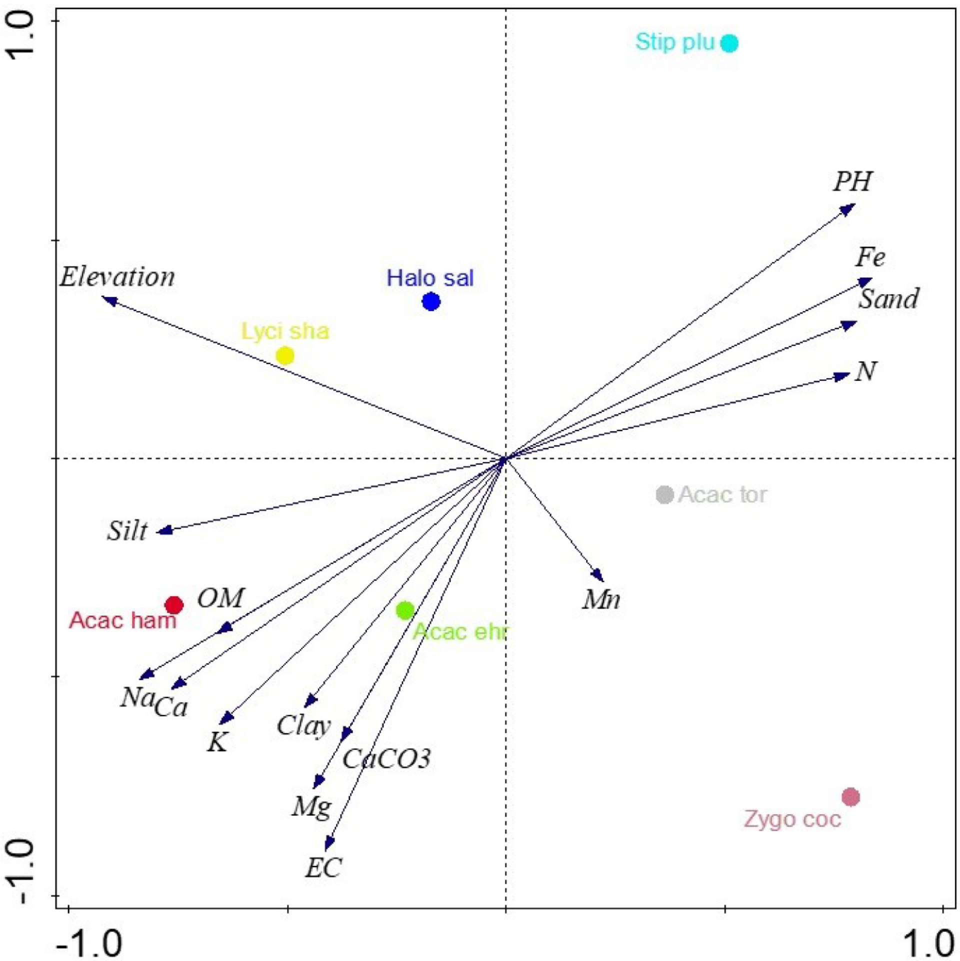

Fig. 6 DCA of environmental factors and vegetation communities with arrow indicating the effects of the environmental variables and the communities are indicated by their abbreviations

Zygophyllum coccineum ($p = 0.0359$) communities. Just like the *Lycium shawii* community, it occurs at high elevations mainly between 600 and 1000 m above sea level. It occurs higher than all the communities of cluster C2, namely: the *Vachellia flava* ($p = 0.01114$), *Vachellia tortilis* ($p = 0.0135$) and *Zygophyllum coccineum* ($p = 0.0095$) communities. Of all plant communities in this study, this community's soil is the finest, on average containing the most clay and the least sand. It also has the lowest average pH and highest average electrical conductivity (EC) values. It contains the highest average concentrations of $CaCO_3$, Na, K, Ca, Mg, and the lowest average values of N and Fe. When compared to the other communities within C1, its soil is characterized by a low average of N and Fe. In addition, this community's soil varies most markedly from that of the *Vachellia tortilis* community, containing more Ca ($p = 0.04337$) and less N ($p = 0.012$) and Fe ($p = 0.0035$). The dominant *Senegalia hamulosa* is sometimes accompanied by *Mearua crassifolia* trees. Other species common in this vegetation type include the dwarf shrub *Indigofera spinosa*, the annual herb *Sclerocephalus arabicus* and the annual grass *Aristida adscensionis*.

3.2.4 *Vachellia tortilis* community

With 28 plots, this community is the most widely represented vegetation type in the study area together with the *Vachellia flava* community. Its main distribution within the study area comprises the area north of the towns of Yanbu up to the Gulf of Aqaba, dominating the vegetation just north of Yanbu as well as between the towns Al Wajh and Duba. The most striking feature of this community is the shrub layer, consisting mainly of *Vachellia tortilis*. It often takes the form of a small tree with an umbrella-shaped crown. This community requires a relatively well-drained substrate and is therefore found on the coarsest soils, consisting of the highest average sand content and the lowest average silt content. The most commonly co-occurring species are the annual herb *Zygophyllum simplex* and the perennial tussock grass *Panicum turgidum,* which both occurred in about half of the plots of this type. Other relatively common co-occurring are the perennial herbs *Blepharis ciliaris* and *Fagonia indica*.

3.2.5 *Zygophyllum coccineum* community

The fifth community is a vegetation dominated by *Zygophyllum coccineum*. This community was represented by 16 plots. *Zygophyllum coccineum* is a perennial dwarf shrub distributed mainly around the Red Sea within the Saharo-Arabian floristic region. This vegetation type is confined to the coastal plains of the Tihamah area in the northern parts of the coastal transect, occurring from the area around the town of Umluj up to the area around the town of Gayal. Bound to the coastal plains, it occurs on the lowest average altitude of all communities. The soils of this community had the highest average concentrations of N and Mn. The species most commonly associated with this community is the annual herb of the same genus *Z. simplex*. The shrub layer of this vegetation community is often populated by the trees *Vachellia tortilis*, *Acacia raddiana* and *Hyphaene thebaica*. The dwarf shrub *Haloxylon salicornicum* also occurs in almost half of the plots of this type.

3.2.6 *Vachellia flava* community

The third *Acacia* dominated community is represented by 28 plots and one of the most common plant communities in the study area. *Vachellia flava* is a phanerophyte taking the form of a small tree or shrub. It is widely distributed within the Saharo-Arabian floristic region, with the centre of the species distribution in the southern parts of the Sahara. This community dominates the coastal plains in the southern part of the coastal transect, between the towns of Yanbu and Jeddah, and is also found in the southern part of the inland transect, up to the town of Almwared. It occurs at lower latitudes than the *Haloxylon salicornicum* ($p = 2.1e^{-7}$, as mentioned previously), *Vachellia tortilis* ($p = 5.9e^{-9}$) and *Zygophyllum coccineum* ($p = 1.4e^{-5}$) communities. Its soil is characterized by a low average N and Fe compared to the other communities within cluster C2. Its soil has a lower N than *the Vachellia tortilis* ($p = 0.00034$) and *Zygophyllum coccineum* ($p = 0.00509$) as well as a lower Fe compared to the *Vachellia tortilis* ($p = 2.6e^{-5}$) and *Zygophyllum coccineum* ($p = 4.1e^{-5}$) communities. In addition, its soil has a lower pH than the *Haloxylon salicornicum* ($p = 0.0205$) and *Vachellia tortilis* ($p = 0.0076$) communities. The shrub layer of this vegetation community is dominated by *Vachellia flava*, occasionally accompanied by the shrub *Leptadenia pyrotechnica*. Dwarf shrubs are a conspicuous element of this vegetation type with *Zygophyllum simplex*, *Senna italica* and *Dipterygium glaucum* all represented in some of the plots. *Astragalus vogelii* var. *fatmensis* is the most common herb in this community, though still only occurring in 21% of the plots of this type.

3.2.7 *Stipagrostis plumosa* community

This pseudo-steppe community is dominated by *Stipagrostis plumosa*. *Stipagrostis plumosa* is a hemicryptophyte taking the form of tussock grass. This community occurred sporadically in the northernmost parts of both the coastal and the inland transect. With only six plots, this community is one of the least represented vegetation types. This community was most abundant on sandy plains without any gravel or stones. Its soil was coarse and poor in nutrients with the lowest clay and organic matter content. It had the highest pH and the lowest EC. Finally, it had the lowest concentrations of $CaCO_3$, Na, K, Ca, Mg, Mn and the highest concentration of Fe. The most common co-occurring plant species were the shrub *Capparis decidua* and the dwarf shrub *Zygophyllum simplex*.

4 Discussion

4.1 Classification challenges

The vegetation units are not very strongly defined, with many species frequently occurring in different communities. The plant cover, therefore, consists of a large number of indifferent species. The occurrence of several pluriregional elements in the study area indicates a large influence of adjacent phytogeographical regions, further complicating the formation of consistent vegetation units. However, this relatively large number of indifferent species is a typical characteristic of desert vegetation, which complicates vegetation classification in the region. This is in accordance with the findings of Kassas (1953), who theorized that the open character of desert communities does not allow the dominant species to exert a controlling influence on the rest of the community. Other authors also experienced problems in describing the vegetation in desert systems adequately using the Braun-Blanquet method (Zohary 1973). Zohary (1973) theorized that the methodology of Braun-Blanquet, which was developed with mesic-temperate vegetation in mind, is not completely suitable to analyze the vegetation of arid zones.

In our opinion, the methodology can be applied to desert vegetation, although the resulting communities are relatively poorly defined. This has been shown with the use of clustering analysis. To present a verified clustering analysis, the clustering tendency was calculated using Hopkins' statistical hypothesis method. The low species numbers of some plots and significant differences among percentage frequencies of species occurrences make the process of classification challenging. These limitations were overcome by applying a modified TWINSPAN followed by the reallocations of nine vegetation plots among the resulting groups based on mathematically verified Silhouette analyses to improve the final result. Nevertheless, the communities, as defined in this study, as well as their zonation, are in accordance with communities described by other authors. The construction of a hierarchical classification system, with associations, alliances, orders and classes remains a huge challenge for desert vegetation of the Sahara and the Arabian Peninsula and requires an extensive data set from a wide range of geographical areas and habitats. The current study contributes to such an overview.

4.2 Community zonation

The northern parts of both the inland and coastal transects were dominated by *Haloxylon salicornicum* communities. These communities have been reported abundantly in the inland sand and gravel (harrah) deserts of northern and central Arabia (Zohary 1973; Danin and Orshan 1999; Kürschner 1998) as well as in similar habitats in the adjacent Sinai Peninsula in Egypt (Hatim et al. 2016, 2021). On the Arabian Peninsula they cover more land than any other type (Mandaville 1990; Al-Khamis et al. 2012), especially on coarse-textured soils (Kürschner and Neef 2011). Its dominance in the northern regions of the coastal transect might be a consequence of the sampling procedure, as the plots along the Gulf of Aqaba were taken inland due to the inaccessibility of the coastal area. Therefore, this part of the transect might be more akin to the inland transect.

In the coastal transect, directly south of the *Haloxylon salicornicum* zone, the *Vachellia tortilis* community dominates the vegetation. This community is an example of the drought-resistant, deciduous *Acacia-Commiphora*-woodlands that are widespread on the Arabian Peninsula in wadis, foothills and lower mountain slopes (Deil and Al Gifri 1998; Kürschner 1998). Such communities in a broad sense have been described from subtropical Northern Africa under the class name *Acacietea tortilis* (Knapp 1968). They have been recorded quite commonly along the Red Sea coast of Saudi Arabia, although the species assemblages and associates differ (Vesey-Fitzgerald 1957; Kassas 1957; Zohary 1973). In addition, vegetation types dominated by *Vachellia tortilis* have been found in the opposing Red Sea coastal region of Egypt (Zahran and Willis 1992) and in the deserts of Israel (Danin and Orshan 1999). In most studies, these communities have been recorded in depressions, wadis and slopes, often covered with rocks, pebbles or gravel (Al Wadie 2002; Danin and Orshan 1999; Fayed and Zayed 1989). *Stipagrostis plumosa* is widely distributed over the Arabian Peninsula, and communities with *Stipagrostis plumosa* are described from stabilized, deep sand habitats in Arabia by Mandaville (1998). In addition, they are recorded as a dominating species in many vegetation types on the Israeli sand sheets (Danin and Orshan 1999). However, the incidents of *Stipagrostis plumosa* communities reported from the Hijaz mountain range are reported either from the southern parts of our study area (Fayed and Zayed 1989) or even further to the south in the Asir mountains. It must be noted, however, that the southern portion of the Hijaz mountains (as well as the Asir mountains) are far more extensively studied than the northern reaches of the mountain range. This, in conjunction with the cryptic nature of this vegetation, might mean that it can easily be missed, especially whilst sampling in the dry season. The apparent absence of this community in the northern portions of the Hijaz mountains might, therefore, be the result of a low total sampling effort. Communities dominated by *Zygophyllum coccineum* are typical coastal communities on coarse soil in the Arabian desert (Deil 1998). They have been recorded on the coastal plains of the study area (Vesey-Fitzgerald 1957; Mahmoud et al. 1982) as well as on the opposing Sinai Peninsula (Abd El-Wahab et al. 2006; Hatim et al. 2016, 2021). In addition, they have been recorded as a dominant species in communities in the south of the Hijaz Mountains (Abd El-Ghani 1996) as well as in the Asir Mountains (El-Karemy and Zayed 1996; El-Deen 2005). In these studies, these vegetation types were recorded in deep alluvial plains, wadis and runnels (El-Karemy and Zayed 1996; Abd El-Ghani 1996).

The southernmost part of both transects was dominated by the *Vachellia flava* community, which is in accordance with the more southerly distribution of the species. The *Vachellia flava*-community fits the description of the wadi communities with Sudanian and Xero-tropical taxa by Kürschner (1998). According to this author, these communities are typical for the western plains (Tihamah) with extensive areas of fluvial deposits and aeolian sands. He mentions *Leptadenia pyrotechnica* as an important associate in places where the wind plays a role in the deposition of sediments. In addition, it has been recorded as a dominant species in communities in the south of the Hijaz Mountains (Abd El-Ghani 1996) as well as in the Asir Mountains (El-Karemy and Zayed 1996; El-Deen 2005). In these studies, these vegetation types were also recorded in deep alluvial plains, wadis and runnels (El-Karemy and Zayed 1996; Abd El-Ghani 1996) at low elevations (Danin and Orshan 1999). *Senegalia hamulosa*-dominated communities have also previously been recorded in the more southern ranges of the western mountains of Saudi Arabia. They were recorded in both the south of the Hijaz mountains (Abd El-Ghani 1996; Batanouny and Baeshin 1982) as well as in the Asir mountain ranges (El-Deen 2005; Fayed and Zayed 1989), where they were mostly found on slopes and runnels covered with rocks (Batanouny and Baeshin 1982; El-Deen 2005; Fayed and Zayed 1989). In addition, the combination of *Senegalia hamulosa*, *V. tortilis* and *Maerua crassifolia* fits the description of a Sudanian thorn woodland type by Kürschner (1998), which he considers typical for the Tihamah coastal plain and the southern coast of the Arabian Peninsula. Plant communities dominated by *Lycium shawii* are common around the Arabian Peninsula (Ghazanfar and Osborne 2010). In addition, Kürschner (1998) mentions *Lycium shawii* as an associate in wadi communities of *Acacia raddiana*, *V. tortilis* and *A. gerrardii*, which he considers typical for the central part of Arabia. These communities have also been recorded within the southern reaches of the study area by Abd El-Ghani (1996) and Mahmoud et al. (1982) and stretching southward along the Asir Mountains by Fayed and Zayed (1989). In these studies, this community is reported on gravel or pebble covered, coarse-textured soils in shallows, runnels and slopes (Abd El-Ghani 1996). To the north, these communities have also been reported in wadi systems (Danin and Orshan 1999).

4.3 Underlying environmental factors

Of the environmental factors measured in this study, latitude and altitude seem to exert the most significant influences on this vegetation pattern. Due to the general circulation of air, the distance from other water sources and local factors like mountain barriers, the rainfall on the Arabian Peninsula mainly comes from the Arabian Sea located to the south of the peninsula (Alyamani and Sen 1993). Therefore, the annual average rainfall increases from north to south, with the southwestern highlands receiving the most rainfall. In addition to the latitudinal gradient, the physiographic features of the landscape exert a heavy influence on local weather conditions going so far as having a bigger influence on the microclimate than the macroclimatic conditions do (Alyamani and Sen 1993; Abd El-Ghani 1996). The coastal plains are generally hot and dry, with hot summers and dry periods all throughout the year (Vesey-Fitzgerald 1957). As the elevation rises, precipitation increases and becomes more equally distributed throughout the year (Fayed and Zayed 1989). Along the same line, the mean air temperature decreases with increasing elevation (Fayed and Zayed 1989), which lowers the potential evapotranspiration in these areas (Alyamani and Sen 1993). Both of these factors contribute to a higher and more consistent level of soil moisture, which has often been described as being the primary distinguishing factor affecting desert vegetation communities (Zohary 1973; Hatim et al. 2016, 2021). An effect that can also be seen, on a larger scale, in the difference in vegetation and species diversity between the Hijaz and the more southerly located Asir mountain ranges.

4.4 Conclusion

In two transects, one coastal and one inland, along the foothills of the Hijaz mountains, 110 vegetation plots were made, the classification of which resulted in a division into seven distinct communities, dominated by: *Senegalia hamulosa*, *Lycium shawii*, *Haloxylon salicornicum*, *Stipagrostis plumosa*, *Vachellia flava*, *Zygophyllum coccineum* and *Vachellia tortilis*. These communities were divided into three clusters based on their floristic composition; a cluster of three communities (*Senegalia hamulosa*, *Lycium shawii* and *Haloxylon salicornicum*) is mainly found in wadis and runnels, another cluster of three communities (*Vachellia flava*, *Zygophyllum coccineum* and *Vachellia tortilis)* found on the coastal plains, and a cluster consisting of only the *Stipagrostis plumosa* community found on the inland plains. The communities displayed clear differences in their distribution patterns, with (1) the *Haloxylon salicornicum* community dominating the inland transect as well as the most northern part of the coastal transect, (2) the *Vachellia tortilis* community dominating the vegetation directly south of the *Haloxylon salicornicum* zone, (3) the *Vachellia flava* community dominating the southernmost part of both transects, (4) the *Stipagrostis plumosa* and *Zygophyllum coccineum* co-occurring with the *Haloxylon salicornicum* and *Vachellia tortilis* communities on the plains in the northern parts of the coastal transect and (5) the *Senegalia hamulosa* and *Lycium shawii* communities co-occurring in the wadis and runnels in the southern part of the transect dominated by the *Vachellia flava* community. These patterns in the distribution of the communities were mainly caused by differences in latitude and altitude affecting local rainfall and through soil moisture.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12210-024-01239-8.

Acknowledgements The authors would like to thank Prof. Dr. L. P. M. Lamers for his helpful comments on the processing of the soil data.

Authors contributions Nick Hofland: Conceptualization, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Visualization. Mohamed Z. Hatim: Conceptualization, Formal analysis, Writing—Review & Editing, Visualization. Jacob Thomas: Conceptualization, Methodology, Investigation, Writing—Review & Editing. John A.M. Janssen: Writing—Review & Editing. Awad S. Alharti: Investigation, Data Curation, Writing—Review & Editing. Ahmed H. Alfarhan: Project administration, Funding acquisition. Abdulrahman A. Alatar: Project administration, Funding acquisition. Joop H. J. Schaminée: Writing—Review & Editing, Supervision. Mohamed A. El-Sheikh: Conceptualization, Methodology, Investigation, Writing—Review & Editing, Supervision

Funding The authors would like to extend their sincere appreciation to Researchers Supporting Project Number (RSP2024R182), King Saud University, Riyadh, Saudi Arabia.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability The data is provided by the first author upon request.

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