



Research Article

Analysis of the vegetation in the King Abdulaziz Royal Nature Reserve, Kingdom of Saudi Arabia

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ARTICLE INFO

Keywords:

Chorological spectrum
Life form spectrum
Plant communities
Plant diversity
Vegetation map
Vegetation structure

ABSTRACT

The study aimed to provide a baseline inventory of the vegetation of the King Abdulaziz Royal Nature Reserve (KARNR), which covers an area of approximately 28,000 km². The identification, mapping, and description of vegetation units across the landscape are crucial to develop scientifically based, ecological management plans and implementing effective conservation strategies. In total, 282 sample plots were surveyed in the dry season. The floristic data were classified into 19 communities with the classification informed by Ward's cluster analysis and Principal Coordinates Analysis ordinations. Sentinel satellite imagery and digital elevation models were used for habitat mapping. Mean species richness, exponent of Shannon-Wiener, and inverse Simpson's diversity indices were calculated per community. Life forms and chorological spectra were also compiled for each community. A total of 172 plant taxa were recorded across 37 families and 126 genera, with the *Asteraceae*, *Poaceae*, *Fabaceae*, and *Amaranthaceae* being the most species-rich families, which collectively comprised 46% of all taxa recorded. Structurally, most communities were dominated by the dwarf shrub layer, although the tree layer was prominent in the wadis. The vegetation on the mobile dunes was dominated by the graminoid layer. Diversity parameters showed an approximately ten-fold range across communities, from the lowest diversity on gravel and rocky plains to the highest diversity on escarpments and rocky ridges with their associated wadis. As is commonly found in arid regions, therophytes and chamaephytes were the dominant life forms. The drought-evading therophytes show a high degree of plasticity in size and phenology, whereas the drought-tolerant chamaephytes may exhibit morphological and physiological adaptations to drought. The chorological spectra of all communities were dominated by Saharo-Arabian species. Comparing the communities occurring predominantly in the northern section of KARNR with the predominantly southern communities revealed that the northern communities had a higher percentage of Saharo-Arabian species but a lower percentage of Sudanian species than the southern communities. Currently, the vegetation across large parts of the reserve is degraded due to past heavy grazing. It is recommended that reference sites be identified to monitor vegetation recovery after introducing controlled grazing and reducing livestock numbers.

1. Introduction

The King Abdulaziz Royal Nature Reserve (KARNR) is one of eight royal nature reserves in the Kingdom of Saudi Arabia (KSA). It was established in 2018 and covers an area of approximately 28,000 km², mainly in the Riyadh region. The objectives of the reserve are: to maintain or improve the inherent biodiversity; ensure that the continued capacity of the area to support life is not compromised; increase community engagement; and attract tourism. Various initiatives have been commenced, such as rehabilitating degraded areas, reintroducing wildlife that formerly roamed the landscape, and waste removal campaigns.

The classification, identification, and description of vegetation units across the landscape are generally regarded as the first steps to establish a framework for scientifically based ecological management plans. Providing baseline information on the spatial, ecological, and

environmental features of the vegetation can lead to an improved understanding of the natural resources and is a prerequisite for making informed, effective, and defensible conservation decisions to manage and protect ecosystems and biodiversity. A sound knowledge of the vegetation of the KARNR area was thus considered essential to develop an ecological management plan for the reserve and to establish conservation priorities (e.g., control overgrazing, restoration needs) and guide land use decisions.

The classification of the vegetation into plant communities followed the Braun-Blanquet phytosociological method (Werger, 1974). Multivariate analytical methods utilized in the classification of the floristic data into communities included cluster analysis and principal coordinates analysis (PCoA) ordinations.

Raunkiaer's life form classification groups plants by the position and protection of their perennating organs during unfavorable conditions (Danin & Orshan, 1990). An analysis of the vegetation based on life

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Received: 25 January, 2025 Accepted: 07 December, 2025 Epub Ahead of Print: 10 February, 2026 Published: 24 February, 2026

DOI: 10.25259/JKSUS_168_2025

forms assumes that the life form of a species reflects its capacity to survive the most unfavorable season, and in arid regions, this reflects the adaptations to water scarcity. Assessing the effects of climate change by life form or plant functional types is increasingly being applied to identify future trends in ecosystem structure (Broennimann et al., 2006).

Saudi Arabia's flora is a complex mix of species from different phytogeographical regions. A chorological study determines the dominance of these different elements, with the most important elements in KSA being Saharo-Arabian, Sudanian, Mediterranean, and Irano-Turanian. Chorological studies provide a baseline for monitoring vegetation changes over time, especially in terms of climate change and human impact such as overgrazing, urbanization, and invasive species.

Patterns of plant diversity are often used to prioritize conservation activities, assuming that conserving diverse areas is the most cost-effective way to maintain biological diversity and key ecological functions (Giam et al., 2011). Diversity parameters used in this study included species richness, the exponent of Shannon-Wiener, and the inverse Simpson's diversity indices. Accurate inventories are essential to determine the spatial distribution of species-rich areas, monitor changes over time, and assess the effectiveness of conservation actions (Gillson et al., 2020).

At present, the vegetation of the KARNR area has not been studied or mapped in its entirety, and the existing data is considered incomplete for developing a comprehensive management plan. The current study aims to classify and map the vegetation, identify plant communities, and provide a baseline description of the floristic composition, vegetation structure, plant diversity, life form spectrum, and phytogeographic affinities of each plant community. The baseline provided here is essential to track changes in plant communities over time and to assess the effectiveness of conservation actions.

1.1 Study area

KARNR, spanning an area of 2,843,192 ha (lat 26.895338° - 25.705221°; long 45.543225° - 46.424436°), is roughly divided into a northern and southern section by the Ad Dahna dune field, which runs in a northwest-to-southeast direction more or less through the center of the reserve (Fig. 1). The Ad Dahna dune field, significantly affects local and regional ecological gradients. As a result of the size and complex topography of this dune field, it acts as a major physical obstacle to regional airflow, and this alters wind direction and speed. Variations in dune shape and height across the field, furthermore, create localized turbulence.



Fig. 1. Location of the King Abdulaziz Royal Nature Reserve.

Geologically, Saudi Arabia is divided into two structural provinces, viz. the Arabian Shield and the Arabian Shelf or Platform. The study area lies on the Arabian Shelf, which lies east of the Arabian Shield. The area consists of a sequence of Cambrian to Pliocene continental and shallow-water marine sedimentary rocks (Powers et al., 1966). Sand accumulations are the most recent geomorphological feature of Saudi Arabia and are represented by the Ad Dahna dune field.

According to the Köppen climate classification, KARNR lies in a hot desert (BWh) climate. The mean annual rainfall and temperature for Riyadh, approximately 70 km south of the study area, are 66 mm and 26.2°C, respectively (<https://en.climate-data.org>). Rainfall occurs primarily in winter and spring and is spread more or less evenly across the months from November to April. The mean annual rainfall and temperature for Hafar Al-Batin, approximately 73 km north of the study area, are 110 mm and 25.1°C, respectively.

Most plant geographers agree that there are two major phytogeographic regions in Saudi Arabia; however, there is controversy about the position of the boundary between these regions. The conventional viewpoint is based largely on the work of Eig (1931-1932 in Al-Nafie, 2008) and the earlier accounts of Zohary (1973). According to this viewpoint, almost the entire inland of Saudi Arabia, and thus the study area, is part of the Saharo-Arabian Region (Zohary, 1973). The Sudanian Region occurs along the coastline of the Arabian Peninsula.

2. Materials and Methods

The study employed a combination of field surveys and quantitative analyses to assess the composition, distribution, and structural features of the plant communities in the study area.

2.1 Field survey

Vegetation surveys were conducted following the Zürich-Montpellier (Braun-Blanquet) School of Phytosociology (Werger, 1974), as has often been the approach for vegetation studies in this arid region of the KSA (Al-Anazi & Al-Qahtani, 2018; Al-Fredan, 2008; Al-Otaibi, 2017; Al-Sodany et al., 2011; Alsalem et al., 2020; El-Sheikh et al., 2013, 2021; Shaltout and Mady, 1996).

Prior to selecting sampling sites, the area was stratified into relatively homogeneous habitat types. The sampling strategy relied on a landscape approach using a grid-based system to subdivide the landscape into manageable sampling units, whereby each grid cell was considered a potential sampling grid. Due to the large size of the study area and the relative homogeneity of the landscape, 16 km² grid cells (4 km by 4 km) were considered appropriate. The 16 km² grid cell represents an upper limit for fine-scale grids, recommended for sub-regional to regional scale work where a balance is required between level of detail and potential management options (Seo et al., 2009; Ardron et al., 2010). To ensure representativeness, the following combined recommendations were used: at least 5 sampling replicates should be collected per Association (Hayek and Buzas, 2010) with the aim of reaching 15 to 20 sampling replicates per Association (Memon et al., 2020) while at least 10% of grid cells defined should be surveyed (Bartlett et al., 2001; Memon et al., 2020).

In total, 282 sample plots (1,000 m²) were surveyed from 17 November to 15 December 2022. The timing of the surveys coincided with the end of the dry season and the beginning of the wet season. Although the ephemeral component was poorly developed at the time of the surveys, the perennial species were present. Using the results of a dry season survey has the advantage of using predominantly the perennial component that can be found reliably year-round. Annual species that were present at the time of the survey were, however, included in the analysis. The ephemeral component is not present in all seasons and is also notoriously variable across years. A classification based predominantly on the ephemeral component would therefore not be recognizable year-round.

At each sample plot, the following assessments were made:

2.1.1 Floristic assessment

All plant species were recorded, and a Braun-Blanquet cover/abundance scale (Mueller-Dombois & Ellenberg, 1974) was allocated

to each species. The primary advantage of using this cover/abundance scale is its speed and cost-effectiveness when conducting field surveys over large areas.

2.1.2 Structural assessment

Estimates were made of mean canopy cover (%) and mean plant height (m) of the:

- o Tall tree layer (>6 m tall);
- o Small tree layer (>2–6 m tall);
- o Shrub layer (>1–2 m tall);
- o Dwarf shrub layer (up to 1 m tall);
- o Graminoid layer; and
- o Forb (herbaceous, non-graminoid) layer.

2.1.3 Habitat assessment

Topography, aspect, slope, altitude, terrain form, degree of erosion, clay content of the soil, pebble, stone, rock, and boulder cover, and degree of drainage were recorded.

2.2 Mapping

As a backdrop for the mapping of plant communities, a 2022 Sentinel 2 (Level 2A; including atmospheric correction) natural colour satellite image with a 10 m resolution was used. The image was a 24-bit composite of bands 4,3,2 as RGB overlaid on a Hill-shading of an interpolated Copernicus Digital Surface Model with a 10 m resolution. Rivers, streams, wadis, rawdats, and depressions were mapped using a Digital Elevation Model (DEM).

2.3 Data analysis

Classification of the floristic data was informed by Ward’s cluster analysis and Principal Coordinates Analysis (PCoA) as an ordination technique, which were run in PC-Ord 6 (McCune and Mefford, 2011). The cover/abundance values were converted to percentages, and the percentage values log-transformed (log_e) to down-weight the disproportionate influence of dominant species and give greater emphasis to species with lower cover values. The Bray-Curtis distance measure was applied for the PCoA, and for the cluster analysis, the Euclidean distance measure. For the cluster analysis, the cut level was set at 50% information remaining. The table of sample plots against species was refined using Braun-Blanquet tabulation procedures (Wenger, 1974) to produce a hierarchical classification.

Vegetation structure was analyzed per community by calculating the mean canopy cover and height for each stratum. Species richness (S), evenness (E), Shannon-Wiener (H’), and Simpson indices of diversity (D’) were computed per plot in PC-Ord 6, and a mean per community was calculated. Diversity indices were converted to the effective number of species, i.e., the exponent of Shannon-Wiener (Exp H’) and inverse Simpson (Inv D’), to compare communities.

Each species was assigned to a life form category according to Raunkiaer’s classification system (Mueller-Dombois & Ellenberg, 1974) (Supplementary material T1), and a phytogeographic region(s) (chorotype) following data in Al-Sodany et al. (2011), Alsalem et al. (2020), Danin & Fragman-Sapir (2016+), and El-Sheikh et al. (2013).

3. Results

The results of this study revealed distinct patterns in plant community composition and structure, highlighting notable variations across the study area.

Sampling effort was considered spatially representative with 11.8% of the grid cells sampled and an additional 18.6% of the grid cells were visited. By combining the cells physically sampled and those traversed to reach the sampling sites, the sampling effort afforded visualization through 30.4% of the grid cells. At least five sites were sampled per Association and >15 sites were sampled for seven associations.

Table 1.

The plant species, with a frequency of occurrence of 20%, was observed in the King Abdulaziz Royal Nature Reserve.

Species	Frequency (%)	Species	Frequency (%)
<i>Moltkiopsis ciliata</i>	20	<i>Stipagrostis plumosa</i>	26
<i>Lycium shawii</i>	21	<i>Haplophyllum tuberculatum</i>	29
<i>Calotropis procera</i>	22	<i>Zygophyllum glutinosum</i>	30
<i>Iftoga spicata</i>	22	<i>Plantago ciliata</i>	35
<i>Rhazya stricta</i>	23	<i>Citrullus colocynthis</i>	40
<i>Schismus barbatus</i> / <i>Rostraria pumila</i>	24	<i>Pulicaria undulata</i>	40
<i>Helianthemum lippii</i>	25	<i>Heliotropium bacciferum</i>	45
<i>Polycarpea repens</i>	26		

3.1 Classification of floristic data

In total, 172 plant species were recorded in 282 sample plots, and on average ten species/subspecies were recorded per sample plot (see Supplementary material T2 for the full species list). The mean frequency of occurrence of a plant species was 5.7%, while 22% of all species were encountered in only one sample plot. Only 15 species occurred in 20% or more of all sample plots (Table 1). The 172 species were spread across 37 families and 126 genera, with the most species-rich families being the *Asteraceae* (27 species), *Poaceae* (26 species), *Fabaceae* (13 species), and *Amaranthaceae* (13 species), which collectively represented 46% of all species recorded.

The classification of the floristic data revealed 19 plant communities (C) (Fig. 2). The first level of division in the cluster analysis separated the dunes and interdunes (C17–C19) from the other habitats. The remaining group was split into two large groups, with the first cluster

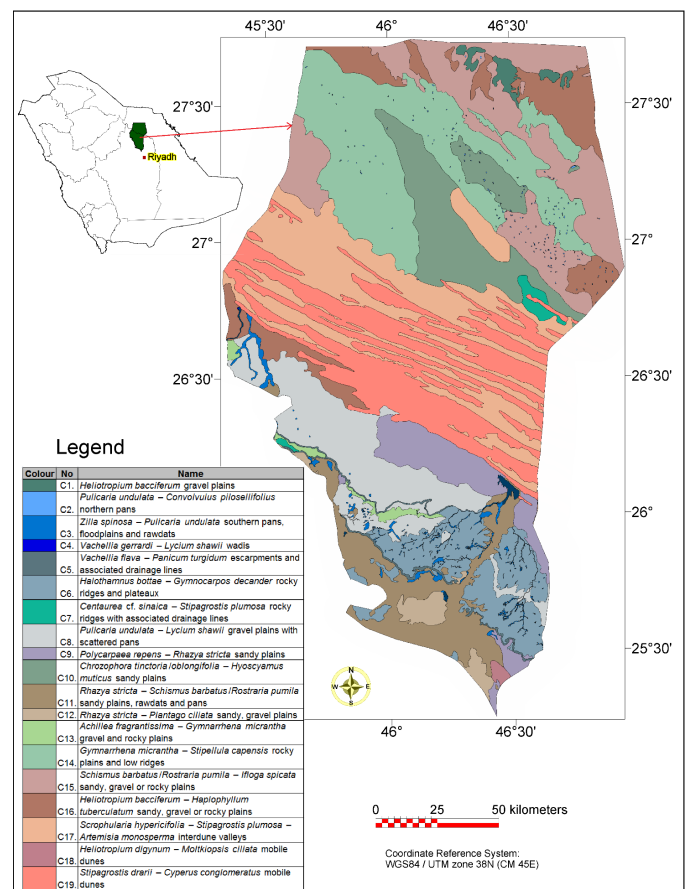


Fig. 2. Vegetation map of the King Abdulaziz Royal Nature Reserve (A2-format of map available in (Suppl-F1)).

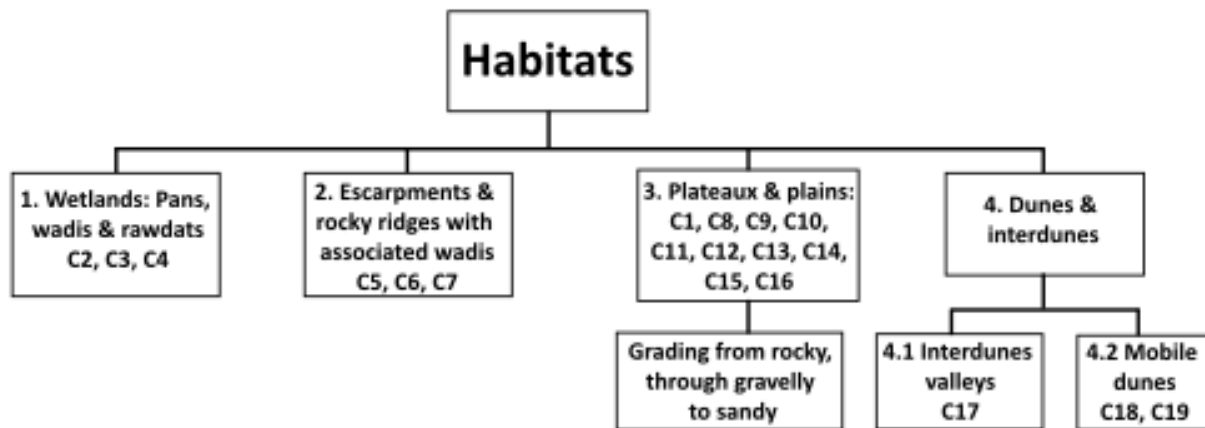


Fig. 3. Schematic representation of the conceptual classification of habitats into four major groups.

containing the wetlands, the escarpments, ridges, and some plateaux and plains (C1–C10). The second cluster comprised predominantly sandy, gravelly, or rocky plains and some rawdat vegetation (C11–C16). As a result of the large number of plots surveyed, these clusters were subsequently analyzed separately and are presented as separate synoptic tables (Supplementary Material T2.1, Supplementary Material T2.2, and Supplementary T2.3). Topographically, communities were grouped into four broad habitat groups (Fig. 3).

Group 1, Wetlands including pans, wadis, rawdats, and floodplains (C2, C3, C4): These communities occur in seasonally wet habitats that are focal points for herbivores. The vegetation is generally distinctly different from the surrounding plains, often being the only vegetated areas in a barren landscape. The wetland habitat is highly sensitive and should be conserved to avoid disrupting the hydrological regime and groundwater recharge. Total vegetation cover (%) was generally highest in this habitat group, and plant diversity was second highest among the habitat groups.

Group 2, Escarpments, rocky ridges with their associated wadis (C5, C6, C7): This habitat group is scenically the most striking and diverse and has a high sensitivity. Communities in this group were closely related floristically. Although these communities generally had the highest plant diversity, the total vegetation cover (%) was low.

Group 3, Gravel, sandy or rocky plains or plateaux (C1, C8–C16): These communities occur in habitats that are not scenically diverse, but occupy large expanses of rather monotonous plains or plateaux. There is generally a grading from rocky plains and plateaux that are related to Group 2 habitats, through gravelly plains and plateaux to sandy plains and plateaux that are in turn more closely related to dune habitats. These communities generally had the lowest plant diversity and plant cover.

Group 4, Dune communities (C17, C18, C19): These floristically closely related communities occupy the fairly stable, sandy interdune valleys and the mobile dunes. Dune crests are typically drier and more exposed to wind, leading to active sand movement and unstable surfaces, and consequently, a very sparse vegetation cover. In contrast, interdune depressions and lower dune slopes tend to accumulate finer sediments and retain more moisture, allowing for increased plant cover and biomass. Plant diversity in this group was generally low, although graminoid cover was often high.

A brief description of each community is provided in the supplementary material, indicating the location and environmental features and the most prominent species encountered. For the full floristic composition, the reader is referred to the synoptic tables (Supplementary Material T2). These descriptions should be read together with the structural and diversity data (Figs. 4 and 5) and the life form and phytogeographic spectra (Fig. 6).

3.2 Vegetation structure

Canopy cover of the strata showed large differences across communities (Fig. 4). In the dry season most of the communities were dominated by the dwarf shrub layer. However, in C2–C5 trees, most

notably *Acacia gerrardi* and *Ziziphus nummularia*, made a noteworthy contribution towards the cover. Shrub cover was highest in C2–C5 and C9–C11. Dwarf shrub cover was highly variable, but highest in the northern pans (C2), followed by rawdats and plains (C11) and interdune valleys (C17). Graminoid cover was notably highest in the Ad Dahna dune communities (C17, C19). Forb cover is expected to be highly variable and dependent on seasonal rainfall. The dry season survey revealed the highest forb cover in the pan (C2, C3) and interdune communities (C17).

3.3 Plant diversity

Species richness, exponent of Shannon-Wiener, and inverse Simpson indices showed an approximately ten-fold range across the communities (Fig. 5). The lowest diversity was generally found on the sandy, gravel, or rocky plains, whereas the highest diversity was associated with the escarpments, rocky ridges, and associated wadis. Plant diversity in the pans, dunes, and some plain communities was intermediate.

3.4 Life forms

Overall, the vegetation was dominated by therophytes and chamaephytes (Fig. 6). The therophytes included annual/ephemeral dicotyledonous plants as well as annual grasses and sedges. Hemicryptophytes included perennial grasses and perennial herbs and contributed from 5% to 50% of the spectra. Geophytes, liana, and parasites were uncommon and constituted small percentages of the total number of species in a community. Considering all species, there were 37% therophytes: chamaephytes (33%), hemicryptophytes (21%), and geophytes (1%).

3.5 Phytogeographic affinities

Species from the Saharo-Arabian phytogeographical region dominated the phytogeographic spectra of all communities (31–65% of species/community) (Table 2) followed by the bi-regional Saharo-Arabian–Sudanian (10–50%) and Irano-Turanian–Saharo-Arabian (0–21%), and the monotypic Sudanian (0–16%) chorotypes. Other chorotypes made small contributions to the community spectra, except for the Mediterranean species in C10.

4. Discussion

The findings of this study provide valuable insight into the structure, diversity, life form, and chorological composition of the plant communities, and point to some anthropogenic influences.

4.1 Flora

Surveys were undertaken at the end of the dry season, and the study was preceded by several drought years. Thus, the species listed per community (Supplementary material) do not represent a full checklist

of species, since many ephemeral species were absent at the time of the surveys. Complete species lists cannot always be recorded in arid areas, because geophytes and annuals display event-driven dynamics by fluctuating in reaction to the timing and quantity of rainfall and might not be visible year-round (Van Rooyen et al., 2015). Complete species lists would thus require multiple visits to each plot site, and the time available for the KARNR study (limited by contractual agreement) did not allow for this. In such cases, it is recommended to use permanently recognizable species. Furthermore, several authors concluded that in arid regions, perennials are generally better indicators of specific habitat factors than ephemerals (Batanouny and Abu El-Souod, 1972; Leistner and Werger, 1973), and annuals are relatively unimportant in vegetation classification in arid regions (Ayyad and Ammar, 1973; Zohary, 1973).

Several other studies in the central and northern arid regions of the KSA concurred with the current study that the *Asteraceae*, *Poaceae*, and *Fabaceae* were the most species-rich families (e.g., Al-Anazi and Al-Qahtani, 2018; Al-Bakre, 2023; Al-Sodany et al., 2011; Alsalem et al., 2020; El-Sheikh et al., 2013, 2021). In a wet season survey of KARNR, the *Brassicaceae* will likely rank higher among the families.

4.2 Plant communities

The analysis of the dry season data identified 19 communities across KARNR. Overall, few communities showed strong diagnostic species groups, and communities often graded progressively from one to the next. The lack of clear diagnostic species groups could possibly be ascribed to the occurrence of an extended drought and the degraded state of the vegetation due to past overgrazing, which is reported to reduce diversity, leading to functional, taxonomic, and phylogenetic homogenization (Saifi et al., 2021; Salgado-Luarte et al., 2019).

Several phytosociological studies have been undertaken in the central, eastern, and northern arid parts of Saudi Arabia, and many of the communities described in the current study share similarities with communities described in previous studies. In particular, the wadi (Abd-ElGawad et al., 2021; Al-Rowaily et al., 2012; Alatar et al., 2012; Alsalem et al., 2020), rawdat (Al-Anazi & Al-Qahtani, 2018; Al Dosari et al., 2019; Al-Farraj et al., 1997; Shaltout and Mady, 1996); and nafud (dune) vegetation (Al-Fredan, 2008; Al-Otaibi, 2017; El-Sheikh et al., 2021) have received much attention in the literature.

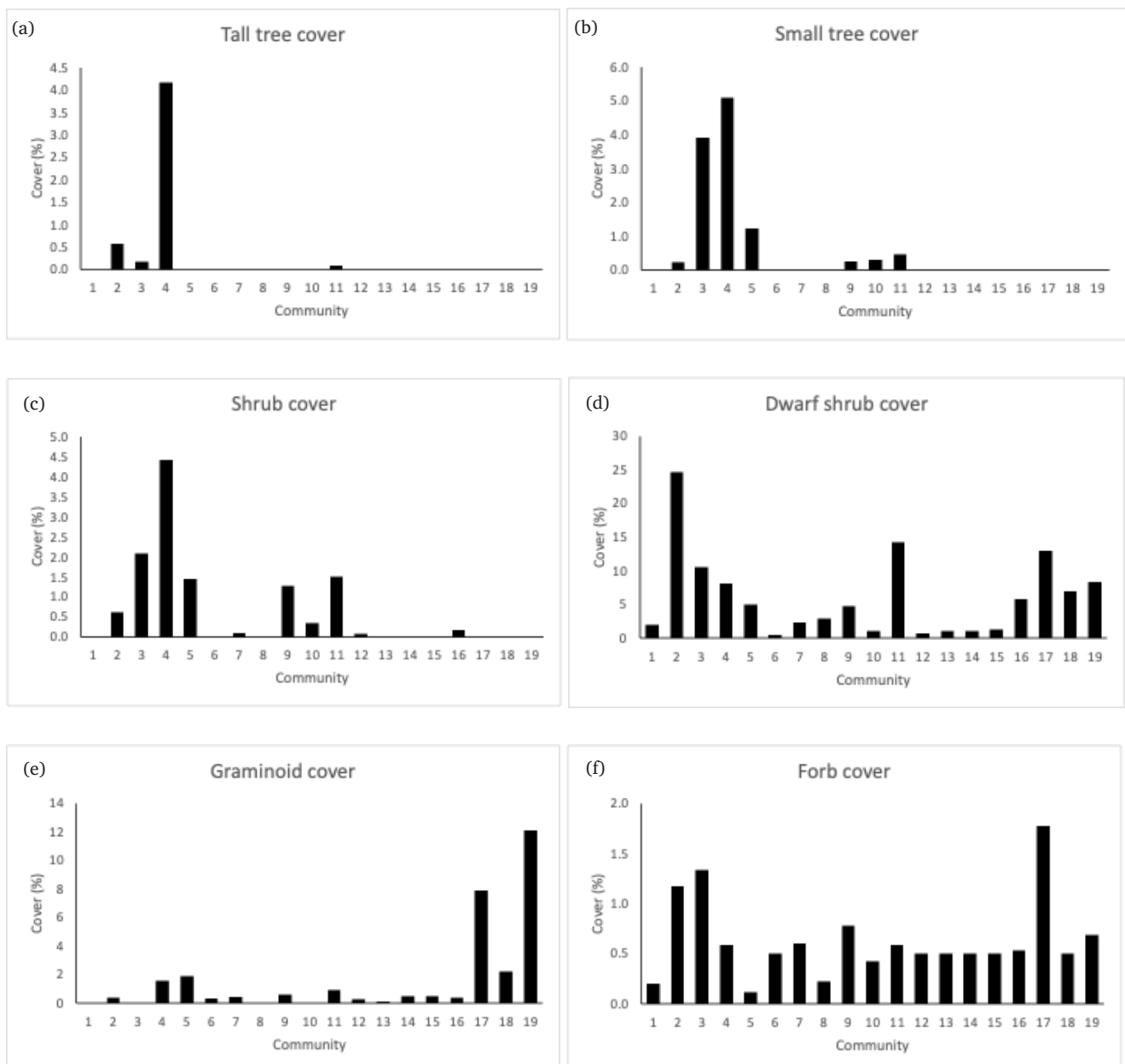


Fig. 4. Mean values for (a) tall tree, (b) small tree, (c) shrub, (d) dwarf shrub, (e) graminoid and (f) forb cover per community.

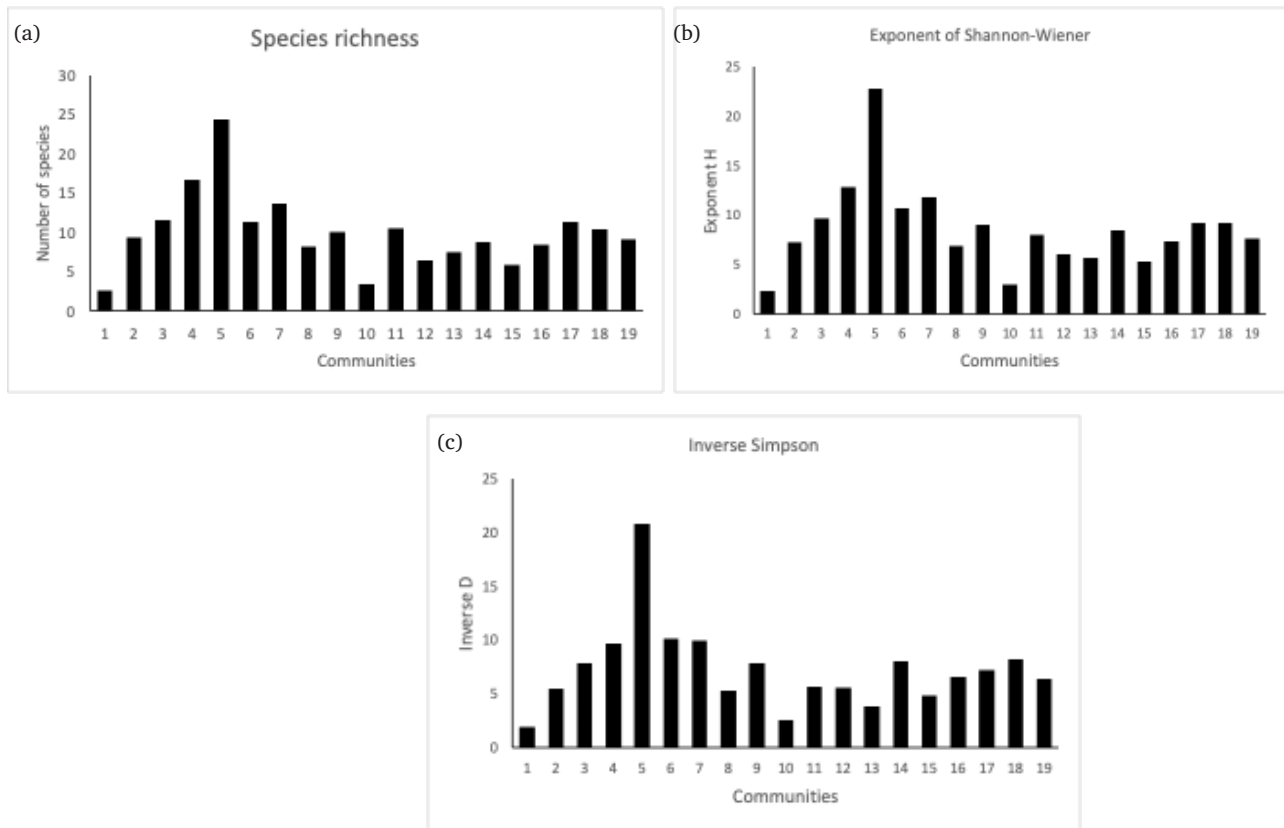


Fig. 5. Mean values for (a) species richness, (b) exponent of Shannon-Wiener, and (c) inverse Simpson indices of diversity per community.

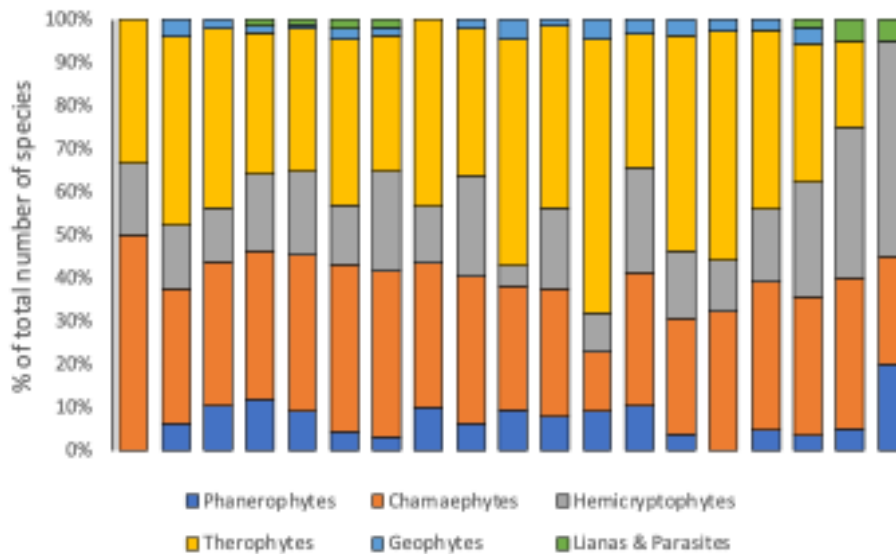


Fig. 6. Life form spectra of the communities in KARNR.

Rhazya stricta communities (C11 & C12) covered large areas in the southern section of KARNR. *Rhazya stricta* is regarded as an indicator of rangeland degradation and is known to replace valuable range plant species in silty soils or shallow sand over silt (Assaeed and Al-Doss, 2002). The plant is poisonous but not deemed as a serious threat to livestock (Mandaville, 1990) and is reported to have allelopathic properties.

The main environmental variables determining plant community assembly in arid Saudi Arabia are moisture availability and the redistribution of water by runoff/run-on and drainage. Other environmental factors playing an important role are soil salinity (Al-Fredan, 2008; Al-Mutairi, 2017; Al-Rowaily et al., 2012), electrical

conductivity and mineral content of the soil (Alatar et al., 2012, 2015), as well as grazing pressure (Al-Rowaily et al., 2015, Shaltout and Mady, 1996). In dune communities, the vegetation is related to dune stability (Bradley et al., 2019).

4.3 Vegetation structure

Most of the communities were dominated by the dwarf shrub layer; however, the vegetation in the wadis could, in some instances, be described as a savanna, while the vegetation in the Ad Dahna dune field could be described as open grassland.

Table 2.
Chorological spectra of the communities in the King Abdulaziz royal nature reserve.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19
SA*	50.0	46.5	31.3	38.1	36.6	51.3	53.6	42.9	37.2	61.9	47.5	63.6	44.8	57.7	55.9	48.7	46.0	47.4	64.7
SA-SUD	50.0	14.0	14.6	12.7	14.6	12.8	16.1	14.3	18.6	9.5	11.5	13.6	20.7	19.2	17.6	15.4	18.0	15.8	11.8
SUD	0.0	7.0	12.5	14.3	15.9	7.7	8.9	10.7	14.0	9.5	8.2	4.5	13.8	3.8	0.0	5.1	6.0	15.8	5.9
IT-SA	0.0	9.3	20.8	14.3	15.9	20.5	8.9	10.7	11.6	0.0	13.1	9.1	10.3	7.7	5.9	12.8	12.0	10.5	11.8
IT	0.0	2.3	2.1	4.8	3.7	5.1	1.8	7.1	2.3	4.8	6.6	4.5	6.9	0.0	5.9	5.1	8.0	0.0	0.0
M	0.0	7.0	6.3	1.6	2.4	0.0	0.0	5.4	4.7	9.5	4.9	0.0	0.0	3.8	5.9	5.1	4.0	0.0	0.0
M-IT	0.0	4.7	2.1	3.2	2.4	0.0	1.8	5.4	2.3	4.8	0.0	4.5	0.0	3.8	5.9	5.1	4.0	5.3	5.9
M-SA	0.0	2.3	2.1	1.6	0.0	0.0	1.8	0.0	2.3	0.0	1.6	0.0	3.4	3.8	2.9	2.6	2.0	5.3	0.0
SUD - AFR	0.0	0.0	4.2	3.2	2.4	2.6	0.0	3.6	2.3	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TROP	0.0	2.3	2.1	1.6	1.2	0.0	1.8	0.0	2.3	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COSM	0.0	2.3	2.1	3.2	2.4	0.0	3.6	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ES-M-IT	0.0	2.3	0.0	1.6	1.2	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M-IT-SA	0.0	0.0	0.0	0.0	1.2	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Afr = African; Cosm = Cosmopolitan; ES = Euro-Siberian; IT = Irano-Turanian; M = Mediterranean; SA = Sudano-Arabian; SUD = Sudanian; Trop = Tropical; Bi-regional and tri-regional species were included exclusively.

4.4 Diversity

Overall, the lowest diversity was found on the gravel and rocky plains, and the highest on the escarpments and rocky ridges with their associated wadis. It is believed that species richness would be appreciably higher, especially in the rawdats, during the wet season when many ephemeral species should be present.

4.5 Life form spectrum

In a study in the Riyadh region, therophytes constituted 52%, chamaephytes 30%, phanerophytes 9%, hemicryptophytes 8% and geophytes 1% of all species (Al Shaye et al., 2020). Hemicryptophyte percentages were noticeably higher in the current study, particularly in the dune communities, and therophyte percentages were mostly substantially lower than reported by Al Shaye et al. (2020). However, surveys done by the same team in a part of the southern section of the reserve in late summer indicated that therophytes constituted 52% of all species (own data), supporting the data reported by Al Shaye et al. (2020).

Therophytes or ephemeral species generally constitute a large proportion of the total species in arid regions (Danin & Orshan, 1990; Van Rooyen et al., 1990). A high percentage of life forms that shed living shoots during times of water shortage is an effective method to control water loss. Drought-evading plant species are represented by therophytes and geophytes. These species exhibit significant plasticity in their growth rate, size, and phenology, and in years of extreme drought, evading species may be completely absent. Although chamaephytes and phanerophytes comprise only 38% of the spectrum in the current study, they represent the permanent vegetation component. These species often display morphological and physiological adaptations to drought (i.e., drought-tolerance), such as a seasonal leaf loss or shoot reduction, whereas others display xeromorphic features.

4.6 Phytogeography

The phytogeographic spectra of the communities were complex but dominated by the monoregional Saharo-Arabian chorotype. Comparing communities occurring predominantly in the southern section of KARNR with the predominantly northern communities revealed a southern to northern shift from Sudanian to Saharo-Arabian plant species. Thus, southern communities had a larger proportion of Sudanian species than the northern communities.

4.7 Grazing and off-road driving

Currently, the vegetation across large parts of the reserve is degraded due to past heavy grazing and browsing. Livestock grazing is

one of the main causes of rangeland degradation in KSA. Al-Rowaily et al. (2015) found that livestock exclusion significantly increased plant cover, density, and species richness of all growth forms. Furthermore, the abundance of palatable species increased in enclosure plots, whereas unpalatable species increased in the open grazing area. Similar conclusions were drawn by (Shaltout and Mady, 1996). El-Sheikh et al. (2013) concluded that it may take 30 to 50 years for the desert perennial vegetation to recover fully from the effects of prolonged grazing and other large-scale human disturbances. Species often associated with overgrazing or disturbance included *Rhazya stricta*, *Calotropis procera*, and *Citrullus colocynthis*, whereas *Acacia* species, various grass species, and *Rhanterium epapposum* were more common in areas that had not been overgrazed.

Although livestock (camels, goats, and sheep) numbers had been controlled across most of the study site for a few years prior to the study, there was no noticeable improvement in range condition across most of the area at the time of the survey. In such an arid region, a recovery in range condition in the absence of grazing and browsing pressure is expected to be slow (El-Sheikh et al., 2013; Van Rooyen et al., 2015, 2018).

Additionally, off-road driving is a main contributor to land degradation in KSA (Assaeed et al., 2019). Forb and grass cover is negatively associated with distance to roads, while woody cover is positively associated. Off-road driving increases soil bulk density and soil electrical conductivity while decreasing porosity. Organic matter and nitrogen were not affected significantly by off-road driving disturbance. It is recommended that off-road vehicle restrictions be introduced via fencing, signage, or remote sensing detection systems.

5. Conclusions

The importance of this study is highlighted by the limited literature currently available on the vegetation in KARNR and the general lack of understanding of the relationships between the various vegetation units. The degraded state of the vegetation across large parts of the reserve is cause for concern. The degraded state is a legacy of the period prior to the proclamation of the KARNR when livestock numbers were not controlled, and overgrazing was widespread. In the meantime, authorities have commenced with a programme of ‘controlled grazing’ and reducing the number of livestock. However, it will take a long time for the vegetation to recover in this arid region.

Arid and hyper-arid areas are notoriously difficult to rehabilitate or restore successfully. There are multiple locations in the reserve where planting programs are underway as a means of greening the desert. These planting programs, however, may create unnatural landscapes and do not necessarily ensure a return of the original vegetation.

An important component in future vegetation studies would be to identify reference sites in the study area where grazing and browsing by large herbivores and off-road driving had been excluded to enable a comparison with the overgrazed areas. These reference sites could be used to identify suitable species to use in the planting programs or in rehabilitation programs. Monitoring sites should also be selected to follow the recovery of the vegetation after the reduction in livestock numbers. It is recommended that monitoring be done every 4 years.

Additionally, some innovative current research approaches could be used, such as analyzing the interactions between fractional vegetation cover (i.e., the proportion of ground covered by vegetation) and climatic variables (Anees et al., 2025) or using MODIS NDVI data and the pixel dichotomy model (PDM) to analyze the spatiotemporal dynamics of fractional vegetation cover across KARNR (Anees et al., 2024).

The identification, mapping, and description of vegetation units across the landscape provided in this paper are crucial to developing ecological management plans and implementing effective conservation strategies. Furthermore, comprehensive inventories of the vegetation at the community level (including floristic composition, vegetation structure, plant diversity, life form composition, and phytogeographic affinities) provided here are essential to monitor changes over time. Monitoring changes in plant communities over time also allows the effectiveness of conservation actions to be assessed.

CRediT authorship contribution statement

Noel Van Rooyen: Conceptualization, methodology, formal analysis, investigation, writing - original draft; **Margaretha Van Rooyen:** Conceptualization, methodology, formal analysis, investigation, writing - original draft; **Graeme Wolfaard:** Investigation, review & editing; **Ben Orban:** Investigation, review & editing; **Hennie van den Berg:** Formal analysis, review & editing; **Abdulrahman S. Alrefae:** Review & editing; **Abdullah M. Alowafeer:** Review & editing; **Jerome Gaugris:** Methodology, formal analysis, review & editing.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work presented in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors confirm that there was no use of Artificial Intelligence (AI)-Assisted Technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

Acknowledgement

We gratefully acknowledge the King Abdulaziz Royal Nature Reserve for commissioning the study and Namariq Engineering Services for their logistical support. All work was conducted under permit 23-43WP, issued by the Reserve Authority. A special thank you goes to Sayd Haj Aissa and Saeed Nezar Alam for their invaluable assistance in ensuring smooth logistics, local arrangements and on-the-ground support during our survey.

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