محمية دبي الصحراوية
DUBAI DESERT CONSERVATION RESERVE

Emirates

Vegetation dynamics and drivers of change in the Dubai Desert Conservation Reserve (2004, 2009 and 2025)

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Abstract

This study presents the most recent assessment of vegetation structure, species composition, and spatial distribution within the Dubai Desert Conservation Reserve (DDCR), building on baseline surveys conducted in 2004 and 2009. A total of 287 quadrats were sampled across the two dominant habitat types—gravel plains and sand dunes—between February and June 2025. A total of 43 plant species and 21,301 individuals were recorded. Diversity indices indicated slightly higher species diversity in sand dune habitats compared to gravel plains. *Zygophyllum indicum* emerged as the dominant species in gravel plains, while *Dipterygium glaucum* dominated sand dune habitats.

Spatial analyses revealed predominantly aggregated distribution patterns for most species, consistent with arid ecosystem dynamics. Community classification using TWINSPAN highlighted clear habitat differentiation, with distinct assemblages associated with substrate type and environmental gradients. Comparison with previous surveys suggests shifts in species dominance and composition over time, likely reflecting long-term conservation measures, changes in grazing pressure, and localized disturbance from recent development activities. These findings provide critical insights into vegetation dynamics within the DDCR and support ongoing conservation management and monitoring efforts.

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Introduction

The Arabian Peninsula lies within the extensive arid belt that stretches from the Sahara Desert in North Africa to the Sind region of India and Pakistan. This vast desert zone is characterized by predominantly cloudless skies, resulting in low humidity, high evaporation rates, and extreme daytime temperatures that can exceed 50°C, making it one of the hottest regions in the world. Due to its broad latitudinal range and varied topography, climatic conditions differ across the Peninsula. Nevertheless, the region generally experiences hot summers and mild to cool winters. Rainfall typically occurs during winter and spring in the northern and eastern areas, while the south may receive precipitation during both spring and summer. Rainfall patterns are highly variable and unpredictable, both in timing and quantity. Some years may bring little or no rain to certain areas, whereas others experience comparatively wetter conditions. Much of the Peninsula receives less than 100 mm of annual rainfall, although dew formation is common, particularly in coastal regions and across extensive desert landscapes, where it provides an important source of surface moisture (Miller & Cope, 1996).

In the United Arab Emirates, most precipitation occurs between December and April, although occasional summer rainfall may occur in mountainous regions such as Fujairah. Annual rainfall generally ranges from approximately 45 mm in the interior deserts to around 150 mm in the northern and eastern mountainous areas. A major challenge in describing vegetation across the Arabian Peninsula is the long-term influence of human activities and livestock grazing, which have shaped landscapes for thousands of years. As a result, the original vegetation can often only be inferred from small remnants of relatively undisturbed plant communities that persist in inaccessible locations. Desert and semi-desert vegetation is often difficult to classify into discrete categories because it typically occurs as a mosaic of sparse and patchily distributed plant communities. Nevertheless, vegetation patterns show a strong relationship with local soil characteristics, allowing classification based on major habitat types (Western, 1989; Miller & Cope, 1996).

Sand deserts (ergs) are generally characterized by open but relatively uniform dwarf shrub communities, with woodland vegetation largely confined to isolated stands of *Prosopis* species. Compared with rocky and gravelly desert environments, sand deserts typically support greater plant biomass and diversity (White, 1983).

Rock and gravel deserts represent the most widespread habitat type across much of the Arabian Peninsula. Vegetation in these areas forms complex mosaics that are often difficult to classify, with extensive sparsely vegetated surfaces and plants largely restricted to rock crevices, drainage lines, and wadis. Following rainfall, temporary annual herbaceous communities may develop in locations where soil and moisture accumulate. Across the northern and central plains, two broad vegetation communities

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are commonly recognised, although both exhibit substantial local variation. The first is a dwarf shrubland dominated by *Rhanterium epapposum*, often associated with *Astragalus*, *Fagonia*, and *Plantago* species. This community typically occurs on well-drained soils with shallow sand cover or among rocky substrates containing pockets of sand and occupies extensive areas of the Arabian Platform while being less common in the Shield regions. The second community is dominated by *Haloxylon salicornicum*, a species that generally favours deeper sandy soils but can also occur on shallow sands, gravel plains, and occasionally rocky surfaces (White, 1983).

In arid regions of the Middle East, vegetation patterns are closely linked to topography and landform characteristics (Zohary, 1973), as these factors largely determine water availability. Consequently, neighbouring areas may support distinctly different habitats, each with its own environmental conditions. Three broad vegetation types have been recognised in these landscapes. The first is *accidental vegetation* (Kassas & Batanouny, 1984), which occurs in hyper-arid regions where rainfall is highly irregular and may not occur annually, such as the Sahara and the Rub' al Khali. The second is *restricted vegetation* (Walter, 1963), found in areas that receive low but recurring annual rainfall. This vegetation is typically confined to favourable microsites, including wadis, drainage channels, and depressions where water accumulates. The third category comprises *diffuse vegetation* (Zohary, 1962), which is distributed relatively evenly across the landscape and is characteristic of deserts receiving more regular precipitation, generally exceeding 100 mm annually. Water availability also influences the physical and chemical properties of soils, including their depth, texture, and composition. As a result, variations in topography create a range of microhabitats with distinct environmental characteristics, even over distances of only a few metres (Batanouny, 1973; Batanouny, 2001).

In the Arabian Peninsula, the distinction between desert and semi-desert environments is often difficult to define, as both are characterised by extensive areas of bare ground, sparse vegetation, and typically less than 15% vegetation cover. In true desert environments, plant growth is generally restricted to wadis, depressions, and other locations that receive concentrated runoff water. Semi-desert habitats, by contrast, receive slightly higher levels of precipitation, supporting sparse but more evenly dispersed vegetation across the landscape. The transition between these two habitat types is gradual, with vegetation communities often merging into one another without distinct boundaries. Semi-desert conditions are generally considered to occur in areas receiving less than 250 mm of annual rainfall (White, 1983).

Although much of the Arabian region has historically been capable of supporting productive vegetation, and even areas classified as desert can provide valuable grazing resources when managed sustainably, vegetation communities across the region have experienced extensive degradation. The primary drivers of this decline include

overgrazing, unsustainable agricultural practices, woodland clearance for firewood, inappropriate irrigation methods leading to soil salinisation, intensive harvesting of plants for medicinal use, and a range of human development activities such as infrastructure construction, tourism, off-road vehicle use, and military operations (Batanouny, 2001). Among these pressures, overgrazing by goats, sheep, cattle, and camels is considered one of the most significant causes of rangeland degradation and continues to affect many parts of the region. The problem is particularly severe in inland desert areas where livestock are allowed to graze throughout the year. Furthermore, only a limited proportion of the region is subject to effective conservation measures, leaving many ecologically important habitats unprotected and vulnerable to continued degradation and loss (Wickens, 1982).

The Dubai Desert Conservation Reserve (DDCR), established in 2003, represents the UAE's first protected desert ecosystem and covers approximately 225 km^2, accounting for 4.7% of Dubai's total land area. The reserve was created to conserve representative desert habitats, along with their associated flora and fauna, within an increasingly urbanized landscape (DDCR, 2026). Desert ecosystems are highly dynamic and sensitive to environmental change, particularly in arid regions where vegetation patterns are strongly influenced by rainfall variability, soil characteristics, and anthropogenic pressures (Hegazy & Lovett-Doust, 2016). Monitoring vegetation over time is therefore essential for detecting ecological changes, assessing habitat condition, and informing adaptive management strategies.

Initial vegetation assessments conducted in 2004 provided baseline data on species composition, diversity, and community structure within the reserve (El Alqamy, 2004). A follow-up survey in 2009 expanded on this work by incorporating additional analytical approaches, including multivariate analysis and spatial mapping, to better understand vegetation dynamics and regeneration processes (Khafaga, 2009). Since these earlier surveys, the DDCR has undergone significant ecological changes, including the removal of livestock grazing and the implementation of conservation measures, as well as localized disturbances associated with recent development activities. These factors provide a unique opportunity to evaluate long-term vegetation responses under differing management regimes.

The present study aims to:

1. Assess current vegetation structure and species composition within the DDCR.
2. Analyse species diversity, spatial distribution, and community structure.
3. Compare results with previous surveys (2004 and 2009).
4. Identify patterns of ecological change and their potential drivers.

Methodology

Vegetation sampling was carried out across the two main habitats of the reserve, gravel plains and sand dunes. The design followed the general framework established in previous surveys which stratified by habitat (El Alqamy, 2004; Khafaga, 2009), ensuring comparability across time. A total of 287 sampling points were surveyed (Annex V). At each point a 5x5 m quadrat ($25m^2$) was established and all plant species within the quadrat were identified, counted and measured. This approach differs from the previous surveys, which used five 10x10m quadrats within a 50m diameter plot (~$500m^2$ sampled area per site). The reduced sampling effort was due to logistical constraints and increases potential variability in estimates of species richness and abundance.

Vegetation parameters

For each species, the following parameters were calculated: density, frequency, abundance, relative density, relative frequency and relative abundance. These metrics were used to compute the Importance Value Index (IVI) and the Significant Importance Value Index (SIVI), which provide integrated measures of species dominance within each habitat (Curtis & McIntosh, 1951). To assess species diversity, three commonly used indices were calculated for each quadrat: Shannon–Wiener Index (H') (Shannon, 1948), Simpson's Index of Diversity (1 – D) (Simpson, 1949), Brillouin Index (HB) (Brillouin, 1956). These indices capture different aspects of diversity, with Shannon and Brillouin being more sensitive to rare species, and Simpson's index emphasizing dominant species. Habitat-level variance and 95% confidence intervals for diversity indices were estimated using the Jackknife resampling method, which reduces bias in small sample sizes (Heltshe & Forrester, 1983). The open-source programming language and statistics environment R (version 4.4.3) was used on the RStudio platform (Posit Software) to compute diversity indices and confidence intervals.

Species dispersion and community classification

Species distribution patterns were analysed for taxa with sufficient sample sizes (>100 occurrences). Observed counts were fitted to three statistical distributions: Poisson distribution (random distribution), binomial distribution (uniform distribution), and negative binomial distribution (aggregated distribution). Goodness-of-fit was assessed using Chi-square (χ^2) tests (Krebs, 1989). To validate these results, Morisita's Index of Dispersion was also calculated (Morisita, 1959). Plant community classification was conducted using Two-Way Indicator Species Analysis (TWINSPAN) (Hill, 1979), applied to the species-by-quadrat matrix. This method groups sampling points based on species composition and identified indicator species for each community. Prior to analysis species occurring in fewer than two quadrats were removed to reduce noise and quadrats with zero abundance after preprocessing (12 of 287) were also excluded. Discriminant Function Analysis (DFA) was used to evaluate whether vegetation plots

could be reliably separated according to habitat type, and whether the historical distinction between Al Maha Reserve (AMR) and the wider DDCR remained analytically meaningful (El Alqamy, 2004; Khafaga, 2009). Two grouping schemes were tested: a two-group model consisting of Gravel Plains and Sand Dunes, and a four-group model consisting of AMR Gravel Plains, AMR Sand Dunes, DDCR Gravel Plains, and DDCR Sand Dunes. Species-level and structural-level datasets were analysed separately. The open-source programming language and statistics environment R (version 4.4.3) was used on the RStudio platform (Posit Software) to perform statistical, TWINSPAN and DFA analysis. TWINSPAN was performed using twinspanR, while DFA was performed using the readxl, deplyr, MASS, vegan, ggplot2, candisc, and CCP packages.

Spatial interpolation and mapping

Spatial patterns of vegetation were analysed using Geographic Information Systems (GIS) program ArcGIS (version 10.8). Diversity indices and species abundance were interpolated across the reserve using Ordinary Kriging – where spatial autocorrelation was present – and Inverse Distance Weighting (IDW) – where spatial structure was weak. Semi-variograms were developed to model spatial dependence, and model performance was evaluated using leave-one-out cross-validation. Community distributions derived from TWINSPAN were mapped using Thiessen polygons, allowing visualization of vegetation types across the landscape. Community type polygons were created using second level classification (L2) and subtypes illustrated using third level classification (L3). All spatial outputs were clipped to the DDCR boundary and overlaid with habitat classifications for interpretation. Thiessen polygons were generated from the vegetation sampling points and assigned the corresponding TWINSPAN community classifications to display the spatial distribution of plant communities across the reserve. Because TWINSPAN classifies only sampled sites, the polygons provide a spatial approximation of community extent by assigning each location to the nearest sampled point.

Results

A total of 287 quadrats were sampled across the Dubai Desert Conservation Reserve between February and June 2025, covering a total area of approximately 7,175 m^2. Of these, 196 quadrats were in sand dune habitats and 91 in gravel plains (Table 1). A total of 21,301 individual plants representing 43 species were recorded. This reflects an increase in species richness compared to the baseline survey conducted in 2004, which reported 37 species, and is broadly comparable to the 2009 survey, which documented substantial increases in species presence following conservation interventions.

Habitat	Sampling points	Sampling area (m^2)
Sand dunes	196	4900
Gravel plains	91	2275

Table 1: number of quadrats and sampling area covered by habitat.

Floral diversity and species richness

Table 2 illustrates the distribution of species in gravel plains and sand dune habitats. Of the 43 species recorded 23 species were common in both gravel plain and sand dune habitats, while 20 were restricted to a single habitat (10 to gravel plains and 10 to sand dunes). Diversity indices indicated moderate levels of species diversity across both habitat types, with slightly higher diversity recorded in sand dunes compared to gravel plains (Table 3). Margalef's Index was slightly higher in gravel plains (3.348) compared to sand dunes (3.23), suggesting marginally higher species richness despite lower overall diversity. Spatial interpolation of diversity indices revealed clear heterogeneity across the reserve (Figures 1-3). The highest modelled diversity values occurred in the central and southern regions of the DDCR, while the lowest values were consistently associated with the DEWA ASR development area, where diversity approached zero. This pattern strongly suggests that recent anthropogenic disturbance has resulted in localized suppression of vegetation diversity, contrasting sharply with surrounding undisturbed habitats.

Species	Gravel Plain	Sand dune	Species	Gravel Plain	Sand Dune
Aerva javanica			*Leptadenia pyrotechnica*		
Aristida adscensionis			*Limeum arabicum*		
Arnebia hispidissima			*Lycium shawii*		
Atractylis carduus			*Moltkiopsis ciliata*		
Bassia muricata			*Monsonia nivea*		
Calligonum comosum			*Panicum turgidum*		
Cenchrus divisus			*Plantago ciliata*		
Centaurea pseudosinaica			*Polycarpaea repens*		
Centropodia forsskaolii			*Polygala erioptera*		
Convolvulus cephalopodus			*Polygala irregularis*		
Crotalaria aegyptiaca			*Prosopis cinerarea*		
Cyperus conglomeratus			*Rhanterium epapposum*		
Dipterigyum glaucum			*Rhynchosia minima*		
Zygophyllum indicum			*Stipagrostis plumosa*		
Farsetia linearis			*Tragus racemosus*		
Haloxylon salicornicum			*Tribulus pentandrus*		
Heliotropium digynum			*Vachellia farnesiana*		
Heliotropium kotschyi			*Vachellia flava*		
Indigofera colutea			*Vachellia tortillis*		
Indigofera intricata			*Ziziphus spina-christi*		
Launaea capitata					

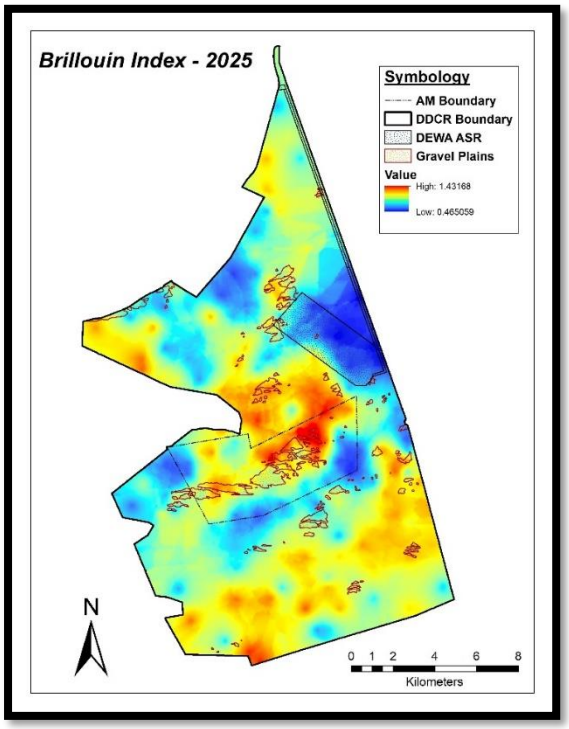
Table 2: Species presence in gravel plains and sand dune habitats.

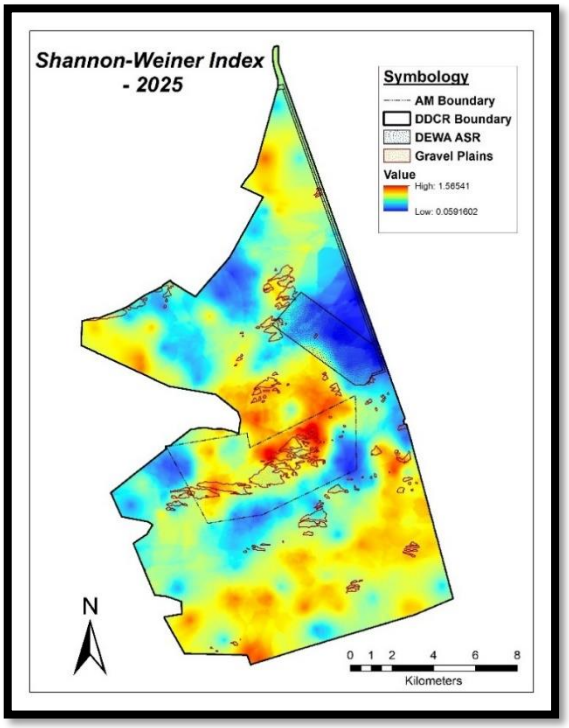
Index	Gravel Plains	Sand Dunes
Simpson	0.76	0.78
Shannon-Weiner	1.815	1.916
Brillouin	1.8	1.9

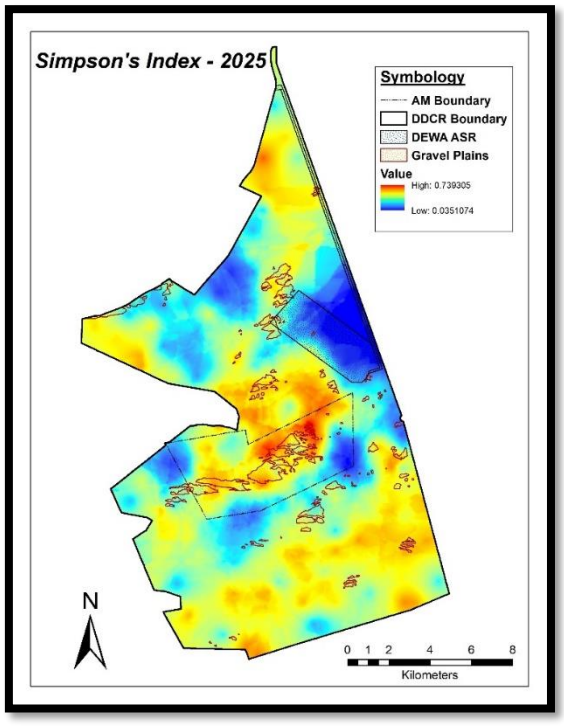
Table 3: Diversity indices across habitats.

	Gravel Plains			Sand Dunes		
	Simpson	Shannon-Weiner	Birllouin	Simpson	Shannon-Weiner	Brillouin
Point estimate	0.501	0.988	0.888	0.387	0.764	0.663
Variance	0.0005	0.002	0.002	0.0004	0.001	0.001
95% CI	0.453 - 0.548	0.889 - 1.087	0.798 - 0.977	0.347 - 0.427	0.683 - 0.844	0.593 - 0.734

Table 4: Calculated values for diversity indices, jackknife variance and 95% confidence intervals.







Figures 1-3: Spatial interpolation of diversity indices.

Community Structure: Gravel Plains

A total of 32 species were recorded in gravel plains habitats. The vegetation community was strongly dominated by *Zygophyllum indicum* (highest SIVI: 190.15), *Stipagrostis plumosa*, and *Arnebia hispidissima* (Table 5). These species can be considered the dominant and co-dominant taxa in this habitat. Compared to previous surveys, *Zygophyllum indicum* shows a substantial increase in dominance, having already been identified as a key species in earlier assessments but now exhibiting markedly higher importance values. This suggests a shift toward species adapted to arid and possibly disturbed conditions. Several species recorded in earlier surveys (e.g., *Heliotropium kotschyi*, *Haloxylon salicornicum*) remain important but show reduced relative dominance, indicating changes in community composition over time. Species with very low SIVI values were typically represented by single individuals, indicating rare or spatially restricted occurrence.

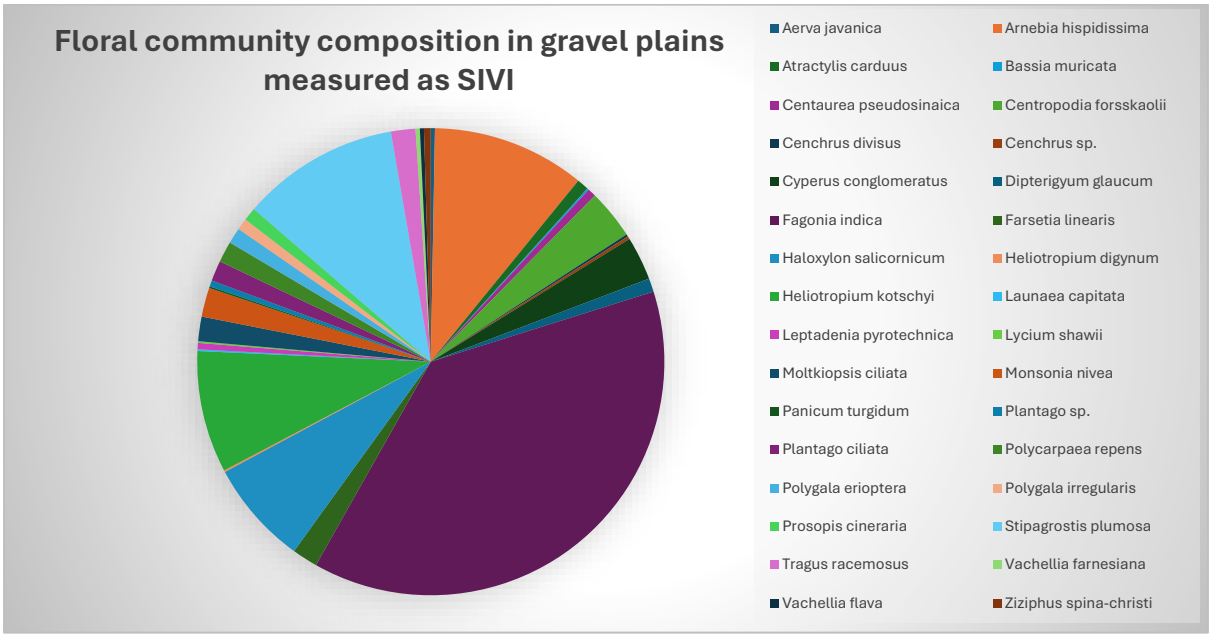


Figure 4: Gravel plain community composition measured as SIVI.

Species list	SIVI 2025	SIVI 2009	IVI 2025	IVI 2009	IVI 2004
Aerva javanica	1.44	9.29	1.24	7.08	1.25
Arnebia hispidissima	52.99	49.41	51.06	46.61	
Atractylis carduus	4.08	9.62	3.96	9.55	
Bassia muricata	0.59	6.53	0.59	6.3	
Calotropis procera		53.02		16.54	10.69
Centaurea pseudosinaica	2.92		2.82		
Centropodia forsskaolii	17.12	50.61	16.48	47	
Cenchrus divisus	0.83	49.26	0.8	38.99	
Cenchrus sp.	1		1		
Chrozophora oblongifolia		7.93		6.63	
Citrillus colocynthis		32.78		19.43	2.35
Crotalaria aegyptiaca		41.37		30.2	10.39
Cyperus conglomeratus	15.1		9.5		

Dipterigyum glaucum	4.67	36.37	3.68	22.93	3.16
Eremobium aegyptiacum		16.99		14.75	
Zygophyllum indicum	190.15	89.43	69.92	76.68	55.71
Fagonia sp.		8.66		8.38	
Farsetia linearis	8.87	15.56	8.56	15.25	
Haloxylon salicornicum	36.11	76.72	4.69	49.33	3.66
Heliotropium digynum	0.59	18.73	0.59	18.11	5.43
Heliotropium kotschyi	42.18	83.8	17.94	45.85	42.08
Indigofera colutea		16.96		15.9	
Indigofera intricata		21.75		20.5	10.27
Launaea capitata	0.59		0.59		
Leptadenia pyrotechnica	2.19	90.57	0.8	27.55	20.06
Limeum arabicum		4.68		4.63	4.25
Lycium shawii	0.59	49.97	0.59	30.9	13.78
Moltkiopsis ciliata	8.48	28.53	8.4	27.7	20.55
Monsonia nivea	10.05	64.24	9.98	63.6	
Neurada procumbens		5.33		5.32	
Panicum turgidum	0.61	9.23	0.59	9.09	
Plantago sp.	2.11		2.11		
Plantago ciliata	7.06		7.06		
Polycarpaea repens	7.28	26.8	7.24	26.55	
Polygala erioptera	5.48		5.47		
Polygala irregularis	4.02		4.01		
Prosopis cineraria	4.56		1		
Rhantherium eppaposum		69.69		47.85	60.95
Sisymbrium erysimoides		5.4		5.4	
Stipagrostis plumosa	54.65	47.77	49.08	44.82	
Tamarix aphylla		28.24		19.42	
Tragus racemosus	8.49		8.49		
Tribulus omanense		9.25		9.2	
Tribulus pentandrus		33.54		30.99	
Vachellia farnesiana	1.47		0.59		
Vachellia flava	1.4		0.59		0.66
Vachellia tortillis		49.89		24.66	8.72
Ziziphus spina-christi	2.34		0.59		

Table 5: IVI and SIVI of species found in gravel plains during 2004, 2009, and 2025.

Community Structure: Sand Dunes

A total of 31 species were recorded in sand dune habitats. The dominant species was *Dipterygium glaucum* (highest SIVI: 141.02) and co-dominant species included *Cyperus conglomeratus*, *Moltkiopsis ciliata*, *Arnebia hispidissima*, and *Zygophyllum indicum* (Table 6) Compared to earlier surveys, *Dipterygium glaucum* shows a marked increase in dominance, whereas species such as *Cyperus conglomeratus*, which previously exhibited extremely high importance values (e.g., in 2009), appear to have declined in relative dominance. This shift may reflect changing environmental conditions, rainfall patterns, or competitive dynamics within dune systems. Figure 6 shows the relative proportions of community structure evaluated as SIVI values.

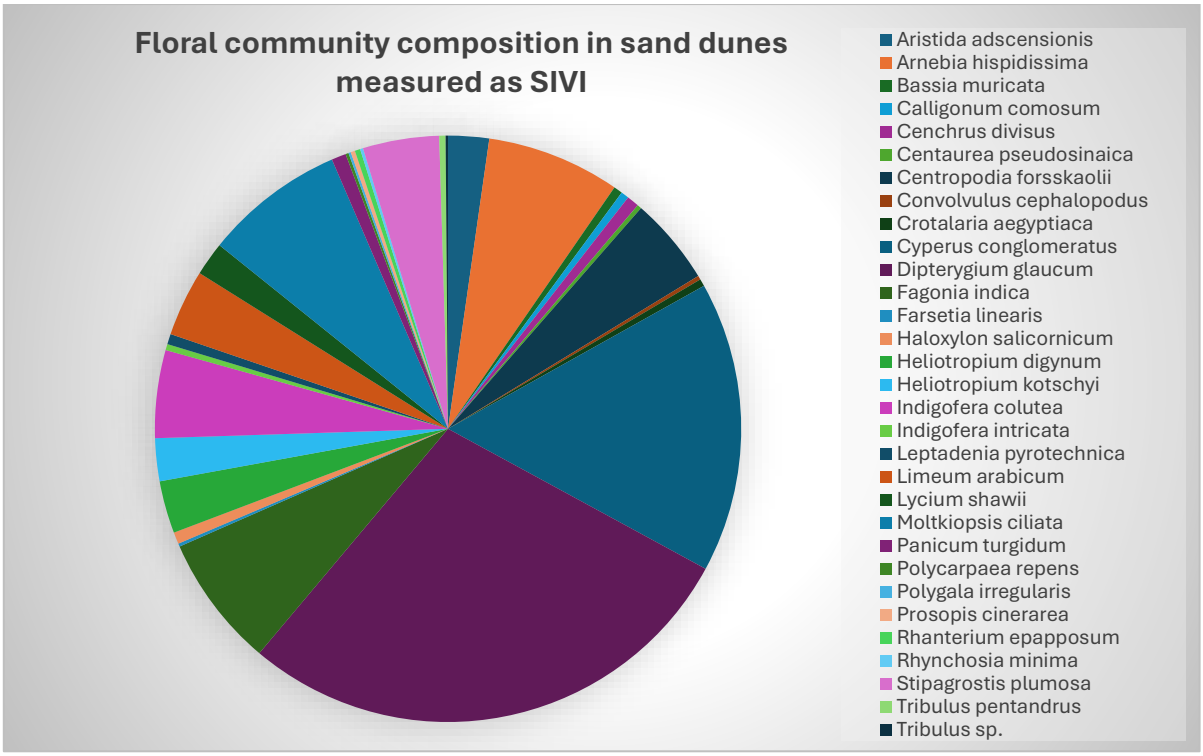


Figure 6: Sand dune community composition measured as SIVI.

Species list	SIVI 2025	SIVI 2009	IVI 2025	IVI 2009	IVI 2004
Aerva javanica		9.4		8.08	0.39
Aristida adscensionis	11.26		11.33		
Arnebia hispidissima	36.8	30.79	37.93	30.29	
Atractylis carduus		6.2		6.2	
Bassia muricata	2.41	14.16	2.66	13.43	
Calligonum comosum	2.19	8.47	7.94	7.98	0.42
Calotropis procera		109.76		46.14	14.25
Cenchrus divisus	3.35	47.67	6.75	38.76	0.19
Centaurea pseudosinaica	1.19	48.16	1.21	46.7	
Centropodia forsskaolii	24.19	116.6	26.2	115.98	
Chrozophora oblongifolia		72.94		70.43	
Cistanche tabulosa					0.22
Citrillus colocynthis		82.58		31.54	4.69
Convolvulus cephalopodus	1.08		1.08		
Crotalaria aegyptiaca	2	52.83	2.57	42.31	16.36
Cyperus conglomeratus	80.17	292.76	78.31	230.6	339.69
Dipterygium glaucum	141.02	82.04	55.95	62.88	1.17
Eremobium aegyptiacum		359.94		328.19	
Erucaria hispanica					1.38
Zygophyllum indicum	36.46	59.01	29.25	48.03	
Farsetia linearis	0.85	20.87	3.08	20.86	
Haloxylon salicornicum	3.23	139.21	3.28	73.91	24.49
Heliotropium digynum	14.45	98.01	18.11	82.77	73.55
Heliotropium kotschyi	11.79	136.05	13.59	110.68	2.53
Indigofera colutea	24.21	67.34	23.54	66.31	8.2
Indigofera intricata	1.67	29.85	5.77	29.67	14.66
Leptadenia pyrotechnica	2.86	209.877	2.99	68.17	43.79

Limeum arabicum	18.36	170.84	23.81	111.72	43.49
Lycium shawii	9.3	9.16	13.85	7.35	1.68
Moltkiopsis ciliata	38.77	38.92		73.16	55.37
Monsonia nivea		56.45		56.34	
Neurada procumbens		58.18		55.65	
Ogastemma pusillum		52.59		52.54	
Panicum turgidum	3.99	37.49	9.43	33.26	12.52
Plantago boissieri		53.08		53.01	
Polycarpaea repens	0.83	37.33	3.3	37.2	
Polygala erioptera		12.57		11.54	
Polygala irregularis	0.66		0.68		
Prosopis cinerarea	1.19	73.24	1.2	73.17	1.26
Rhanterium epapposum	1.49	87.44	1.56	76.11	7.59
Rhynchosia minima	0.83		1.6		1.41
Salvadora persica		6.77		4.93	
Silene villosa		12.58		12.58	
Stipagrostis plumosa	21.01	70.68	21.07	69.81	
Tribulus macropterus		40.8		39.75	3.62
Tribulus omanense		15.66		15.54	1.26
Tribulus pentandrus	1.75	45.97	7.12	45.54	
Tribulus sp.	0.66		0.75		

Table 6: IVI and SIVI of species found in sand dunes during 2004, 2009, and 2025.

Notable species record: Polygala irregularis

A key finding of the present study is the recording of *Polygala irregularis* within the DDCR. This species represents a new record for the reserve and is classified as *Endangered* in the UAE. Previously known from only four localities within the country (Allen D. J., et al., 2021; Jongbloed, 2003), it was recorded within the DDCR primarily in gravel plain habitats, particularly in the Al Maha area and near the Arabian Adventures concession. *Polygala irregularis* is absent from long-term monitoring quadrants, suggesting either a recent colonization or previously undetected presence. Individuals of *P. irregularis* displayed two distinct flower colour morphs: mauve-flowered and yellow-flowered individuals. This variation may indicate intraspecific phenotypic plasticity, environmental influence, or potential genetic differentiation, and warrants further investigation. The presence of this species highlights the conservation value of the DDCR, particularly for rare and potentially overlooked taxa.

Figure 7: Individuals of Polygala irregularis with yellow (left) and mauve (right) flowers.

Species Spatial Distribution and Community Patterns

Analysis of species dispersion patterns indicated that most species exhibited aggregated (clustered) distributions, as confirmed by both distribution fitting and Morisita's Index. This is consistent with typical arid ecosystem dynamics, where resource availability (water/nutrients) is patchy and microhabitats strongly influence plant establishment. Only a limited number of species showed random or uniform distributions (Figures 11 & 14). The vegetation structure across both habitats was dominated by shrubs and dwarf shrubs, with herbaceous species occurring mainly during favourable seasonal conditions. Gravel plains were dominated by perennial shrubs (e.g. *Zygophyllum indicum*), while sand dunes showed a more mixed structure including grasses and annuals. The presence of annual species in both habitats suggests episodic recruitment linked to rainfall events, consistent with observations from earlier surveys.

Spatial distribution patterns for the twelve most abundant species were assessed using plot-level abundance data collected from the survey plots. Observed frequencies were fitted to Poisson, binomial and negative binomial distributions, and chi-square goodness-of-fit tests were used to identify the best-fitting distribution. Morisita's Index of dispersion was calculated to complement distribution fitting and to quantify the degree of spatial aggregation.

All selected species showed clustered distributions. Variance-to-mean ratios were greater than 1 for all species indicating aggregated rather than random spatial patterns. Chi-square goodness-of-fit tests showed that negative binomial distribution consistently provided the best fit while Morisita's index confirmed aggregation for all species, but degree varied among species. Based on Morisita's Index values, *Zygophyllum indicum, Indigofera colutea, Centropodia forsskaolii* and *Arnebia hispidissima* show the strongest aggregation while *Limeum arabicum, Dipterygium glaucum, Farsetia linearis* and *Monsonia nivea* show the weakest aggregation (Table 7).

Species	Distribution	Morisita's Index of Dispersion	Variance-Mean Ratio
Arnebia hispidissima	Negative binomial (clustered)	8.4314	99.9993
Centropodia forsskaolii	Negative binomial (clustered)	25.1154	112.2174
Cyperus conglomeratus	Negative binomial (clustered)	2.7907	29.0681
Dipterygium glaucum	Negative binomial (clustered)	10.4016	8.0018
Zygophyllum indicum	Negative binomial (clustered)	14.3111	192.5217
Farsetia linearis	Negative binomial (clustered)	24.2375	13.35
Heliotropium kotschyi	Negative binomial (clustered)	10.5759	27.0157
Indigofera colutea	Negative binomial (clustered)	89.0294	158.8989
Limeum arabicum	Negative binomial (clustered)	6.4714	3.847
Moltkiopsis ciliata	Negative binomial (clustered)	13.6446	86.5055
Monsonia nivea	Negative binomial (clustered)	23.5761	14.0246
Stipagrostis plumosa	Negative binomial (clustered)	9.5938	92.196

Table 7: Distribution patterns for selected species.

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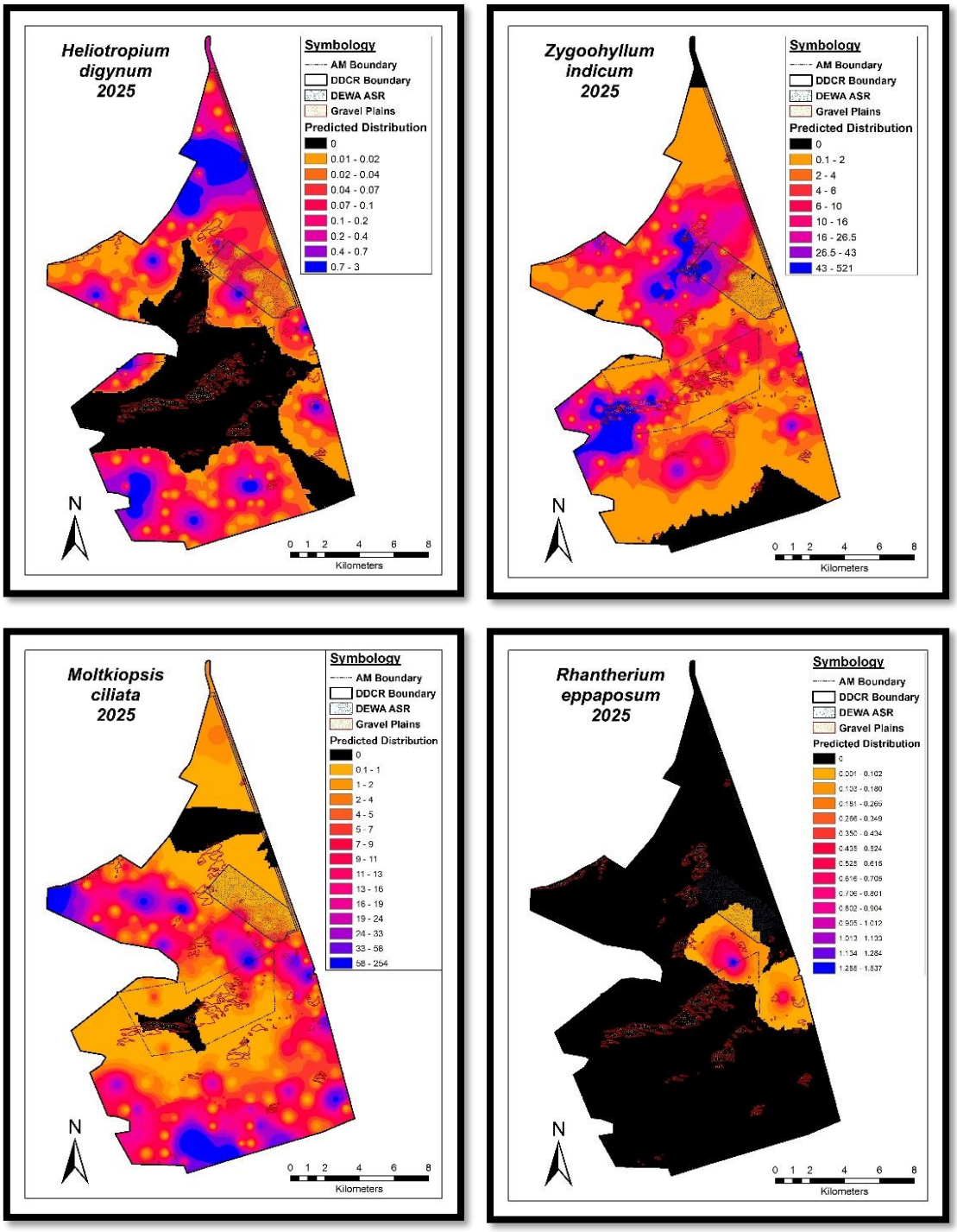
Herb Layer

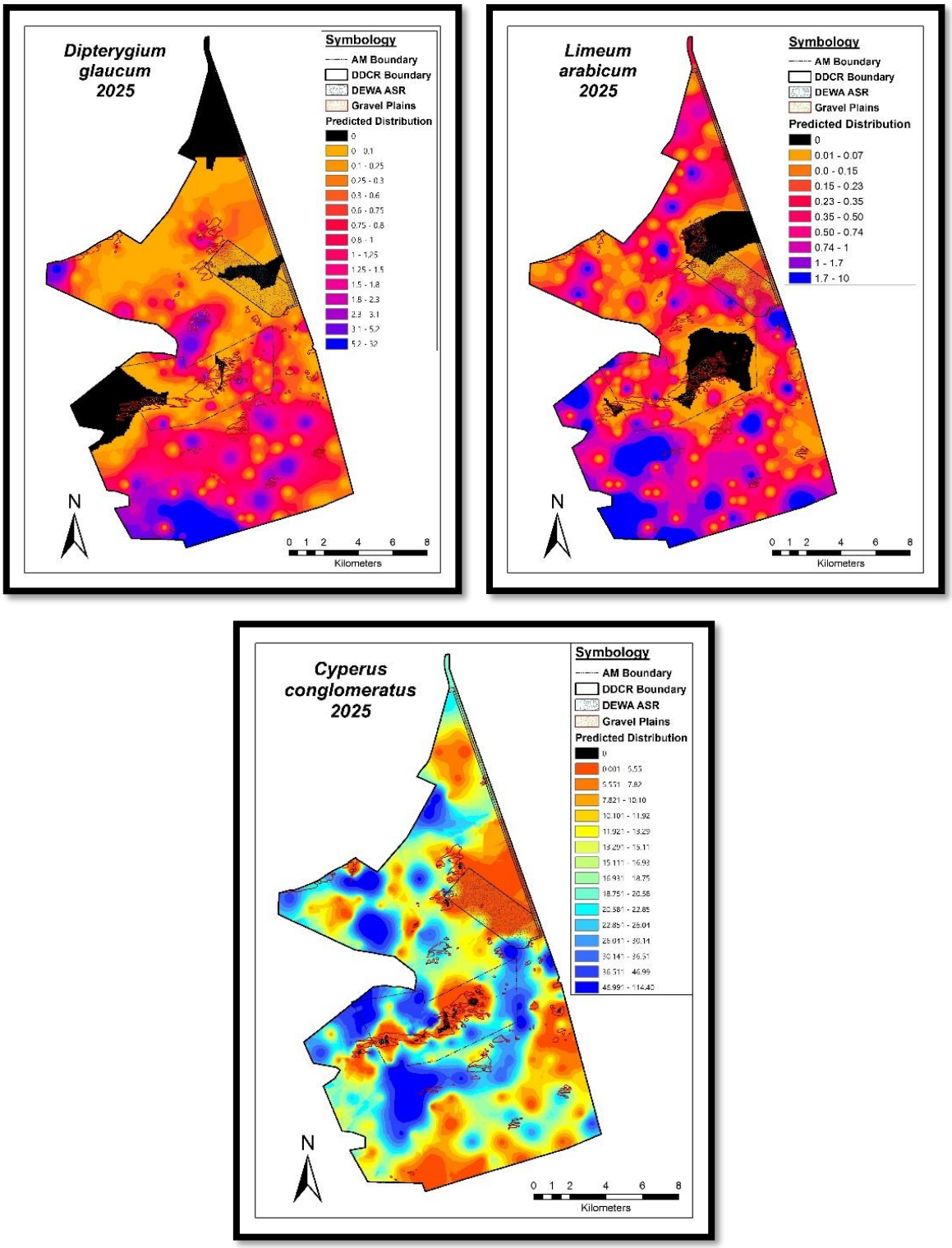
Seven species were selected for this layer: *Heliotropium digynum, Dipterigyum glaucum, Moltkiopsis ciliata, Limeum arabicum, Rhanterium epapposum, Cyperus conglomeratus* and *Zygophyllum indicum*. These species were initially chosen in the 2004 report for being either restricted to gravel plains, restricted to sand dunes, or common in both. All species were common in both habitats in 2009 and only *Limeum arabicum* and *Rhanterium eppaposum* have been restricted to sand dune habitats in 2025 (Annex II). Figures 8-14 illustrate each species's predicted distribution with DEWA project shown only as visual representation for distribution.

- *Heliotropium digynum* – This species showed a reduced but aggregated distribution compared to previous years, concentrated mainly on sand dunes with the highest densities observed in the northern and southwestern sections of the reserve while being completely absent from the Al Maha gravel plains.
- *Zygophyllum indicum* – The species shows a wide dispersion covering both surveyed habitats. Although widespread, the greatest densities were found on gravel plains in the north and west of the reserve, where they dominated the landscape.
- *Moltkiopsis ciliata* – This species showed a reduced distribution but more intense clustering. Although it was found in both gravel plain and sand dune habitats, the species was completely absent from some of the gravel plains to the west of Al Maha Resort. The highest densities were found in sand dune habitats especially in interdunal plains, where they tended to be the dominant species.
- *Rhanterium epapposum* – The species showed significantly reduced distribution, recorded in only three locations in sand dunes habitat. However, like mentioned in the 2004 and 2009 reports (references), its general distribution trend remains east of 55^{O} 33.9'.
- *Dipterygium glaucum* – This species is widely distributed although absent from the north and a midwestern section of the reserve extending into the Al Maha gravel plains. The highest densities were recorded towards the centre and south of the reserve, where several hotspots are visible.
- *Limeum arabicum* – The species was completely absent from gravel plains habitats and showed a distribution favouring the south of the reserve, where several hotspots are visible. It was completely absent from the Tawi Ruwayyan area and the eastern half of the Al Maha area.
- *Cyperus conglomeratus* – This is the most widespread species in the reserve, present in both gravel plains and sand dunes. Despite this, it continues to be absent in some of the gravel plains, mainly those in the Ruwayyan and Al Maha area. It shows high abundance and tends to be either the dominant or co-dominant in most quadrats. Lowes densities were found in the central gravel

plains area, followed by the south and southeastern areas, and a patch in the north.



Figures 8-11: Predicted distribution for Helotropium digynum, Zygophyllum indicum, Moltkiopsis ciliata, and Rhanterium epapposum.

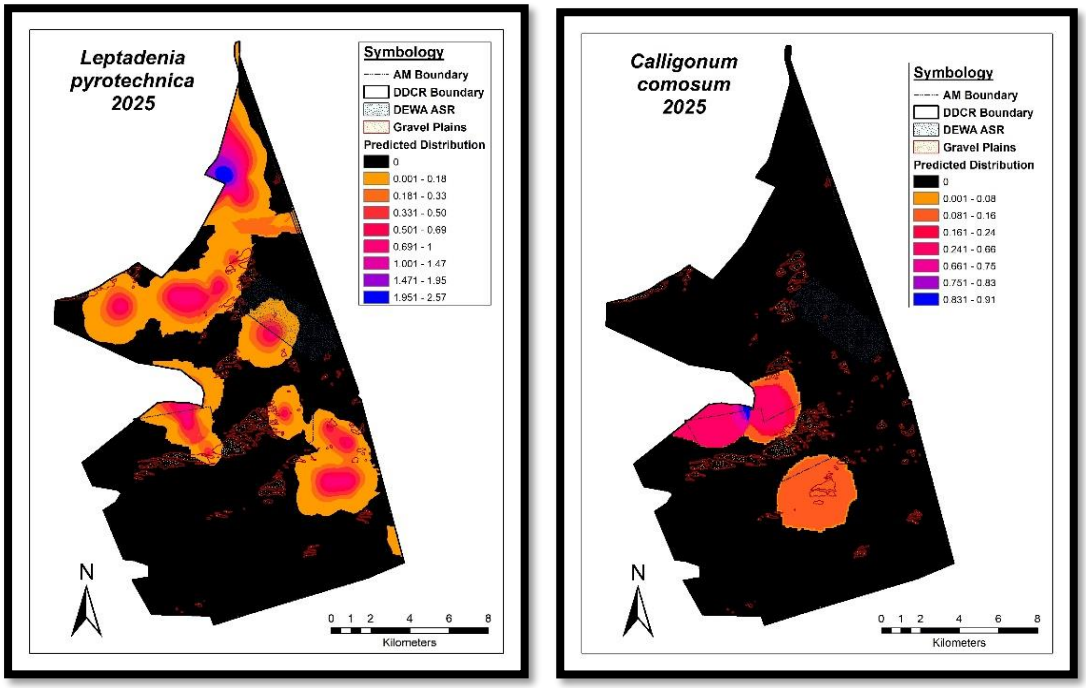


Figures 12-14: Predicted distribution for Dipterygium glaucum, Limeum arabicum and Cyperus conglomeratus respectively.

Shrub Layer

Three species were selected for this layer: *Calligonum commosum, Leptadenia pyrotechnica* and *Haloxylon salicornicum*. Like with the herb layer, predicted distribution includes the DEWA area only as visual representation of the whole landscape (Figures 15-17). *Calotropis procera*, included in previous reports, was excluded from this selection as it was not recorded during the present study.

- *Haloxylon salicornicum* – This species showed an increased dispersion and was recorded in two main patches, one towards the north and a larger one along the west and south ranges of the reserve. The highest concentrations were found in the westernmost gravel plains.
- *Leptadenia pyrotechnica* – This shrub species was recorded during the study in only a few, scattered locations. However, in this instance, the data does not provide an accurate representation of distribution as daily observations show this is one of the most abundant and widespread shrub species in the reserve.
- *Calligonum comosum* – The species was recorded in only a few locations in the centre and south of the reserve in sand dune habitats. It has never been recorded in gravel plains.
-



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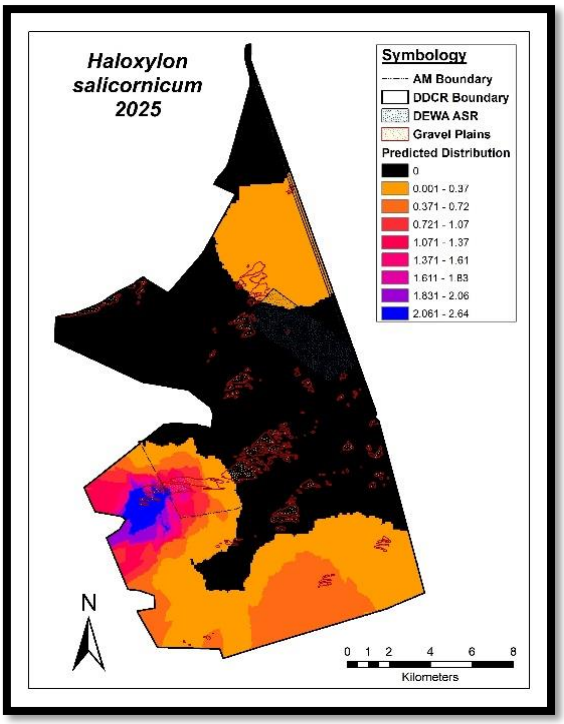
  - *Figures 15-16: Predicted distribution for Leptadenia pyrotechnica and Calligonum comosum.*



Figures 17: Predicted distribution for Haloxylon salicornicum.

TWINSPAN Community analysis

TWINSPAN analysis revealed clear separation between vegetation communities associated with gravel plains and sand dunes. Further subdivision identified distinct sub-communities within each habitat, reflecting substrate variation, local environmental conditions and potential effects of management history (e.g. grazing exclusion). Spatial representation using Thiessen polygons showed that community boundaries align closely with habitat types, supporting the robustness of the classification. TWINSPAN analysis identified four primary vegetation groups at the second hierarchical level (L2) with weak indicator species. Each group further subdivided into two subtypes (L3) with clear indicator species where subtypes were associated with a distinct set of species, reflecting variation in species composition across habitats.

- Gravel plain with mixed annual forb assemblage (00) – This group was characterized by *Monsonia nivea* as an indicator species. Two subtypes were identified:
    - (000) – This subtype showed no clear indicator species. It was consistently dominated by *Zygophyllum indicum*, with frequent occurrence of *Arnebia hispidissima* and low abundance of most other species. Sites were located in gravel plains east and west of the Al Maha area, including areas near the DEWA project and the old Margham gate.
    - (001) – This subtype was defined by the indicator species *Farsetia linearis*, *Monsonia nivea*, and *Polycarpaea repens*. It contained a broader representation of gravel plain species, with the exception of *Heliotropium*

digynum. The most abundant species were *Zygophyllum indicum*, *Arnebia hispidissima*, and *Stipagrostis plumosa*, although no single species dominated consistently across sites. This subtype was primarily associated with gravel plains within the Al Maha area.

- Mixed soil assemblage: gravel and interdunal plains (01) – No indicator species were identified at the primary group level. Two subtypes were distinguished:
    - (010) – This subtype was defined by *Heliotropium kotschyi* as an indicator species. It included gravel plains located at Tawi Ruwayyan and scattered locations within Al Maha. The most abundant species were *Zygophyllum indicum*, *Heliotropium kotschyi*, and *Arnebia hispidissima*, with *Cyperus conglomeratus* and *Stipagrostis plumosa* also widely present.
    - (011) – This subtype consisted mainly of interdunal plains and was defined by *Dipterygium glaucum* and *Moltkiopsis ciliata* as indicator species. *Arnebia hispidissima* was the dominant species, with *Centropodia forsskalii* and *Panicum turgidum* as co-dominant grasses. A high representation of perennial species was observed. The exotic species *Vachellia farnesiana* was recorded at a single site near the DEWA project.
- Sand dunes with perennial grass-forb assemblage (10) – This group was characterized by *Moltkiopsis ciliata* as an indicator species. Two subtypes were identified:
    - (100) – This subtype included sites across a range of sandy environments, including dunes, interdunal plains, and Ghaf groves. Indicator species included *Dipterygium glaucum* and *Moltkiopsis ciliata*. *Cyperus conglomeratus* was the dominant species, with *Moltkiopsis ciliata* and *Arnebia hispidissima* as co-dominants. Perennial species were consistently present across sites.
    - (101) – This subtype occurred primarily along the western and southern boundaries of the reserve. Indicator species included *Indigofera colutea*, *Limeum arabicum*, and *Moltkiopsis ciliata*. *Moltkiopsis ciliata* was dominant, with *Cyperus conglomeratus* as co-dominant. Perennial grasses such as *Stipagrostis plumosa* and *Centropodia forsskalii* were widely distributed.
- Sand dune shrubland with annual understory (11) – No indicator species were identified at the primary group level. Two subtypes were distinguished:
    - (111) – This subtype was associated with dunes surrounding the Al Maha gravel plains and was defined by *Heliotropium kotschyi* as an indicator species. *Cyperus conglomeratus* and *Heliotropium kotschyi* were dominant across sites, with few additional species present.
    - (110) – This subtype was widespread across sand dunes throughout the reserve, excluding the DEWA project area. No indicator species were identified. Sites were strongly dominated by *Cyperus conglomeratus*, often

as the only species present, with other species occurring at very low abundance.

Presence-absence analyses emphasized floristic similarity rather than dominance and resulted in weaker group separation, indicating that community types are driven by changes in species dominance rather than wholescale species replacement. This is typical of arid and semi-arid vegetation (Hegazy & Lovett-Doust, 2016).

Thiessen Polygons

The resulting map showed broad spatial continuity in the distribution of the main vegetation groups, with clear separation between gravel plain and sand dune communities (Figure 18). Gravel plain assemblages were concentrated around the Al Maha area, Tawi Ruwayyan, and other known gravel plain systems, whereas sand dune assemblages occupied most of the remaining reserve area. Within these broader habitat divisions, the Thiessen polygons also illustrated subdivision into local community types, particularly around transitions between gravel plains, interdunal plains, and dunes. The northern part of the reserve was classified predominantly as sand dune habitat with low species richness and strong dominance by *Cyperus conglomeratus*.

Although Jebel Nazwa represents a distinct geomorphological feature, no vegetation sampling points were located directly within this habitat, and it was therefore not resolved as a separate vegetation class in the present analysis. In contrast, the southern and western sectors of the reserve showed greater internal heterogeneity, with several adjacent polygon groups corresponding to different sand dune and mixed-soil assemblages. Sampling points from the DEWA ASR project area were excluded from the TWINSPAN-based Thiessen polygon analysis because they recorded zero abundance and would have introduced artificial distortion into the classification. As a result, the Thiessen polygon map represents the spatial distribution of vegetation communities in the vegetated portion of the reserve rather than the full reserve footprint.

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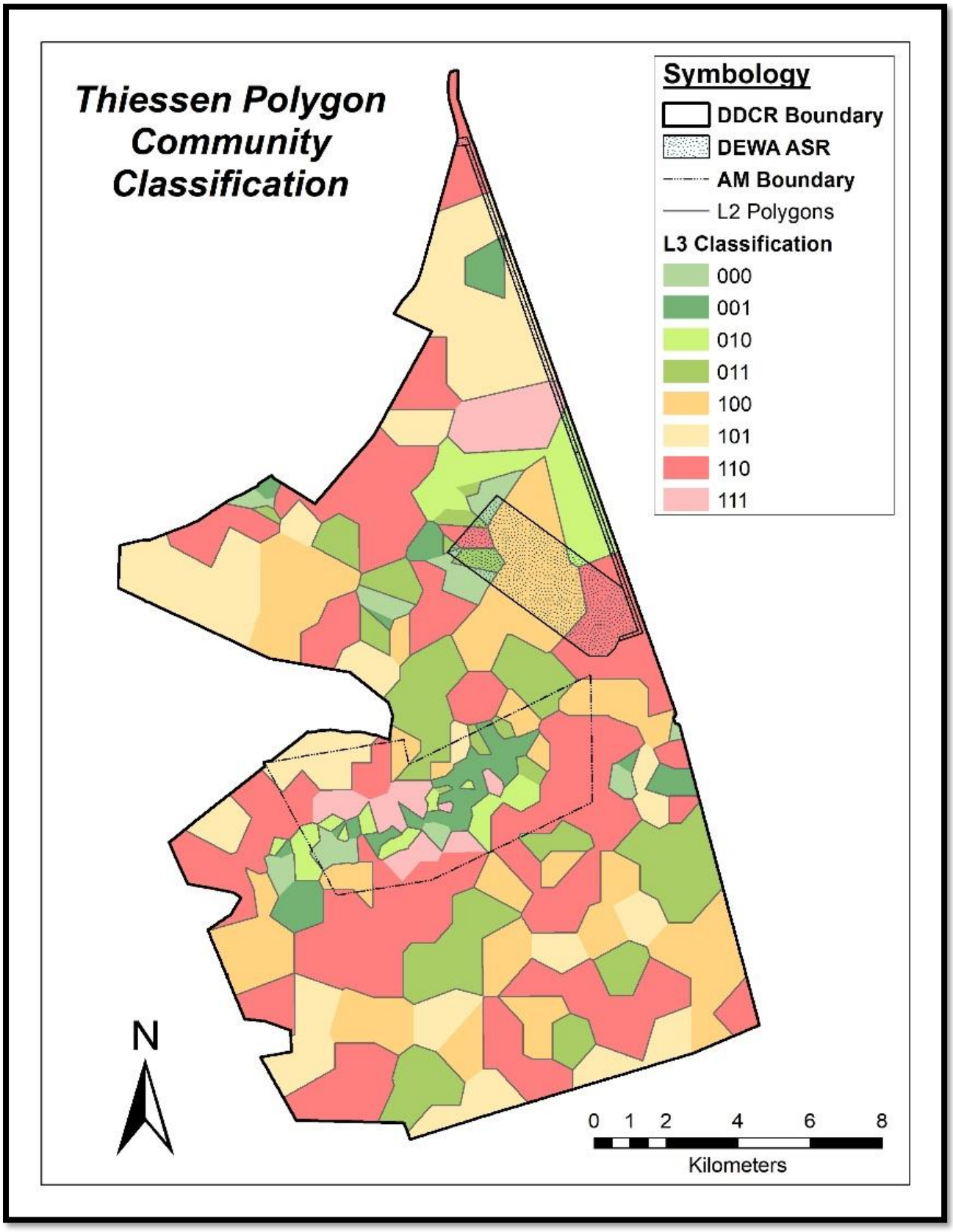

Figure 18: Spatial representation of TWINSPAN communities using Thiessen polygons.

Discriminant Function Analysis (DFA)

DFA showed clear floristic differentiation between gravel plain and sand dune habitats across both two-group and four-group datasets, but separation was clearer in the two-group DFA than the four-group DFA, indicating that habitat type remains the strongest source of floristic differentiation within the reserve. Species-level analyses produced stronger discrimination than structural-level analyses, with higher classification success and clearer group separation (93.7% & 72.1% accuracy in two-group and four-group respectively) (Figure 19). Wilki's Lambda indicated that habitat type significantly explained variation in species composition for both datasets ($p > 0.001$ in both datasets) (Table 8).

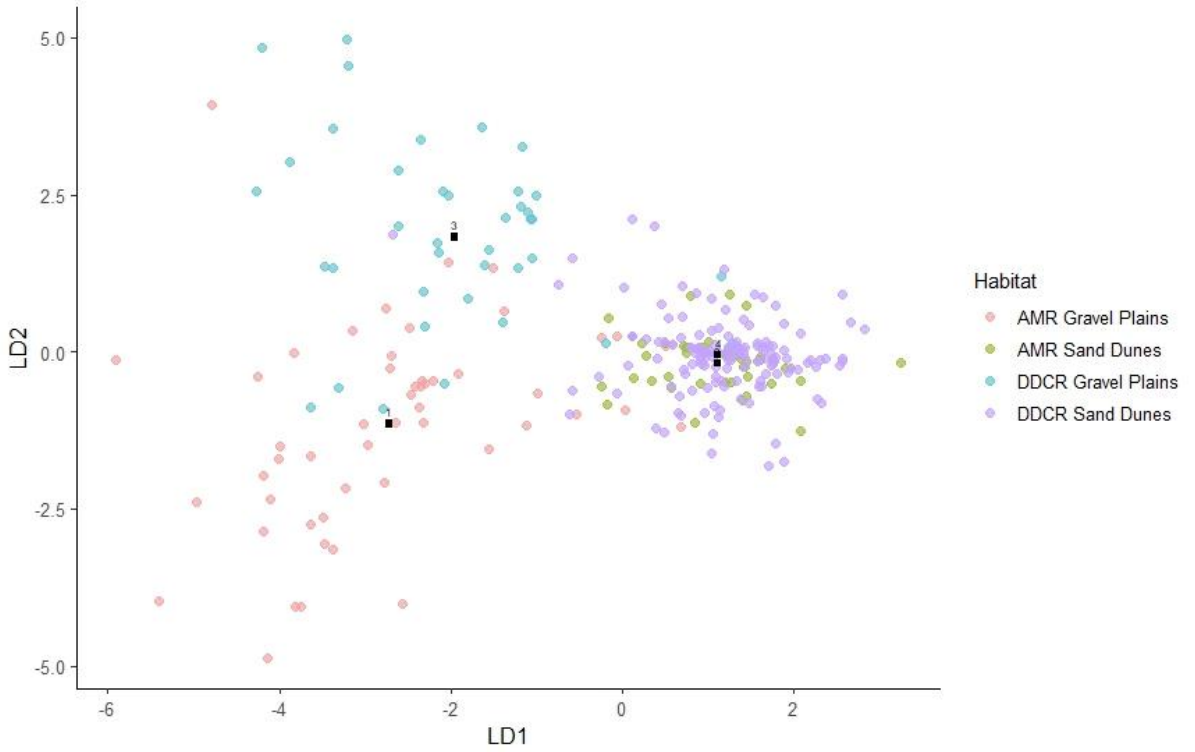

Figure 19: Species-level DFA scatter plot.

Test of Function(s)	Wilk's Lambda	Chi-square	df	Sig.
1 – 2	0.002	851.909	9	0.0000
2 – 3	0.057	447.351	4	0.0000
3	0.434	368.691	1	0.0000

Table 8: Significance of DFA to explain variation in species composition.

Structural variables nevertheless retained explanatory value and showed that habitat differences were still reflected in overall vegetation properties such as richness, abundance, cover, and diversity (accuracy of 72.8% & 52.9% in two-group and four-group datasets respectively) (Figure 20). This suggests that while diversity metrics differ, floristic composition is the main driver for habitat differentiation. In the structural DFA, the first discriminant function (LD1) was associated primarily with species richness, abundance, and diversity indices, whereas the second function (LD2) was associated mainly with cover (Table 9). LD 1 accounted for the entirety of between-group separation, reflecting compositional turnover associated with substrate type.

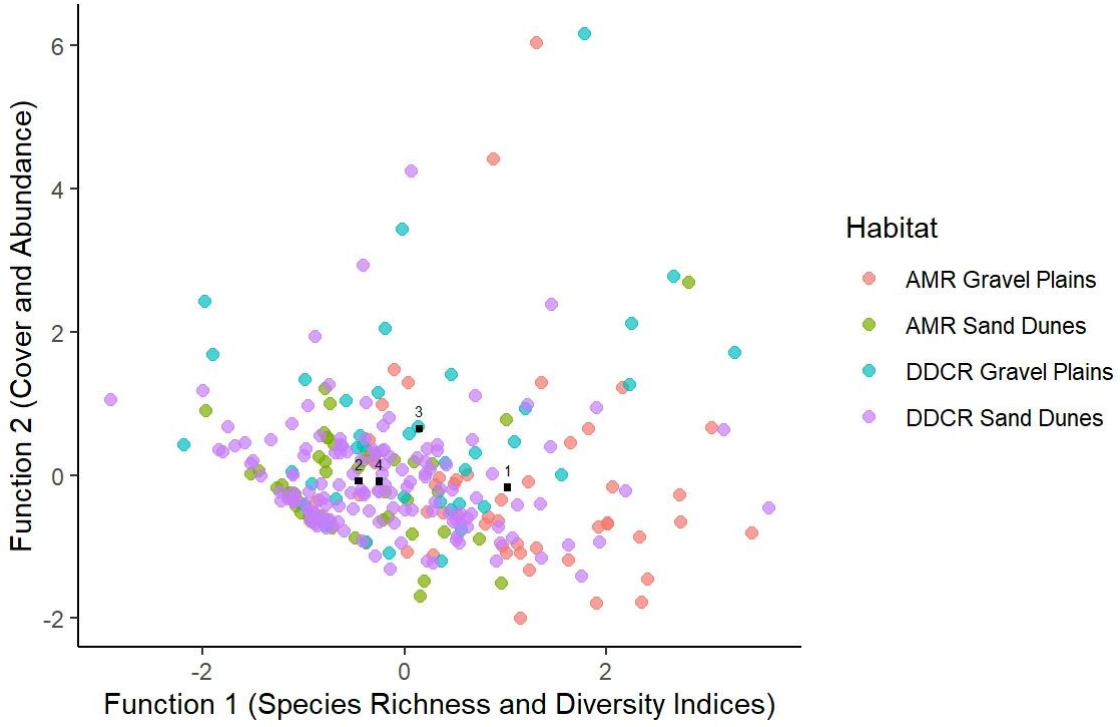

Figure 20: Structural-level DFA scatter plot.

Coefficients of Linear Discriminants			
	LD1	LD2	LD3
Species Richness	**0.733**	-0.124	-0.353
Species Abundance	0.**585**	**0.680**	-0.014
Cover	0.117	**0.795**	-0.197
Shannon	0.**561**	-0.040	-0.351
Simpson	0.**515**	0.054	-0.420
Brillouin	0.601	0.013	-0.257

Table 9: Correlation between variables and discriminant functions.

Species with the strongest LD1 positive loadings included *Calligonum comosum*, *Panicum turgidum*, and *Cenchrus sp*., which are typically associated with sand substrates (Hegazy & Lovett-Doust, 2016). On the other hand, *Aerva javanica*, *Prosopis cineraria*, and *Centaurea pseudosinaica* loaded negatively and were characteristic of gravel plain environments (Figure 20). The four-group DFA showed partial separation among AMR and DDCR habitat subsets, but overlap between comparable habitats was substantial, especially within the sand dune groups (Figures 21-22). Mahalanobis distances among the four habitat groups had the greatest separation between gravel plain and sand dune combinations and the weakest separation between AMR and DDCR sand dune groups (Table 10).

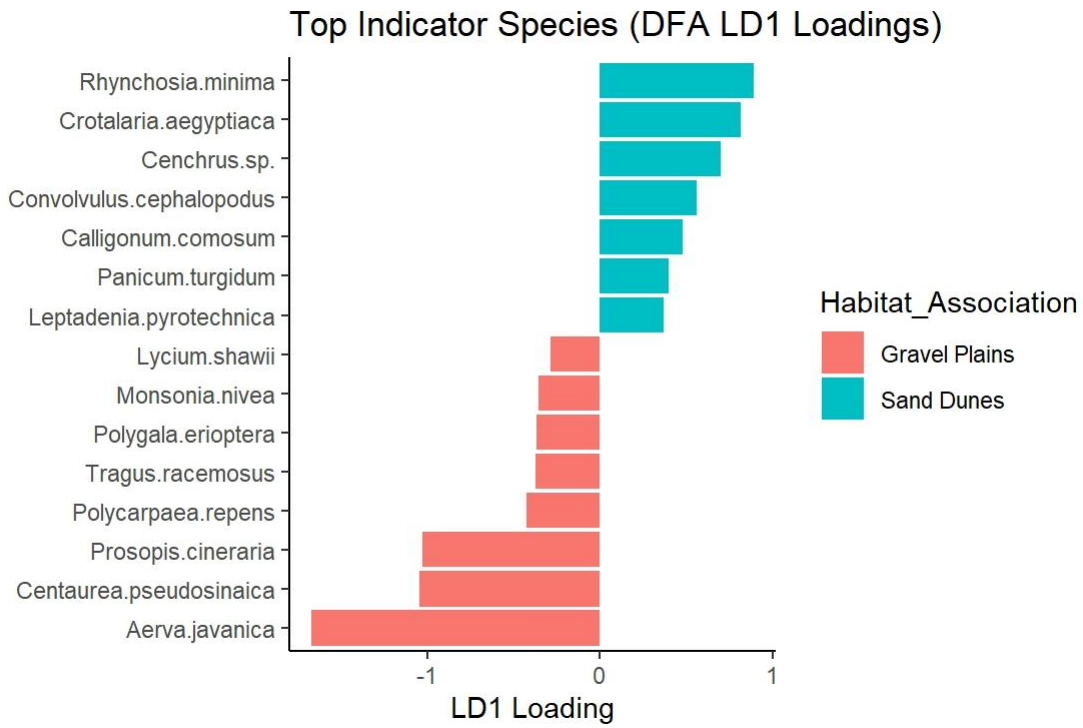

Figure 20: DFA indicator species according to substrate type.

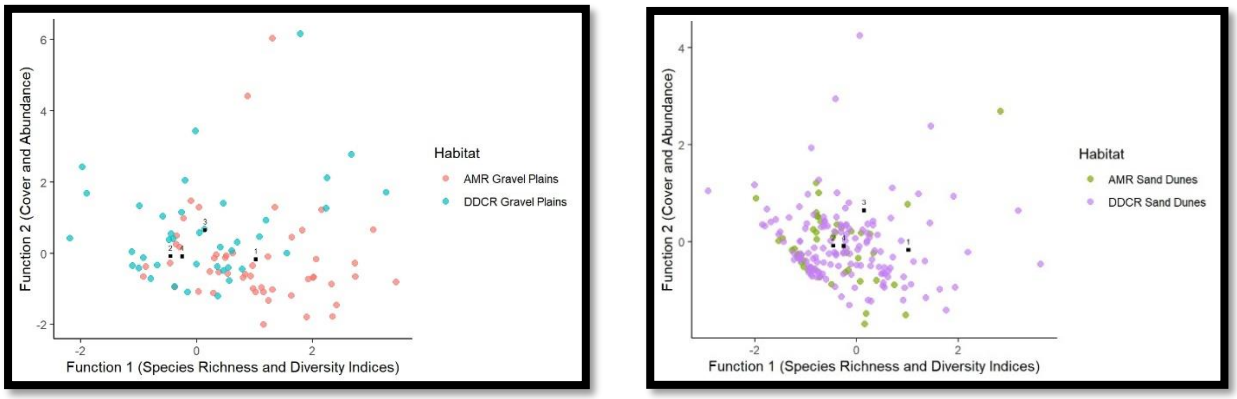

Figure 21: DFA structural-level scatter plots for gravel plains (left) and sand dune (right) habitats.

Habitats	Function		
	1	2	3
AMR Gravel Plains	1.02	-0.170	-0.0334
AMR Sand Dunes	-0.451	-0.0854	-0.247
DDCR Gravel Plains	0.147	0.647	-0.00355
DDCR Sand Dunes	-0.250	-0.0884	0.0858

Table 10: Canonical discriminant functions at group means (centroids).

Discussion

The current study does not distinguish between AMR and DDCR areas and only considers two major types of habitats: sand dunes and gravel plains. This decision came from the fact that the DDCR has been managed as a whole, single unit for 14 years. During this time wildlife has been able to move freely among habitats and natural processes have been allowed to take place without barriers restricting movements to or from any one area (Gordon & Prins, 2019). This, in turn, has allowed vegetation to be mixed and distributed through natural seed dispersal throughout the reserve (Sabo, 2019; Gallacher & Hill, 2005; El-Kablawy, Ksiksi, & El Alqamy, 2009).

Comparison with previous surveys (2004 and 2009) indicates that vegetation in the DDCR has undergone notable shifts in composition, dominance, and structure over the past two decades. While overall species richness has increased from 37 species in 2004 to 43 species in 2025, this increase does not necessarily reflect improved ecological condition. Instead, the data suggest a reorganization of community structure characterized by an increased dominance of a small number of highly adapted species (e.g., *Zygophyllum indicum*, *Dipterygium glaucum*), reduced relative importance of previously dominant/co-dominant species (e.g., *Cyperus conglomeratus*, *Haloxylon salicornicum*), and persistence of rare species with very low abundance and restricted distributions. Such patterns are typical of arid ecosystems experiencing environmental stress, where competitive hierarchies shift toward stress-tolerant species (Youssef, et al., 2024; El-Ghareeb, El-Sheikh, & Testi, 2006).

One of the most important factors influencing vegetation dynamics in the DDCR is herbivore density within a fenced system. At the time of this survey the reserve had ~760 Arabian oryx (*Oryx leucoryx*), ~560 Arabian gazelle (*Gazella arabica*), and ~ 270 sand gazelle (*Gazella marica*). However, the estimated carrying capacity for Arabian oryx within the reserve is 300-350 individuals, indicating the current population is more than double the sustainable level (unpublished data). In a closed system of approximately 215 km^2, this level of herbivore pressure likely results in selective grazing on palatable species, suppression of regeneration – particularly for shrubs and perennial grasses – and competitive release of less palatable/grazing-resistant species such as *Zygophyllum indicum* (Augustine & McNaughton, 1998). These processes help explain the increase in dominance of stress tolerant species, decline in abundance of some historically

dominant taxa and reduced structural complexity in certain areas. Although carrying capacity has not yet been calculated for gazelle species, their combined population further contributes to cumulative grazing pressure, intensifying these effects.

The 2025 survey period was characterized by extremely low rainfall, with virtually no precipitation recorded across the DDCR. In desert ecosystems, rainfall is the primary driver of germination of annual species, recruitment of perennials and overall productivity (Hegazy & Lovett-Doust, 2016; Siegal, Tsoar, & Karnieli, 2013). The lack of rainfall during the survey period likely contributed to reduced abundance of ephemeral species, lower overall vegetation cover and increased spatial patchiness. This climatic constraint, combined with high grazing pressure, likely amplified stress on vegetation communities, particularly in already marginal habitats (Gordon & Prins, 2019).

The detection of *Polygala irregularis* is a significant finding from both a conservation and biogeographical perspective. Its presence in the DDCR extends its known distribution within the UAE (Jongbloed, 2003; Allen, et al., 2021) and confirms the reserve as a refuge for rare and potentially overlooked species. The occurrence of both mauve and yellow flower morphs within the population is particularly noteworthy. This may indicate phenotypic plasticity in response to environmental conditions, genetic variation within the population and the possibility of unresolved taxonomic complexity. Additionally, the species was not recorded in long-term monitoring quadrats which suggests a localized distribution and potential sensitivity to disturbance or grazing. This highlights the importance of maintaining and monitoring heterogeneous microhabitats within the reserve.

Spatial Structure and Community Patterns

Spatial distribution pattern results indicate that individuals are not independently distributed. The predominance of aggregated species distributions is consistent with arid ecosystem dynamics, where plant establishment is strongly influenced by microtopography, soil moisture retention and facilitation by existing vegetation (Hegazy & Lovett-Doust, 2016). The strong dominance of *Zygophyllum indicum* in gravel plains and *Dipterygium glaucum* in sand dunes suggests a shift toward species with high tolerance to aridity, grazing, and disturbance. In earlier surveys, species such as *Heliotropium kotschyi* and *Cyperus conglomeratus* played more prominent roles. Their reduced dominance may reflect selective grazing pressure, reduced recruitment under drought conditions or competitive displacement (Augustine & McNaughton, 1998; Gordon & Prins, 2019; Youssef, et al., 2024).

Spatial analysis revealed that the DEWA ASR development area corresponds to zones of extremely low or zero vegetation diversity. This represents a clear departure from patterns observed in earlier surveys and indicates direct habitat loss, soil disturbance and compaction, and disruption of natural regeneration processes. While the impact appears

spatially localized, its presence within a protected area is significant. The contrast between this disturbed zone and surrounding areas highlights the sensitivity of desert vegetation to physical disturbance, particularly under drought conditions (Siegal, Tsoar, & Karnieli, 2013). TWINSPAN analysis confirmed clear differentiation between gravel plains and sand dune communities, with further subdivision reflecting environmental gradients and local conditions. These results reinforce the premise that habitat type remains the primary driver of vegetation structure, but is increasingly modified by grazing pressure, climatic variability and anthropogenic disturbance.

Herb Layer

Heliotropium digynum – This species has undergone a marked shift in spatial distribution over the past two decades. In 2004, the species was widely dispersed across sand dune habitats, with high predicted abundance also extending into gravel plains. By 2009, its distribution became more structured, forming a ring around the Al Maha area, with highest predicted densities in the north-western sector and localized absences in the northern part of the reserve. In 2025, the species exhibits a more restricted and clustered distribution, largely confined to sand dune habitats and almost entirely absent from the central reserve. Highest densities are now concentrated in the northern and south-western regions, with near-complete absence from the Al Maha area and most gravel plains (Figure 22). This shift is likely linked to changes in grazing regime. In 2004, livestock such as camels and goats were present within the reserve, whereas free-roaming livestock had been removed by the time of the 2009 survey. Domestic herbivores often exhibit different grazing preferences compared to native ungulates, frequently targeting different plant functional groups (El-Kablawy, Ksiksi, & El Alqamy, 2009). The transition from livestock to high densities of wild ungulates may therefore have altered grazing pressure on *H. digynum*, contributing to its reduced distribution and increased spatial clustering over time.

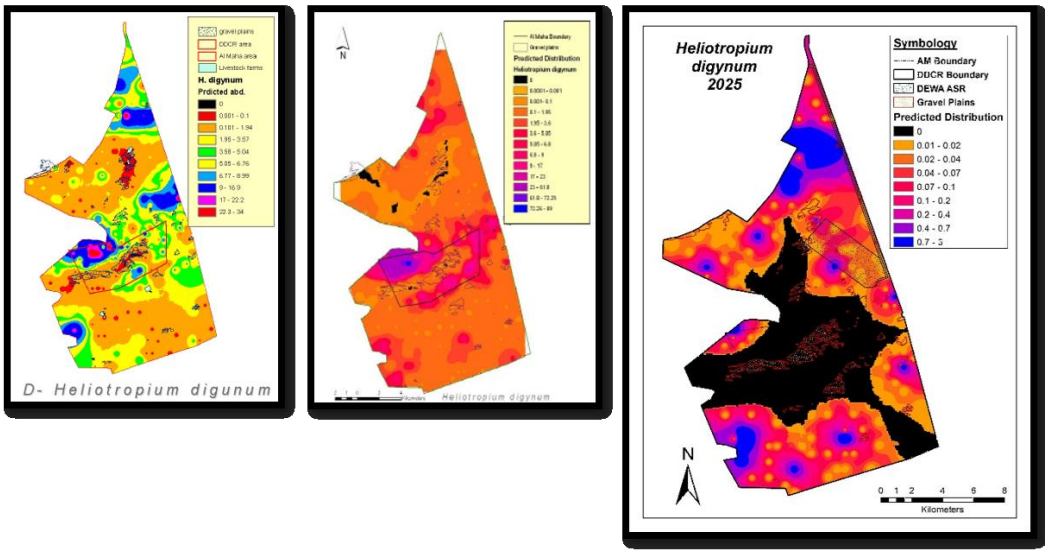

Figure 22: Predicted spatial distribution of H. digynum in 2004 (left), 2009 (middle), and 2025 (right).

Zygophyllum indicum – In 2004, this species showed a restricted distribution, largely confined to gravel plains within the Al Maha area and occurring only sporadically elsewhere. Later, in 2009, the species expanded significantly, acting as a colonizing species in recovering gravel plain habitats, particularly within Al Maha, with some encroachment into sand dune systems. By 2025, *Z. indicum* has become widely distributed across both gravel plains and sand dunes, with highest densities observed in gravel plains in the northern reserve and west of the Al Maha area (Figure 23). This steady expansion suggests strong pioneer characteristics (El-Ghareeb, El-Sheikh, & Testi, 2006). The continued increase in distribution is likely linked to both post-disturbance recovery processes and changes in grazing pressure. The removal of livestock and subsequent dominance of native ungulates may have altered competitive dynamics, allowing *Z. indicum* to expand. Its success highlights the influence of grazing regime on vegetation recovery and composition within the reserve.

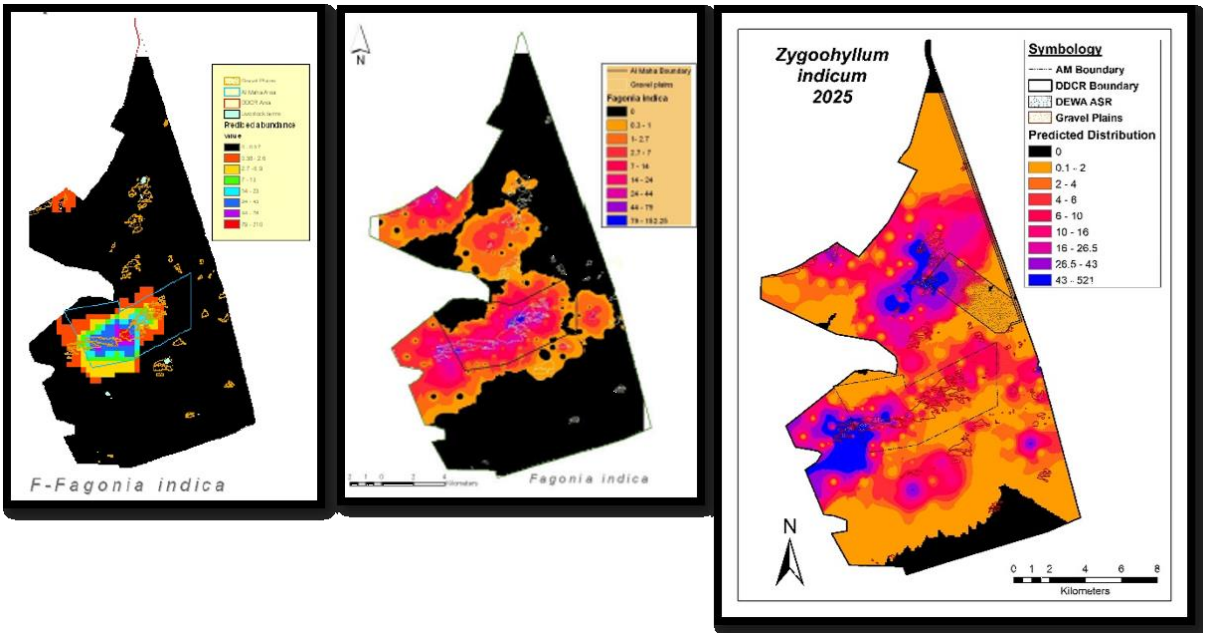

Figure 23: Predicted spatial distribution of Z. indicum in 2004 (left), 2009 (middle), and 2025 (right).

Moltkiopsis ciliata – This species has shown dynamic changes in distribution over time. In 2004, it was largely concentrated within the Al Maha area, with only limited extension into the wider reserve. By 2009, the species expanded substantially, occupying much of the reserve and forming pronounced hotspots around the Al Maha gravel plains and in southern regions. In 2025, the species shows a partial contraction, particularly from the Al Maha area, where it is now absent from several gravel plains. A distinct absence belt is also evident in the northern reserve (Figure 24). Despite this, the species remains common in sand dune habitats, particularly in the southern sectors. These changes suggest that *M. ciliata* distribution is more strongly linked to habitat characteristics, particularly sand stability and substrate conditions, than to grazing pressure alone. Its persistence in stable dune systems and decline in certain gravel plain areas may reflect

shifts in soil conditions, microhabitat suitability, or longer-term vegetation dynamics rather than direct grazing effects.

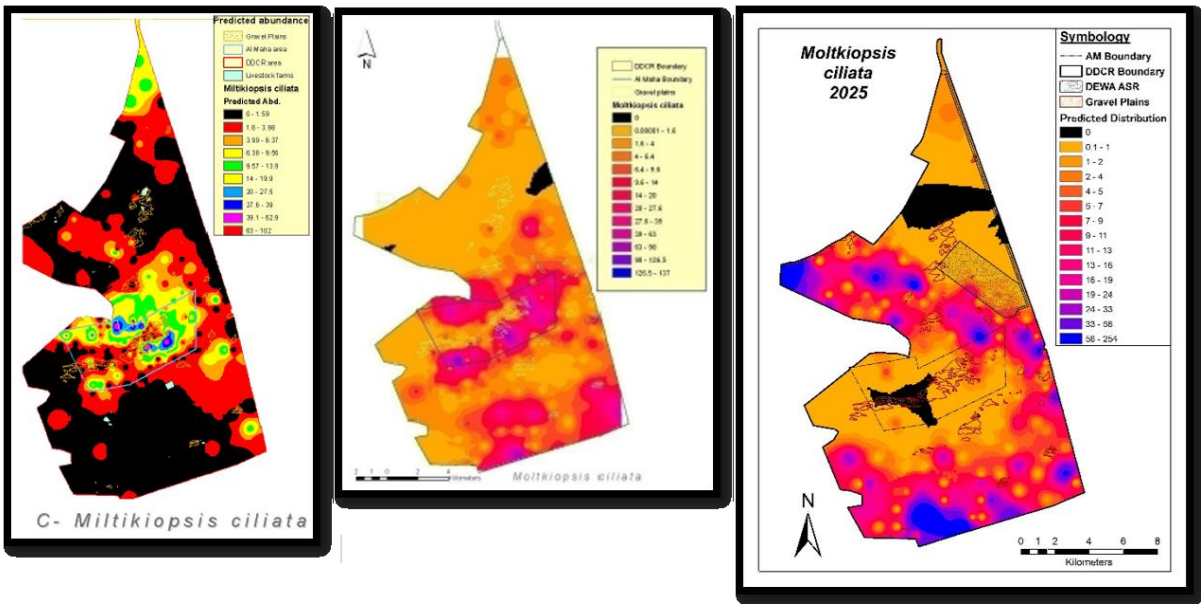

Figure 24: Predicted spatial distribution of M. ciliata in 2004 (left), 2009 (middle), and 2025 (right).

Rhanterium epapposum – In 2004, *Rhanterium epapposum* exhibited localized abundance but limited overall distribution, with a clear preference for gravel plains. Although it was not considered strongly affected by grazing at the time, this assumption appears inconsistent with current field observations. By 2009, its distribution had declined but remained associated with gravel plains. In contrast, the 2025 survey recorded the species in only three locations, all within sand dune habitats, indicating a substantial reduction in observed distribution (Figure 25). However, these results likely underestimate the true distribution of the species, as ongoing surveys have recorded *R. epapposum* in previously unsampled gravel plain areas. Importantly, field observations indicate that the species is now heavily grazed by native ungulates, despite earlier suggestions that it was relatively unaffected by grazing (El Alqamy, 2004). The only consistently ungrazed individuals have been observed within protected research areas, suggesting that *R. epapposum* is in fact palatable to wild herbivores. Hegazy and Lovett-Doust (2016) in fact mention this species as an important grazing resource from winter into early summer in parts of the Arabian Peninsula. This grazing pressure may be a key factor influencing its apparent decline and fragmented distribution, particularly in accessible areas of the reserve.

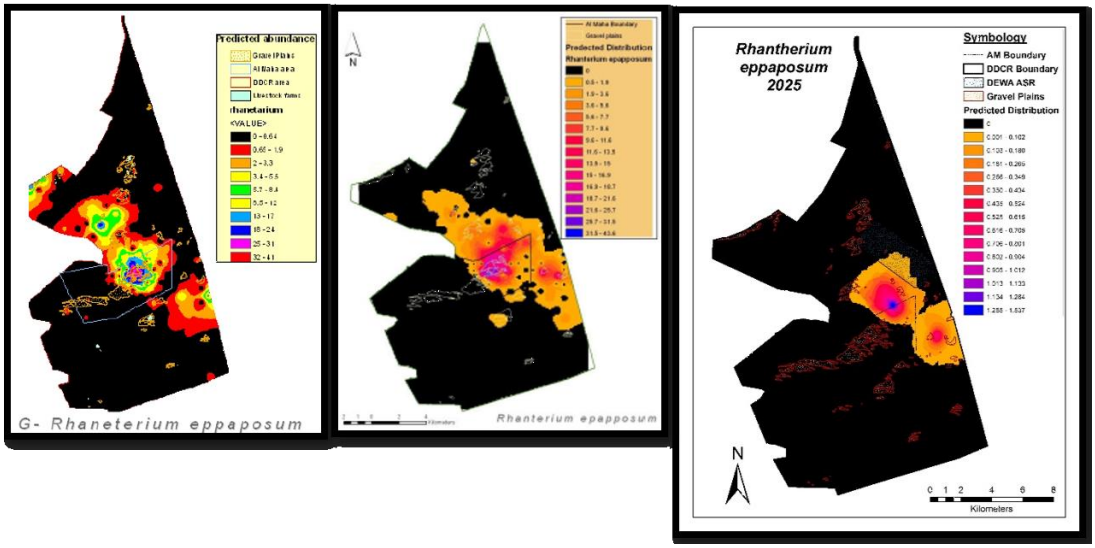

Figure 25: Predicted spatial distribution of R. epapposum in 2004 (left), 2009 (middle), and 2025 (right).

Dipterygium glaucum – In 2004, this species had a relatively restricted distribution, primarily within the Al Maha area. By 2009, it underwent a significant expansion, becoming widely distributed across the reserve. This widespread distribution has largely persisted into 2025, with high-density areas becoming more pronounced. While the species has expanded slightly northwards, a persistent absence remains in the northernmost areas of the reserve (Figure 26). A notable recent change is its absence from parts of the western reserve, which may be linked to localized grazing pressure associated with feeding stations. Large aggregations of Arabian oryx and gazelles in these areas likely increase grazing intensity. Previously identified as a palatable species for livestock, *D. glaucum* may also be highly palatable to wild ungulates (Hegazy & Lovett-Doust, 2016). Its localized decline in areas of concentrated herbivore activity suggests that overgrazing is influencing its distribution, despite its overall success across the reserve.

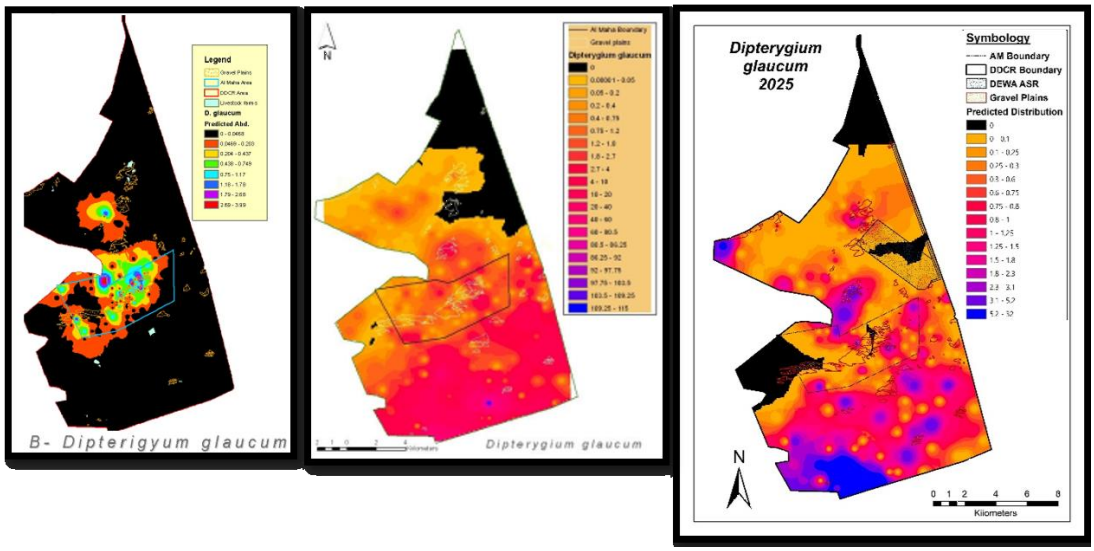

Figure 26: Predicted spatial distribution of D. glaucum in 2004 (left), 2009 (middle), and 2025 (right).

Limeum arbicum – In 2004, this species was primarily associated with sand dune habitats, with limited presence in gravel plains and higher densities in the Al Maha region. Its distribution was strongly influenced by livestock grazing. By 2009, the species expanded across much of the reserve while maintaining its preference for sand dunes, with absences attributed to livestock overgrazing, particularly by camels. In 2025, *L. arabicum* shows a further increase in distribution and density, particularly in the southern and southeastern regions (Figure 27). However, notable absence zones persist in the Tawi Ruwayyan area and have newly developed in the Al Maha region. Given that camel grazing has been strictly controlled for over a decade, these absence zones are more likely attributable to intense grazing by wild ungulates, particularly in areas where animals aggregate around feeding stations. This suggests that, despite changes in grazing regime, herbivory remains a key driver of species distribution.

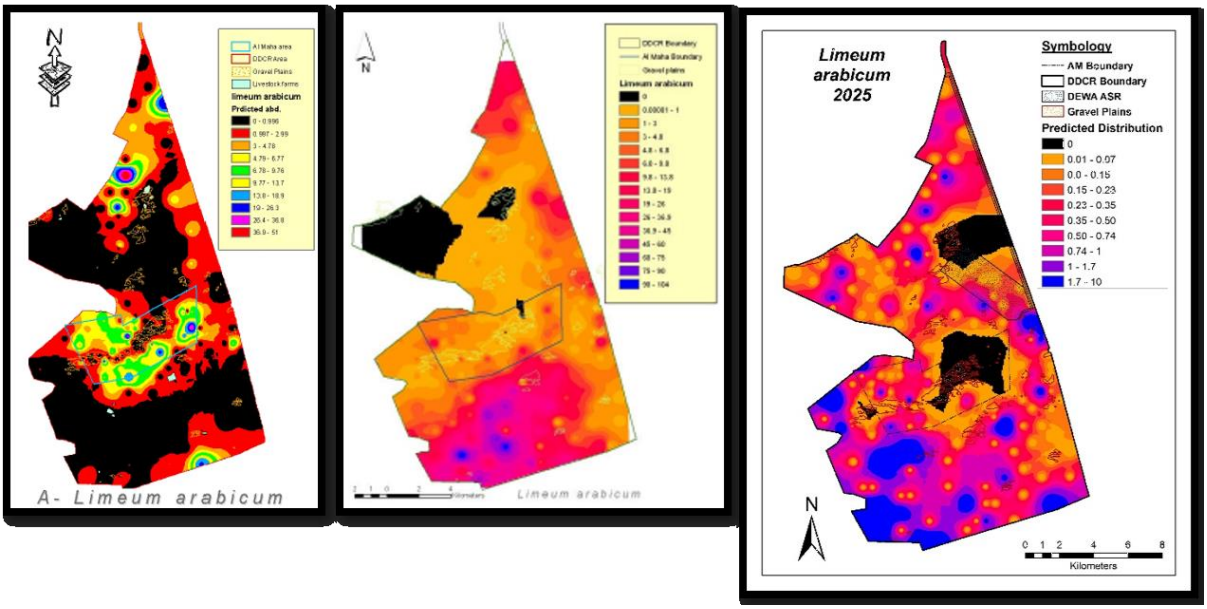

Figure 27: Predicted spatial distribution of L. arabicum in 2004 (left), 2009 (middle), and 2025 (right).

Cyperus conglomeratus – This species has maintained a near-continuous distribution across the reserve over the past 21 years (Figure 28). In both 2004 and 2009, it was considered a sand dune specialist, with no records in gravel plains. In 2025, it remains the most widespread and abundant species in the reserve. While still primarily associated with sand dunes, it is now also recorded in gravel plains, indicating an expansion of its ecological range. This species is recognized as a pioneer species with strong colonization ability, particularly in disturbed environments (Khafaga, 2009; Hegazy & Lovett-Doust, 2016). Its increasing abundance across the reserve may therefore reflect habitat disturbance and vegetation simplification, rather than improved ecological condition. The dominance of *C. conglomeratus* in dune areas where it occurs almost as a monoculture suggests that parts of the reserve may be experiencing functional degradation despite appearing visually "green." This highlights the importance of interpreting vegetation patterns in terms of ecological quality, not just coverage.

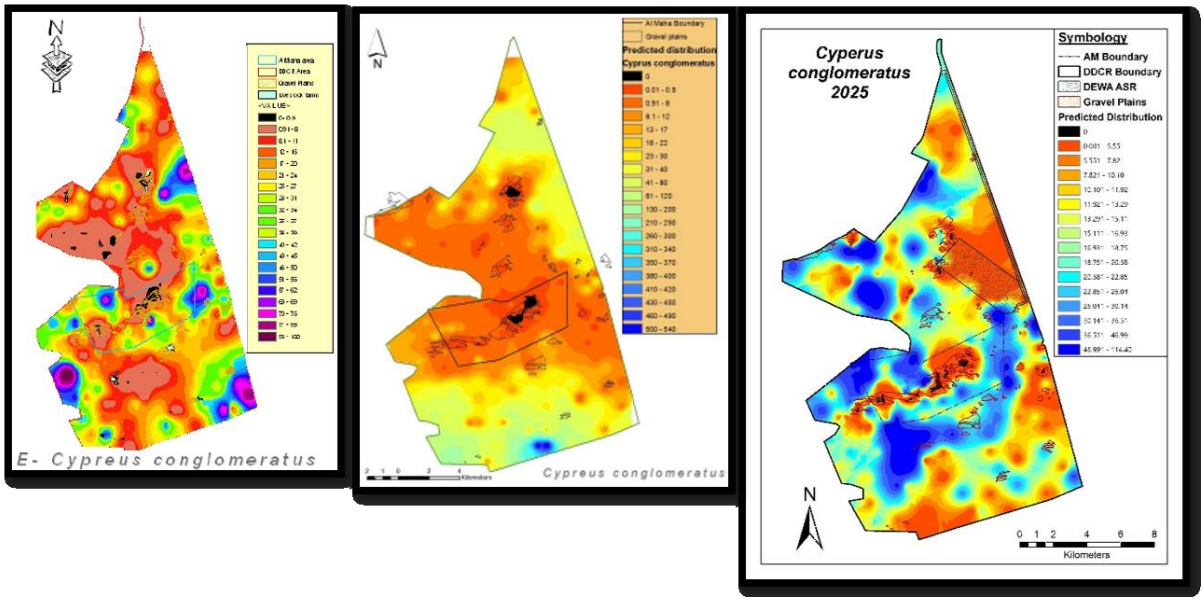

Figure 28: Predicted spatial distribution of C. conglomeratus in 2004 (left), 2009 (middle), and 2025 (right).

Shrub Layer

Haloxylon salicornicum – This species was initially recorded as having a restricted distribution in the southwestern portion of the DDCR in 2004, with only a modest expansion by 2009. At the time, this limited distribution was tentatively attributed to factors such as soil composition and habitat specificity. In 2025, the species shows a shifted but still discontinuous distribution, with highest densities occurring in the western part of the southern reserve, absence from parts of the southern area where it was previously recorded, and the emergence of a distinct patch in the northern reserve (Figure 29). However, field observations indicate that *H. salicornicum* is more widespread than suggested by the sampled data. The species was frequently observed outside surveyed quadrats, suggesting that its apparent patchy distribution may partly reflect sampling limitations rather than true absence. Given that the current methodology relies on small (5 × 5 m) quadrats, it is likely that this species—often occurring in scattered individuals or low-density stands—is underrepresented in the dataset (Bonham, 2013). While habitat preferences, including soil characteristics and microtopography, may still play a role in structuring its distribution, the observed patterns should be interpreted with caution.

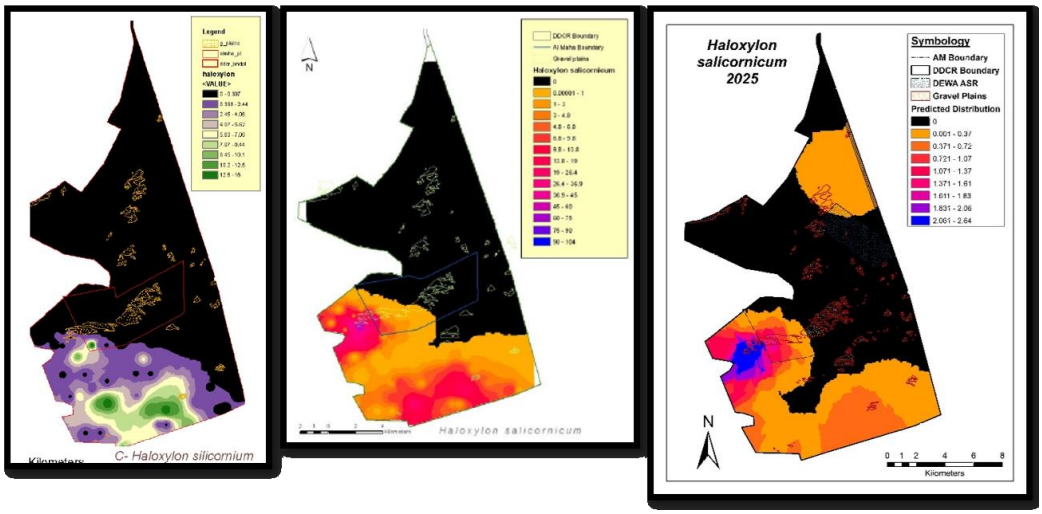

Figure 29: Predicted spatial distribution of H. salicornicum in 2004 (left), 2009 (middle), and 2025 (right).

Leptadenia pyrotechnica – This species has shown contrasting patterns between mapped results and field observations. In 2004, the species was primarily concentrated in the central region of the reserve, with its distribution thought to be influenced by the presence of livestock farms. By 2009, its distribution expanded significantly, covering much of the reserve while still showing higher concentrations in central areas associated with previous livestock activity. In contrast, the 2025 results suggest a highly fragmented and limited distribution, with only a few scattered occurrences recorded (Figure 30). This pattern is inconsistent with extensive field observations and other vegetation monitoring data, which indicate that *L. pyrotechnica* remains widespread and locally abundant across the DDCR. This discrepancy is most likely attributable to methodological constraints, particularly the reduced sampling area used in the current study. As a large, widely spaced shrub, *L. pyrotechnica* is poorly captured by small quadrats (25 m^2), which may fail to intersect individuals even in areas where the species is common (Bonham, 2013). These findings highlight a key limitation of the current sampling design for detecting large, sparsely distributed species.

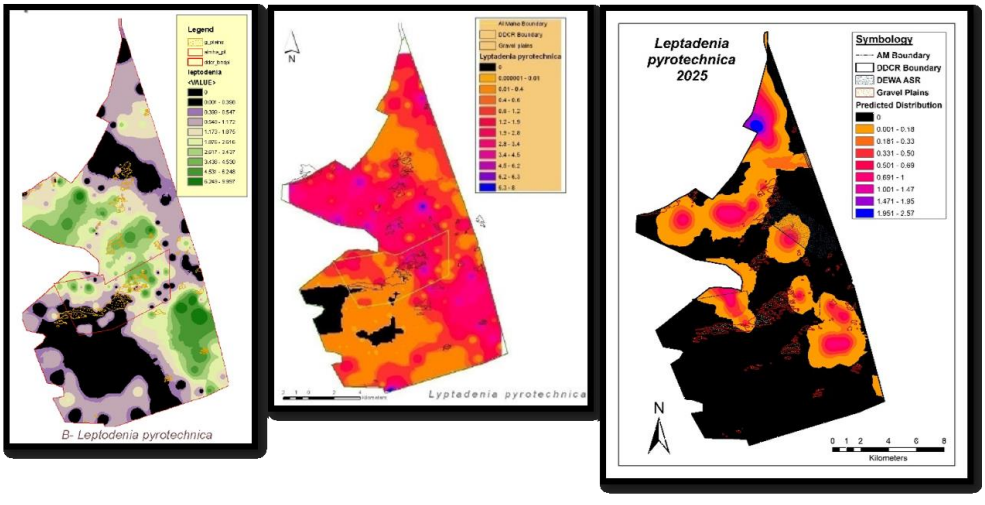

Figure 30: Predicted spatial distribution of L. pyrotechnica in 2004 (left), 2009 (middle), and 2025 (right).

Calligonum commosum – In 2004, *Calligonum* species were described as very rare and poorly represented, with only a few individuals recorded. The genus was not featured in the 2009 report, likely due to similarly low representation in sampled plots. In the present study, *Calligonum comosum* was recorded at only a small number of locations in sand dune habitats within the central and southern reserve and has not been recorded in gravel plains (Figure 31). However, extensive field observations indicate that *Calligonum* species are locally abundant in specific areas of the DDCR, particularly near the southeastern boundary of the Al Maha area and along the eastern fenceline (Figure 32). These areas have not been included in systematic vegetation sampling, suggesting that the current dataset underrepresents the true distribution and ecological importance of this genus. Furthermore, while previous reports assumed the presence of a single species (*Calligonum comosum*), recent field observations indicate the presence of *Calligonum crinitum*. These species are difficult to distinguish outside of flowering or fruiting stages, which may have contributed to underreporting and taxonomic uncertainty in earlier surveys (Figure 33). The combination of sampling limitations and identification challenges highlights the need for targeted surveys focusing on *Calligonum* populations. These species play an important ecological role in dune stabilization and habitat structure (Hegazy & Lovett-Doust, 2016), and their apparent rarity in plot-based analyses likely does not reflect their actual abundance within the landscape.

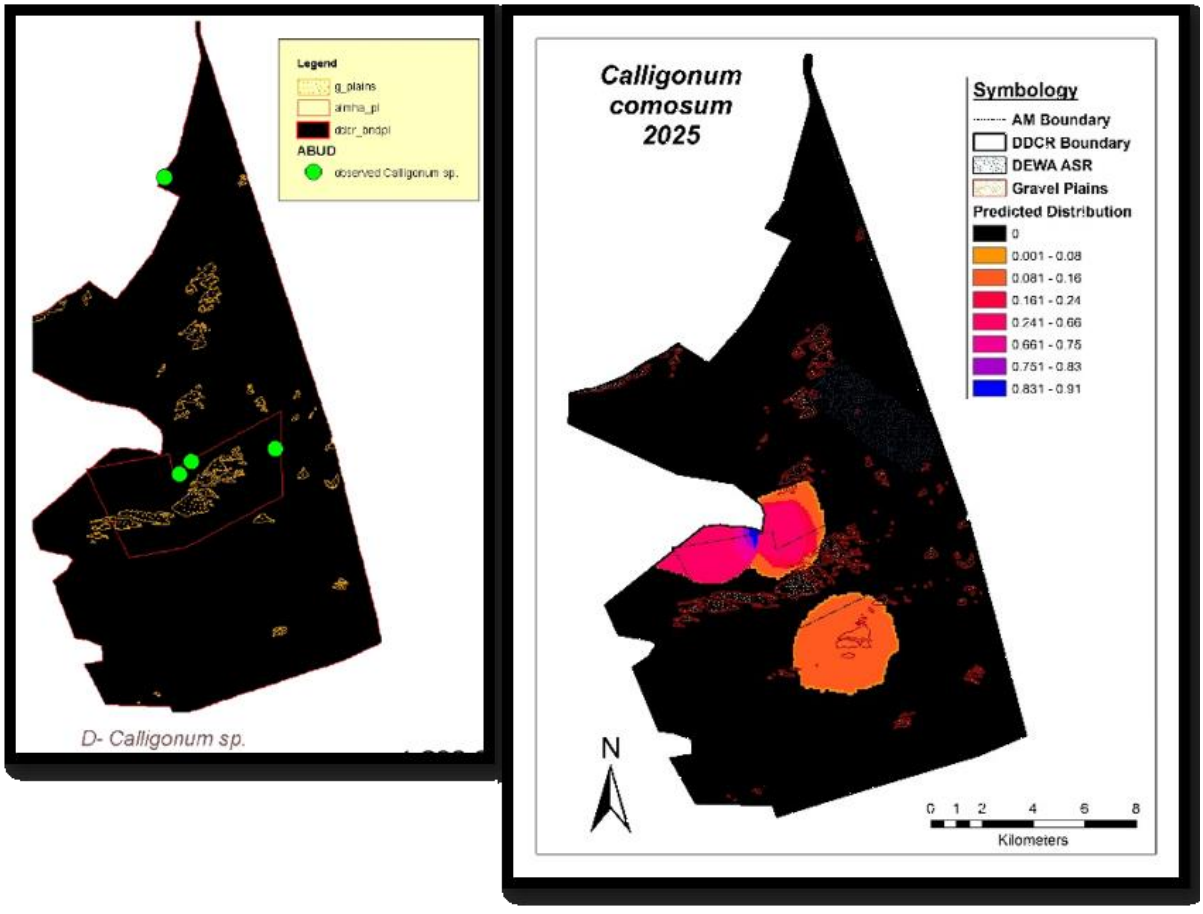

Figure 31: Predicted spatial distribution of C.comosum in 2004 (left), 2009 (middle), and 2025 (right).

Figure 32: Calligonum distribution areas at the eastern fence line (top) and southern AMR area (bottom).

Figure 33: Calligonum comosum fruits and flowers (top left) compared with C. crinitus flowers (top left) and fruits (bottom).

TWINSPAN Community analysis

TWINSPAN classification revealed clear structuring of vegetation communities along habitat and environmental gradients within the DDCR. The primary division separated gravel plains from sand dune systems, reflecting the strong influence of substrate type on species composition. Within gravel plains, the distinction between subtypes (000) and (001) suggests variation in habitat quality and resource availability. Subtype (001), associated with the Al Maha area, supports higher species richness and more even species distribution, likely reflecting long-term protection and reduced disturbance. In contrast, subtype (000), which occurs near the DEWA development area and other peripheral zones, is characterized by low diversity and dominance by a few species, indicating environmental stress or disturbance effects.

The mixed-soil assemblage (01) highlights transitional environments between gravel plains and dunes. The presence of stress-tolerant species such as *Heliotropium kotschyi* in subtype (010) suggests environmentally constrained conditions, potentially linked to grazing pressure or reduced soil moisture (Gordon & Prins, 2019). In contrast, subtype (011) shows greater perennial development, which may indicate more stable substrates or reduced disturbance intensity. Within sand dune habitats, the differentiation between subtypes (100) and (101) reflects variation in vegetation structure and possibly management history. Subtype (101), with multiple indicator species and well-developed perennial grasses, represents a more structured and stable community. Conversely, subtype (100), although containing similar species, shows lower overall abundance, which may reflect recent environmental stress, including drought conditions during 2025.

The sand dune shrubland group (11) is particularly notable for its low diversity and strong dominance by *Cyperus conglomeratus*, especially in subtype (110). This pattern suggests intense environmental filtering, where only a limited number of highly adapted species can persist. Such conditions are likely reinforced by the combined effects of high grazing pressure and low rainfall, both of which restrict recruitment of less tolerant species (Gordon & Prins, 2019; Augustine & McNaughton, 1998; Fisher, et al., 1997). Overall, the TWINSPAN results indicate that while habitat type remains the primary driver of vegetation structure, local disturbance, grazing intensity, and climatic variability are increasingly shaping community composition, leading to simplified and more homogeneous plant assemblages in some areas.

Thiessen Polygons

The Thiessen polygon analysis supports the TWINSPAN results by showing that vegetation communities are not randomly distributed across the reserve, but instead form broad, spatially coherent habitat units. This is important because TWINSPAN alone identifies floristic groupings but does not show how those groups are arranged across the

landscape (Hill, 1979; El Alqamy, 2004; Khafaga, 2009). The polygon map therefore provides a practical visualization of vegetation continuity, fragmentation, and transition zones. Comparison with earlier surveys suggests a marked change in reserve-wide vegetation pattern (Figure 35). The 2004 report described stronger fragmentation outside the Al Maha Reserve, whereas the 2009 survey noted improved continuity and homogeneity of habitat structure across the DDCR. The present results are more consistent with the 2009 pattern, with broad habitat continuity still apparent across much of the reserve. This suggests that large-scale vegetation organization remains intact despite local stress.

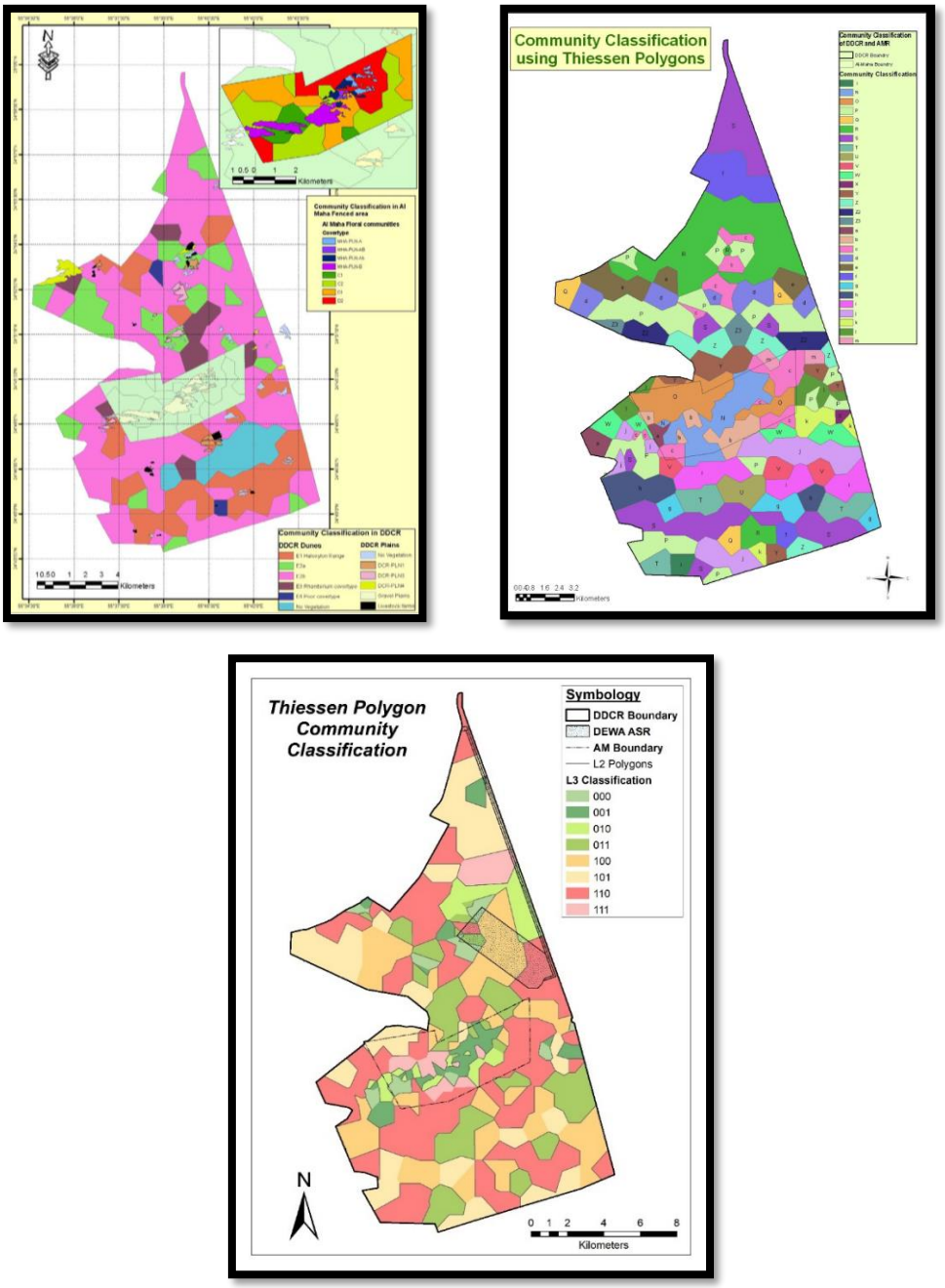

Figure 35: Spatial representation of TWINSPAN vegetation communities using Thiessen Polygons in 2004 (top left), 2009 (top right), and 2025 (bottom).

However, the polygon analysis also indicates simplification in some areas. In particular, the large extent of the 110 sand dune subtype, characterized by overwhelming dominance of *Cyperus conglomeratus* and very low representation of other species, suggests that some dune systems may now be structurally simplified. This may reflect a combination of prolonged drought, reduced annual recruitment, and high grazing pressure. In that sense, continuity of habitat should not automatically be interpreted as ecological stability or high condition. A landscape can appear spatially continuous while still being biologically simplified. The exclusion of the DEWA ASR points from TWINSPAN and Thiessen analysis is also ecologically meaningful. These sites were omitted for technical reasons because zero-abundance samples cannot contribute usefully to floristic classification, but their absence from the classified vegetation map is itself a signal of severe disturbance. Rather than representing an analytical gap, this highlights the contrast between the vegetated reserve matrix and a newly disturbed area where vegetation was effectively absent at the time of sampling.

Discriminant Function Analysis (DFA)

The DFA results reinforce the conclusion that the strongest ecological distinction within the DDCR remains the contrast between gravel plains and sand dunes. This is unsurprising, as substrate type, soil texture, moisture retention, and associated plant strategies differ fundamentally between these habitats. What is more informative is that the historical distinction between AMR and DDCR appears weaker than the basic habitat contrast, particularly in 2025. Figure 36 shows how these results reflect over the years. Points form clear clusters in 2004 with clear separation along Function 1 and centroids are reasonably separated. This points to habitats that differ mainly by number of individuals and, although communities are distinguishable as groups, variability is caused by disturbances on account of AMR and DDCR areas being subject to different management strategies (El-Kablawy, Ksiksi, & El Alqamy, 2009). In 2009 there's more overlap between habitats with centroids closer together and a point distribution that looks more cloud-like than clustered. This suggests that differences are no longer about abundance and now reflect community composition, diversity, and habitat structure which points to species redistribution across habitats. Currently, points show heavy overlap between habitats with centroids very close together indicating habitats now differ along a shared ecological gradient and variables are more correlated with each other.

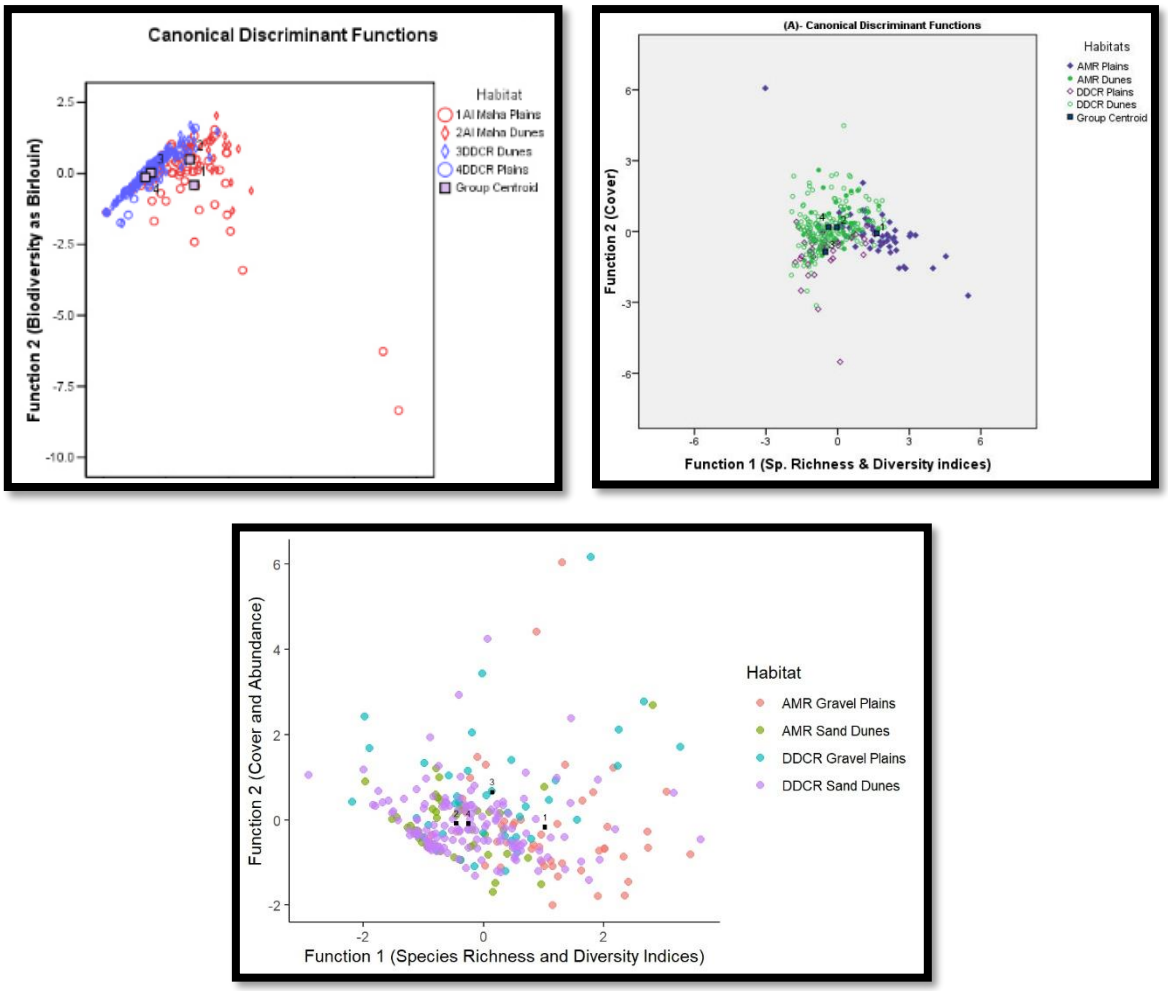

Figure 36: DFA scatter plots for 2004 (top left), 2009 (top right), and 2025 (bottom.

Conclusions

This study provides an updated assessment of vegetation dynamics within the Dubai Desert Conservation Reserve, revealing a system undergoing continuous ecological change driven by interacting pressures. Key findings include:

- An increase in species richness compared to the 2004 baseline, but with shifts toward dominance by stress-tolerant species.
- Clear evidence of localized disturbance impacts associated with recent government project developments.
- Strong indications that herbivore populations exceeding ecological carrying capacity are influencing vegetation structure.
- Confirmation of aggregated spatial patterns typical of arid ecosystems.
- Identification of *Polygala irregularis* as a rare and ecologically significant species within the reserve.

Together, these findings highlight the importance of integrated management approaches that consider grazing pressure, climate variability, and land-use impacts. Continued long-term monitoring will be essential to track these dynamics and support effective conservation of the DDCR's unique desert ecosystem.

Management Implications

The findings of this study have several important implications for the management of the DDCR:

1. **Herbivore Population Management** – Current Arabian oryx numbers significantly exceed carrying capacity, therefore it is imperative to consider population reduction strategies (such as cropping or culling), translocation programs, and adaptive stocking based on rainfall conditions.
2. **Monitoring of Grazing Impacts** – Establishing a vegetation monitoring program linked explicitly to herbivore density and identify indicator species sensitive to overgrazing within the reserve.
3. **Protection of Sensitive and Rare Species** – Map and monitor populations of *Polygala irregularis* (EN), *Rhanterium epapposum* (EN), and *Vachellia flava* (NT). Avoid disturbances in known distribution areas of these species and consider microhabitat protection measures.
4. **Management of Development Impacts** – Implement vegetation restoration or rehabilitation in the DEWA ASR and surrounding areas upon project completion and monitor recovery over time with permanent plots.
5. **Climate-Responsive Management** – Recognize that drought years significantly alter vegetation patterns and interpret monitoring data within the context of rainfall variability. Additionally, investigate and interpret historical vegetation variations between drought and pluvial years.

Difference among habitats has shifted from simple abundance differences to structural and multidimensional differences holding higher within-group variability relative to between-group differences. This may indicate that some of the larger-scale vegetation differences between protected and more heavily used parts of the reserve, which were more evident in earlier surveys, have become less pronounced over time. One possible explanation is that post-livestock recovery and long-term reserve-wide management have reduced some of the past differences between AMR and DDCR. Another is that current pressures, especially drought and high herbivore density, are now acting across the reserve strongly enough to override some management-history effects.

The structural DFA is especially useful in this context. The association of Function 1 with richness, abundance, and diversity indices, and Function 2 with cover, suggests that present-day habitat differences are expressed first through floristic composition and diversity, and second through vegetation structure. This fits with broader results: gravel

plains and sand dunes still differ in their species assemblages, but both are being shaped by low rainfall, local disturbance, and grazing pressure (El-Kablawy, Ksiksi, & El Alqamy, 2009; Hegazy & Lovett-Doust, 2016; Augustine & McNaughton, 1998).

The partial overlap among the four AMR/DDCR habitat categories should not be interpreted as a failure of the analysis. Rather, it suggests that reserve vegetation is better understood as a continuum structured primarily by habitat, with local management and disturbance effects superimposed on that broader template. For management purposes, this means that reserve-wide monitoring should continue to prioritize gravel plain and sand dune comparisons, while still tracking special cases such as development zones, rare-species sites, and areas under particularly intense herbivore use.

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Appendices

Annex I – Vegetation Parameters (formulas)

In each stand several parameters were assessed as follows:

1- Density of species (*i*) =

$$\frac{total\ number\ of\ individuals\ of\ species\ (i)\ in\ all\ sampled\ plots}{area\ of\ sampled\ plots}$$

2- Relative density of the species (*i*)

$$\frac{total\ number\ of\ individuals\ of\ species\ (i)}{total\ number\ of\ individuals} \times 100$$

3- Frequency

$$\frac{total\ number\ of\ plots\ in\ which\ species\ (i)\ occurs}{total\ number\ of\ plots\ sampled} \times 100$$

4- Relative frequency of a species (*i*)

$$\frac{Frequency\ of\ species(i)\ in\ plot\ (x)}{total\ frequencies\ of\ all\ species\ in\ plot(x)} \times 100$$

5- Abundance of a species (*i*)

$$\frac{total\ number\ ofi\ ndividuals\ of\ species\ (i)}{total\ number\ of\ plots\ in\ which\ species(i)\ occured}$$

6- Relative abundance

$$\frac{Abundance\ of\ species(i)\ in\ plot\ (x)}{total\ abundance\ of\ all\ species\ in\ plot(x)} \times 100$$

7- Relative cover

$$\frac{Total\ cover\ of\ species(i)\ in\ all\ plots}{Total\ cover\ ofall\ species\ in\ allplots} \times 100$$

Significant Important Value Index (S.I.V.I.) = the sum of all the four relative values recorded for each species which show the overview picture of the ecological importance and to measure the dominance and the co-dominance species per each stand (Shukla and Chandle, 1996).

Annex II – Vegetation Parameters (table)

D= Density; F= Frequency; A= Abundance; C= Cover; RD= Relative Density; RF= Relative Frequency; RA= Relative Abundance; RC= Relative Cover, SIVI= Significant Important Value Index; IVI= Important Value Index.

Vegetation parameters recorded in Gravel Plains

	Species	D	F	A	C	RD	RF	RA	RC	SIVI	IVI
1	*Aerva javanica*	0.04	4.4	1	0.001	0.04	0.83	0.37	0.00	1.44	1.24
2	*Arnebia hispidissima*	25.5	47.3	54	1.987	22.14	8.90	20.03	1.19	52.99	51.06
3	*Atractylis carduus*	0.27	16.5	2	0.003	0.24	3.11	0.62	0.00	4.08	3.96
4	*Bassia muricata*	0.01	1.1	1	0.000	0.01	0.21	0.37	0.00	0.59	0.59
5	*Centaurea pseudosinaica*	0.24	7.69	3	0.002	0.21	1.45	1.16	0.00	2.92	2.82
6	*Centropodia forsskaolii*	4.91	41.8	12	0.254	4.26	7.87	4.36	0.15	17.12	16.48
7	*Cenchrus divisus*	0.02	2.2	1	0.000	0.02	0.41	0.37	0.00	0.83	0.80
8	*Cenchrus sp.*	0.03	2.2	2	0.000	0.03	0.41	0.56	0.00	1.00	1.00
9	*Cyperus conglomeratus*	2.1	22	10	1.103	1.82	4.14	3.54	0.66	15.10	9.50
10	*Dipterigyum glaucum*	0.29	14.3	2	0.030	0.25	2.69	0.74	0.02	4.67	3.68
11	*Zygophyllum indicum*	41.4	89	47	145.361	35.91	16.77	17.25	87.23	190.15	69.92
12	*Farsetia linearis*	1.67	24.2	7	0.050	1.45	4.55	2.56	0.03	8.87	8.56
13	*Haloxylon salicornicum*	0.46	17.6	3	1.498	0.40	3.31	0.97	0.90	36.11	4.69
14	*Heliotropium digynum*	0.01	1.1	1	0.000	0.01	0.21	0.37	0.00	0.59	0.59
15	*Heliotropium kotschyi*	5.54	46.2	12	10.548	4.80	8.70	4.45	6.33	42.18	17.94
16	*Launaea capitata*	0.01	1.1	1	0.000	0.01	0.21	0.37	0.00	0.59	0.59
17	*Leptadenia pyrotechnica*	0.02	2.2	1	0.003	0.02	0.41	0.37	0.00	2.19	0.80
18	*Lycium shawii*	0.01	1.1	1	0.000	0.01	0.21	0.37	0.00	0.59	0.59
19	*Moltkiopsis ciliata*	1.65	14.3	12	0.013	1.43	2.69	4.28	0.01	8.48	8.40
20	*Monsonia nivea*	1.82	34.1	5	0.012	1.58	6.42	1.98	0.01	10.05	9.98
21	*Panicum turgidum*	0.01	1.1	1	0.000	0.01	0.21	0.37	0.00	0.61	0.59
22	*Plantago sp.*	0.05	1.1	5	0.000	0.05	0.21	1.85	0.00	2.11	2.11
23	*Plantago ciliata*	0.67	4.4	15	0.000	0.58	0.83	5.65	0.00	7.06	7.06
24	*Polycarpaea repens*	0.78	29.7	3	0.003	0.68	5.59	0.97	0.00	7.28	7.24
25	*Polygala erioptera*	0.73	17.6	4	0.001	0.63	3.31	1.53	0.00	5.48	5.47
26	*Polygala irregularis*	0.45	7.69	6	0.000	0.39	1.45	2.17	0.00	4.02	4.01
27	*Prosopis cineraria*	0.03	2.2	2	0.012	0.03	0.41	0.56	0.01	4.56	1.00
28	*Stipagrostis plumosa*	25.7	69.2	37	5.764	22.28	13.04	13.76	3.46	54.65	49.08
29	*Tragus racemosus*	0.82	4.4	19	0.000	0.71	0.83	6.95	0.00	8.49	8.49
30	*Vachellia farnesiana*	0.01	1.1	1	0.001	0.01	0.21	0.37	0.00	1.47	0.59
31	*Vachellia flava*	0.01	1.1	1	0.001	0.01	0.21	0.37	0.00	1.40	0.59
32	*Ziziphus spina-christi*	0.01	1.1	1	0.002	0.01	0.21	0.37	0.00	2.34	0.59

Vegetation parameters recorded in Sand Dunes

	Species	D	F	A	C	RD	RF	RA	RC	SIVI	IVI
1	*Aristida adscensionis*	0.22	1.064	21	0.000	0.38	0.26	10.61	0.00	11.26	11.33
2	*Arnebia hispidissima*	7.91	29.26	27	1.066	13.77	7.25	14.00	1.60	36.80	37.93
3	*Bassia muricata*	0.04	1.064	4	0.000	0.07	0.26	2.07	0.00	2.41	2.66
4	*Calligonum comosum*	0.06	2.66	2	0.007	0.11	0.66	1.24	0.01	2.19	7.94
5	*Cenchrus divisus*	0.15	5.319	3	0.025	0.27	1.32	1.50	0.04	3.35	6.75
6	*Centaurea pseudosinaica*	0.01	0.532	2	0.000	0.02	0.13	1.04	0.00	1.19	1.21
7	*Centropodia forsskaolii*	4.64	33.51	14	0.355	8.08	8.30	7.17	0.53	24.19	26.20
8	*Convolvulus cephalopodus*	0.02	2.128	1	0.000	0.04	0.53	0.52	0.00	1.08	1.08
9	*Crotalaria aegyptiaca*	0.06	4.787	1	0.001	0.11	1.19	0.69	0.00	2.00	2.57
10	*Cyperus conglomeratus*	22.8	96.28	24	2.751	39.74	23.85	12.28	4.13	80.17	78.31
11	*Dipterygium glaucum*	1	32.45	3	44.875	1.74	8.04	1.60	67.37	141.02	55.95
12	*Zygophyllum indicum*	1.84	13.3	14	10.110	3.20	3.29	7.16	15.18	36.46	29.25
13	*Farsetia linearis*	0.01	0.532	1	0.001	0.01	0.13	0.52	0.00	0.85	3.08
14	*Haloxylon salicornicum*	0.14	8.511	2	0.000	0.25	2.11	0.87	0.00	3.23	3.28
15	*Heliotropium digynum*	0.12	7.979	2	0.893	0.21	1.98	0.79	1.34	14.45	18.11
16	*Heliotropium kotschyi*	1.46	13.83	11	0.152	2.54	3.43	5.46	0.23	11.79	13.59
17	*Indigofera colutea*	2.73	22.34	12	3.775	4.76	5.53	6.34	5.67	24.21	23.54
18	*Indigofera intricata*	0.01	0.532	1	0.004	0.01	0.13	0.52	0.01	1.67	5.77
19	*Leptadenia pyrotechnica*	0.1	8.511	1	0.000	0.17	2.11	0.58	0.00	2.86	2.99
20	*Limeum arabicum*	0.7	29.79	2	2.450	1.21	7.38	1.21	3.68	18.36	23.81
21	*Lycium shawii*	0.01	0.532	1	0.033	0.01	0.13	0.52	0.05	9.30	13.85
22	*Moltkiopsis ciliata*	9.49	39.36	24	0.003	16.52	9.75	12.49	0.00	38.77	38.92
23	*Panicum turgidum*	0.1	4.255	2	0.101	0.18	1.05	1.23	0.15	3.99	9.43
24	*Polycarpaea repens*	0.01	0.532	1	0.001	0.01	0.13	0.52	0.00	0.83	3.30
25	*Polygala irregularis*	0.01	0.532	1	0.000	0.01	0.13	0.52	0.00	0.66	0.68
26	*Prosopis cinerarea*	0.01	0.532	2	0.000	0.02	0.13	1.04	0.00	1.19	1.20
27	*Rhanterium epapposum*	0.03	1.596	2	0.000	0.06	0.40	1.04	0.00	1.49	1.56
28	*Rhynchosia minima*	0.01	1.064	1	0.000	0.02	0.26	0.52	0.00	0.83	1.60
29	*Stipagrostis plumosa*	3.71	38.83	10	0.000	6.45	9.62	4.94	0.00	21.01	21.07
30	*Tribulus pentandrus*	0.02	1.596	1	0.009	0.03	0.40	0.52	0.01	1.75	7.12
31	*Tribulus sp.*	0.01	0.532	1	0.000	0.01	0.13	0.52	0.00	0.66	0.75

Species presence across habitats for 2004, 2009 and 2025

	2004		2009		2025	
Species	**Gravel Plain**	**Sand Dune**	**Gravel Plain**	**Sand Dune**	**Gravel Plain**	**Sand Dune**
Aerva javanica						
Aristida adscensionis						
Arnebia hispidissima						
Atractylis carduus						
Bassia muricata						
Calligonum comosum						
Calotropis procera						
Cenchrus divisus						
Centaurea pseudosinaica						
Centropodia forsskaolii						
Chrozophora oblongifolia						
Cistanche tabulosa						
Citrillus colocynthis						
Convolvulus cephalopodus						
Crotalaria aegyptiaca						
Cyperus conglomeratus						
Dipterigyum glaucum						
Eremobium aegyptiacum						
Erucaria hispanica						
Zygophyllum indicum						
Farsetia linearis						
Haloxylon salicornicum						
Heliotropium digynum						
Heliotropium kotschyi						
Indigofera colutea						
Indigofera intricata						
Launaea capitata						
Leptadenia pyrotechnica						
Limeum arabicum						
Lycium shawii						
Moltkiopsis ciliata						
Monsonia nivea						
Neurada procumbens						
Ogastemma pusillum						
Panicum turgidum						
Plantago boissieri						
Plantago ciliata						
Polycarpaea repens						
Polygala erioptera						
Polygala irregularis						
Prosopis cinerarea						
Rhanterium epapposum						
Rhynchosia minima						
Salvadora persica						
Silene villosa						
Sisymbrium erysimoides						
Stipagrostis plumosa						
Tamarix aphylla						
Tragus racemosus						
Tribulus macropterus						
Tribulus omanense						
Tribulus pentandrus						
Vachellia farnesiana						
Vachellia flava						
Vachellia tortillis						
Ziziphus spina-christi						

Annex III – Diversity Indices

Shannon's Index: Where p_i is the proportion of individuals in species (i) and (S) the total number of species in the sample.

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Brillouin Index: Where n_i is the number of individuals in species (i), N is the total number of individuals in the sample and (S) the total number of species.

$$HB = \frac{\ln N! - \sum_{i=1}^{S} \ln n_i!}{N}$$

Simpson's Index = 1 – λ: Where n_i is the number of individuals in species (i), N is the total number of individuals in the sample.

$$\lambda = \sum_{iI=1}^{S} \frac{n_i(n_i - 1)}{N(N-1)}$$

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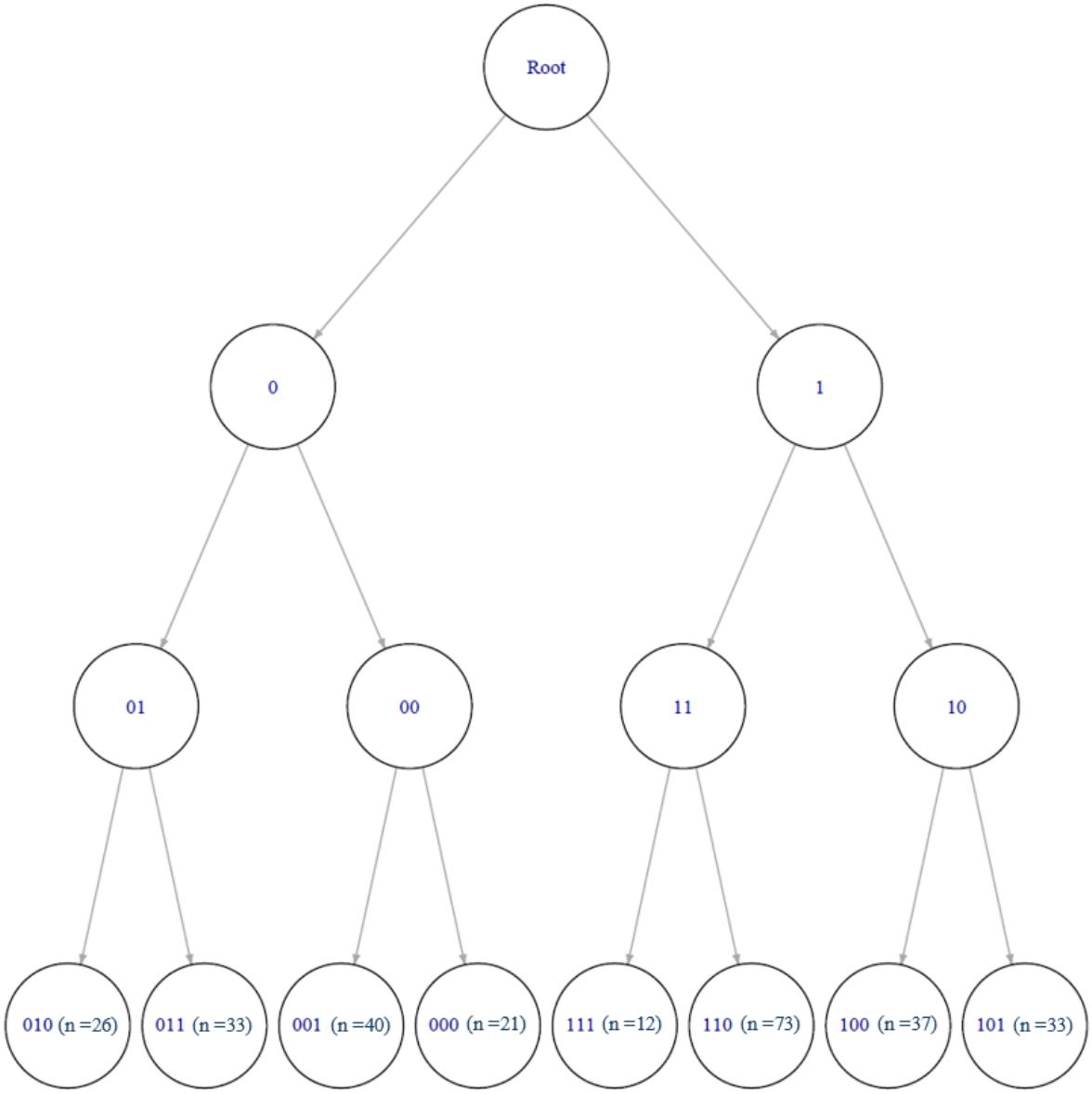
Annex IV – TWINSPAN Dendrogram



Annex V – Sampling points for the 2025 vegetation survey