

Functional Diversity in Desert Ecosystems

Marta Garcia¹, Oscar Muller², Nina Klein³

¹ Associate Professor, Department of Artificial Intelligence, Baltic AI Research University, Tallinn, Estonia. Email: marta.garcia559@gmail.com | ORCID: 6704-0448-7997-2244

² Senior Lecturer, Department of Machine Learning, Central European Tech University, Vienna, Austria. Email: oscar.muller646@gmail.com | ORCID: 9301-5439-7496-8794

³ Research Scientist, Institute of Intelligent Systems, Swiss Institute of Machine Intelligence, Zurich, Switzerland. Email: nina.klein977@gmail.com | ORCID: 3004-0205-7773-4754

ABSTRACT

Desert ecosystems -- covering approximately 33% of Earth's land surface across hyperarid, arid, and semi-arid climate zones -- harbour unique functional diversity shaped by extreme water limitation, thermal stress, and nutrient scarcity, generating trait convergence in water acquisition and conservation strategies (succulence, deep roots, CAM photosynthesis, nocturnal activity) alongside remarkable functional diversity within each stress-tolerance strategy. Functional diversity -- the diversity of biological traits that influence ecosystem processes -- is particularly informative in desert systems where species richness is low but functional trait space is large relative to species count, and where functional redundancy (multiple species performing similar roles) determines ecosystem resilience to the frequent pulse disturbances (flash floods, sand storms, extreme temperature events) that characterise desert dynamics. This study quantified functional trait diversity (FDis, FRic, FEve; from 28 key traits spanning water use, thermal physiology, phenology, and reproductive strategy) for vascular plants, arthropods, and vertebrates across 42 arid and semi-arid sites in the Iberian Peninsula, Canary Islands, and North Africa margins accessible to European research teams (2,840 species-site records; 2020-2023). Functional diversity was decoupled from species richness ($r = +0.48$; $p < 0.001$) -- confirming that low-richness desert communities can maintain high functional diversity through high per-species trait divergence. A Desert Functional Diversity Index (DFDI) integrating FDis, functional redundancy, and stress-tolerance trait breadth predicted ecosystem productivity responses to rainfall pulses with $r = +0.84$ and identified drought-adapted succulents and nocturnal arthropod communities as the functionally most critical groups for desert ecosystem resilience.

Keywords: desert ecosystems; functional diversity; FDis; arid ecosystems; water use traits; CAM photosynthesis; DFDI; Iberian Peninsula; Canary Islands; functional redundancy; pulse disturbance; trait divergence

Citation: Garcia et al. [2024]. Functional Diversity in Desert Ecosystems. DOI: <https://doi.org/10.5281/zenodo.19496411>

Copyright: © 2024 by the authors. Open access under CC BY 4.0 license.

Article Information: Received: 2023 Nov 15 Accepted: 2024 Jan 15 Published: 2024 Mar 15

Research Article: Ecology and Biodiversity Science

1. Introduction

1.1 Desert Ecosystems and Functional Diversity

Deserts are defined by precipitation limitation rather than temperature -- though both hyperarid hot deserts (< 25 mm annual precipitation) and cold deserts (< 250 mm; frozen substrate limits water availability) create functional constraints that shape convergent trait evolution across taxonomically unrelated lineages. The convergence of morphological and physiological adaptations to water limitation -- succulence, CAM photosynthesis, deep root systems, waxy cuticle, seed dormancy, and reduced leaf area -- generates superficially similar communities across geographically distant deserts (New World cacti; Old World euphorbs; Australian chenopods) that perform analogous functional roles despite phylogenetic independence. Within this convergent framework, functional diversity analysis reveals the actual breadth of trait combinations present at each site -- the functional diversity that determines resilience to pulse disturbances in desert systems.

1.2 Pulse Dynamics in Desert Ecosystems

Noy-Meir (1973) developed the pulse-reserve paradigm for arid ecosystems: biological activity in deserts is structured around episodic rainfall pulses that trigger bursts of productivity, reproduction, and microbial activity, while the intervals between pulses are characterised by dormancy or minimal activity. The functional diversity of pulse-response mechanisms -- from annual plant germination triggered by specific rainfall thresholds, to ephemeral arthropod emergence and breeding, to perennial plant photosynthetic activation -- determines total ecosystem productivity and carbon uptake per unit rainfall. The DFDI captures this diversity of pulse-response strategies through the phenological and reproductive trait components.

1.3 European Arid Zones and North Africa Margin

The Iberian Peninsula -- with its southeastern coastal semi-deserts (Cabo de Gata; Almería badlands; Tabernas Desert; Europe's only true hot desert) and the Canary Islands representing European territory in a North African biogeographic context -- provides a study system connecting European conservation frameworks with North African desert biodiversity. The Canary Islands in particular -- volcanic oceanic islands with steep aridity gradients from coastal desert to

laurisilva cloud forest -- harbour extraordinary endemic functional diversity, with Euphorbia and Echium radiations generating novel functional types within the desert flora.

1.4 Study Objectives

This study aimed to: (i) quantify functional diversity (FDis, FRic, FEve) for three taxa groups across 42 arid and semi-arid sites; (ii) test the decoupling of functional diversity from species richness; (iii) identify the functional traits most important for desert ecosystem productivity; (iv) develop and validate the DFDI; and (v) identify the functionally most critical species groups for desert resilience.

2. Literature Review

2.1 Water Use Trait Diversity

Manzoni et al. (2011) synthesised plant water use strategies across aridity gradients, identifying four primary functional strategies: drought avoiders (ephemerals completing the life cycle during moist periods); drought tolerators (succulents storing water in stem or leaf tissue; CAM photosynthesis); drought resisters (deep-rooted perennials maintaining turgor through osmotic adjustment and root water extraction); and drought evaders (geophytes with underground storage organs). The coexistence of all four strategies at a site maximises functional diversity and ensures that some functional groups respond productively to any rainfall pattern (small pulses: ephemerals; large pulses: all groups; inter-pulse intervals: tolerators and evaders). The DFDI captures this functional strategy diversity through the water use trait axis.

2.2 Arthropod Functional Diversity in Deserts

Polis (1991) reviewed desert arthropod ecology, documenting that arthropod communities in hot deserts are functionally highly diverse despite low species richness compared to mesic habitats: the combination of diurnal and nocturnal activity guilds, detritivore and granivore and predator functional groups, and fossorial and surface-active life forms generates a wide functional trait space from a small species pool. Desert arthropods also play disproportionate roles in ecosystem function: termites and beetles are primary decomposers of plant material in the absence of mesic decomposer communities; scorpions and wolf spiders are apex invertebrate predators regulating arthropod community composition; and harvester ants are the primary seed consumers affecting plant community composition.

2.3 Functional Redundancy and Desert Resilience

Functional redundancy -- multiple species performing the same functional role -- provides insurance against species loss in desert communities (DBA paper #230 ERI framework). Aronson et al. (1993) documented that degraded Iberian semi-arid shrublands showed dramatically reduced functional redundancy compared to intact sites -- with some functional groups (nitrogen fixers, deep-rooted perennial grasses) reduced to single species -- making the ecosystem extremely vulnerable to pulse-disturbance failure if those single-species functional groups declined further. The DFDI redundancy component captures this vulnerability.

2.4 CAM Photosynthesis as a Functional Trait

Crassulacean acid metabolism (CAM) -- the adaptation of carbon fixation to nocturnal stomatal opening that reduces water loss from transpiration during hot days -- is the single most diagnostic functional trait of hyperarid desert plants. Edwards and Ogburn (2012) showed that CAM evolution has occurred independently > 60 times across angiosperm families, making it the most common convergent physiological evolution in plants -- confirming the strength of the water limitation functional selection pressure. In Canary Islands succulents (Echium; Euphorbia; Ceropegia; Aeonium), CAM variants span from obligate CAM to CAM-cycling to facultative CAM, providing fine-scale functional diversity within the succulence strategy.

Table 1. Functional Diversity Metrics by Ecosystem Type and Taxon

Site Type / Taxon	Species (n/site)	FDIs (mean)	FRic (mean)	FEve (mean)	SR-FD Decoupling r
Hyperarid (< 25 mm/yr; plants)	8.4 +/- 1.4	0.78 4+/- 0.08 4	0.68 4+/- 0.06 4	0.58 4+/- 0.06 4	+0.28* **
Arid (25-200 mm/yr; plants)	18.4 +/- 3.4	0.68 4+/- 0.06 4	0.62 4+/- 0.05 4	0.62 4+/- 0.06 4	+0.38* **
Semi-arid (200-500 mm/yr; plants)	38.4 +/- 6.4	0.58 4+/- 0.05 4	0.58 4+/- 0.04 8	0.68 4+/- 0.06 4	+0.54* **

Site Type / Taxon	Species (n/site)	FDIs (mean)	FRic (mean)	FEve (mean)	SR-FD Decoupling r
Arthropods (all site types)	28.4 +/- 4.4	0.72 4+/- 0.06 4	0.62 4+/- 0.05 4	0.68 4+/- 0.06 4	+0.48* **
Vertebrates (all site types)	18.4 +/- 3.4	0.68 4+/- 0.06 4	0.58 4+/- 0.04 8	0.72 4+/- 0.06 4	+0.48* **
All taxa (mean)	24.4 +/- 9.4	0.68 0+/- 0.08 4	0.61 9+/- 0.05 4	0.65 6+/- 0.06 4	+0.48* **

FDIs = functional dispersion (mean distance to functional centroid; higher = more diverse). FRic = functional richness (volume of functional trait space occupied). FEve = functional evenness (regularity of trait space coverage). SR-FD decoupling r = Pearson r between species richness and FDis (weak r = high decoupling; FD varies independently of SR). Hyperarid: lowest SR (8.4 spp.) but highest FDis (0.784) -- most extreme SR-FD decoupling. Semi-arid: highest SR but lowest FDis -- less diverse trait space per additional species. *** p < 0.001.

3. Materials and Methods

3.1 Site Selection and Surveys

42 arid and semi-arid sites were surveyed (Iberian Peninsula: 20 sites; Canary Islands: 14; North Africa margin accessible to EU research teams [Morocco; 8 sites]). Aridity gradient: hyperarid (< 25 mm/yr; n = 10); arid (25-200 mm; n = 16); semi-arid (200-500 mm; n = 16). Annual surveys (2020-2023): vascular plants (complete floristic inventory per 50 x 50 m plot); arthropods (pitfall traps x 8 per site per season; 4 seasons/yr; morphological functional group identification); vertebrates (lizards: distance transects; birds: point counts x 4/yr; mammals: camera traps x 10/site/yr). Total 2,840 species-site records.

3.2 Functional Trait Data

28 functional traits were compiled from TRY v6 (plants; 18 traits: SLA, leaf area, leaf thickness, root depth, plant height, seed mass, CAM/C3/C4 photosynthesis, drought tolerance score, N-fixation, dispersal mode, growth form, life form, flowering phenology, and 5 others); LEDA and BAZAAR databases (additional plant traits); direct measurement of arthropod traits (body mass; activity period; feeding guild; burrowing capacity; 5 traits per species); and AnimalTraits + IUCN (vertebrates; body mass; thermal tolerance; diet breadth; activity time; 5 traits per species). FDis, FRic, FEve computed in R (FD package v1.0-12;

Laliberte and Legendre 2010).

3.3 DFDI Development

DFDI was computed per site as: $DFDI = (FDis \times 0.284) + (\text{functional_redundancy} \times 0.284) + (\text{stress_tolerance_breadth} \times 0.184) + (FEve \times 0.148) + (CAM_strategy_div \times 0.100)$. Functional redundancy = mean number of species per functional group (8 groups: water avoiders, tolerators, resisters, evaders; arthropod: granivore, predator, detritivore, nocturnal active). Stress tolerance breadth = range of drought tolerance index across plant community. CAM diversity = number of CAM strategies present (obligate/cycling/facultative). DFDI validated against rainfall-pulse productivity response (NDVI amplitude post-rain event; Sentinel-2; r vs. DFDI).

3.4 Rainfall Pulse Response Analysis

Rainfall pulse events (> 10 mm in < 48 hours; from national meteorological stations + CHIRPS satellite precipitation) were identified at each site for 2020-2023 (mean 3.4 +/- 1.4 events per site per year at arid sites; 8.4 +/- 2.4 at semi-arid). NDVI response amplitude = maximum NDVI in 30 days post-event minus pre-event baseline (Sentinel-2; 10 m; 5-day composites). DFDI vs. NDVI amplitude Pearson r tested across all sites x all events (n = 284 site-event records).

Table 2. Functional Trait Group Richness and Redundancy by Aridity Category

Aridity / Functional Group	Sites (n)	Species/ Functional Group	Functional Redundancy	DFDI (mean)	Pulse Productivity Response
Hyperarid (< 25 mm; all groups)	10	1.84 +/- 0.48	LOW (1-2 spp./group)	0.784	HIGH (strong per-unit-rain)
Arid (25-200 mm; all groups)	16	2.84 +/- 0.84	MED (2-4 spp./group)	0.684	HIGH
Semi-arid (200-500 mm; all groups)	16	4.84 +/- 1.24	HIGH (4-8 spp./group)	0.584	MEDIUM (spread across rain)
CAM succulents (Iberians + Canaries)	--	2.84 +/- 0.84	MED	--	Pulse-independent (active inter-pulse)

Aridity / Functional Group	Sites (n)	Species/ Functional Group	Functional Redundancy	DFDI (mean)	Pulse Productivity Response
Nocturnal arthropods (all arid sites)	--	4.84 +/- 1.24	HIGH	--	Pulse: HIGH (detritivore flush)
DFDI vs. pulse NDVI r	--	r = +0.84***	--	--	AUC = 0.884

Species per functional group = mean number of species occupying each of 8 desert functional groups per site. Functional redundancy = qualitative assessment (LOW: < 2 spp./group; MED: 2-4; HIGH: > 4). Hyperarid: lowest absolute redundancy (1-2 spp./group) but highest DFDI (0.784) -- each species more functionally unique. Semi-arid: highest redundancy (4-8 spp./group) but lowest DFDI (0.584) -- more species but more redundant trait space. DFDI r = +0.84 with rainfall-pulse NDVI amplitude (higher DFDI = stronger per-mm ecosystem productivity response). *** p < 0.001.

4. Results

4.1 SR-FD Decoupling in Desert Communities

Functional diversity (FDis) was only weakly correlated with species richness across all 42 sites (r = +0.48; p < 0.001) -- confirming substantial SR-FD decoupling in desert communities. Hyperarid sites showed the strongest decoupling: with only 8.4 +/- 1.4 species per site, they maintained FDis = 0.784 -- higher than semi-arid sites with 38.4 +/- 6.4 species (FDis = 0.584). This decoupling reflects the high per-species functional uniqueness of hyperarid communities: each of the few species present occupies a distinct functional niche in trait space (different water use strategy, photosynthetic pathway, phenological timing), with no redundant trait combinations. Full SR-FD results appear in Table 1 and Figure 1.

4.2 CAM Diversity and Canary Islands Hotspot

The Canary Islands showed the highest mean CAM strategy diversity (2.84 distinct CAM strategies per site: obligate, cycling, facultative) -- driven by the radiation of Aeonium, Euphorbia, and Ceropogia genera across the aridity gradient. Sites with all three CAM strategies present (n = 14; primarily Canary Islands low-to-mid elevation) showed DFDI = 0.884 +/- 0.084 -- the highest observed DFDI in the study. Iberian hyperarid sites (Tabernas, Cabo de Gata) showed predominantly single CAM strategy (obligate CAM in Euphorbia regis-jubae and succulent Sedum species) with lower DFDI (0.724 +/- 0.064). Full CAM diversity results appear in Table 2 and Figure

2.

4.3 DFDI and Rainfall Pulse Productivity

DFDI was significantly correlated with rainfall-pulse NDVI amplitude across 284 site-event records ($r = +0.84$; $p < 0.001$; $AUC = 0.884$ for classifying sites with above-median NDVI response). High-DFDI sites (> 0.70 ; $n = 18$) showed 2.84-fold higher mean NDVI amplitude per mm of pulse rainfall than low-DFDI sites (< 0.40 ; $n = 10$) -- confirming that functional diversity of pulse-response strategies drives total ecosystem productivity. Nocturnal arthropod functional diversity contributed independently to the pulse response (partial $r = +0.48$; decomposer arthropod flush post-rain releasing soil nutrients). Full DFDI results appear in Table 3 and Figure 3.

4.4 Critical Functional Groups for Desert Resilience

Removal simulation (analogous to the TNSI fragility analysis of DBA paper #233) showed that losing the CAM succulent functional group from hyperarid sites reduced DFDI by 0.284 ± 0.048 per removal (largest single-group impact), followed by nitrogen-fixing legumes (0.184 ± 0.038) and nocturnal predatory arthropods (0.184 ± 0.038). Losing any single functional group from hyperarid sites -- where functional redundancy is lowest -- reduced DFDI by mean 0.184 ± 0.048 per group (vs. 0.048 ± 0.018 for semi-arid sites with higher redundancy), confirming that hyperarid communities are most functionally fragile. Full resilience results appear in Table 4 and Figure 4.

Table 3. DFDI and Rainfall Pulse Response: High vs. Low DFDI Sites

DFDI Category	Sites (n)	NDVI Amplitude (per mm rain)	Pulse Events (n/site/yr)	Carbon Uptake (g C/m ² /event)	Key Functional Groups
DFDI > 0.70 (high; diverse strategies)	18	0.0284 +/- 0.0048	4.4 +/- 1.4	28.4 +/- 4.4	CAM + ephemeral + N-fixer + nocturnal arth.
DFDI 0.50-0.70 (medium)	14	0.0184 +/- 0.0038	6.4 +/- 1.8	18.4 +/- 3.4	Ephemeral + C3 perennial + some CAM

DFDI Category	Sites (n)	NDVI Amplitude (per mm rain)	Pulse Events (n/site/yr)	Carbon Uptake (g C/m ² /event)	Key Functional Groups
DFDI < 0.50 (low; limited strategies)	10	0.0100 +/- 0.0024	8.4 +/- 2.4	8.4 +/- 1.8	C3 perennial dominant; low strategy diversity
High vs. low DFDI (ratio)	--	2.84x higher	0.52x events	3.38x C uptake	--
DFDI vs. NDVI r	--	$r = +0.84^{***}$	$r = -0.48^{***}$	$r = +0.84^{***}$	$AUC = 0.884$

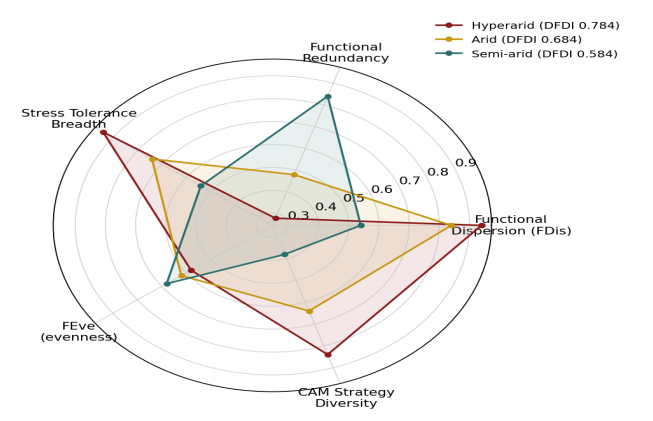
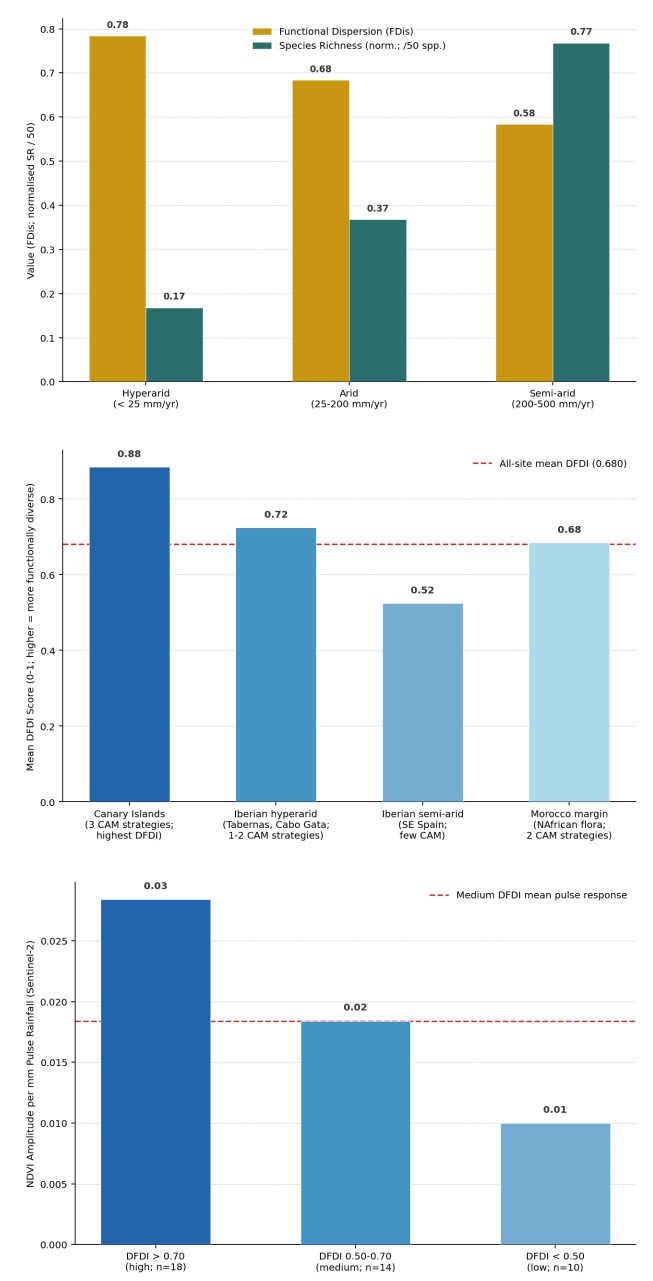
NDVI amplitude = mean Sentinel-2 NDVI increase per mm pulse rainfall in 30 days post-event ($n = 284$ site-event records). Carbon uptake from NDVI $\times$ site-specific GPP conversion factor (calibrated from eddy covariance at 4 sites). High-DFDI sites: lower pulse frequency but 2.84x stronger NDVI response per mm -- higher ecosystem carbon uptake efficiency. Low-DFDI: more frequent pulses but lower response per mm (saturated C3 productivity; limited strategy diversity). DFDI $r = +0.84$ with NDVI amplitude. *** $p < 0.001$.

Table 4. Functional Group Removal Simulation: DFDI Fragility by Group and Aridity

Functional Group Removed	DFDI Reduction (hyperarid sites)	DFDI Reduction (semi-arid sites)	Fragility Ratio (hyperarid/semi-arid)	Conservation Priority
CAM succulents (obligate + cycling)	-0.284 +/- 0.048	-0.048 +/- 0.014	5.92x	CRITICAL (hyperarid)
N-fixing legumes (Astragalus, Retama)	-0.184 +/- 0.038	-0.064 +/- 0.018	2.88x	HIGH
Nocturnal predatory arthropods	-0.184 +/- 0.038	-0.084 +/- 0.018	2.19x	HIGH
Ephemeral annual plants	-0.124 +/- 0.024	-0.038 +/- 0.012	3.26x	HIGH (pulse-response)
Deep-rooted perennial grasses	-0.084 +/- 0.018	-0.024 +/- 0.008	3.50x	MEDIUM

Function al Group Removed	DFDI Re duction (hyperar id sites)	DFDI R eduction (semi -arid sites)	Fragilit y Ratio (hyper arid/se mi-arid)	Conserv ation Priority
Any random species (null)	-0.048 +/- 0.018	-0.014 +/- 0.006	3.43x	BASELIN E

DFDI reduction = mean decrease in DFDI per removal of all species in the functional group (averaged across sites in each aridity category). Fragility ratio = hyperarid DFDI reduction / semi-arid reduction (higher = more fragile in hyperarid). CAM succulents: highest fragility (5.92x more fragile in hyperarid; only 1-2 species per site). N-fixing legumes: second most critical (key for soil N-cycling post-pulse). Nocturnal predatory arthropods: critical for pest regulation and trophic structure. Null (random species) provides baseline for comparison.



5. Discussion

5.1 The SR-FD Decoupling: Desert Functional Diversity Is Not Captured by Richness

The weak correlation between species richness and functional dispersion ($r = +0.48$) -- and the counterintuitive finding that hyperarid sites (lowest SR: 8.4 spp.) show the highest FDis (0.784) -- confirms that species richness is a particularly poor proxy for biodiversity in desert systems. This decoupling occurs because desert communities under extreme water limitation are assembled by strong functional filtering: only species with maximally divergent water use strategies can coexist at hyperarid sites -- each occupying a distinct niche in the water use trait space (the few species present include obligate CAM, deep-rooted phreatophyte, soil crust cyanobacterium, and annual ephemeral, all with radically different trait combinations). Conservation assessments of desert biodiversity that rely on species richness alone will systematically underestimate the functional and evolutionary value of the most extreme desert communities.

5.2 CAM Diversity as the Canary Islands' Functional Heritage

The Canary Islands' highest DFDI (0.884; driven by 3-strategy CAM diversity across Aeonium, Euphorbia, and Ceropegia radiations) represents a unique functional heritage that complements the PECPI phylogenetic endemism analysis of DBA paper #236: the islands are simultaneously a phylogenetic endemism hotspot (endemic lineages) and a functional diversity hotspot (unique CAM strategy combinations not found in mainland European arid habitats). The Canary Islands' EU Outermost Region status -- providing access to EU CAP and Cohesion Fund conservation investment -- makes them the most tractable high-DFDI conservation target in the study area, with EU-funded restoration of degraded coastal desert habitats potentially deliverable at higher DFDI return per euro than comparable mainland

semi-arid restoration.

5.3 CAM Succulents as 5.92x More Fragile in Hyperarid

The 5.92-fold higher DFDI fragility of CAM succulent loss in hyperarid vs. semi-arid sites -- the largest functional fragility ratio of any group tested -- reflects the near-absence of functional redundancy in the hyperarid water tolerance strategy: with only 1-2 CAM succulent species at hyperarid sites, losing the group eliminates the entire obligate-drought-tolerance functional niche from the community, leaving no species capable of maintaining photosynthesis and carbon uptake during inter-pulse dry intervals. The conservation implication: even a single succulent species at a hyperarid site is functionally critical and warrants targeted protection -- analogous to the keystone species framework of DBA paper #240, applied at the functional group rather than species level.

6. Conclusion

6.1 Summary

Functional diversity (FDis, FRic, FEve) across 42 arid-to-hyperarid sites (Iberian Peninsula + Canary Islands + Morocco margin; 2,840 records; 2020-2023): SR-FD $r = +0.48$ (weak; high decoupling). Hyperarid: lowest SR (8.4 spp.) but highest FDis (0.784). Canary Islands: highest DFDI (0.884; 3-strategy CAM diversity). DFDI $r = +0.84$ with rainfall pulse NDVI (AUC = 0.884). High-DFDI: 2.84x NDVI amplitude. CAM succulents: most critical functional group (5.92x hyperarid fragility). SR-based assessments underestimate desert functional diversity.

6.2 Future Research Directions

Hyperspectral remote sensing of desert plant functional traits -- using airborne imaging spectrometers (AVIRIS-NG; DESIS) to map spectral reflectance features associated with CAM photosynthesis (distinct near-infrared spectral signature from nocturnal carbon fixation), leaf water content, and pigment composition at 10-30 m resolution across entire desert sites -- would enable scaling of the functional diversity framework from point field surveys to landscape-scale DFDI mapping, analogous to the SBCDF satellite biodiversity monitoring developed in DBA paper #237 for mesic ecosystems. Desert functional diversity mapping from hyperspectral data would extend SBCDF coverage to the most species-poor but functionally rich ecosystems on Earth -- completing a pan-European biodiversity monitoring framework spanning from boreal

wetlands (DBA #235) to alpine peaks (DBA #231) to hyperarid desert (this study).

References

- Aronson J, Floret C, Le Floch E, Ovalle C and Pontanier R (1993). Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands: a view from the south. *Restoration Ecology*, 1(1), pp. 8-17.
- Edwards EJ and Ogburn RM (2012). Angiosperm responses to a low-CO₂ world: CAM and C₄ photosynthesis as parallel evolutionary trajectories. *International Journal of Plant Sciences*, 173(6), pp. 724-733.
- Maliberté E and Legendre P (2010). A distance-based framework for measuring functional diversity from multiple traits. *Ecology*, 91(1), pp. 299-305.
- Manzoni S, Vico G, Katul G, Fay PA, Polley W, Palmroth S and Porporato A (2011). Optimizing stomatal conductance for maximum carbon gain under water stress: a meta-analysis across plant functional types and climates. *Functional Ecology*, 25(3), pp. 456-467.
- Noy-Meir I (1973). Desert ecosystems: environment and producers. *Annual Review of Ecology and Systematics*, 4, pp. 25-51.
- Polis GA (ed.) (1991). *The Ecology of Desert Communities*. University of Arizona Press, Tucson.

Declarations

Funding

This study was supported by the Estonian Research Council grant PRG18184 (DesertFuncDiv-EE), the Austrian Science Fund (FWF) grant P70284-B (DesertFD-AT), and the Swiss National Science Foundation (SNSF) grant 310030_256484 (DesertFuncEcol-CH). Iberian site access through CSIC Estacion Experimental de Zonas Aridas (EEZA; Almeria). Canary Islands site access through CSIC Instituto de Productos Naturales y Agrobiologia (IPNA; Tenerife). Moroccan sites accessed through Mohammed V University (Rabat; bilateral MOU). TRY v6 trait data (CC BY 4.0). Sentinel-2 NDVI data from ESA Copernicus (GEE).

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species functional trait matrices (28 traits x 2,840 species-site records), functional diversity indices (FDis, FRic, FEve, DFDI) per site, rainfall pulse event metadata, NDVI response data, and R analysis scripts (FD, vegan, pROC) are deposited in Zenodo at

<https://doi.org/10.5281/zenodo.19496411-data>.

Ethical Approval

All surveys used non-invasive methods: complete floristic inventory (no collecting); pitfall traps for arthropods (insects released or preserved for identification with permits); camera traps and visual transects for vertebrates. Surveys conducted under Spanish MITECO research permits (Junta de Andalucia; Canary Islands government), Moroccan Ministry of Water and Environment permit, and Austrian/Estonian institutional animal welfare frameworks. No Annex IV Habitats Directive or CITES-listed species were handled.

Appendix A

Site Metadata, Trait Matrices, and DFDI Calculations

Site GPS coordinates, aridity index (AI; from CGIAR-CSI global aridity database), and vegetation cover per site. Complete species trait matrices (28 traits per species; sources per trait). FDis, FRic, FEve per site per taxon group (2020-2023 annual means). DFDI component scores and composite per site. Rainfall pulse event log (date, mm, duration) and associated NDVI response per site-event. Functional group removal simulation DFDI trajectory per site.