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Vegetation dynamics under long-term protection in arid and semiarid ecosystems— A case study of the Karkheh River Watershed (SW Iran)

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ABSTRACT

Vegetation restoration in arid and semiarid ecosystems is crucial for mitigating ecological degradation and contributing to global climate change mitigation and ecosystem recovery. These regions present exceedingly challenging conditions for plant growth and development. Only a relatively limited number of plant species are capable of surviving in such environments. Therefore, identifying these flora is highly important. The current research aims to analyze changes in the vegetation cover of a semiarid ecosystem during a 20-year enclosure period. In this study, the plant species were identified via a field survey in the fenced and protected areas. Also, long-term changes in soil moisture and vegetation cover were investigated via Landsat satellite images. We found that in this region in 2005, a total of 23 plant species, 11 families, and one plant community type were reported, while in 2025, this number increased to 70 species, 29 families, and six distinct vegetation types, indicating a significant increase in floristic richness. The findings reveal a complex interaction between vegetation recovery and the persistence of water stress in protected rangelands. This study highlights the importance of developing targeted conservation strategies to promote sustainable management, mitigate land degradation, and enhance the resilience of fragile arid and semiarid ecosystems.

Keywords: Remote sensing, Floristic richness, Ecological restoration, Fragile ecosystems, Ecological trajectories, Microclimate regulation

Introduction

Arid and semiarid regions are highly sensitive to global climate change and are characterized by fragile ecosystems. They describe regions subject to permanent or seasonal water deficiency, which currently occupy ~42% of the global land surface¹. Vegetation restoration in these areas is crucial not only for mitigating regional ecological degradation but also for contributing to global climate change mitigation, desertification control, and ecosystem recovery². Vegetation can offset some of the negative impacts of climate warming by increasing carbon sequestration, improving soil stability, and enhancing biodiversity³. The ability of vegetation to recover in fragile ecosystems such as arid and semiarid areas is usually not uniform and can be affected by climate change and various environmental factors. Sui et al.⁴ reported that despite a significant increase in the vegetation greenness index in Northwest China between 1981 and 2019, vegetation recovery has not been completed because of environmental constraints and unfavorable climatic conditions. Large areas of land in marginal areas of the world's deserts have been degraded, and it is estimated that desertification is now occurring on approximately 12 million hectares per year⁵. Desertification results in a seriously undesirable situation for farmland and settlement, and it is a critical environmental threat worldwide, e.g.,^{6,7,8}, as well as for Iran⁹. Iran is situated within the arid and semiarid belt of the world and is considerably distant from major sources of atmospheric moisture; approximately 0.33 million km² (20% of Iran's total land) is covered by desert¹⁰, and approximately one million km² of land is also at risk of desertification¹¹. An area equivalent to 737790 hectares of the Khuzestan plain in southwestern Iran is considered a dryland and dust source¹². In recent years, research on vegetation restoration in arid and semiarid regions has gained momentum worldwide. An example is the study of vegetation cover and its dynamic changes in dust centers in the hot and dry regions of southwestern Iran^{13,14,15,16,17,18}. The results revealed that plants play a pivotal role in the stability of natural ecosystems and that the stability of an ecosystem depends upon biodiversity parameters. One of the emerging and widely used approaches for studying vegetation dynamics in arid and semiarid regions is the use of remote sensing data and their processing in advanced computing environments such as the Google Earth Engine (GEE). This environment, which provides a long-term archive of satellite images and the ability to connect to the Python programming environment, is a suitable platform for calculating various vegetation and moisture indices (such as the NDVI, EVI, and NDWI) that are highly sensitive to changes in chlorophyll, canopy cover, and soil and plant moisture contents. Therefore, this tool is considered to have a high ability to observe and monitor temporal and spatial changes in sensitive and fragile ecosystems such as

desert areas^{19,20}. In recent years, various studies have been conducted using this approach. Liu et al.²¹, using Landsat satellite images and their time series analysis in the GEE environment, were able to examine the trend of changes in the NDVI vegetation index on Zhushan Island, China, from 1985–2022 and revealed that topographic and climatic variables play a decisive role in the spatial distribution of vegetation. Additionally, Dinarvand et al.²² used vegetation indices extracted from satellite images in dust centers in southeastern Iran to measure the dynamics of vegetation. In southern and eastern Africa, Sazib et al.²³ used some vegetation and soil moisture indices, such as the NDVI and NDWI, in the GEE framework to examine the relationships between these indices and drought severity. Overall, this evidence indicates the ability and efficiency of this approach in analyzing changes in dry ecosystems at different spatial and temporal scales.

Arid and desert regions present exceedingly challenging conditions for plant growth and development due to moisture deficits, elevated temperatures, intense winds, soil erosion, and land degradation resulting from anthropogenic activities. Consequently, only a relatively limited number of plant species are capable of surviving in such environments. The native flora of these regions is considered highly valuable because of its adaptability to harsh environmental conditions, and it plays a critical role in climate moderation, pedogenesis, and the local hydrology of an area. Therefore, their identification is highly important. With the aim of monitoring and recording spatial data statistics of climatic parameters, meteorology, hydrometry, erosion and sedimentation, vegetation cover, soil and groundwater, the Shush Reference Basin Station was established in 2007 by the General Directorate of Natural Resources and Watershed Management of Khuzestan Province. Despite the long period of time since the establishment of this area, a proper analysis of the vegetation of the area, its role, and the changes that have occurred during the period of enclosure has not been presented thus far. In this study, the floristic composition of the area, species richness, and changes in species richness were examined over a period of 20 years.

Materials and methods

Study area

Geography

This study was carried out in the Shush (Susa) Watershed Nature Reserve, Khuzestan Province, southwestern Iran, covering an area of approximately 200 ha ($48^{\circ}05'29''$ – $48^{\circ}07'09''$ E; $32^{\circ}12'57''$ – $32^{\circ}13'43''$ N) (Fig. 1). The elevation of the basin ranges from 90–147 m above sea level. The Karkheh River is the closest permanent water body to the study area.

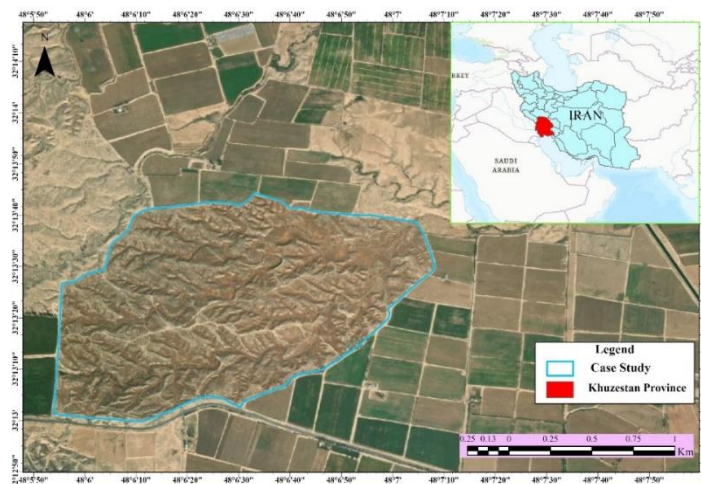


Fig. 1 Study area, Shush (Susa) Watershed Nature Reserve, Khuzestan Province, southwestern Iran

Climate

According to the Amberge method, the region's climate is classified as hot mid-desert²⁴. Meteorological records from the nearest synoptic station show a mean annual precipitation of approximately 300 mm, the majority of which occurs between November and March. The mean annual temperature ranges from 25 to 29 °C. July and August are the hottest months, with absolute maximum temperatures of 45–50 °C and mean monthly values of 34–36 °C, whereas January is the coldest month, with mean temperatures of 11–16 °C. According to the ombrothermic diagram, the study area experiences seven months of the year with no or minimal precipitation and maximum temperatures (Fig. 2).

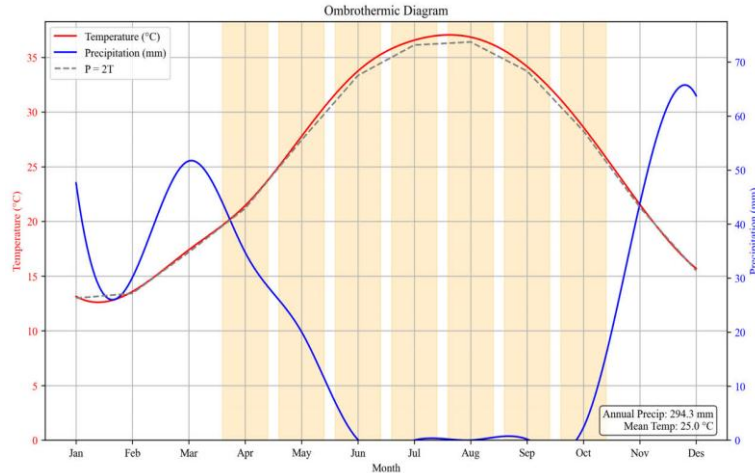


Fig. 2 Ombrothermic diagram

The natural landscape

The Shush Watershed Nature Reserve is located in the Saharo-Sindian phytogeographical region. The natural landscape of the area consists of low hills, and the soils are characterized by a loamy texture within an extensive plain²⁵. The vegetation is predominantly short-steppe species, including annual grasses and scattered xerophytic shrubs. Occasional trees and shrubs of the genus *Ziziphus* (*Z. spina-christi*, *Z. nummularia*) are also present. During the spring, the area appears lush because of the growth of short annual plants, but by summer, the landscape quickly takes on a dry appearance. The vegetation (especially annual plants) is highly seasonal, exhibiting distinct spring and dormancy phases.

Floristic survey

In accordance with the prevailing climatic conditions of Khuzestan Province, systematic floristic surveys were conducted during the optimal growing season (early February to late April). Field sampling was performed both in the initial year of station establishment (2005) and in a subsequent survey in 2025. The collected samples were pressed, dried, and mounted on herbarium sheets following standard protocols. Taxonomic determination of the ranks of subspecies and varieties was achieved via authoritative floristic references, namely, the Flora of Khuzestan²⁶, Flora of Iranica²⁷, Flora of Iran²⁸, and Flora of Iraq²⁹. The vegetation typology of the study area was delineated on the basis of the dominance and constancy of shrubs and perennial taxa.

Satellite Data and Image Selection

Landsat satellite images for two time periods, 2005 and 2025, were used to examine long-term variations in soil moisture and vegetation cover throughout the research area. Pictures taken during the spring season (March 21–June 21) were chosen to reduce seasonal changes and draw attention to the ecological conditions of the rangeland; they coincided with the growth season of the herbaceous vegetation apex.

The Google Earth Engine (GEE) environment was used to carry out the first picture selection, preprocessing, and index extraction. For 2005, Landsat 5 TM and Landsat 7 ETM+ were used as imagery from the study area, defined as a vector layer (ROI). For 2025, Landsat 8 OLI and Landsat 9 OLI-2 data are presented in Table 1. To maintain data quality, pixels influenced by haze, snow, cloud shadows, and clouds were masked via the QA_PIXEL band^{30,31}.

Table 1. Specifications of the satellite imagery used in the study

Year	Sensor(s)	Selected Time Period	Spatial Resolution (m)	Season
2005	Landsat 5 TM + Landsat 7 ETM+	March 21 – June 21	30	Spring
2025	Landsat 8 OLI + Landsat 9 OLI-2	March 21 – June 21	30	Spring

Vegetation and moisture index extraction

To analyze ecological changes, a set of spectral indices related to vegetation and soil moisture was computed from the selected imagery. The indices used in this study are presented in Table 2.

Table 2. Vegetation and moisture indices used in the study

Index	Full Name and General Formula	Main Application	Reference
NDVI	Normalized Difference Vegetation Index = $(\text{NIR} - \text{RED})/(\text{NIR} + \text{RED})$	Assessing vegetation greenness and health	Xiong et al., 2023 ³¹
EVI	Enhanced Vegetation Index = $2.5 \times (\text{NIR} - \text{RED})/(\text{NIR} + 6\text{RED} - 7.5\text{BLUE} + 1)$	Improved evaluation of dense vegetation	Rodriguez et al., 2024 ³²

SAVI	Soil Adjusted Vegetation Index = $1.5 \times (\text{NIR} - \text{RED})/(\text{NIR} + \text{RED} + 0.5)$	Reducing soil background effects in sparsely vegetated areas	Okoduwa et al., 2024 ³³
NDWI	Normalized Difference Water Index = $(\text{GREEN} - \text{NIR})/(\text{GREEN} + \text{NIR})$	Estimating surface moisture	Rad et al., 2021 ³⁰
NDMI	Normalized Difference Moisture Index = $(\text{NIR} - \text{SWIR})/(\text{NIR} + \text{SWIR})$	Assessing vegetation and soil moisture	Das et al., 2023 ³⁴
MSI	Moisture Stress Index = SWIR/NIR	Evaluating moisture stress	Lupa et al., 2024 ³⁵

The computation of these indices was carried out in **GEE**. After masking the invalid pixels, the indices were calculated and exported as GeoTIFF raster files for each year to Google Drive.

Change Analysis and Ecological Dynamics Assessment

To evaluate the rangeland ecosystem dynamics over the study period, pixelwise comparisons were performed between the index maps of 2005 and 2025. Change maps were generated by computing the difference between corresponding indices (2025 – 2005). Additionally, histograms were plotted to examine the statistical distribution of changes.

For the NDVI and NDWI, categorical change detection was applied using a ± 0.05 threshold. Overlapping these results produced a seven-class composite map that illustrates simultaneous changes in vegetation cover and soil moisture.

Statistical analysis and visualization

Statistical analyses and data visualization were conducted in Python (v3.11). Array processing and basic statistical computations were performed via NumPy³⁶, whereas tabular data management utilized pandas. Descriptive plots were generated with Matplotlib, and raster data processing was conducted via Rasterio. Furthermore, geemap was employed for direct interaction with GEE and spatial data processing.

Results

Floristic composition

During the spring season, a field survey was conducted in the fenced and protected area of the Shush demonstration watershed, where a total of 70 plant species belonging to 29 families were identified (Table 3). Among these, annual herbaceous plants (therophytes) were dominant, accounting for 67% of the flora. The collected plant specimens are kept in the herbarium of the Khuzestan Agricultural and Natural Resources Research Center. The botanical experts of that department have identified these species based on reliable references. The identifier of these species is the first author of the article. All plants listed in Table 3 are wild^{26, 27, 28, 29, 30}.

Table 3. Floristic list of plants in the study area

Species	Family	Life forms	Ecological value	.Herbarium No	Threat category [Ref.]
<i>Aegilops triuncialis</i>	Poaceae	Annual	P	5343	Non-endemic
<i>Ammi majus</i>	Apiaceae	Annual	P	1663	Non-endemic
<i>Anagalis arvensis</i>	Primulaceae	Annual	P	10259	Non-endemic
<i>Anchosa strigose</i>	Boraginaceae	Annual	P	3470	Non-endemic
<i>Anisosciadium orientale</i>	Brassicaceae	Annual	P	3935	Non-endemic
<i>Anthemis Susiana</i>	Astraceae	Annual	P	10330	Non-endemic
<i>Arnebia decumbens</i>	Brassicaceae	Annual	P	3462	Non-endemic
<i>Asphodelus tenuifolius</i>	Liliaceae	Annual	P	10077	Non-endemic
<i>Astragalus ensifer</i>	Fabaceae	Bush	S.c	370	Endemic, EN (1)
<i>Astragalus fasciculifolius*</i>	Fabaceae	Bush	S.c	10751	Endemic, LR (1)
<i>Astragalus obtusifolius*</i>	Fabaceae	Bush	S.c	4530	Non-endemic
<i>Avena ludoviciana*</i>	Poaceae	Annual	P	10075	Non-endemic
<i>Bromus danthomiae</i>	Poaceae	Annual	P	10547	Non-endemic
<i>Bromus sericeus*</i>	Poaceae	Annual	P	10446	Non-endemic
<i>Capparis spinosa*</i>	Capparidaceae	Bush	S.c	3531	Non-endemic
<i>Carthamus oxyacantha</i>	Astraceae	Annual	P	1133	Non-endemic
<i>Centaurea bruguierana*</i>	Astraceae	Annual	P	10339	Non-endemic
<i>Centaureum erythraeae</i>	Gentianaceae	Annual	P	53507	Non-endemic
<i>Cleome glaucesens</i>	Capparidaceae	Perennial herb	S.c	1703	Non-endemic
<i>Convolvulus kotschymanus</i>	Convolvulaceae	Perennial herb	S.c	10167	Non-endemic
<i>Convolvulus oxyphyllus*</i>	Convolvulaceae	Perennial herb	S.c	780	Non-endemic
<i>Crepis foetida</i>	Astraceae	Annual	P	3166	Non-endemic
<i>Diplotaxis harra*</i>	Brassicaceae	Annual	P	9037	Non-endemic

<i>Echinops dichorus*</i>	Astraceae	Perennial herb	S.c	79444	Endemic, DD (1)
<i>Ephedra foliata</i>	Ephedraceae	Bush	S.c	10245	Non-endemic
<i>Eruca sativa*</i>	Brassicaceae	Annual	P	9049	Non-endemic
<i>Erucaria hispanica*</i>	Brassicaceae	Annual	P	4527	Non-endemic
<i>Fagonia bruguieri</i>	Zygophyllaceae	Perennial herb	P	10177	Non-endemic
<i>Fumaria bracteosa</i>	Fumariaceae	Annual	P	10442	Non-endemic
<i>Galium aparine*</i>	Rubiaceae	Annual	P	10284	Non-endemic
<i>Galium ceratopodum</i>	Rubiaceae	Annual	P	715	Non-endemic
<i>Gentiana olivieri</i>	Gentianaceae	Annual	P	10122	Non-endemic
<i>Gundelia tournefortii</i>	Astraceae	Perennial herb	S.c	10160	Non-endemic
<i>Haplophyllum tuberculatum</i>	Rutaceae	Perennial herb	S.c	10184	Non-endemic
<i>Helianthemum aegyptiacum</i>	Cistaceae	Annual	P	1761	Non-endemic
<i>Helianthemum lippii</i>	Cistaceae	Bush	S.c	1279	Non-endemic
<i>Heliotropium crispum*</i>	Boraginaceae	Bush	S.c	10185	Non-endemic
<i>Hippocrepis bicontorta</i>	Fabaceae	Annual	P	3212	Non-endemic
<i>Hordeum bulbosum</i>	Poaceae	Perennial herb	S.c	10161	Non-endemic
<i>Hordeum murinum*</i>	Poaceae	Annual	P	11052	Non-endemic
<i>Hymenocarpus circinnatus</i>	Fabaceae	Annual	P	10043	Non-endemic
<i>Ixiolirion tataricum</i>	Ixioliriaceae	Perennial herb	S.c	10046	Non-endemic
<i>Linum corymbulosum</i>	Linaceae	Annual	P	1308	Non-endemic
<i>Lolium rigidum</i>	Poaceae	Annual	P	10164	Non-endemic
<i>Malva aegyptica*</i>	Malvaceae	Annual	P	62856	Non-endemic
<i>Matthiola longipetala</i>	Brassicaceae	Annual	P	1295	Non-endemic
<i>Medicago minima*</i>	Fabaceae	Annual	P	4535	Non-endemic
<i>Medicago polymorpha*</i>	Fabaceae	Annual	P	10090	Non-endemic
<i>Notobasis syriaca</i>	Astraceae	Annual	P	10746	Non-endemic
<i>Oliveria decumbens</i>	Apiaceae	Annual	P	10179	Non-endemic
<i>Onobrychis crista-galli</i>	Fabaceae	Annual	P	10036	Non-endemic
<i>Onobrychis ptolemaica</i>	Fabaceae	Perennial herb	S.c	10183	Non-endemic
<i>Onopordum leptolepis*</i>	Astraceae	Annual	P	3664	Non-endemic
<i>Orobancha ceruna</i>	Orobanchaceae	Perennial herb	S.c	62383	Non-endemic
<i>Papaver macrostomum</i>	Papaveraceae	Annual	P	1211	Non-endemic
<i>Phalaris minor*</i>	Poaceae	Annual	P	256	Non-endemic
<i>Plantago ovata*</i>	Plantaginaceae	Annual	P	4000	Non-endemic
<i>Pteranthus dichotomus</i>	Caryophyllaceae	Annual	P	873	Non-endemic
<i>Reseda aucheri</i>	Resedaceae	Annual	P	3169	Non-endemic
<i>Salvia macrosiphon</i>	Lamiaceae	Perennial herb	P	70183	Non-endemic
<i>Scabiosa calocephala</i>	Dipsacaceae	Annual	P	3901	Non-endemic
<i>Scabiosa leucactis</i>	Dipsacaceae	Annual	P	3466	Non-endemic
<i>Stipa arabica</i>	Poaceae	Perennial herb	P	11054	Non-endemic
<i>Stipa capensis*</i>	Poaceae	Annual	P	10083	Non-endemic
<i>Teucrium oliverianum</i>	Lamiaceae	Perennial herb	S.c	1378	Non-endemic
<i>Trifolium campestre</i>	Fabaceae	Annual	P	10488	Non-endemic
<i>Trifolium tomentosum</i>	Fabaceae	Annual	P	10099	Non-endemic
<i>Urtica pilulifera</i>	Urticaceae	Annual	P	1518	Non-endemic
<i>Ziziphus nummularia*</i>	Rhamnaceae	Shrub	S.c	5808	Non-endemic
<i>Ziziphus spina-christi*</i>	Rhamnaceae	Shrub	S.c	5876	Non-endemic

EN (Endangered), DD (Data Deficient), LR (Lower Risk), Jalili & Jamzad (1999)³⁷

Soil conservation: S.c., Pedogenesis: P

* Species that persisted from the initial survey year (2007)

Among the 29 identified families, Fabaceae, Asteraceae, Poaceae, and Brassicaceae (with 11, 8, 8, and 6 species, respectively) were the largest families in terms of species richness. Among the 70 identified species, 45 species, such as *Astragalus ensifer*, *A. fasciculifolius*, and *A. obtusifolius*, possess soil conservation value and are considered permanent components of the vegetation. Native tree and shrub species include *Ziziphus spina-christi* and *Z. nummularia*, whereas *Prosopis juliflora* and *Eucalyptus camaldulensis* represent nonnative trees planted in recent years.

After 20 years of protection since the establishment of the Shush demonstration station, six vegetation types were identified in this study (Table 4), whereas only one vegetation type (*Astragalus fasciculifolius*–*Stipa capensis*) was reported in the first year (2005)²⁴.

Table 4. Identified types and their associated species in the Shush watershed (2025)

Num. Type	Species
Type 1	<i>Astragalus obtusifolius</i> , <i>Fagonia bruguieri</i> , <i>Astragalus fasciculifolius</i>
Companion species	<i>Gundelia tournefortii</i> <i>Pteranthus dichotomus</i> <i>Anchosa strigosa</i> <i>Salvia macrosiphon</i> <i>Bromus sericeus</i> <i>Avena ludoviciana</i> <i>Pteranthus dichotomus</i>
Type 2	<i>Echinops dichorus</i> , <i>Capparis spinose</i> , <i>Ziziphus nummularia</i>
Companion species	<i>Bromus sericeus</i> <i>Hordeum bulbosum</i> <i>Stipa capensis</i> <i>Erucaria hispanica</i>
Type 3	<i>Echinops dichorus</i> , <i>Gundelia tournefortii</i> , <i>Ziziphus nummularia</i>
Companion species	<i>Notobasis syriaca</i> <i>Haplophyllum tuberculatum</i> <i>Avena ludoviciana</i> <i>Trifolium campestre</i>
Type 4	<i>Astragalus obtusifolius</i> , <i>Teucrium oliverianum</i>
Companion species	<i>Diplotaxis harra</i> <i>Stipa capensis</i> <i>Bromus sericeus</i> <i>Avena ludoviciana</i> <i>Erucaria hispanica</i>
Type 5	<i>Convolvulus kotschyanus</i> , <i>Salvia macrosiphon</i> , <i>Haplophyllum tuberculatum</i>
Companion species	<i>Avena ludoviciana</i> <i>Trifolium campestre</i> <i>Bromus sericeus</i> <i>Stipa capensis</i>
Type 6	<i>Astragalus fasciculifolius</i> , <i>Convolvulus oxyphyllus</i> , <i>Onobrychis ptolemaica</i>
Companion species	<i>Stipa arabica</i> <i>Gundelia tournefortii</i> <i>Astragalus obtusifolius</i> <i>Teucrium oliverianum</i> <i>Haplophyllum tuberculatum</i>

3. Satellite-based vegetation and moisture dynamics

3.1 Descriptive statistics

The analysis of spectral indices from Landsat data between 2005 and 2025 revealed a clear divergence between vegetation cover and water availability (Table 5). On the one hand, there was a remarkable improvement in the vegetation indices: the mean NDVI strongly increased by +0.070, a trend reflected by the EVI and SAVI, which both increased by +0.041. On the other hand, the state of water resources deteriorated, as indicated by a decline of –0.061 in the NDWI and a drop of –0.020 in the NDMI. This developing moisture deficit is further confirmed by a +0.051 increase in the MSI, indicating that water stress became more severe within the watershed.

Table 5. Descriptive statistics of the vegetation and moisture indices in 2005 and 2025 and their changes (Δ = 2025–2005) in the Shush watershed.

Index	Year	Mean	Median	Std	Min	Max
NDVI	2005	0.072	0.072	0.008	0.045	0.136
	2025	0.142	0.140	0.016	0.088	0.254
	Δ	+0.070	+0.068	0.015	+0.002	+0.174
EVI	2005	0.058	0.057	0.006	0.036	0.107
	2025	0.099	0.096	0.010	0.075	0.172
	Δ	+0.041	+0.039	0.010	+0.007	+0.115
SAVI	2005	0.061	0.060	0.007	0.038	0.110
	2025	0.102	0.100	0.010	0.079	0.178
	Δ	+0.041	+0.040	0.010	+0.007	+0.118

NDWI	2005	-0.208	-0.208	0.010	-0.260	-0.175
	2025	-0.269	-0.267	0.015	-0.356	-0.225
	Δ	-0.061	-0.060	0.015	-0.158	-0.008
NDMI	2005	-0.096	-0.097	0.009	-0.125	-0.047
	2025	-0.116	-0.119	0.021	-0.179	-0.002
	Δ	-0.020	-0.021	0.020	-0.077	+0.100
MSI	2005	1.213	1.214	0.023	1.100	1.287
	2025	1.264	1.271	0.052	1.003	1.436
	Δ	+0.051	+0.053	0.050	-0.223	+0.207

3.2 Comparative statistics

The comparative analysis of boxplots for all indices across the periods 2005 and 2025 reveals significant shifts in the distribution of values for each index (Figure 3).

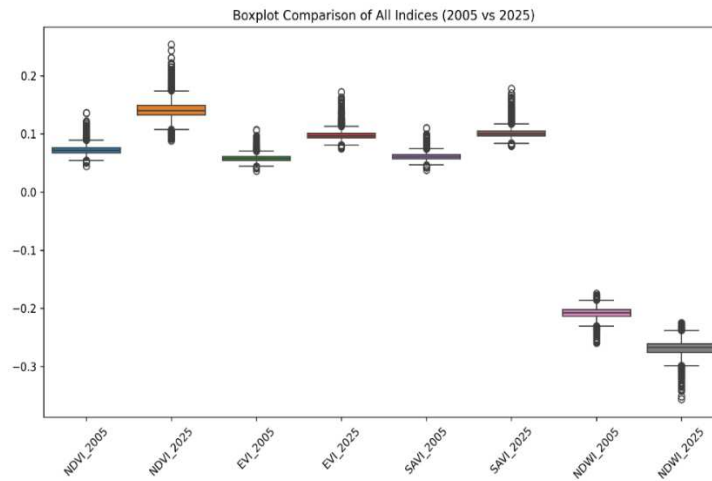


Fig. 3 Boxplot comparison of vegetation and moisture indices (2005 vs 2025).

Vegetation indices (NDVI, EVI, and SAVI):

In this group of indices, the boxes clearly shift toward higher values, indicating an increase in their medians by 2025. Furthermore, a notable expansion in both the interquartile range (IQR) and the overall data range is observed. This widening suggests an increase in spatial heterogeneity in vegetation conditions. The presence of new outliers in the upper ranges in 2025 confirms the existence of specific areas that have experienced exceptionally strong improvements in vegetation density.

Moisture-Related Indices (NDWI, NDMI, MSI):

For the NDWI and NDMI indices, the boxes have shifted toward lower values, demonstrating a decrease in their medians by 2025. Concurrently, a contraction of these boxes indicates a reduction in data dispersion around the lower median values. In contrast, the MSI exhibited an inverse trend; its box distinctly shifted and expanded toward higher values, reflecting both an increased median and a wider range of moisture stress conditions in 2025.

The bar chart comparing the mean, median, and standard deviation values (Figure 4) provides further insights into the observed trends:

- **Vegetation indices (NDVI, EVI, SAVI):** These indices demonstrated notable increases in both the mean and median values from 2005--2025, indicating a positive shift in overall vegetation conditions.
- **Moisture Indices (NDWI, NDMI):** Both indices decreased, with median values becoming more negative in 2025, reflecting a decrease in moisture availability.

- **Moisture stress index (MSI):** The MSI exhibited increases in both the mean and median values, highlighting an intensification of water stress in the region over the same period

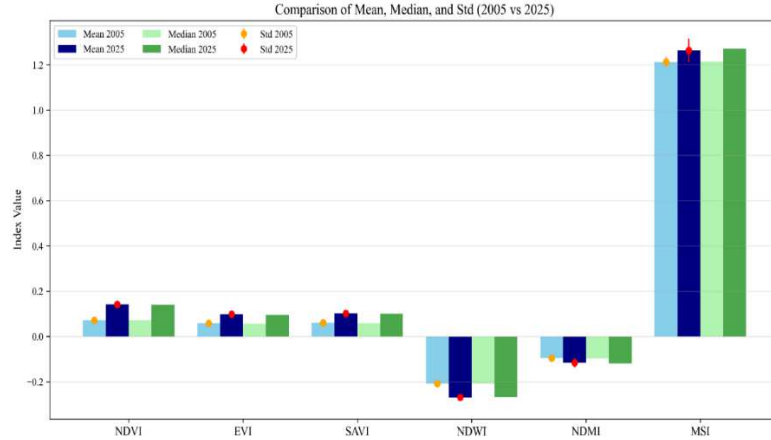


Fig. 4 Comparison of the means, medians, and standard deviations of the indices (2005 vs 2025).

3.3 Correlation analysis of vegetation and moisture indices (2025)

The per-pixel correlation matrix of the vegetation and moisture indices for 2025 (Figure 5) illustrates strong and systematic relationships among the indices:

- **Vegetation and moisture indices:** Strong negative correlations were identified between the vegetation indices and the NDWI, with the NDVI and NDWI having $r = -0.95$, the EVI and NDWI having $r = -0.94$, and the SAVI and NDWI having $r = -0.91$. This suggests that areas with greater vegetation greenness tend to have lower NDWI values, revealing a paradox where vegetation recovery occurs alongside declining surface water availability.
- **Moderate correlations with the NDMI:** Moderate positive correlations were found between the SAVI and NDMI ($r = 0.26$) and between the EVI and NDMI ($r = 0.20$). This finding indicates that the NDMI captures certain aspects of the vegetation moisture content, but its alignment with the greenness indices is less pronounced.
- **MSI Relationships:** The moisture stress index (MSI) displayed contrasting relationships; it was positively correlated with the NDWI ($r = 0.80$), indicating shared sensitivity to water stress. However, it was negatively correlated with the NDVI ($r = -0.21$), EVI ($r = -0.16$), and SAVI ($r = -0.19$). These findings underscore the role of MSIs as indicators of stress, which is inversely related to vegetation health.
- **NDMI and MSI correlation:** The correlation between the NDMI and MSI was moderately negative ($r = -0.40$), reinforcing the notion that as vegetation moisture decreases, the MSI tends to increase.

In summary, the correlation analysis reveals that while the vegetation indices (NDVI, EVI, and SAVI) are closely interrelated, their relationships with moisture indices (NDWI, NDMI, and MSI) tend to be either inverse or weak. This highlights a dual trajectory of vegetation greening occurring in the context of increasing water stress.

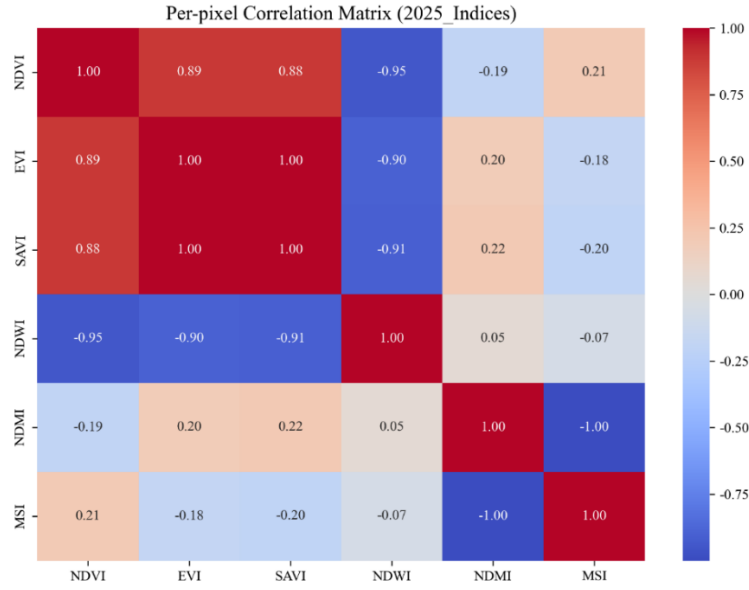


Fig. 5 Per-pixel correlation matrix of the vegetation and moisture indices in 2025.

3.1 Vegetation indices (NDVI, EVI, and SAVI)

The analysis of vegetation indices derived from Landsat imagery revealed a consistent upward trend in vegetation cover between 2005 and 2025. Spatial distribution maps and histograms indicated that the NDVI, EVI, and SAVI values increased markedly in 2025 compared with those in 2005, particularly in lowland areas adjacent to the Karkheh River.

For example, the NDVI histogram (Figure 6a) clearly shifts toward higher values, whereas the spatial distribution maps (Figures 6b and 6c) confirm the expansion of greener patches across the watershed.

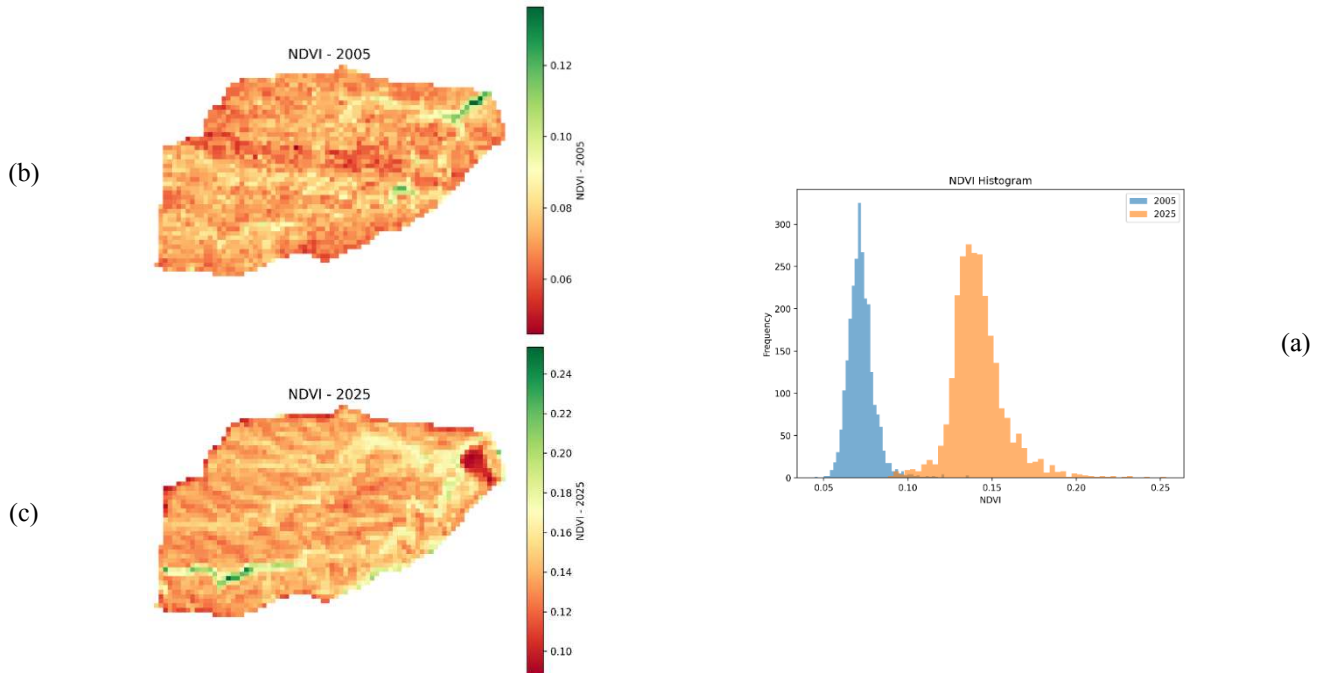


Fig. 6 NDVI histogram (a), spatial distribution in 2005 (b), and spatial distribution in 2025 (c).

Similarly, the EVI increased from a mean of 0.058 in 2005 to 0.099 in 2025. Given its reduced sensitivity to canopy saturation, the EVI highlighted improvements not only in sparse vegetation but also in moderately dense stands (Figure 7a–c).

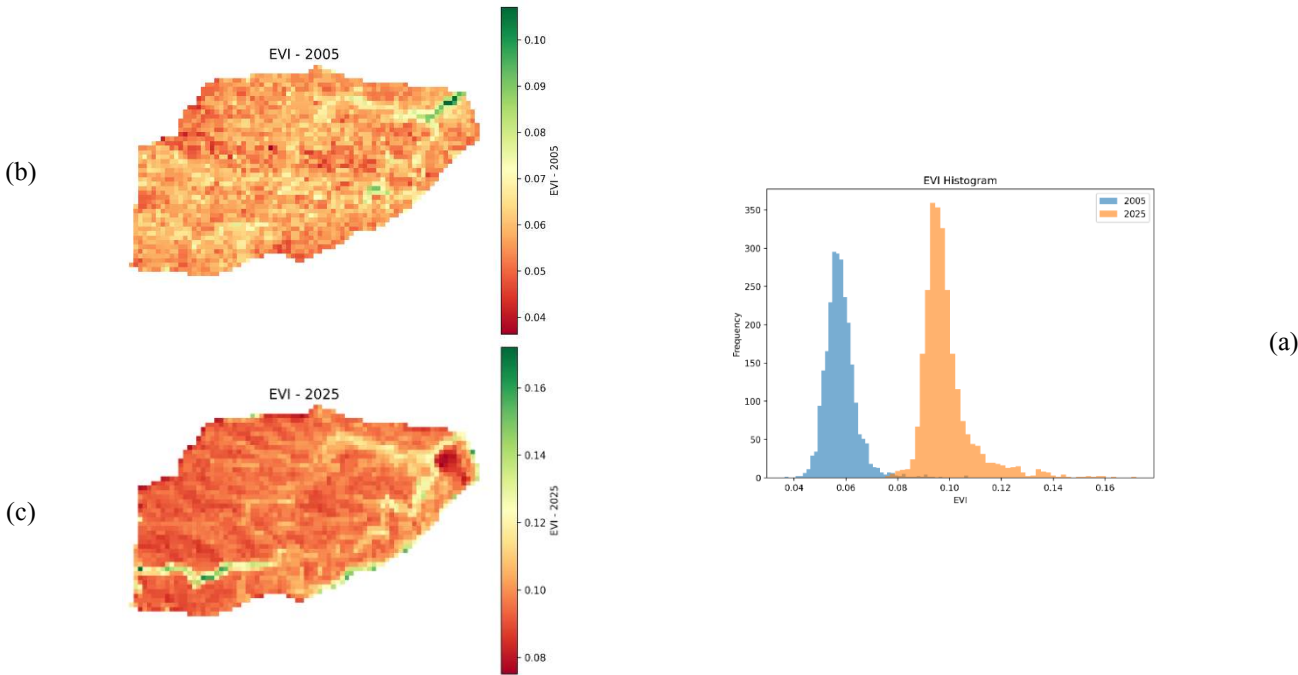


Fig. 7 EVI dynamics in 2005 and 2025: EVI histogram (a), spatial distribution in 2005 (b), and spatial distribution in 2025 (c).

The SAVI also exhibited a comparable trend, with its mean value rising from 0.061 to 0.102. This increase reflects a reduction in the influence of the soil background and the establishment of more continuous vegetation cover (Figure 8a–c).

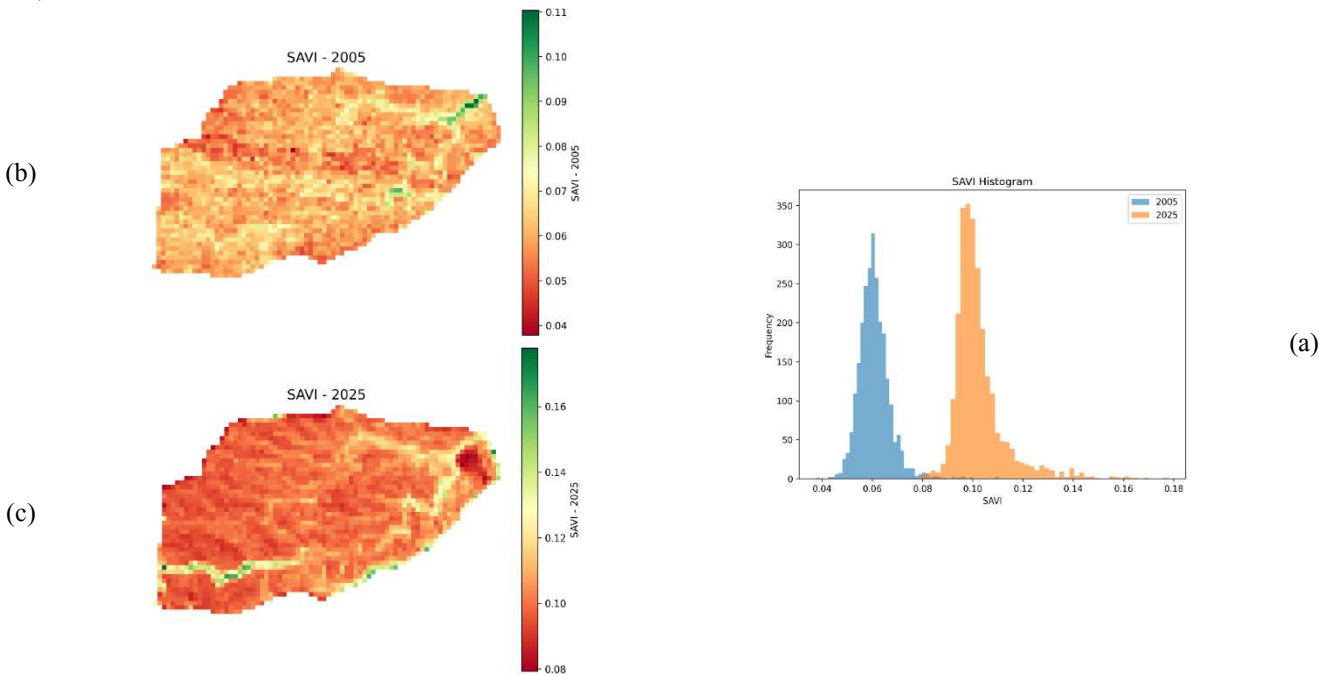


Fig. 8 SAVI dynamics in 2005 and 2025: SAVI histogram (a), spatial distribution in 2005 (b), and spatial distribution in 2025 (c).

3.2 Moisture-related indices (NDWI, MSI)

The normalized difference water index exhibited a marked decline over the study period. The mean values decreased from -0.208 in 2005 to -0.269 in 2025, with the histogram shifting toward more negative ranges (Figure 9a). Spatial maps (Figures 9b–c) highlight that this reduction was most evident in the central and southern sectors of the watershed, suggesting a progressive depletion of surface water resources.

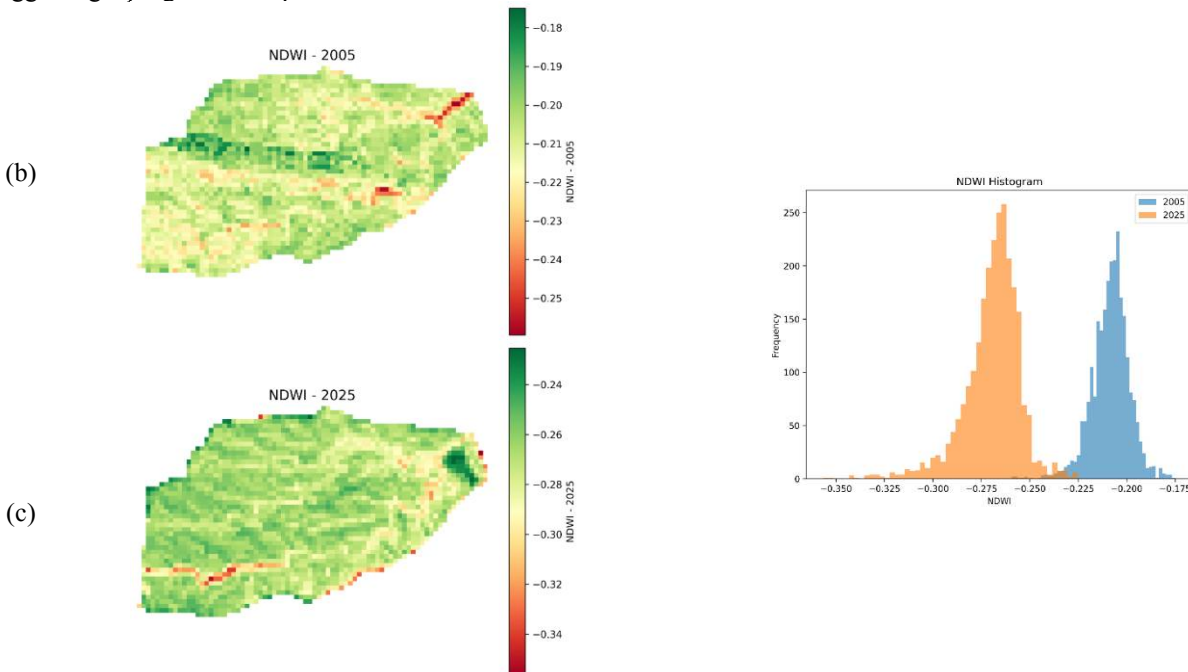
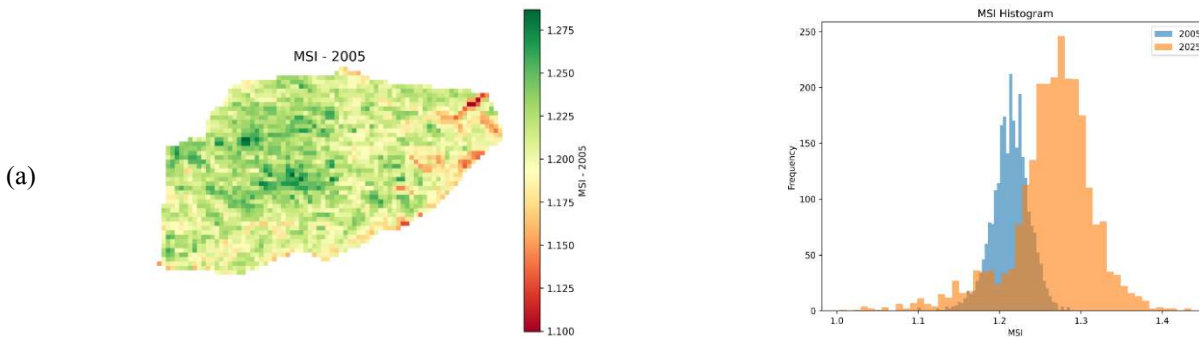


Fig. 9 NDWI dynamics in 2005 and 2025: NDWI histogram (a), (b) spatial distribution in 2005, (c) spatial distribution in 2025.

The moisture stress index displayed the opposite trend, increasing from 1.213 in 2005 to 1.264 in 2025. This increase, together with the broader spread of values (Figure 10a), points to intensifying drought stress. The spatial maps (Figures 10b–c) reveal that upland areas were particularly affected, whereas low-lying zones presented relatively moderate stress levels. Such divergence suggests that topography plays a role in modulating the severity of water scarcity.



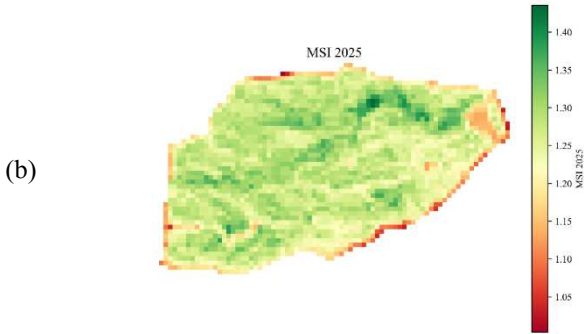
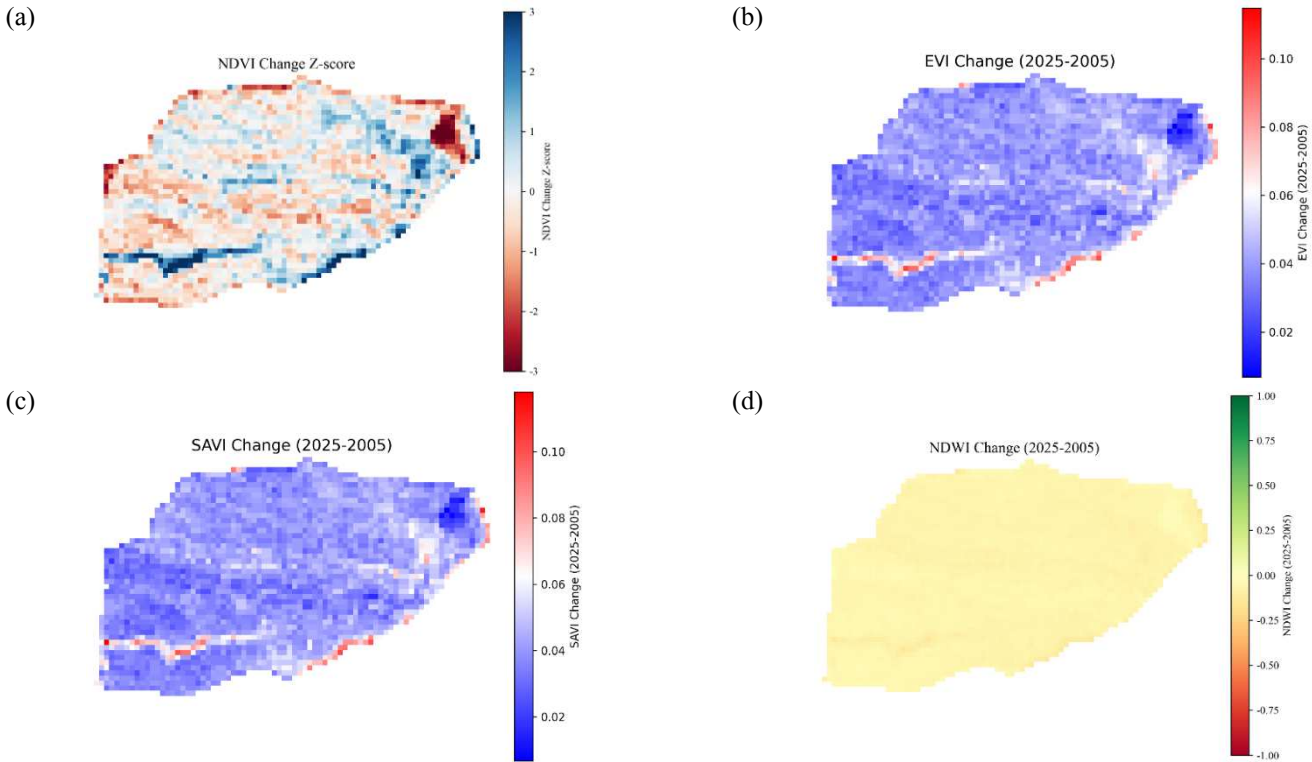


Fig. 10 MSI dynamics in 2005 and 2025: histogram (a), spatial distribution in 2005 (b), and spatial distribution in 2025 (c).

3.3 Change detection and spatial patterns

The spatial differences in the vegetation and moisture indices between 2005 and 2025 revealed contrasting ecological trajectories across the watershed. The NDVI change map (Figure 11a) highlights a widespread greening trend, with the most pronounced gains concentrated along riparian corridors and lowland depressions where soil moisture is relatively high. The EVI change map (Figure 11b) complements this pattern by capturing improvements in moderately dense vegetation stands, indicating that recovery was not limited to sparse cover but extended to areas with more complex canopy structures. Similarly, the SAVI change map (Figure 11c) illustrates a reduction in soil background influence, particularly in degraded patches that have transitioned toward more continuous vegetation cover. In contrast, the NDWI change map (Figure 11d) clearly shows a decrease in surface water availability, with negative anomalies dominating the central and southern portions of the basin. This reduction suggests that, despite vegetation recovery, hydrological resources have become increasingly constrained. The NDMI change map (Figure 11e) presents a more heterogeneous picture: while large areas experienced moisture loss, scattered patches retained stable or slightly improved conditions, reflecting localized resilience linked to soil properties and microtopography.



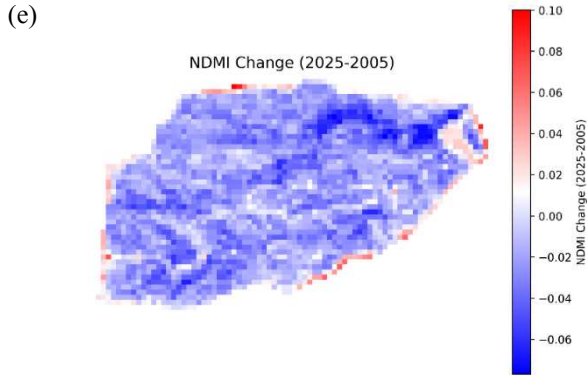


Fig. 11 Change maps and distributions of vegetation and moisture indices ($\Delta = 2025-2005$): (a) NDVI change map; (b) EVI change map; (c) SAVI change map; (d) NDWI change map; (e) NDMI change map;

The spatial overlay of the changes in the NDVI and NDWI provides clear evidence of how vegetation recovery interacts with moisture dynamics across the watershed (Figure 12). Areas mapped in yellow indicate zones where vegetation expanded despite declining surface moisture, suggesting adaptation through drought-tolerant species establishment or increased rooting depth that allows plants to sustain growth under drier conditions. In contrast, the blue regions mark areas where vegetation declined while surface moisture slightly improved, likely due to reduced evapotranspiration following canopy loss. The gray to black areas represent zones of relative stability, where both vegetation and surface moisture remained largely unchanged during the study period.

This spatial relationship underscores the heterogeneous nature of ecosystem responses: while some sectors of the watershed benefited from protective measures and exhibited parallel gains in vegetation and moisture, a considerable portion experienced vegetation recovery under progressively water-limited conditions.

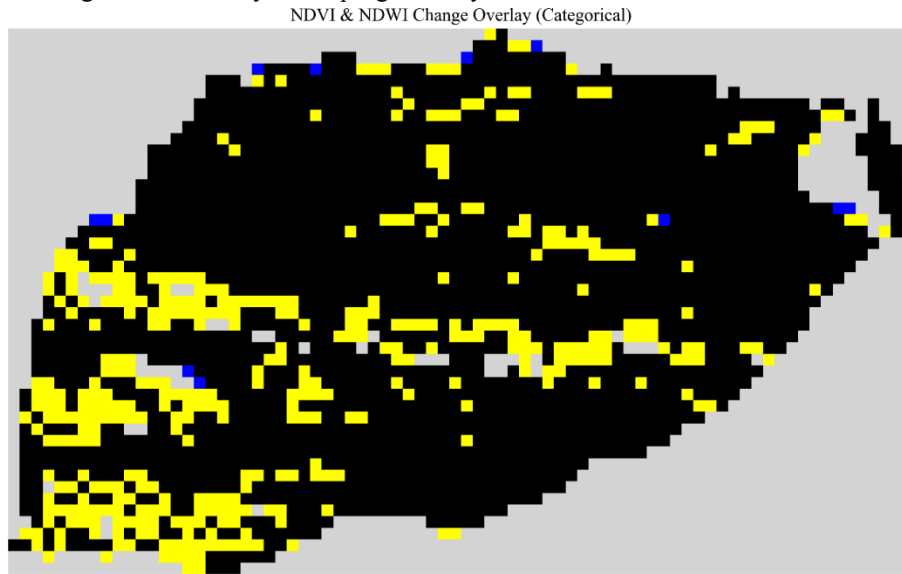


Fig. 12 Categorical overlay of the changes in the NDVI and NDWI. Legend: Yellow = NDVI↑ & NDWI↓; blue = NDVI↓ & NDWI↑; gray/black = stable (no significant change).

3.5 Vegetation–Moisture Resilience Index (VMRI)

The vegetation–moisture resilience index (VMRI) was developed to quantify this behavior by integrating normalized normalized normalized normalized difference vegetation index (NDVI) gains (reflecting vegetation improvement) with penalties for NDMI losses (representing soil moisture decline). The spatial distribution of VMRI values (Figure 13) reveals distinct gradients of resilience across the watershed. Areas with high VMRI scores—mainly along riparian corridors and lowland depressions—demonstrate high ecological stability, supported by sustained soil

moisture and consistent vegetation recovery. These areas function as ecological strongholds, where long-term protection has promoted both structural and functional resilience.

Conversely, low-VMRI regions, which are concentrated in the upland and peripheral sectors, exhibit limited vegetation recovery and severe moisture deficits. These zones, often near downstream watercourses or on steep terrain, appear to have crossed ecological thresholds where the recovery potential is minimal. Without timely management intervention, such regions are likely to experience continued degradation under future drought or climate variability, emphasizing the need for targeted restoration to safeguard residual resilience.

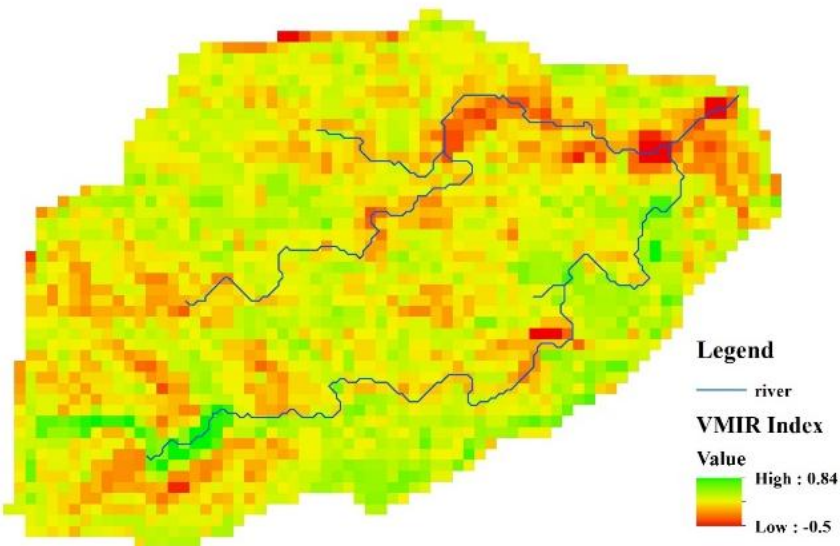


Fig. 13 Vegetation–moisture resilience index (VMRI) across the Shush watershed.

3.6 Ecological Clusters (K-means on Change Indices)

Unsupervised K-means clustering of multitemporal NDVI, NDWI, and NDMI change layers (2005–2025) identified several ecological zones with distinct vegetation and moisture responses across the watershed (Figure 14). The spatial configuration of the clusters revealed clear hydrological control on ecosystem behavior. Areas situated near the main river network displayed stable vegetation cover and relatively constant moisture conditions, suggesting that sustained soil–water interactions and shallow groundwater availability supported ecological recovery. In contrast, the upper and interfluvial sectors were characterized by moisture reduction and only moderate vegetation improvement, reflecting the effects of limited water storage and steeper slopes. The downstream and outlet zones presented concurrent declines in vegetation and soil moisture, indicating progressive degradation and reduced ecological resilience. Overall, the clustering pattern illustrates a watershed-scale gradient where hydrological connectivity and topographic setting jointly govern vegetation recovery potential and long-term ecosystem stability.

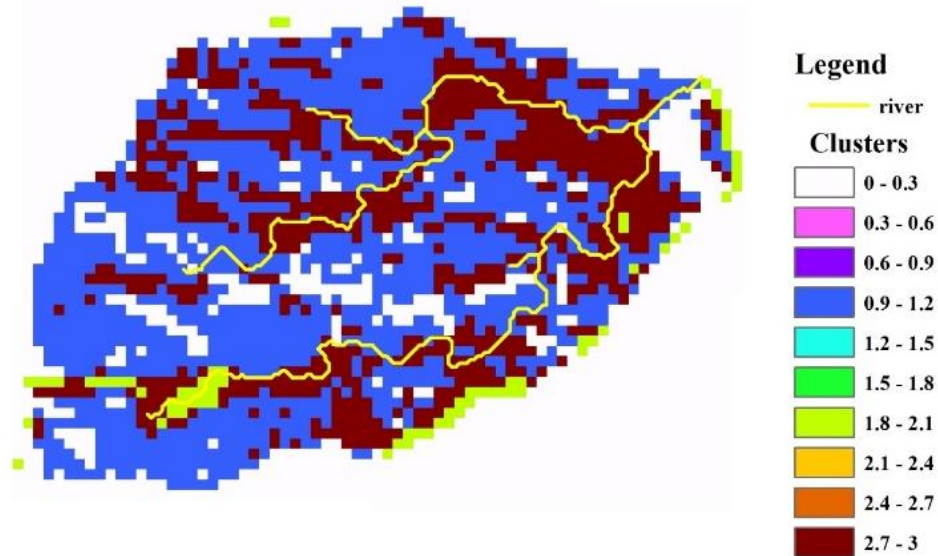


Fig. 14 Ecological clusters derived from K-means analysis of the changes in the NDVI, NDWI, and NDMI (2005–2025).

3.8 Synthesis of remote sensing results

Overall, the remote sensing results clearly indicate that prolonged protection efforts have led to substantial improvements in vegetation cover, as reflected by the continuous increases in the NDVI, EVI, and SAVI values. Moreover, decreasing NDWI and NDMI trends, along with an increase in MSI, reveal that vegetation recovery has taken place under progressively drier conditions. These contrasting signals suggest that, while vegetation greenness has improved, soil and canopy moisture have simultaneously declined.

The integrated analyses provide a deeper ecological interpretation of this trend. The VMRI captures spatial differences in resilience, the K-means clustering distinguishes various ecological response zones, and the NDVI–NDWI overlay illustrates the spatial interaction between vegetation recovery and declining moisture. Together, these approaches confirm that the observed “greening” is occurring under persistent water limitation — a pattern that can be described as *greening under drying*. This outcome offers a spatially explicit understanding of ecosystem resilience, highlights areas at risk of degradation, and supports the design of adaptive management strategies to cope with future climate variability.

Discussion

Floristic composition and community dynamics under long-term protection

A floristic survey of the Shush demonstration watershed after two decades of protection revealed clear changes and dynamic trends in vegetation cover. In 2005, a total of 23 plant species belonging to 11 families were identified, whereas in 2025, this number increased to 70 species belonging to 29 families, indicating a remarkable increase in species richness. During the early years of protection, only one plant community type was reported, whereas in 2025, six distinct vegetation types were recorded in field observations, reflecting a substantial increase in floristic richness. This increase demonstrates the positive effects of long-term protection through livestock exclusion and improved soil stability on the restoration of the soil seed bank and the establishment of plant species in arid rangelands. In other words, the identification of six distinct vegetation types after 20 years, compared with only one in 2005, highlights the structural and compositional diversification of the plant community as a result of continuous protection. This finding confirms the crucial role of minimizing human disturbance in activating natural regeneration processes, self-organization, and the development of more complex and stable plant communities. From the perspective of life form, the dominance of annual herbaceous plants (therophytes), which constitute 67% of the flora, is a common feature of arid and semiarid ecosystems³⁸. This group of plants, which complete their life cycle within a short period of favorable conditions, exhibit a high degree of adaptation to the extreme climatic variability typical of such environments³⁹. Nevertheless, the number of perennial and shrub species increased from 6 in 2005 to 21 in 2025. The presence of stable and soil-protecting species such as *Astragalus ensifer*, *A. fasciculifolius*, *A. obtusifolius*, *Capparis spinosa*, *Helianthemum lippii*, and *Convolvulus oxyphyllus* indicates that long-term protection has led to the partial recovery of the stable components of the plant community. These species play key roles in soil formation and erosion control. The dominance of the families Fabaceae, Asteraceae, Poaceae, and Brassicaceae is consistent with patterns reported from other arid and steppe regions of Iran and Khuzestan Province^{13, 14, 15, 16, 17, 18, 40, 41, 42}. Among them, the Fabaceae family is ecologically significant because of its ability to fix atmospheric nitrogen, thereby increasing soil fertility and

facilitating vegetation succession. Overall, these findings indicate that long-term protection in arid rangelands can effectively increase floristic diversity and richness, restore ecological functions, and improve vegetation stability. Similar results have been reported by ^{8, 43, 44, 45, 46} who demonstrated that human activities such as livestock grazing and agriculture contribute to habitat degradation and a decline in species richness and diversity.

Remote sensing analysis of vegetation and moisture dynamics

The findings of this study reveal a complex interaction between vegetation recovery and the persistence of water stress in the protected rangeland of Shush. Although vegetation indices such as the NDVI, EVI, and SAVI markedly increased from 2005–2025, the moisture-related indices (NDWI, NDMI, and MSI) exhibited the opposite trend. This apparent contradiction, which can be termed “asymmetric ecological recovery,” indicates that long-term protection has effectively reduced anthropogenic pressures and facilitated vegetation regeneration, yet the ecosystem remains constrained by increasingly limited water availability. An important contextual factor that must be considered is the influence of climate change and recurrent droughts in recent decades. Climate change, as one of the most pressing environmental challenges of the modern era, has had substantial impacts on water resources and agricultural systems worldwide. Owing to its distinct geographical and climatic characteristics, Khuzestan Province ranks among the regions most vulnerable to climate change and is experiencing a growing frequency and intensity of droughts. Climatic data over the past three decades (1990–2024) show a consistent rise in mean annual temperature and a significant decline in precipitation, posing multiple challenges for both natural ecosystems and human livelihoods. Since the early 1990s, the mean annual temperature has steadily increased, and during summer, temperatures above 45 °C have become common. This warming has intensified surface evapotranspiration, directly depleting water resources. The increase in temperature has not only reduced surface water but also decreased groundwater recharge due to lower rainfall infiltration and excessive water extraction. Rainfall records also demonstrate a noticeable reduction in total annual precipitation, with a shift from regular, prolonged rainfall toward irregular, short-duration convective storms. These changes have lowered the groundwater recharge capacity, reduced surface runoff, and increased soil erosion and water loss during heavy rain events. Moreover, recent studies have shown that Khuzestan, particularly the nearest synoptic station to the study area, experienced its driest years between 2008 and 2016, according to the total storage deficit index (TSDI) ⁴⁷. These climatic shifts provide a critical backdrop for interpreting the vegetation–moisture dynamics observed in this study. The contrasting vegetation and moisture trends observed in Shush rangeland are, therefore, not only ecological responses but also reflect regional climatic stress. This pattern is consistent with findings from large-scale ecological restoration projects. For example, Sun et al. ⁴⁸ reported that afforestation and grassland restoration programs on the Loess Plateau of China, while promoting regional greening, simultaneously caused severe declines in river discharge and groundwater levels due to increased evapotranspiration. Although their “engineered greening” differs from the natural and gradual recovery observed in Shush, both cases provide crucial insight: vegetation expansion in arid regions does not necessarily enhance hydrological stability and may, paradoxically, intensify drought stress. Conversely, several studies highlight that under certain conditions, positive synergies between vegetation and water availability can occur. Cui and Shi ⁴⁹ demonstrated that climate change in northern China may simultaneously increase vegetation cover and reduce soil moisture through enhanced local evapotranspiration. Similarly, Wang et al. ⁵⁰ reported that appropriate management of river flow in the Tarim Basin, an extremely arid region, can foster simultaneous increases in riparian vegetation and soil moisture. These findings emphasize that access to external or stable water sources can disrupt the typical “greener but drier” pattern. In the present study, the higher VMRI values observed near the Karkheh River further confirm that sustainable hydrological interactions are vital to maintaining ecosystem resilience in arid landscapes. The diversity of plant species that thrive under these extremely dry conditions also demonstrates the adaptive capacity of vegetation to cope with water scarcity. Plants in arid zones have evolved a range of morphological, physiological, and biochemical strategies to survive drought stress ^{51, 52, 53, 54}. Leaves, the main organ for transpiration, are crucial indicators of water stress and exhibit adaptive traits such as increased thickness, high tissue density, and reduced surface area ⁵⁵. Leaf size, which directly influences photosynthetic efficiency, is also closely linked to drought tolerance⁵⁶. A large proportion of the identified species in the study area are short-lived annuals (67%), which represents an adaptive life-history strategy to avoid prolonged exposure to water stress. The high proportion of annual species in this area compared with the overall percentage of such species in Khuzestan Province (33%)⁴¹ highlights the harsh environmental conditions of the region. Short-lived plants usually dominate dry and low-rainfall areas; they complete their life cycle rapidly and disappear after seed production³⁹. Recent studies in other plain areas of Khuzestan Province have also shown that annual herbaceous species consistently form the dominant vegetation cover ^{13, 14, 15, 16, 17, 18, 40}. The remaining species are perennial herbs (20%), shrubs (7%), and subshrubs (6%). Although these plants usually disappear from the landscape during the hot season, they play an important role in soil formation and the enrichment of soil organic matter¹³. Moreover, perennial shrubs present structural and reproductive traits suited to aridity, including woody stems, spinescence, small leaves, dense trichomes, ornamented or hairy seeds, abundant achene production, and deep root systems. Examples include spiny species such

as *Astragalus fasciculifolius*, *Astragalus ensifer*, *Capparis spinosa*, *Echinops dichorus*, and *Fagonia bruguieri* and pubescent species such as *Astragalus obtusifolius*, *Convolvulus oxyphyllus*, and *Convolvulus kotschyanus*. These traits collectively increase drought resistance and ensure the persistence of native vegetation under severe arid stress. Spatial analysis supports these ecological interpretations. Cluster 2 (increased vegetation but decreased moisture) likely represents areas where drought-tolerant species have expanded at the expense of remaining soil moisture, whereas Cluster 4 (simultaneous decline in vegetation and moisture) identifies critical degradation zones where ecological thresholds have been surpassed. These patterns correspond well with ⁵⁷, who emphasized that sustained access to water resources is central to ecosystem resilience under climatic stress. In summary, the contrasting trajectories of vegetation and moisture dynamics in Shush rangeland underscore that protection alone is insufficient to counteract the prolonged effects of drought and climate change. While fencing and protection have maintained the potential for vegetation recovery, the realization of this potential remains severely constrained by water scarcity. As Huang and Zhai ⁵⁸ argued, postdrought recovery involves numerous ecological and hydrological challenges. The present study extends this perspective by demonstrating that even when apparent greening occurs, the underlying hydrological stability may remain compromised. These findings call for a strategic shift in management approaches for protected drylands, moving beyond the goal of simply increasing vegetation cover toward an integrated framework that jointly enhances vegetation vitality and water resource sustainability.

Conclusion

Arid and semiarid ecosystems are increasingly vulnerable to environmental stressors and climate change, making them fragile ecosystems that are severely limited by harsh environmental conditions such as water scarcity, extreme temperatures, and anthropogenic pressures. These areas highlight the critical importance of vegetation restoration for maintaining the ecological balance, combating desertification, and enhancing biodiversity. Native plant species in these regions exhibit remarkable adaptations to harsh conditions and play key roles in soil stabilization, microclimate regulation, and local hydrological cycles. Thus, the identification, monitoring, and conservation of these species are highly important. In this study, although the recent floristic changes indicate an increasing presence of xerophytic (drought-tolerant) species, this trend should not be interpreted merely as a sign of degradation. In contrast, this reflects the remarkable capacity of the ecosystem for self-organization and natural recovery under harsh and stressful environmental conditions. The establishment of these stress-adapted species demonstrated that even in arid rangelands, ecological processes such as succession and adaptation continue to operate, gradually leading to new functional stability.

This study demonstrated that the application of advanced remote sensing tools, particularly cloud-based platforms such as the Google Earth Engine, is an effective and reliable method for long-term monitoring of vegetation dynamics across various spatial and temporal scales. Vegetation and moisture indices such as the NDVI, EVI, and NDWI provide valuable information regarding canopy cover, chlorophyll content, and soil and plant water status. The findings of this study show that despite significant vegetation recovery over two decades of protection in the Shush Reference Basin, water scarcity remains a major challenge. This paradoxical trend can be described as "asymmetric ecological recovery," where long-term protection has facilitated vegetation regeneration, but the ecosystem still faces significant water limitations.

Furthermore, this research highlights the importance of conserving water resources and promoting sustainable hydrological interactions to increase ecosystem resilience in arid regions. Areas near the Karkheh River were identified as more resilient, with higher vegetation–moisture resilience index (VMRI) values, highlighting the critical role of stable hydrological interactions in supporting vegetation recovery. These findings indicate that effective management of water resources can simultaneously improve vegetation cover and soil moisture. However, this study also has limitations, particularly regarding the effects of climatic changes and human pressures on water resources in the Shush region. Future research could expand on predictive models to assess the impact of climate change on vegetation and water resources in these areas, providing insights into potential management strategies to cope with drought and water scarcity.

In conclusion, this study highlights the importance of developing targeted conservation strategies, implementing long-term ecosystem monitoring, integrating advanced remote sensing technologies to promote sustainable management, mitigating land degradation, and enhancing the resilience of fragile arid and semiarid ecosystems. The results of this study can guide the design of adaptive management strategies that aim to improve both vegetation vitality and water resource sustainability, offering insights into the future of ecological restoration in these critical regions.

Data availability

Data are contained within the article

Reference

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Contributions

M.D.: Author of the main text; conceived the idea and designed the study, conducted floristic studies. involved in data collection and analysis, methodology, formal analysis, and research methods. **K.H.:** conceptualization; formal analysis; data Visualization, made tables and figures, and was involved in text writing. **S.P.:** formal analysis; writing review and editing, and other work. **S.H.A.:** Participated in field data collection. All authors have read and agreed to the published version of the manuscript.

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Ethics declarations

Competing interests

The authors declare no competing interests.

Ethics approval

All authors have read, understood, and complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors. "Plants were collected under the necessary permissions issued by the Natural Resources and Watershed Management Organization of Iran and the Research Institute of Forests and Rangelands (RIFR), Agricultural Research, Education and Extension Organization (AREEO). The study area is not part of the protected areas managed by the Department of Environment of Iran. All fieldwork and plant collection were conducted in accordance with the applicable institutional and national regulations of Iran."

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