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Monitoring the Impact of Precipitation on Vegetation Dynamics and Species Diversity in a Semi-Steppe Rangeland in Iran

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ABSTRACT

Aims: Despite the critical role of semi-steppe rangelands in Iran's agro-pastoral systems, long-term quantitative data on vegetation dynamics in response to climatic variability, particularly in the semi-steppe rangelands of Bardemar of Khuzestan Province, remain scarce.
Materials & Methods: This study addresses this gap by using a random systematic method, providing a comprehensive 7-year longitudinal dataset (2018-2024) that tracks changes in vegetation cover, productivity, and diversity. In four transects, a total of 40 plots, each measuring 1 square meter, were established to determine the density, vegetation canopy cover, plant species, and above-ground biomass. Margalef and Menhinick indices were calculated to compare species richness, and Shannon-Wiener and Simpson indices were used to assess species diversity. Finally, the Repeated Measures method was used to compare the biodiversity.
Findings: The results showed that the percentage of canopy cover varied significantly between years, ranging from 18.80% to 37.10%, while above-ground production fluctuated between 140.59 and 400.49 (kg.ha^{-1}). The highest values were recorded in 2019 and 2023, corresponding to precipitation levels of 312.75 mm and 320.65 mm, respectively. Species richness (Taxa) averaged 2.5–3.6 species per plot, and the Shannon diversity index ranged from 0.76 to 1.05 across the study period. Significant correlations were found between precipitation and both vegetation cover ($r = 0.704$, $p = 0.005$) and production ($r = 0.760$, $p = 0.002$).
Conclusion: This Study provides an empirical baseline for climate-responsive rangeland management in semi-arid regions. Implement short-term rest during wet years (rainfall ≥300 mm) to enable natural seed production and recovery of the soil seed bank, offering a low-cost strategy for long-term rangeland restoration.

Keywords: Rangelands; Random Systematic Method; Canopy Cover; Khuzestan.

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Introduction

One of the primary factors disrupting ecosystem functioning and contributing to global biodiversity loss is the invasion of plants [1, 2, 3]. Rangelands host a significant proportion of global biodiversity, despite covering only a fraction of continental areas [4,5,6]. Species diversity is an index for the sustainability of rangeland ecosystems [7]. These ecosystems constitute 28% of natural and semi-natural habitats and are second only to forests in importance [8]. Obtaining basic and timely information on rangelands requires long-term and continuous measurements of vegetation cover, or, in other words, their sequential distribution over a period of several years [6]. Habitat diversity can be calculated to achieve sustainable rangeland management, which helps protect plant species, ensures stability, and prevents degradation [9]. Over the years, several formulas have been proposed to measure species diversity based on the relative abundance and number of species. Biodiversity at different levels, including genes, species, and ecosystems, is a valuable concept in ecology and vegetation management. It is vital for assessing how ecosystems function and their impact on habitats [10]. Species diversity is one of the appropriate characteristics in the region and indicates changes in rangelands [11]. By studying and measuring species diversity, the dynamics of plant communities and the distribution of species in the environment can be examined. With an emphasis on the dynamics of these communities, necessary management recommendations can be provided [12,13]. The study of relationships and changes in species diversity of the community and biomass under grazing disturbance is one of the most important elements in the restoration and rehabilitation of rangeland ecosystems [14]. Many researchers have conducted extensive studies on the effects of grazing in rangelands. Some studies have shown that grazing not only alters the physical and chemical properties of rangeland soil but also indirectly affects soil fauna and microbial communities [15]. These effects interact in rangeland ecosystems through a specific form of dependence. A review of the types of biodiversity indicators has also been provided by researchers [16, 17, 18]. The results of the research by Fakhimi et al. [19] investigating the effect of grazing on the vegetation cover of the Nadushan steppe rangelands in Yazd showed that grazing has led to a reduction in the canopy cover of palatable plants, as well as a decrease in rangeland production and litter accumulation. Dinarvand et al. [20] conducted a study to assess species diversity and vegetation cover richness in two dust source areas in Khuzestan Province by conducting a field survey of 5 permanent 100-meter transects with 50-meter intervals in a random-systematic manner from 2017 to 2019. The results showed a significant difference between the time of water distribution and the times without irrigation in Mansourieh Wetland. Additionally, the Simpson and Shannon indices indicated that after water distribution, diversity gradually increased. Dinarvand et al. [21] conducted a study to assess the trend of vegetation cover changes in the dust source area of Khuzestan Province over 4 years in the Hanitiyeh Region. The results showed a significant difference between the mean indices of dominance, Simpson, and Shannon, as well as the coverage percentage and the number of species, across different harvest years in the spring. The research by Fakhimi et al. [22] revealed that the percentage of vegetation cover at the site varied from 22.15% to 32.76% in different years. The amount of above-ground biomass in the site varied from 693 to 1025.6 ($kg.ha^{-1}$) during the survey period, and the production rate in the protected site varied from 1215 to 1908 ($kg.ha^{-1}$) of dry matter per hectare in different years. Studies by Holland and Winkler [12] on three islands in freshwater lakes Winnipesaukee and New Hampshire, regarding changes in vegetation cover and diversity indices over 33 years, showed that Shannon's species diversity index increased on each island. The dominant herbaceous species also exhibited a distinct change in the region. Dinarvand et al. [23] evaluated the changes in the native vegetation cover in the dust source area of Khuzestan under different irrigation systems and rainfall patterns in the afforestation areas. The results indicated a significant difference between the mean dominance index, Simpson and Shannon indices, and vegetation cover, as well as the number of species across different years. Akbarzadeh and Mirhaji (2006) investigated changes in vegetation cover in the semi-steppe rangelands of Rudshur over 9 years. They showed that, from the second year following a five-year drought, the canopy cover of perennial species decreased by 40% [24].

While most studies focus on short-term effects, this research addresses the global knowledge gap in long-term ecological monitoring of semi-arid rangelands. Our work innovatively integrates multi-year vegetation dynamics, precipitation threshold analysis, and soil seed bank resilience assessment to establish a predictive framework for climate-adaptive rangeland management contributing directly to global efforts in combating dryland degradation under changing climate patterns. This study aimed to monitor changes in vegetation cover, production, and biodiversity indices over a 7-year period (2018–2024) and to quantify the relationship between precipitation fluctuations and these ecological parameters.

Materials & Methods

Study Area

The study area is located at the geographical coordinates of 32° 07′ 54″ to 32° 08′ 72″ North latitude and 49° 01′ 85″ to 49° 02′ 14″ East longitude (Figure 1). This site is located in Khuzestan Province, Masjed-

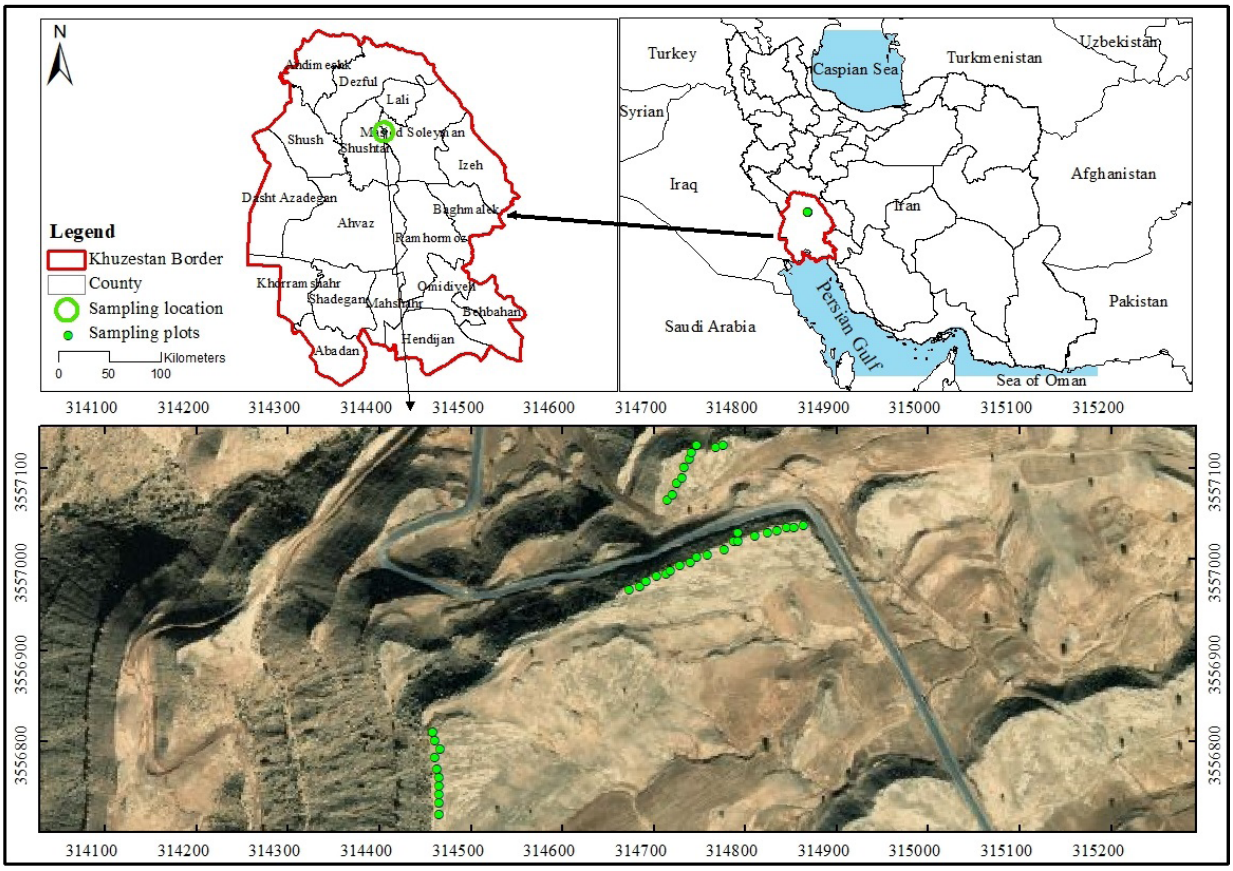

Figure 1) The study area in Khuzestan Province, Iran.

Soliman County, and Indika District, with an area of 10 hectares, at an altitude of approximately 421 to 442 meters above sea level. This area is also situated on the main road from Ahvaz to Masjed-Soliman, on the Indika side, 15 km from Masjed-Soliman City, and within the Haft Shahidan Region. This site is situated in a mountainous area with a dominant west-east and north-south orientation, characterized by slopes ranging from approximately 20% to 60%. The rangelands in this region are among the few with an audited lowland plan and are utilized by the region's nomads through a collective utilization system. The grazing season in this region spans from January to May, encompassing both winter and spring. The predominant grazing livestock are sheep and goats of the native Bakhtiari breed.

The mean annual precipitation of the area is 234.68 mm using data from the Masjed-Soliman Station (Figure 2). The annual variations in the studied area indicate irregular annual changes in precipitation during the survey years [4].

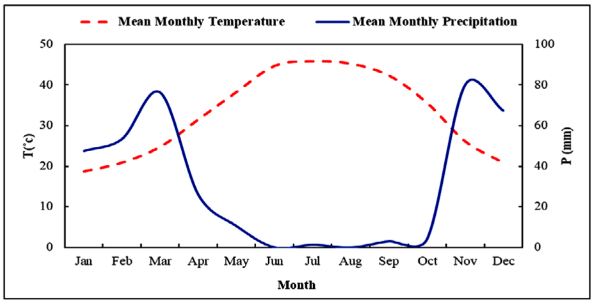

Figure 2) Ombrothermic graph prepared using 2018–2024 data from Masjed-Soliman Synoptic Station.

The dominant plant types at the Bardemar Site are *Echinops dichorus*, *Convolvulus oxyphyllus*, *Hyparrhenia hirta, Centaurea virgata, Acanthophyllum khuzistanicum*, and important companion species within the site include *Crepis sancta, Plantago ovata,* and *Scabiosa flavida*. Savannah areas do not specifically exist in Iran, but regions with vegetation similar to grasslands and hot steppes are found. These areas include temperate grasslands and hot steppes, floodplain grasslands and hot steppes, and montane grasslands and shrublands [24].

Methods

Based on the field survey, the Bardemar Site was identified in the Indica site. Vegetation sampling was conducted using a random systematic approach across four permanent 100-meter transects, spaced 100 meters apart. Along each transect, 10 plots (each 1 m^2) were systematically placed at 10-meter intervals, resulting in a total of 40 plots per year over the 7-year study period (2018–2024) [25,26]. This design ensured spatial representation and temporal consistency. In each plot, the following parameters were recorded: Canopy cover (%) via visual estimation, density by counting all individual plant bases, Above-ground biomass ($g.m^{-2}$) using the double-sampling method (destructive harvesting of a subset of plots correlated with visual estimates), Species identity and palatability class (I, II, III) based on local ecological knowledge and published resources [27]. The statistical analysis was conducted using a comprehensive approach to evaluate temporal changes and relationships within the data. All biodiversity indices, including species richness, Shannon-Wiener, Simpson, Evenness, Margalef, and Menhinick, were calculated annually using PAST software (v4.03). The condition of the rangeland was assessed using two methods, including the four-factor and the modified six-factor methods. For the rangeland condition trend, two comparative and scale methods were used [13]. The survey was conducted over a period of 7 years, from 2018 to 2024, during the plant's growing season. After collecting data over different years, the Kolmogorov-Smirnov test was used in SPSS 27 software to examine the normality of the cover percentage data. Finally, the Repeated Measures method was used to compare the plant diversity indices of 7 years (2018-2024). This test is used to analyze measurements taken more than twice from the same experimental units. If the repeated measures test was significant, the LSD test was used to compare the means of the measurements [28]. To quantify the relationship between climatic factors and vegetation parameters, a Pearson correlation analysis was conducted. The study assessed the linear correlation between annual precipitation (mm) and mean temperature (°C) as independent variables, and total vegetation cover percentage and total above-ground production (kg.ha^{-1}) as dependent variables. The analysis was performed using SPSS software. The significance level was set at α = 0.05, and the correlation coefficients (r) along with their two-tailed p-values are reported in Table 7. This statistical approach allowed us to determine the strength and direction of the influence of climatic variability on the rangeland's primary productivity.

Findings

The list of vegetation parameters and the amount of above-ground biomass of the plant species present in the sampling area at the Bardemar Site, along with the canopy cover percentage and some vegetation cover indices, is presented in Table 1. The results related to vegetation cover and species diversity indices are also presented in Table 2. The results of the statistical analysis of biodiversity indices of the measurements at the Bardemar Site are presented in Table 3. The results indicate a significant difference at the 1% level between the values of the studied indices across different years. Figure 3 also shows the results of the comparison of the LSD mean of vegetation cover and species diversity indices.

According to the results regarding the changes in the Taxa index over 7 years (2018-2024), the highest values of this index were recorded in 2021, 2023, and 2024, while the lowest value was observed in 2018. This index has intermediate values in 2019, 2022, and 2020 (from highest to lowest, respectively). Despite having equal averages, this index was categorized into groups A and B in 2019 and 2022, respectively, due to the difference in the upper and lower bounds of the variations (Figure 3-A).

The changes in the mean values of the Margalef index over the study years indicate that the highest value occurred in 2021, followed by 2022 and 2024. The values of this index in the years 2018, 2019, 2020, and 2023 were slightly lower and ranked in the lower positions (Figure 3-B). Figure 3-D shows the changes in the Simpson index over the period. According to this chart, the highest average of this index is in the years 2019 and 2021, followed by 2023, 2024, 2022, and 2020, respectively. The year 2018 has the lowest value of the Simpson index. Based on the results related to the change in the average Shannon index over a period of 7 years (2018-2024), the highest values of this index, in descending order, were observed in 2021, 2023, 2024, and 2019, while the lowest value was recorded in 2018. This index showed intermediate values in the years 2022 and 2020 (Figure 3-E).

The average Evenness index generally shows a decreasing trend over the 7 years (2018-2024). Specifically, the average value of this index from highest to lowest was recorded in the years 2018, 2019, 2020, 2021, 2022, 2023, and 2024, respectively (Figure 3-F).

According to the graph of changes in the Menhinic index (Figure 3-G), the highest average value of this index was observed in 2022, 2018, and 2021, while the lowest value occurred in 2019 and 2023. The years

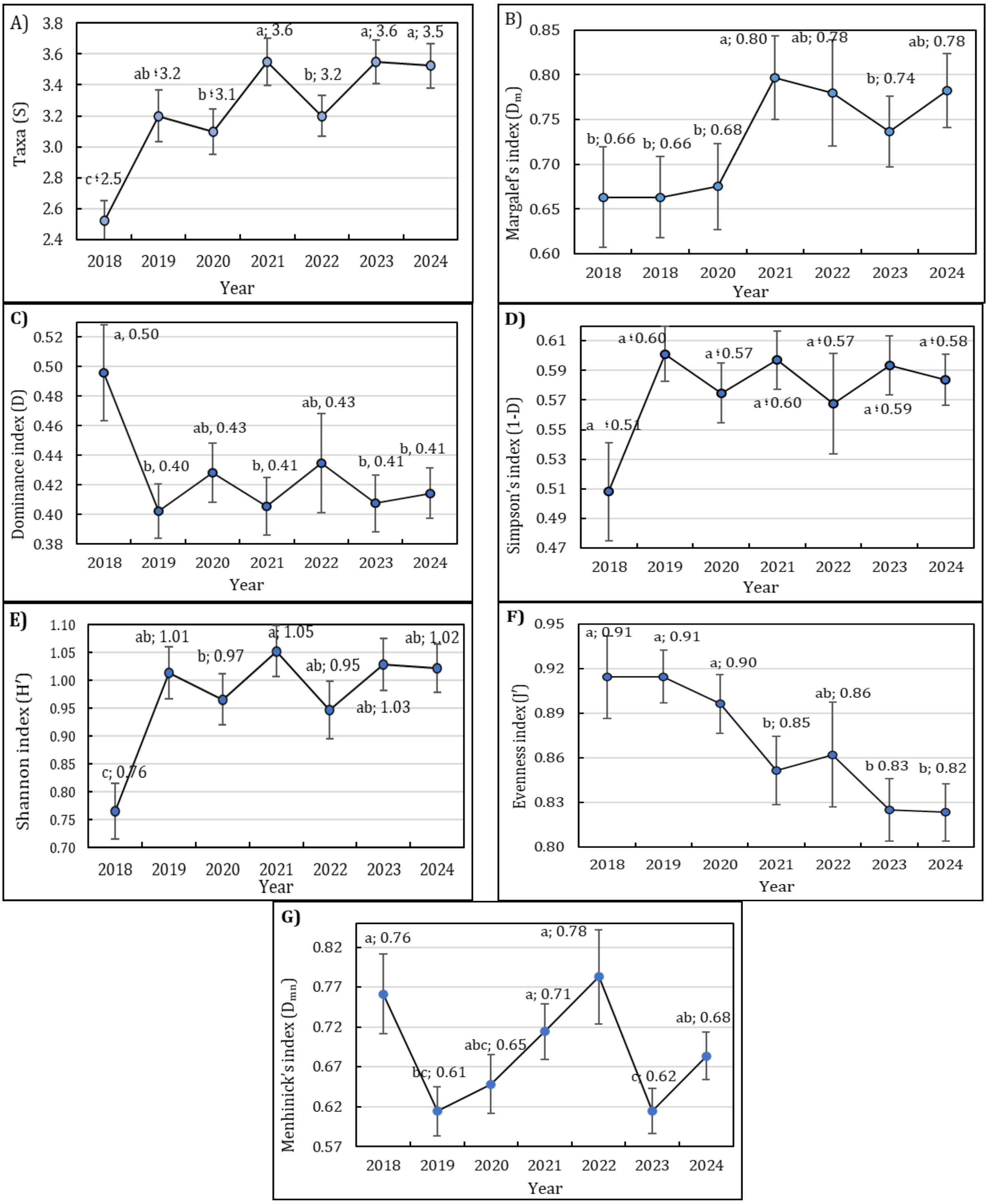

Figure 3) Graph of mean variations in vegetation cover and species diversity indices; A) species richness index, B) Margalef richness index, C) dominance index, D) Simpson diversity index, E) Shannon diversity index, F) Evenness index, G) Menhinick index at the Bardemar Site, Khuzestan Province, Iran.

2020 and 2024 have intermediate values. The results of the rangeland condition assessment (based on two four- and six-factor methods) and rangeland trend (by scale and deductive methods) during the survey period indicate that the area exhibited a poor to fair condition and a negative trend (Tables 4, 5, and 6).

The results of the Pearson correlation (Table 7) indicate a positive and significant relationship

Table 1) Percentage of vegetation parameters and amount of aerial biomass (g.m^{-2}) at the Bardemar Site, Khuzestan Province, Iran.

Variables	Year						
	2018	2019	2020	2021	2022	2023	2024
Total Canopy Cover (%)	18.80	3.40	26.60	27.70	24.5	37.10	29.70
Litter (%)	1.57	2.00	2.00	2.00	6.00	2.70	3.60
Rock and Gravel (%)	27.20	44.00	55.00	53.00	38.00	35.10	34.80
Bare Soil (%)	46.17	24.00	16.00	16.00	32.00	25.10	31.90
Canopy Cover in Vegetation Class 1 (%)	0.10	0.03	0.44	0.60	0.01	0.18	0.19
Canopy Cover in vegetation class II (%)	6.10	5.46	4.55	5.49	7.61	6.90	6.18
Canopy Cover in vegetation class III (%)	0.00	1.12	0.92	1.12	2.70	1.67	1.72
Canopy Cover of Gramineous Plants (%)	3.22	3.06	3.21	3.61	4.10	3.94	2.90
Canopy Cover of Herbaceous Plants (%)	0.47	1.58	2.04	2.45	2.89	2.42	2.57
Canopy Cover of Shrub Plants (%)	2.50	1.98	0.66	1.15	3.33	2.40	2.63
Canopy Cover of Annual Plants (%)	12.57	23.81	20.66	20.50	14.18	28.34	21.58
Canopy Cover of Perennial Plants (%)	6.20	6.61	5.91	7.21	10.32	8.76	8.10
Total Above-Ground Biomass	172.94	400.49	280.99	306.47	140.59	197.33	146.02
Above-Ground Biomass of Class I Vegetation	0.54	0.48	3.09	3.23	76.32	145.19	97.39
Above-Ground Biomass of Class II Vegetation	12.16	138.42	207.05	91.27	61.60	48.80	45.42
Above-Ground Biomass of Class III Vegetation	0.00	19.66	9.03	70.06	2.67	3.34	3.21
Above-Ground Biomass of Graminaceous	90.80	43.15	93.47	55.38	21.83	23.62	21.57
Above-Ground Biomass of Herbaceous Plants	10.99	102.20	103.75	89.29	31.82	19.06	18.82
Above-Ground Biomass of Shrub Plants	14.21	14.21	21.95	19.89	10.75	9.93	8.78
Above-Ground Biomass of Annual Plants	241.93	241.93	61.82	141.91	71.17	144.71	96.85
Above-Ground Biomass of Perennial Plants	158.56	158.56	219.17	164.56	64.40	52.61	49.17

Table 2) Descriptive statistics of vegetation cover and species diversity indices at the Bardemar Site, Khuzestan Province, Iran.

Year	Statistical Index	Species Richness	Dominance	Simpson	Shannon	Evenness	Manhinik	Margalef
2018	Mean	2.53	0.50	0.51	0.76	0.91	0.76	0.66
	SD	0.78	0.21	0.21	0.32	0.18	0.32	0.36
	Min	1.00	0.00	0.00	0.00	0.61	0.32	0.00
	Max	4.00	1.00	1.00	1.40	1.28	1.50	1.44
2019	Mean	3.20	0.40	0.60	1.01	0.91	0.61	0.66
	SD	1.04	0.12	0.12	0.30	0.11	0.19	0.29
	Min	2.00	0.17	0.35	0.61	0.65	0.26	0.24
	Max	5.00	0.65	0.83	1.66	1.06	1.29	1.48
2020	Mean	3.10	0.43	0.57	0.97	0.90	0.65	0.68
	SD	0.93	0.13	0.13	0.29	0.12	0.23	0.30
	Min	2.00	0.23	0.24	0.49	0.54	0.26	0.24
	Max	5.00	0.76	0.77	1.53	1.07	1.27	1.30
2021	Mean	3.55	0.41	0.59	1.05	0.85	0.71	0.80
	SD	0.96	0.12	0.12	0.29	0.14	0.22	0.30
	Min	2.00	0.20	0.32	0.61	0.56	0.26	0.25
	Max	5.00	0.68	0.80	1.55	1.10	1.09	1.31
2022	Mean	3.20	0.43	0.57	0.95	0.86	0.78	0.78
	SD	0.82	0.21	0.21	0.32	0.22	0.37	0.37
	Min	2.00	0.35	0.09	0.26	0.32	0.25	0.00
	Max	5.00	0.91	1.35	1.58	1.62	2.18	1.82
2023	Mean	3.55	0.41	0.59	1.03	0.83	0.62	0.74
	SD	0.90	0.12	0.12	0.30	0.13	0.18	0.25
	Min	2.00	0.19	0.36	0.61	0.53	0.26	0.25
	Max	5.00	0.65	0.81	1.63	1.06	1.02	1.17
2024	Mean	3.53	0.41	0.59	1.02	0.82	0.68	0.78
	SD	0.91	0.11	0.11	0.27	0.12	0.19	0.26
	Min	2.00	0.19	0.41	0.66	0.57	0.36	0.29
	Max	5.00	0.59	0.81	1.64	1.04	1.30	1.56

Table 3) Univariate analysis of repeated measures of biodiversity indices at the Bardemar Site, Khuzestan Province, Iran.

Variable	Source	Sum of Squares	Degree of Freedom (df)	Mean Square	F-Value	Significance Level (Sig.)	Eta Squared
Species richness (Taxa)	Intercept	2931.56	1	2931.56	1331.42	0.00	0.97
	Error	85.87	39	2.20			
Dominance	Intercept	90.27	1	90.27	2683.09	0.00	0.99
	Error	1.28	38	0.03			
Simpson	Intercept	51.05	1	51.05	1503.48	0.00	0.97
	Error	1.32	39	0.03			
Shannon	Intercept	263.64	1	263.64	1394.37	0.00	0.97
	Error	7.37	39	0.19			
Evenness	Intercept	211.75	1	211.75	5086.04	0.00	0.99
	Error	1.62	39	0.04			
Manhinik	Intercept	132.76	1	132.76	982.19	0.00	0.96
	Error	5.27	39	0.14			
Margalef	Intercept	148.52	1	148.51	763.15	0.00	0.95
	Error	7.59	39	0.19			

between precipitation, vegetation cover percentage, and production at the 1% level. Additionally, a significant negative relationship was observed between temperature, vegetation cover percentage, and production at the 1% significance level.

The results showed that the vegetation cover percentage in the studied site varied from 18.80% to 37.10% over different years, depending on the amount of precipitation. The amount of production in the studied site ranged from 140.59 to 400.49 ($kg.ha^{-1}$) of dry matter per hectare across different years, with the highest forage yield and canopy percentage observed in 2019 and 2023, corresponding to precipitation amounts of 312.75 and 320.65 mm, respectively. The 7-year average plant species density was 10437 plants per hectare.

Discussion

The findings of this study on precipitation thresholds (≥300 mm) are consistent with well-established patterns observed in other semi-arid rangelands worldwide, while simultaneously providing novel insights specific to the ecological context of Iranian semi-steppe ecosystems. The vegetation composition was dominated by annual or short-lived species (such as *Erucaria hispanica, Bromus scoparius, Medicago polymorpha, Stipa capensis*). Although these species exhibit short lifespans and rapid turnover and are quickly removed with the onset of the hot season, they contribute significantly to the phenomenon of soil formation and the enhancement of the percentage of organic matter in the substrate. Shrubs play an essential role in soil protection and preventing all types

Table 4) Rangeland condition factor scores based on the four-factor method during the years studied at the Bardemar Site, Khuzestan Province, Iran.

Investigated Factor	2018	2019	2020	2021	2022	2023	2024
Soil Factor	14	12.8	12	15	15	16.8	15.5
Vegetation Attributes	5.8	6	4.8	5.5	4.5	6.5	4.9
Species Composition and Age Classes	5	6.1	4.5	5.5	5	6	5.5
Plant Vigor and Vitality	4	5.3	4.5	5	6	5.5	5.5
Total Score	25.8	30.2	25.8	31	30.5	34.8	31.4
Condition Class	Poor	Poor	Poor	Moderate	Poor	Moderate	Moderate

Table 5) Rangeland condition factor scores based on the six-factor method during the years studied at the Bardemar Site, Khuzestan Province, Iran.

Investigated Factor	2018	2019	2020	2021	2022	2023	2024
Canopy Cover	5.3	5.84	4.3	7.5	7	11.2	8.5
Canopy Cover Composition	12	15.01	13	15.5	11	12.5	12
Soil Conservation	12	17.98	15	20	17	18	17
Forage Production	5.5	9.62	9.5	10.5	4.5	6.5	5
Plant Propagation	11	11.67	13	12	11	12	11
Litter Recurrence	0.5	0.95	0.5	0.5	1	1	1
Total Score	46.3	61.07	54.85	66	51.5	61.2	54.5
Condition Class	Poor	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate

Table 6) Rangeland trend changes factor based on the scale and analogy method at the Bardemar Site, Khuzestan Province, Iran.

Method	Trend	Positive Scores	Negative Scores	Algebraic Sum of Scores	Conditions Trend
Moqaddam Method	Vegetation Canopy	0	-0.2	-0.2	Negative
	Soil	0	-1.5	-1.5	Negative
Deductive-Inductive Method	Vegetation Canopy	0	-1.25	-1.25	Negative
	Soil	0	-5	-5	Negative

Table 7) Results of correlation between Precipitation and Temperature with Vegetation cover (%) and Production at the Bardemar Site, Khuzestan Province, Iran.

		Correlations			
		Precipitation	Temperature	Production	Vegetation cover (%)
Precipitation (mm)	Pearson Correlation	1	-0.925**	0.760**	0.704**
	Sig. (2-tailed)		0.000	0.002	0.005
Temperature (°c)	Pearson Correlation	-0.925**	1	-0.603*	-0.510
	Sig. (2-tailed)	0.000		0.022	0.062
Production	Pearson Correlation	0.760**	-0.603*	1	0.798**
	Sig. (2-tailed)	0.002	0.022		0.001
Vegetation cover (%)	Pearson Correlation	0.704**	-0.510	0.798**	1
	Sig. (2-tailed)	0.005	0.062	0.001	

**: significant at the 1% probability level of soil erosion [29]. In the Bordmar Region, there are shrub species such as *Convolvulus oxyphyllus, Scrophularia deserti, Echinops dichorus, and Hyparrhenia hirta*. These species can be used to restore and improve rangeland in the area by producing seedlings or sowing seeds. There are three endemic species in the study area: *Acanthophyllum khuzistanicum*, *Centaurea lurestanica, and Scabiosa flavida* [30]. The first two species are shrub forms, and the third species was an annual, which needed to be protected before it became extinct in the area. It is worth noting that seeds of these species were collected and sent to the National Plant Gene Bank of Iran. The species *Anthemis susiana*, *Teucrium capitatum*, and *Plantago psyllium* are among the medicinal plants used by local people in the region. The degraded state (poor to fair condition) of this site reflects a common global challenge in semi-arid rangelands, where overgrazing and climate variability interact to reduce ecosystem function. The assessment of soil indices revealed no significant changes in these indices throughout the evaluation period. Statistical analysis revealed that, during the study years, most rangeland assessment indices exhibited significant differences at the 1% level. The results of the mean comparisons showed that the highest vegetation cover and production were observed in 2019 and 2023, while the lowest values were recorded in 2018.

Overall, during the years under study, despite the lack of any restoration activities in the rangeland, the increase in precipitation levels had a positive impact on the rangeland condition in various aspects. The persistent soil seed bank demonstrates a universal resilience mechanism in drylands [31], offering a critical leverage point for restoration strategies worldwide. It also indicates that the limiting factor for the growth of rangeland plants in these areas is the lack of precipitation, which is consistent with the findings of Fakhimi et al. [22] and Dinarvand et al. [20]. Bagheri et al. [32] also stated that the presence of annual plants and the growth of grasses, which mainly cover the region, depend on short-term moisture. Therefore, under current circumstances, where climate change and potential precipitation decreases are challenges, the best option for rangeland restoration is the use of native perennial species. The analysis of the trend and condition of the rangeland also indicates that the area is in poor condition with a negative trend, which is consistent with the findings of Madadizadeh et al. [33]. In wetter years, the increase in rainfall led to a rise in the percentage of vegetation cover and plant vitality, which significantly contributed to the improvement in rangeland condition.

Conclusion

Degraded semi-arid rangelands, such as those studied in this research, represent a significant global challenge. However, their residual regenerative potential highlights an opportunity for climate-adaptive management. The findings of this study provide clear evidence to accept the proposed research hypotheses. The analysis confirms that interannual precipitation variability serves as the primary driver of significant changes in vegetation canopy cover, biomass production, and biodiversity indices. A strong positive correlation was observed between rainfall and vegetation productivity, while temperature exhibited a negative influence. The rapid recovery of annual species during high-rainfall years demonstrates the persistence of a resilient soil seed bank, highlighting the rangeland's innate capacity for regeneration despite its chronically degraded state. However, the overall condition remained poor to fair, with a negative trend, and climatic fluctuations induced measurable short-term ecological responses. These results highlight the crucial role of precipitation in shaping the dynamics of semi-arid rangelands and underscore the need for climate-adaptive management strategies to leverage natural recovery mechanisms during favorable periods.

Based on the findings of this study, the following practical management recommendations are proposed to enhance rangeland resilience and productivity:

- Climate-Adaptive Grazing Management: Livestock grazing should be restricted during high-rainfall years (≥300 mm) to facilitate complete seed set and natural recruitment of dominant species, thereby reinforcing the soil seed bank and promoting vegetation recovery.
- Soil Seed Bank Conservation: Areas with high densities of annual and perennial seed-producing species should be protected to maintain their regenerative potential and support ecosystem stability under variable climatic conditions.
- Native Species Utilization: Restoration efforts should prioritize resilient native perennial species (e.g., *Convolvulus oxyphyllus, Hyparrhenia hirta*) to improve soil stabilization, enhance biodiversity, and ensure long-term adaptation to local environmental stresses.
- These evidence-based strategies provide a scalable framework for mitigating degradation and improving ecological resilience in semi-arid rangelands facing climate uncertainty.

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