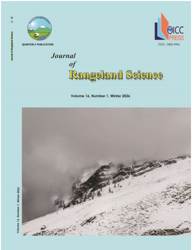

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The Impact of *Peganum Harmala* L. Invasion on the Density and Species Diversity of Native Plants

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Original Research

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Abstract:

Given the increased human activity, its destructive impacts on natural resources are no longer confined to specific regions. Among these impacts is the introduction of non-native and invasive plant species. The adverse effects of these species on natural and agricultural communities, human and livestock health, and ecosystem characteristics are significant, leading to continuous research in this field. In this study, the effects of varying frequencies of the invasive plant Peganum harmala L. on the density, composition, richness, diversity, and species dominance of native plants were examined in the rangelands surrounding the integrated livestock farming project for nomadic communities in the Zirkouh region of South Khorasan Province. Livestock presence and changes in plant composition were assessed using photographs taken in 2002, 2012, and 2022. Following the initial assessment with 0% frequency (enclosure area), plots with 15%, 30%, 45%, 60%, and 75% frequencies of the invasive plant were selected, with three representative zones chosen in each area. In each zone, twenty randomly placed four-square-meter plots were established. In each plot, density, plant cover percentage, litter percentage, bare soil and gravel percentage, and rangeland condition classes were determined. Based on the counted plant bases, indices of richness, species diversity (Shannon-Wiener and Simpson indices), species evenness (Pielou index), and species dominance (Simpson index) were calculated. The Jaccard index was employed to assess the species similarity. Statistical comparisons were made using one-way ANOVA and modified LSD means comparison tests. The results showed that the effect of frequency of P. harmala on the percentage of vegetation cover, litter, and soil and gravel, as well as the density of annual native plants in the area was significant ($p \leq 0.05$). The highest Shannon-Wiener diversity index (2.48) was calculated in the area with 45% frequency of the invasive plant. The highest species richness was observed in the areas with 15% and 45% frequency of the invasive plant (with 19 and 18 plant species, respectively). Due to the invasion of P. harmala, the density of annual native plants initially decreased and then increased. However, no significant change was observed in the density of perennial native plants. The results indicate that high livestock pressure favors annual plants.

Keywords: Grazing intensity, Non-native Species; Peganum harmala; Species diversity; Rangeland

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1. Introduction

The invasion of non-native species has been recognized as one of the greatest threats to global biodiversity, playing a significant role in global changes. The introduction of invasive species into an ecosystem represents a form of biological stress that is related to interactions among organisms and is exerted through mechanisms such as competition, herbivory, predation, parasitism, and disease. Invasive species have seriously threatened local natural resources and ecosystem biodiversity, leaving long-lasting damage (Panahande et al., 2019). Non-native species have demonstrated superior abilities compared to native species in exploiting environmental disturbances to their advantage. The highest densities and abundances of non-native species have been observed in the areas that have undergone the most significant changes due to human activities (Amini Eshkevari et al., 2020).Although invasive plant species possess characteristics such as rapid growth, high reproductive output, strong reproductive potential, high dispersal ability, great adaptability and competitiveness, and long seed viability, they have not been considered valuable for livestock grazing due to traits such as thorniness, the presence of essence or toxicity (Jangjou, 2009). Invasive alien plants, through competition with native species, have occupied space and resources, thereby threatening native biodiversity (Feng & Zhu, 2010). In the composition of vegetation in rangelands, toxic plants were also present. Although in certain cases, toxic plants dominated the rangeland vegetation, their abundance was primarily due to mismanagement of the rangeland in previous years (Moghadam, 2012).

Overgrazing has been identified as one of the main factors contributing to vegetation degradation and soil erosion in the arid and semi-arid rangelands of Iran, leading to changes in diversity, species composition, vegetation cover, and soil properties (Bakhshi et al., 2020; Mahmoudi et al., 2021). Alongside overgrazing, the occurrence of frequent droughts has resulted in the reduction or loss of many useful, nutritious, and palatable forage plants for livestock. This situation has promoted the growth and spread of less palatable plants, which are often toxic (Azarnivand & Zare Chahouki, 2008). Excessive grazing around water sources and livestock pens has led to the presence of unpalatable and undesirable species such as P. harmala (Karimpour et al., 2021). P. harmala belongs to the Zygophyllaceae family and has been classified as a toxic, invasive, and undesirable species in rangelands, with its presence serving as an indicator of rangeland degradation (Moghadam, 2012). P. harmala is one of the toxic and invasive plants in rangelands, and it has been reported to cause chronic to acute poisoning in various livestock, including sheep, cattle, and camels. All parts of the plant were reported to be toxic, leading to severe poisoning in domesticated animals. Symptoms of poisoning included tremors, excessive salivation, urinary frequency, staggering, and, in some cases, abortion and death of the livestock (Kuete, 2014; Li et al., 2017).

Research has shown that the alkaloid content in the seeds and roots of P. harmalais is higher, followed by the leaves and stems, and the presence of these alkaloids, along with other secondary metabolites, and explains the plant toxicity to animals (Apostolico et al., 2016). (Briske, 2017), after reviewing 865 scientific references, identified factors such as climatic regimes, wildfires, livestock grazing and browsing, increased CO_2 concentrations, and the conversion of rangelands to agricultural lands as significant contributors to the proliferation of undesirable plants. Among the articles reviewed, only 289 specifically addressed the relationship between livestock grazing and the invasion of these plants. In addition to grazing and climate, local disturbances such as mining, abandonment of low-yield rainfed farms, invasion of pests and plant diseases, and other factors may have facilitated the introduction, establishment, and spread of new plant species (Jangjou, 2009). Beyond examining the causes of invasive plant invasions in rangelands, studying the impact of toxic and unwanted plants on the native vegetation of rangelands has been of significant concern to rangeland managers for a long time (Briske, 2017). In certain regions of North America, southern Australia, and South Africa, P. harmala has been recognized as an invasive alien species, not only reducing biodiversity but also causing significant economic losses in the invaded areas (Abbott et al., 2008). This species has thrived in arid and semi-arid conditions, such as steppe regions and sandy soils, and its strong competitive ability, along with tolerance to drought and salinity, has led to its consideration as a wild rangeland species and a tool for erosion control (Li et al., 2021).

Plants like P. harmala can release phytotoxic allelochemicals into the environment, which not only suppress the growth of other plants but also alter the soil microbiota structure (Shi & Shao, 2022). Allelopathic compounds play a crucial role in biodiversity within ecosystems (Ricki Maryshany et al., 2018). (Bitchagno et al., 2022) reviewed research on the allelopathic effects of P. harmala on plants and insects. Various studies have examined the allelopathic and cytotoxic effects of P. harmala extracts on plants such as Arabidopsis thaliana (L.) Heynh (Álvarez Rodríguez et al., 2023), Avena fatua L. and Convolvulus arvensis L. (Sodaeizadeh et al., 2010), Triticum aestivum L. and Sinapis alba (Aslam et al., 2016), Lactuca sativa L., Triticum aestivum L., and Lolium perenne L. (Shao et al., 2013), and Zea mays (Liu et al., 2007). These studies indicated that P. harmala extracts reduced seed germination and negatively influenced seedling growth characteristics. However, no research has been found that specifically investigates the impact of P. harmala on vegetation cover and species diversity of native plants. Therefore, the present study aimed to assess the effects of varying levels of P. harmala frequency on the density, composition, richness, diversity, and dominance of native plant species in rangelands under livestock grazing, specifically in the area of the livestock consolidation project in Zirkouh County, South Khorasan Province, Iran.

2. Materials and Methods

This study was conducted in the rangelands surrounding the site of the livestock consolidation project for nomadic communities in Zirkouh region, South Khorasan Province (Figure 1). This project was initiated after the 1997 earthquake in the Zirkouh region, aiming to organize and settle the nomadic populations. The area

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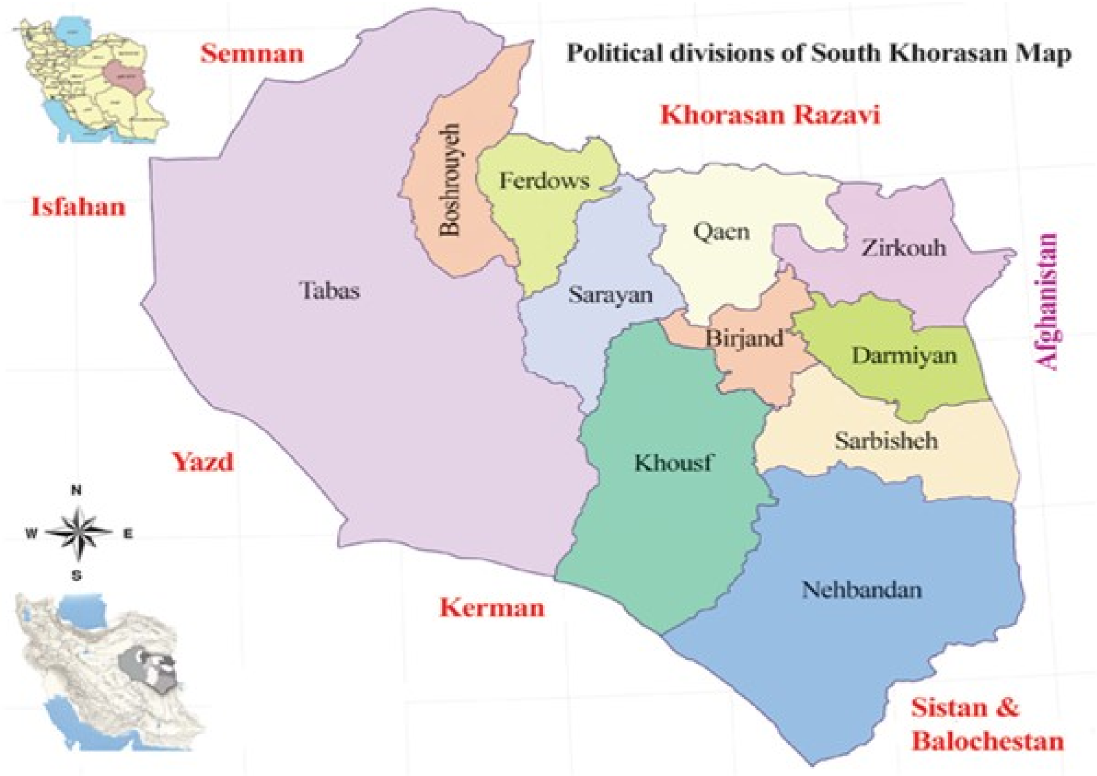

Figure 1. Geographical map of South Khorasan province, Eastern Iran.

has been subjected to overgrazing for approximately 25 years. The average annual rainfall in the study area was 156.4 mm. The soil was classified as sandy-loam, and the general slope of the land was less than 5% (Rostampour, 2022).

The presence of livestock and changes in vegetation composition during the years 2002, 2012, and 2022 were assessed with a digital camera. The primary sampling for this study was conducted in the spring of 2022. For this purpose, after a field survey and initial sampling, the frequency of the invasive species P. harmala was evaluated. Following the initial assessment, five areas with 0% (enclosure area), 15%, 30%, 45%, 60%, and 75% frequency of the invasive plant were selected. Frequency is the number of times a species is present in a given number of sampling units. It is usually expressed as a percentage (Moghadam, 2012). In each area, three representative sites were chosen, and within each representative site, 20 randomly placed quadrats, each measuring four square meters, were established (a total of 60 quadrats per area). The number and size of quadrats were determined based on previous studies (Rostampour & Saghari, 2023). In each quadrat, after identifying the plant species, the values for plant density, percentage of vegetation cover, percentage of litter, and percentage of soil and gravel cover were recorded. The rangeland condition class in each of the studied areas was determined using the modified four-factor method (Arzani & Abedi, 2015).

2.1 Statistical Analysis

Based on the counted individuals, indices for species richness and diversity (Shannon-Wiener and Simpson), species evenness (Pielou), and species dominance (Simpson) were calculated (Ejtehadi et al., 2008). The Jaccard dissimilarity index was used to assess beta diversity. For statistical comparisons, a one-way ANOVA test and modified LSD means comparison test were employed. Additionally, the Hill diversity profile was used to compare the overall species diversity components. The frequency distribution of plants in each of the studied areas was compared using the geometric model, which indicates the degraded and polluted ecosystems (Ejtehadi et al., 2008), and its fit was assessed using the chi-square test. All statistical analyses were performed using R software (R Core Team, 2020).

3. Results

The original vegetation in the study area was dominated by Artemisia sieberi along with the shrub Astragalus. Field observations indicated that within five years of the nomadic settlement (from 1997 to 2002), Artemisia had been eliminated and replaced by invasive species such as Sophora, Alhagi, and Salsola (Figure 2). After 15 years, the invasive herbaceous species were replaced by P. harmala (Figure 3). In the final stage, after 25 years, due to overgrazing and the drought of 2021, the invasive species P. harmala was also eliminated (Figure 4).

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Figure 2. First stage: Livestock introduction and absence of P. harmala (Author, 2002).

Figure 3. Second stage: Changes in vegetation composition and dominance of P. harmala (Author, 2012).

Figure 4. Third stage: Elimination of P. harmala (Author, 2022).

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Based on the floristic list of the study area (Table 1), 17 families, 39 genera, and 45 plant species were identified. Among these, 25 species were annuals and 20 species were perennials. Approximately 29% of the plants belonged to Class I, 27% to Class II, and 44% to Class III. Therophytes, with 24 species, constituted the largest proportion (54%), while geophytes, with one species (2%), represented the smallest proportion of the vegetation cover in the area (Figure 5).

The results of the one-way ANOVA indicated that the effect of frequency of P. harmala on the percentage of vegetation cover, percentage of litter, and percentage of soil and gravel, as well as the density of annual native plants in the area, was significant (Table 2). However, the density of perennial native plants in the area was not affected by the invasive species.

The results of the study indicated that by increasing the P. harmala frequency, the percentage of native plant vegetation cover decreased. The highest percentage of native plant cover, approximately 66%, was observed in the protected area (where the invasive plant was absent). Similarly, by increasing the P. harmala frequency, the percentage of litter decreased, while the percentage of bare soil increased. There was no significant difference in vegetation cover, litter, and bare soil in the P. harmala frequency higher than 30%. Due to the invasion of P. harmala, the density of annual native plants initially decreased and then, increased in the frequency of 75%. For the density of perennial native plants, there were no significant differences between frequency classes. However, the higher value was observed in 15% frequency (Table 2).

Based on the life form, the density of the two dominant grasses of Poa bulbosa and Bromus tectorum, and grass-like species Carex humilis in the area is illustrated in (Table 3). As the presence of the invasive plant increased, the density of Carex humilis decreased, while the density of Poa bulbosa increased. The mean density of the two main bush species of Ammothamnus lehmannii and Artemisia sieberi in the study area showed that the highest density of Ammothamnus lehmannii was observed at 30% and 45% frequency of the invasive plant. The density of Artemisia sieberi decreased in the areas with a low frequency of the invasive plant and increased in the areas with 45% or higher frequency of the invasive plant. The highest density of dominant shrub species in the region (Ammodendron persicum, Salsola richteri, and Astragalus squarrosus) was observed in the area with 15% frequency of the invasive plant. As the frequency of the invasive plant increased, the density of shrub plants decreased. In the protected area, the density of shrub plants was even lower than that in the area with 30% frequency of the invasive plant (Table 3). The changes in the density of poisonous plants in conjunction with the invasive P. harmala showed that the density of poisonous plants increased in the areas with 30 30% or greater frequency of the invasive plant.

The results of the one-way ANOVA on species diversity components in the study area indicated that the effect of the frequency of P. harmala on the species diversity components was significant (Table 4). The highest species richness was observed in the areas with 15% and 45% frequency of the invasive plant (with 19 and 18 plant species, respectively). Additionally, the highest Shannon-Wiener diversity index (2.48) was calculated in the area with 45% frequency of the invasive plant. No significant difference in species diversity was observed between the areas with 0% and 75% frequencies. The results of the means comparison of species evenness (Pielou's index) indicated that the areas with 30%, 40%, and 75% frequencies of the invasive plant had higher evenness indices, whereas the protected area had the lowest evenness index. Species dominance, which inversely correlates with species evenness, was the highest in the protected area compared to other regions. With the increasing frequency of the invasive plant, species dominance initially decreased and then, increased (Table 4).

The Hill diversity profile results indicated that although the abundance curve for the area with 45% invasive plant frequency was higher than the other areas indicating greater diversity, the fact that all curves intersected each other meant that the areas were not directly comparable (Figure 6). The Hill method ranking profile for species evenness also supported this finding. Although the curves for the areas with 30%, 40%, and 75% frequencies of the invasive plant intersected each other and showed no significant differences among them, they were higher than the curves for the areas with 60%, 15%, and 0% frequencies of the invasive plant (Figure 6).

One method for assessing beta diversity involves using dissimilarity indices. The results indicated that the greatest dissimilarity in species composition was found between the areas with 30% and 75% frequencies of the invasive plant. Additionally, the least change in species composition was observed between the areas with 30% and 45% frequencies of the invasive plant (Table 5).

The frequency distribution of plants in each study area was compared with the geometric-series model, and the fit was assessed using the chi-square test. The results indicated that the areas with 0%, 15%, 30%, and 45% frequencies of the invasive plant did not conform to the geometric model, and thus were considered non-invaded. In contrast, the areas with 60% and 75% frequency of the invasive plant conformed to the geometric model and were therefore classified as invaded (Table 6). Additionally, the condition of the rangeland deteriorated from excellent to poor with increasing frequency of the invasive plant (Table 6).

4. Discussion

The results indicated that as the frequency and dominance of the invasive species P. harmala increased, the percentage of vegetation cover and litter decreased, while the percentage of bare soil increased. The presence of the toxic and allelopathic species P. harmala exerted a negative and competitive impact on native plant species in the area. Due to its broader ecological range,

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Table 1. List of terrestrial plant species at the Zirkouh site along with their biological characteristics.

Family	Species	Life Cycle	Life form#	Palatability*
Apiaceae	*Dorema ammoniacum* D. Don.	Perennial	He	III
	Ferula foetida (Bunge) Regel.	Perennial	He	I
Araceae	*Eminium alberti (*Rgl.) Engl.	Annual	Ge	III
Asteraceae	*Achillea nobilis* L.	Annual	Th	III
	Anthemis hyalina DC.	Annual	Th	III
	Artemisia sieberi Besser	Perennial	Ch	II
	Carthamus oxyacantha M.Bieb.	Annual	Th	III
	Ceratocarpus arenarius L.	Annual	Th	III
	Echinops adenocaulis Boiss.	Perennial	Ch	III
	Gundelia tournefortii L.	Perennial	He	II
	Launaea acanthodes (Boiss.) Kuntze	Perennial	He	II
	Onopordum heteracanthum C.A.Mey.	Perennial	Ch	III
Boraginaceae	*Heliotropium aucheri* DC.	Annual	Th	III
	Heliotropium peruvianum L.	Perennial	He	III
Brassicaceae	*Alyssum dasycarpum* Stephan ex Willd.	Annual	Th	II
	Alyssum marginatum Steud. ex Boiss.	Annual	Th	I
	Malcolmia strigosa Boiss.	Annual	Th	II
Caryophyllaceae	*Acanthophyllum glandulosum* Bunge ex Boiss.	Perennial	Ch	III
Chenopodiaceae	*Aellenia subaphylla* (C.A.Mey.) Aellen	Perennial	Ch	II
	Salsola crassa M.Bieb.	Annual	Th	II
	Salsola richteri (Moq.) Karel ex Litv.	Perennial	Ph	I
Cyperaceae	*Carex humilis* Leyss.	Annual	Th	II
Euphorbiaceae	*Euphorbia* helioscopia L.	Annual	Th	III
Lamiaceae	*Ziziphora tenuior* L.	Annual	Th	II
Liliaceae	*Tulipa biflora* Pall.	Annual	Ge	III
Orobanchaceae	*Orobanche aegyptiaca* Pers.	Annual	Th	III
Papaveraceae	*Papaver arenarium* M.Bieb.	Annual	Th	III
	Papaver rhoeas L.	Annual	Th	III
Papilionaceae	*Alhagi persarum* Boiss. & Buhse	Perennial	Ch	III
	Ammodendron persicum Bunge ex Boiss.	Perennial	Ph	I
	Ammothamnus lehmannii Bunge	Perennial	He	I
	Astragalus campylorhynchus Fisch. & C. Mey.	Annual	Th	I
	Astragalus commixtus Bunge	Annual	Th	I
	Astragalus squarrosus Bunge	Perennial	Ph	I
Poaceae	*Agropyron desertorum* (Fisch. ex Link) Schult.	Annual	Th	I
	Avena fatua L.	Annual	Th	I
	Bromus tectorum L.	Annual	Th	III
	Poa bulbosa L.	Annual	Th	I
	Stipagrostis plumosa Munro ex T.Anderson	Perennial	He	I
Polygonaceae	*Calligonum comosum* L'Hér.	Perennial	Ph	II
	Polygonum aviculare L.	Annual	Th	I
	Pteropyrum aucheri Jaub. & Spach	Perennial	Ph	II
Solanaceae	*Hyoscyamus senecionis* Willd.	Annual	Th	III
	Peganum harmala L.	Perennial	He	III
Zygophyllaceae	*Tribulus terrestris* L.	Annual	Th	III
	Zygophyllum eurypterum Boiss. & Buhse	Perennial	Ph	II

Th = Therophytes; He = Hemicryptophytes; Ch = Chamaephytes; Ph = Phanerophytes; Ge = Geophytes.
* Palatability class: I = high palatable; II = medium palatable; III = low-unpalatable (Rostampour, 2022).

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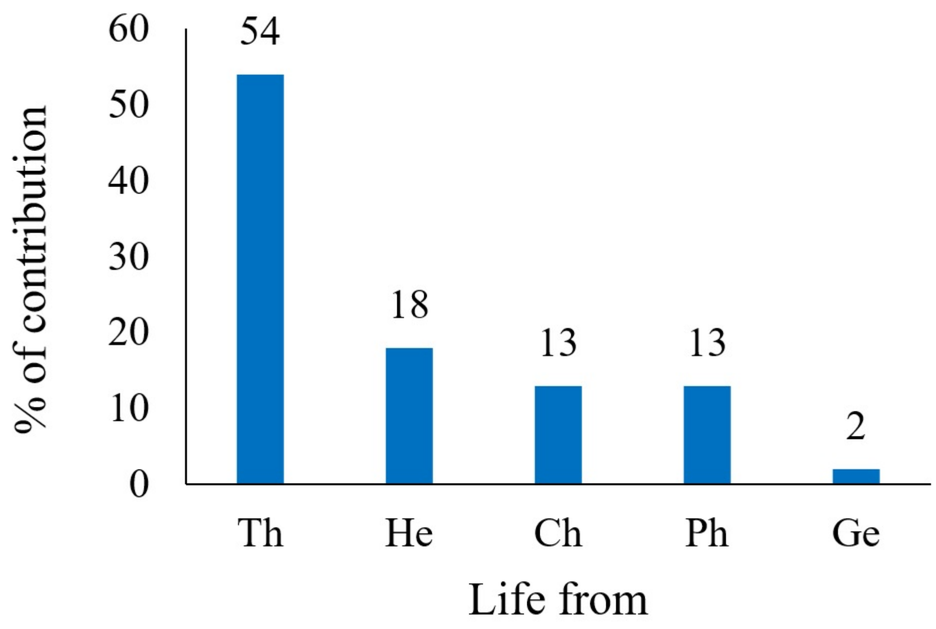

Figure 5. Plant life-form spectrum of the vascular flora in the study area (Th=Therophytes; He=Hemicryptophytes; Ch = Chamaephytes; Ph = Phanerophytes; Ge = Geophytes).

Table 2. Mean of vegetation cover characteristics in P. harmala frequency classes.

Frequency classes %	Vegetation Cover %	Litter %	Bare soil %	Annuals density (plant/m^2)	Perennials density (plant/m^2)
Protected area	65.8 a	11.3 a	22.87 c	49.00 a	1.33 ab
15 %	34.1 b	2.80 b	58.68 b	7.52 bc	2.48 a
30 %	13.0 c	2.30 b	84.68 a	10.28 bc	2.08 a
45 %	11.9 c	1.57 bc	86.57 a	7.93 bc	1.15 ab
60 %	10.9 c	1.23 bc	87.84 a	5.68 c	0.83 b
75 %	18.2 c	0.00 c	91.77 a	23.15 b	1.58 ab
F value	27.3**	60.33**	24.6**	11.05**	2.32^{ns}

**: significant at 0.01 probability level.
Means of columns followed by similar letters have no significant differences according (LSD $p \leq 0.05$).

Table 3. Mean of plant density according to the life form of selected species in different P. harmala frequency classes.

Species name	*P. harmala* Frequency classes					
	Protected area	15%	30%	45%	60%	75%
	Plant density (plant/m^2)					
Poa bulbosa	6.00	12.5	17.2	12.00	11.30	50.00
Carex humilis	140.00	25.00	8.65	16.30	3.85	17.60
Bromus tectorum	0.60	5.00	2.10	4.15	4.50	1.15
Ammothamnus lehmannii	0.35	0.35	3.80	2.45	1.20	0.00
Artemisia sieberi	0.20	0.05	0.06	0.95	1.15	1.2
Astragalu squarrosus	0.10	1.50	0.60	0.30	0.00	0.00
Ammodendron persicum	1.45	4.50	0.65	0.15	0.00	0.00
Salsola richteri	0.40	2.25	1.95	0.80	0.20	0.00
Eminium alberti	0.00	0.00	2.05	1.90	0.55	0.75
Heliotropium aucheri	0.10	0.20	0.35	0.25	0.30	0.20
Euphorbia helioscopia	0.00	0.00	0.85	0.50	0.50	1.00

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Table 4. Mean of vegetation cover characteristics in P. harmala frequency classes

Frequency classes	Species Richness	Species Diversity	Species Evenness	Species Dominance
Protected area	13 bc	1.19 d	0.49 d	0.52 a
15 %	19 a	2.22 ab	0.79 ab	0.17 b
30 %	11 c	1.95 bc	0.85 a	0.16 b
45 %	18 a	2.48 a	0.88 a	0.11 b
60 %	17 a	1.84 bc	0.69 c	0.23 b
75 %	8 d	1.63 cd	0.86 a	0.23 b
F value	8.45**	10.86**	13.41**	14.08**

**: significant at 0.01 probability level.
Means of columns followed by similar letters have no significant differences according (LSD $p \leq 0.05$).

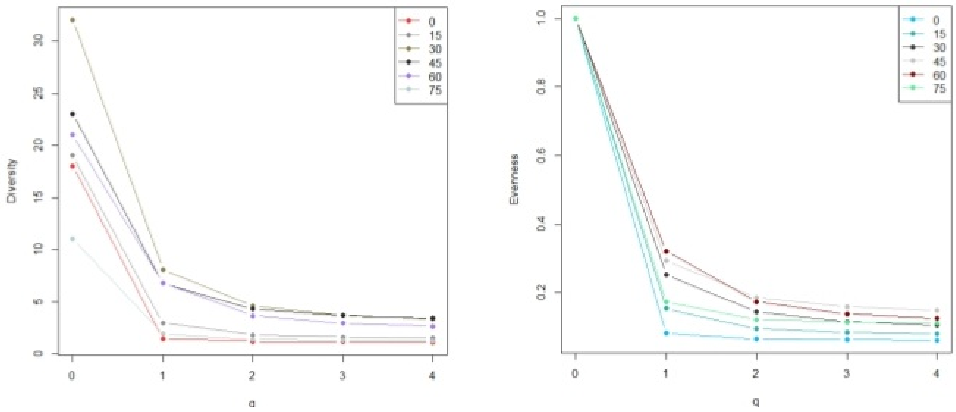

Figure 6. Diversity profile for assemblages of differing diversity and evenness. The x-axis is the order q in the Hill number, and is illustrated for values of q from 0 to 4. The y-axis is total richness (S) and Pielou's evenness index (J').

Table 5. Beta-diversity (Jaccard dissimilarity) analysis in P. harmala frequency classes.

Frequency classes	0	15%	30%	45%	60%	75%
0	1					
15%	0.46	1				
30%	0.68	0.66	1			
45%	0.54	0.5	0.43	1		
60%	0.70	0.75	0.49	0.53	1	
75%	0.79	0.75	0.81	0.69	0.67	1

Table 6. Chi-square goodness of fit test of geometric-series model for P. harmala frequency classes.

Frequency classes	Range condition	Chi-square	P. Value	Interpretation
Protected area	Excellent	298.6	0.00**	non-invaded
15 %	Good	25.01	0.00**	non-invaded
30 %	Fair	15.84	0.01**	non-invaded
45 %	Fair	59.67	0.00**	non-invaded
60 %	Poor	1.86	0.97	invaded
75 %	Poor	1.31	0.73	invaded

**: significant at 0.01 probability level.

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higher adaptability, and stronger competitiveness, the invasive species reduced vegetation cover, leading to a decline in litter and organic matter in the soil.

The invasion of non-native species globally has become one of the most prevalent biological threats stemming from increased human activity. Biological invasions are regarded as one of the primary factors contributing to ecosystem degradation, which leads to a major decrease in biodiversity (Vantarová et al., 2023). With the increased density and frequency of Peganum harmala, the results showed that the density of annual species initially declined and then, increased. In general, the frequency of P. harmala, due to its competitiveness, reduced the density of annual herbaceous and grass species, and over time, annual invasive species, typically weedy, opportunistic, and low in palatability and nutritional value, began to increase. Invasive species persisted even under heavy grazing due to traits like low palatability, a short growth period with compounds like phenols, tannins, lignin, and cellulose, adaptability to poor soil conditions, and effective seed dispersal (directly or via livestock) (Zeynivand et al., 2020).

The findings revealed that as the frequency and density of the invasive species and the intensity and duration of grazing increased, species richness and diversity initially increased; however, with the continued grazing pressure, species richness and diversity eventually declined. The initial introduction of any plant species created a microclimate that facilitated the establishment of opportunistic plants. Yet, with the sustained grazing intensity and increased density of the invasive species, the competition reduced plant species richness and diversity due to the invasive species' competitive advantage. Similar to the results of this study, (Zare Kia et al., 2012) also stated that Overgrazing results in excessive defoliation of herbaceous plants, which reduces basal cover, standing biomass, and plant species diversity. In addition, uninterrupted heavy animal grazing and trampling can adversely affect some rare plant species populations (Gemechu & Dalle, 2023).

(Livingstone et al., 2020) demonstrated that plant invasions consistently led to significant reductions in native plant community diversity. In most cases, the first noticeable change in heavily grazed areas was a decrease in plant biodiversity, resulting in a pure stand of invasive plants. (Moaven et al., 2014) also noted that the invasion of the weed Acroptilon repens L. hindered the growth of other plants, reduced biodiversity, and posed control challenges due to its rhizomes, high vegetative growth potential, and root penetration.

The present study demonstrated that overall, as the frequency of invasive species increased, the frequency of toxic, unpalatable, and low-preference species in the rangeland increased. With the increased frequency of Peganum harmala, the density of Euphorbia rigida L., Heliotropium aucheri DC, and Eminium alberti (Rgl.) Engl. increased. The introduction of the invasive species fostered conditions conducive to the rise of opportunistic, unpalatable, and ecologically low-demanding species.

This study also showed that with the increased invasion of the invasive species, species evenness increased. The growing abundance of invasive and opportunistic species initially led to an increase in plant density and diversity. However, as abundance continued to rise, species diversity indices declined, and high-demand species were eventually outcompeted. As species diversity and richness declined, plants with broader ecological ranges and lower demands spread uniformly across the rangeland, ultimately increasing species evenness indices, particularly for the invasive species. Novoa et al. (2014) found that heavy grazing promoted the growth of unpalatable invasive plants and increased species evenness, while Rutherford and Powrie (2013) observed similar results. (Zeynivand et al., 2020) and (Mahmoudi et al., 2021)concluded that different grazing intensities (from light to heavy) had no significant effect on species evenness, yet increased density and frequency of the invasive allelopathic species led to an increase in species evenness.

Results also indicated that the density of native shrub species in the area, such as Ammodendron persicum Bunge ex Boiss. Astragalus squarrosus Bunge, and Salsola richteri (Moq.) Karel ex Litv. initially increases but eventually decreased with the increasing frequency of the invasive species and the intensity and duration of livestock grazing. Native species, due to their lower ecological range and adaptability, could not compete with the invasive species. In rangelands with constant livestock presence and high grazing intensity, even resistant and tolerant plants failed to survive, affecting abundance, species evenness, and ultimately species diversity (Zeynivand et al., 2020). Also, the results showed that the density of annual native plants (Poa bulbosa and Carex humilis) initially decreased and then, increased. This indicates that moderate and heavy grazing significantly decreased the density of perennial plants but increased annual plants, and high livestock pressure favors annual plants (Li et al., 2024).

(Gholizadeh et al., 2024) and (Rakotoarivony et al., 2024) emphasized the importance of assessing functional diversity in such studies, arguing that invasive plants could alter ecosystem composition, structure, and function, significantly affecting species and functional diversity. Future studies should therefore assess not only the impact of invasive plant invasion on native rangeland plant species diversity but also investigate functional diversity, distribution patterns, species distribution models (SDM), and trends in rangeland status in response to invasive plant invasion.

5. Conclusion

The results of the present study showed that the effect of invasive species frequency on the vegetation cover, litter, soil and gravel, and density of native annual plants in the area was significant. However, the invasive plant did not affect the density of native perennial plants in the area. The results indicate that with increasing in-

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vasive plant frequency, the percentage of native plant cover decreases and the density of poisonous plants increases. The results of the alpha diversity analysis showed that there was no significant difference in terms of the Shannon-Wiener index between areas with frequencies of 0 and 75%. However, the beta diversity analysis showed that with increasing frequency of the invasive species, about 79% of plant species have been changed. The range condition also changed from excellent to poor with the increasing frequency of the invasive plant.

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Authors contributions
Authors have contributed equally in preparing and writing the manuscript.
Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
We certify that there is no actual or potential conflict of interest concerning this article.

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