RESEARCH ARTICLE

Spatiotemporal dynamics of rare plant diversity in the Gurbantunggut desert based on GIS spatial analysis and multidimensional classification

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As the second largest desert in China, the Gurbantunggut desert has a unique and fragile ecosystem, and studying its rare plant diversity is of great significance for maintaining regional ecological balance. To investigate the plant ecological status of the Gurbantunggut desert, this study conducted field surveys from 2009 to 2022 by combining geographic information system spatial analysis technology and multidimensional classification theory to explore the spatiotemporal dynamics of rare plant diversity. The survey was conducted on 14 fixed plots using the "transect-plot" method, and a total of 96 species were recorded. The results showed that a total of 48 species with narrow geographical distribution and multiple low abundance species were identified. The Shannon-Wiener index for rare species decreased from 1.98 in 2009 to 1.05 in 2022, indicating a shrinking overall distribution range. The rate of change in the number of sample plots for the distribution of naked-fruit trees reached -66.7%, and the rate of change in the distribution area reached -76.4%. The diversity of rare species in the Gurbantunggut desert showed a decreasing trend, and species with narrow initial distributions were more significantly affected. This research provided a scientific basis for the development of conservation strategies for rare plants in the Gurbantunggut desert, which would promote regional ecological protection and sustainable development.

Keywords: Gurbantunggut desert; rare plants; geographic information system; Rabinowitz; spatiotemporal dynamics.

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Introduction

As an important component of the global terrestrial ecosystem, desert ecosystems have core environmental characteristics of extreme drought and drastic temperature differences, nurturing numerous rare plant species with unique adaptability. These species play an irreplaceable role in maintaining the ecological balance of deserts, curbing desertification expansion, and providing special ecological services [1, 2]. As the largest fixed and semi-fixed desert in China, the Gurbantunggut desert (GutD) is in the hinterland of the Junggar basin in Xinjiang, China. Due to the diversity of sand dunes and high heterogeneity of habitats, its southern region has become a natural "refuge" for rare plants such as Nitraria and Red Sand, forming a unique pattern of species distribution [3, 4]. In recent years, due to the combined effects of global climate change and regional human activities, the living environment of rare plants in the region has faced significant pressure [5]. Some species have experienced shrinking distribution ranges and declining population numbers, posing a potential threat to the stability of desert ecosystems. Geographic information system (GIS) as an integrated spatial information technology can effectively collect, manage, analyze, and display data with spatial attributes. In ecological research, GIS spatial analysis theory provides a powerful tool for revealing the spatial distribution patterns of species, identifying hotspot areas, and understanding the spatial relationships between species and environmental factors.

Extensive research has been conducted on the relationship between desert plants and the environment. Shiyomi *et al*. used a transect survey method to investigate the changes in soil water and salt, vegetation, and livestock carrying capacity along the water gradient in desert grasslands and found that the soil water content within 20 meters from the shore was high, and it could carry a large amount of biomass [6]. Dong *et al*. used gene sequencing and labeling methods to investigate how the succession of desert shrubs in semi-arid areas drove changes in soil microbial communities and demonstrated that shrubs could directly shape soil microbial communities or indirectly affect these communities by altering the soil matrix [7]. Ning *et al*. studied the composition of desert vegetation and the spatial distribution of soil nutrients to effectively construct and manage vegetation in the transition zone between desert and oasis. The results showed that the plant composition in the middle section of the Hexi Corridor and the southwestern edge of the Badain Jaran desert was single with low diversity, and plant species concentrated in a few families [8]. Liu *et al*. proposed a structural equation model to explore the influencing factors of soil organic carbon (OC) and found that evapotranspiration, annual average precipitation, and soil moisture were the main factors affecting OC accumulation [9]. Zhu *et al*. selected areas covered with different desert vegetation types to investigate the relationship between changes in soil carbon content and precipitation and identified that the soil OC increased with the increase of precipitation [10]. Wright *et al*. conducted a field survey in Uluru Katachuta National Park in central Australia to investigate the effects of drought and heat waves on arid flora and fauna in the Australian interior. The results suggested that drought could cause widespread animal and plant death and extensive plant regeneration in Australia [11]. Mandakovic *et al*. used high-throughput sequencing combined with random forest and symbiotic network analysis to investigate the relationship between soil organisms and plants. The results confirmed that the soil bacterial community (SBC) around the Andes Mountains in the Atacama desert was regulated by plant communities, and SBC could promote plant growth [12]. Although existing research has laid a solid foundation, there are still significant shortcomings. Most studies focus on a single environmental factor or ecological process, lacking multi-dimensional quantification and systematic analysis of spatial patterns of rare plant rarity. Moreover, the lack of characterization of long-term spatiotemporal dynamics makes it difficult to fully reflect the complex relationship between rare species and the environment. Such research gaps result in a lack of sufficient scientific support for the development of targeted conservation strategies, which cannot effectively address the practical challenges of the decline in regional rare plant diversity (RPD).

To reveal the spatiotemporal dynamic patterns of RPD in the GutD, this study proposed a spatial analysis and multidimensional classification method combined with GIS by innovatively integrating GIS spatial analysis technology with field survey data, quantifying species spatial aggregation characteristics through methods of Kernel density estimation (KDE) and hotspot analysis, overcoming the shortcomings of traditional research in analyzing spatial heterogeneity. The Rabinowitz multidimensional classification framework was introduced to classify rare species types from three dimensions including geographical distribution, population abundance, and habitat specificity, filling the limitations of a single indicator to evaluate species rarity. Theoretically, this study filled the gaps in traditional research's insufficient analysis of spatial heterogeneity, single-rarity evaluation, and lack of long-term dynamic characterization, and improved the technical and methodological system for studying the diversity of rare desert plants. Practically, this study clarified the rare types, spatiotemporal change characteristics, and endangered status of rare plants in desert areas and provided an accurate scientific basis for the formulation of conservation strategies for rare plants in desert areas, which would promote regional ecological protection and sustainable development with great significance for maintaining the stability of desert ecosystems.

Materials and methods

Study area

The study area was the southern part of GutD with the coordinates of 44°11′ - 46°20′ N, 84°31′ - 90°00′ E, located in the hinterland of the Junggar basin, Xinjiang, China. It is the 2nd largest desert in China with an area of about 48,800 km^2. The climate type belongs to a typical temperate arid continental climate with cold and long winters and hot and dry summers. The annual average temperature (AAT) is 6.5 - 8.2℃. The annual precipitation is 80 – 150 mm, mainly concentrated in spring and summer. The desert is mainly composed of fixed and semi-fixed sand dunes with a rich variety of dune morphology types including crescent-shaped dunes, honeycomb-shaped dunes, and sand ridges. Different sand dunes are combined with each other to form a complex and diverse geomorphic pattern. The height of sand dunes is generally between 10 m and 50 m with moderate overall relief, but significant local micro-topography differences, providing differentiated habitat conditions for various plants. This region is not only a concentrated distribution area of rare plants but also one of the highly sensitive ecosystem types to climate change.

GIS spatial analysis theory

The core structure of GIS analysis was to quantify the clustering, heterogeneity, and correlation of species in space through spatial statistical methods such as KDE, hotspot analysis, and spatial autocorrelation analysis [13]. KDE could generate continuous density surfaces, visually displaying the degree of spatial aggregation of species as follows [14].

$$\hat{\lambda}(s) = \frac{1}{h^2}\sum_{i=1}^{n} K\left(\frac{\| s - p_i \|}{h}\right) \cdot w_i \tag{1}$$

where $\hat{\lambda}(s)$ was the estimated kernel density at spatial position s, reflecting the potential aggregation intensity of species at that point. h was the bandwidth (smoothing parameter), which controlled the smoothness of the density surface. $K(g)$ was a kernel function (Gaussian kernel). $\|s - p_i\|$ was the Euclidean distance between point s and observation point p_i of the i-th species. w_i was the weight of the i-th p_i. n was the total number of p_i. Hotspot analysis could identify high or low value spatial clusters with statistical significance. Moran's I index (MII) was utilized to evaluate global spatial autocorrelation and determine whether species distribution is clustered, random, or discrete. The global MII was calculated below [15].

$$I = \frac{N\sum_{i=1}^{N}\sum_{j=1}^{N} \vartheta_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{N}\sum_{j=1}^{N} \vartheta_{ij} \sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{2}$$

where I was the global MII with a value range of [-1, 1], while the values closed to 1, -1, and 0 represented aggregation, dispersion, and randomness, respectively. N was the total number of spatial units such as the number of sample plots. x_i and x_j were the species abundance values of the i-th and j-th spatial units. $\bar{x}$ was the average species abundance of all spatial units. ϑ_{ij} was an element of the spatial weight matrix. These methods could extract valuable ecological information from complex geographic data, providing scientific basis for biodiversity conservation and ecosystem management.

Multidimensional classification theory

The multidimensional classification theory emphasizes the comprehensive evaluation of research objects from multiple independent dimensions to overcome the limitations of single indicator classification [16]. In the study of rare plants, this theory was applied based on the Rabinowitz classical framework to divide the rarity of species into three core dimensions including geographic distribution range, population abundance, and habitat specificity. Each dimension was quantified into different levels based on actual survey data including "narrow/widespread", "low/high abundance", and "specialized/generalized", thus classifying species into different rare types. The definition of the stenosis index was shown below [17].

$$R = \frac{A_{occ}}{A_{total}} \quad (3)$$

where R was the narrowness index of the species distribution range with a value of (0, 1), and the smaller the value, the narrower it was. A_{occ} was the actual effective distribution area of the species. A_{total} was the total area of the research region. The calculation of habitat specificity index was shown as follows [18].

$$H = 1 - \frac{D_{obs}}{D_{max}} \quad (4)$$

where H was the habitat specificity index with a value of [0, 1]. The closer it was to 1, the more specific the habitat. D_{obs} was the actual number of habitat types occupied by the species. D_{max} was the gross of possible habitat types within the study area. This classification method not only comprehensively reflected the ecological characteristics and rarity of species but also helped to identify those species with special conservation value such as those with narrow distribution ranges, scarce numbers, and specific habitats.

Field investigation methods

This study conducted a comprehensive and systematic field survey from late May to early June every year from 2009 to 2022, which was the maturity period of plant seeds. The survey adopted the "spline plot" method and constructed a rigorous sampling system. The study accurately set up three main transects along the north-south direction, each with a length of 50 km and an interval of 10 km. Five auxiliary transects were set up in the east-west direction, all with a length of 30 km and an interval of 8 km. This transect layout could comprehensively cover different geographical areas in the study area and effectively capture the spatial heterogeneity of vegetation distribution. Each plot was planned as a rectangular area of 100 m × 10 m, strictly arranged perpendicular to the direction of the sand dunes to ensure that the vegetation information of different parts of the sand dunes could be covered within the plot. The sample plot was further subdivided into 10 sub-plots of 10 m × 10 m, and detailed plant information was recorded for the inter-dune area, sub-dune area, uphill area, and top area. This hierarchical recording method helped to gain a deeper understanding of vegetation characteristics in different environments. In each sub-sample plot, this study identified and recorded the species of plants, referring to the *Flora of China* and *Flora of Xinjiang*, and reviewed by professional plant classification experts to ensure the accuracy of species identification [19]. Meanwhile, the number of plants were accurately counted, while the crown width (length × width) and height were measured. The coverage was recorded by using visual inspection. The coverage was divided into 5 levels including level 1 (< 10%), level 2 (10 - 30%), level 3 (30 - 50%), level 4 (50 - 70%), and level 5 (> 70%). Over the course of 14 years, a total of 14 fixed plots were surveyed. In 2016, due to extreme drought, one plot (plot 9) was temporarily reduced, and the survey was resumed in 2020, recording a total of 96 species and constructing a rich and time-continuous dataset.

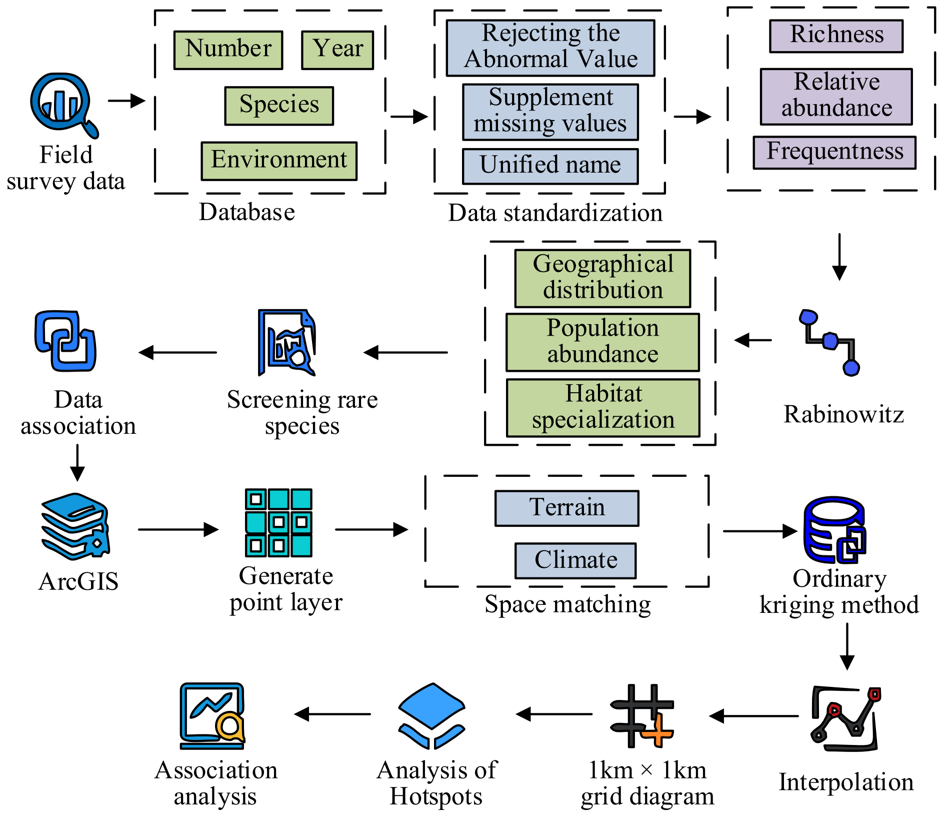

Figure 1. Data processing flow chart.

Environmental data sources

To further analyze the relationship between rare plants and the environment, this study introduced multi-source environmental data including key climate data such as AAT, annual maximum/minimum temperature, and annual precipitation. The data were sourced from the National Qinghai Tibet Plateau Science Data Center (https://data.tpdc.ac.cn). These data had a high spatial resolution of 1 km and a time span from 2009 to 2022, which could accurately reflect the climate characteristics and trends of the study area over the years. The terrain data such as altitude and slope were obtained from ASTER GDEM V3 (https://www.igadc.cn/page/agdem), which had a high resolution of 30 m and could finely depict the terrain undulations in the study area [20]. ArcGIS 10.8 software (https://www.arcgis.com/index.html) was employed to extract and process data, convert terrain information into digital layers that could be used for analysis, and lay the foundation for exploring the impact of terrain factors on the spatial distribution of rare plants.

Data processing

Due to the different types of data collected, there were issues such as significant dimensional differences, missing data, and outliers among the data. To accurately analyze plant diversity, data was processed through three stages including raw data organization, statistical analysis, and spatial visualization (Figure 1). The species abundance, coverage, and other data recorded from a 14-year field survey were first entered into Microsoft Excel (Microsoft, Redmond, WA, USA) to establish a database containing items of plot number, survey year, species name, and growth environment type. Missing values were interpolated using the mean values of adjacent years in the same habitat, while extreme outliers (data exceeding three times the standard deviation of the mean) were excluded. The species names were standardized according to the *Flora of China*. Subsequently, the data were standardized, and species richness (total number of species within the sample plot), relative abundance (proportion of individuals of a certain species to the gross of individuals), and frequency (proportion of sample plots where species appeared) were calculated. The Rabinowitz classification framework was adopted, and the geographic distribution (narrow distribution below the 25th percentile), population abundance (low abundance below the 25th percentile), and habitat specialization (occupying ≤ 2 habitat types) were classified using the quartile method. This screening met all three criteria for rare species. Then, the coordinates of the sample plot were associated with the species data, and point layers were generated in ArcGIS for spatial matching with climate and terrain data. This study used the ordinary kriging method to spatially interpolate the richness of rare species, generating a 1 km × 1 km grid map. The spatial clustering areas were identified through hotspot analysis, and a Z-value greater than 1.96 was considered a significant hotspot (P < 0.05). Finally, the Spearman rank correlation test was used in R-language (https://www.r-project.org/) to analyze the correlation between the rare species diversity index and climate factors, which quantified the explanatory power of environmental factors on species distribution through redundancy analysis (P < 0.05).

Results and discussion

Narrow distribution and low abundance of species in the GutD

This study systematically investigated plants in the southern GutD combined with multidimensional classification standards to clarify the specific classification of rare species in the region, which included narrow geographical distribution, low abundance, habitat specialization, and the final composition of rare species diversity. The species with a narrow distribution in the GutD demonstrated that a total of 48 species were classified as geographically narrow species based on continuous years of field surveys and data analysis statistics, covering multiple families and genera including *Zygophyllaceae*, *Tamaricaceae*, *Plumbaginaceae*. Among them, *Zygophyllaceae* included species of *Nitraria*, *Zygophyllum*, *Camelthorn*, which had unique adaptability in desert ecosystems. *Tamaricaceae*'s *Reaumuria songarica* also belonged to this category. In addition, there were plants from families of *Asteraceae*, *Fabaceae*, and *Poaceae* (Table 1). The limited distribution range of these species indicated their high dependence on specific habitats, possibly due to long-term adaptation to the unique climate and soil conditions of the GutD. These narrowly distributed species were of great significance for maintaining the stability and biodiversity of desert ecosystems and were also important indicators of ecosystem health. Due to their limited distribution range, they might be more vulnerable to environmental changes and human activities, requiring special attention and protection. The low-abundance species in the GutD demonstrated that there were various rare plants with low abundance in the southern part of the GutD. These plants covered multiple families and genera, including *Zygophyllaceae*, *Tamaricaceae*, *Plumbaginaceae*, *Fabaceae*, *Poaceae*, *Brassicaceae*, *Polygonaceae*, *Orobanchaceae*, *Apiaceae*, *Caryophyllaceae*, *Amaranthaceae*, *Iridaceae*. Among them, *Zygophyllaceae*'s white thorns and tyrants as well as *Tamaricaceae*'s *Reaumuria songarica* were plants with unique ecological adaptability in desert ecosystems, but their populations were relatively small (Table 2). The low abundance characteristic meant that these species had more stringent habitat requirements, possibly because they could only adapt to the unique climate and soil conditions of the GutD. These rare plants played a crucial role in maintaining the balance and diversity of desert ecosystems. However, due to their rarity, they were more vulnerable to environmental changes and human activities, and effective protective measures needed to be taken to avoid further reduction and extinction of the species.

Table 1. Species with narrow distribution in the Gurbantunggut desert.

Family	Genus	Species
	Nitraria	*Nitraria sphaerocarpa* Maxim.
Zygophyllaceae	*Zygophyllum*	*Zygophyllum potaninii* Maxim.
	Camelthorn	*Camelthorn* L.
Tamaricaceae	*Reaumuria*	*Reaumuria songarica* (Pall.) Maxim.
Plumbaginaceae	*Limonium*	*Limonium bungei* (Bunge) Kuntze
Liliaceae	*Leucocrinum*	*Leucocrinum montanum*
Lamiaceae	*Phlomoides*	*Phlomoides tuberosa*
Euphorbiaceae	*Chrozophora*	*Chrozophora sabulosa* Kar. & Kil.
	Trigonella	*Trigonella arcuata* CA Mey.
		Astragalus sinicus L.
	Astragalus	*Astragalus leptostachys*
Fabaceae		*Astragalus multistriatus*
	Oxytropis	*Oxytropis aciphylla* Ledeb.
	Alhagi	*Alhagi pseudalhagi*
	Eremosparton	*Eremosparton songoricum* (Litv.) Vassilcz.
	Eragrostis	*Eragrostis minor* Host.
Poaceae	*Bromus*	*Bromus tectorum* L.
	Aeluropus	*Aeluropus pungentus* (M. Bieb.) K. Koch
	Arabidopsis	*Arabidopsis thaliana* (L.) Heynh.
	Cladonia	*Cladonia rangiferina* (Schreb.) Hoffm.
Brassicaceae	*Artemisia*	*Artemisia sphaerocephala* Krasch.
	Cornulaca	*Cornulaca aucheri* Boiss.
	Epilasia	*Epilasia acrolasia* (Bunge) Bunge
Polygonaceae	*Hypecoum*	*Hypecoum procumbens* (L.) DC.
	Calligonum	*Calligonum junceum* (Fisch. & C.A.Mey.) Litv.
Orobanchaceae	*Orobanche*	*Orobanche coerulescens* Step. ex Willd.
	Ferula	*Ferula fukanensis* K.M.Shin
Apiaceae	*Isatis*	*Isatis indigotica* Fort.
	Sphaerophoria	*Sphaerophoria scripta* (L.)
Amaryllidaceae	*Allium*	*Allium pungens*
Caryophyllaceae	*Acanthophyllum*	*Acanthophyllum pungens* (Bunge) Boiss.
	Silene	*Silene vulgaris* (Moench) Garcke
	Sibiraea	*Sibiraea laevigata* (L.) Rchb.
	Oxybasis	*Oxybasis glauca* (L.) S.Fuentes, Uotila & Borsch
	Suaeda	*Suaeda glauca* (Bunge) Bunge
		Suaeda microsperma (Bunge) Akhani & B.E.Persson
Amaranthaceae	*Bassia*	*Bassia scoparia* (L.) A.J.Scott
	Krascheninnikovia	*Krascheninnikovia ceratoides* (L.) Poljakov
	Grubovia	*Grubovia dasyphylla* (Fisch. & C.A.Mey.) GL Chu
	Caroxylon	*Caroxylon nitidum* (Pall.) Iljin
	Salsola	*Salsola passerina* Bunge
Iridaceae	*Iris*	*Iris tenuifolia*
Boraginaceae	*Lithospermum*	*Lithospermum officinale* L.

GIS spatial analysis and multidimensional classification

To investigate the spatial distribution patterns and classification characteristics of rare species in the GutD, this study combined GIS spatial analysis technology with Rabinowitz's multidimensional classification framework to systematically analyze the spatial patterns and

Table 2. Species with low abundance in the Gurbantunggut desert.

Family	Genus	Species
Zygophyllaceae	*Nitraria*	*Nitraria sphaerocarpa* Maxim.
	Zygophyllum	*Zygophyllum potaninii* Maxim.
Tamaricaceae	*Reaumuria*	*Reaumuria songarica* (Pall.) Maxim.
Plumbaginaceae	*Limonium*	*Limonium bungei* (Bunge) Kuntze
Fabaceae	*Astragalus*	*Astragalus leptostachys*
	Oxytropis	*Oxytropis aciphylla* Ledeb.
Poaceae	*Eragrostis*	*Eragrostis minor* Host.
Brassicaceae	*Arabidopsis*	*Arabidopsis thaliana* (L.) Heynh.
	Sphaerophoria	*Sphaerophoria scripta* (L.)
Polygonaceae	*Calligonum*	*Calligonum junceum* (Fisch. & C.A.Mey.) Litv.
Orobanchaceae	*Orobanche*	*Orobanche coerulescens* Step. ex Willd.
Apiaceae	*Ferula*	*Ferula fukanensis* K.M.Shin
	Isatis	*Isatis indigotica* Fort.
Caryophyllaceae	*Silene*	*Silene vulgaris* (Moench) Garcke
Amaranthaceae	*Salsola*	*Salsola passerina* Bunge
	Grubovia	*Grubovia dasyphylla* (Fisch. & C.A.Mey.) G.L.Chu
Iridaceae	*Iris*	*Iris tenuifolia*

Table 3. Distribution pattern characteristics of rare species in the Gurbantunggut desert.

Statistical indicators	Peak nuclear density (plant/km^2)	Global Moran's I	*P*	Proportion of hotspot area (%)	Cold spot spatial correlation
All rare species	3.2	0.41**	0.003	28.6	Significant negative correlation
Calligonum junceum	5.8	0.63**	<0.001	42.1	No association
Ferula fukanensis	1.9	0.22*	0.021	12.7	Significant negative correlation
Eremosparton songoricum	4.1	0.57**	0.002	38.5	Significant positive correlation

Note: The estimated bandwidth of kernel density was 5 km. *: $P < 0.05$. **: $P < 0.01$. Hotspot zone determination Z > 1.96.

rarity levels of species. The distribution pattern characteristics of rare species in the GutD showed that *Calligonum junceum* exhibited the highest clustering intensity with its peak nuclear density of 5.8 plants/km^2), 1.8 times the mean, and MII of 0.63 ($P < 0.001$), indicating the presence of significant high-density clusters in sand dune areas. This strong agglomeration was highly correlated with its sand fixation ability and adaptability to cellular sand dune microenvironments. Although *Eremosparton songorium* was distributed in a narrow area, its hotspot area accounted for 38.5%, reflecting that, although its total amount was rare, it formed dense patches with core density of 4.1 plants/km^2 in specific depressions. The cold spot area of *Ferula fukanensis* was significantly negatively correlated (Moran's I = 0.22), indicating its tendency towards isolated distribution. The proportion of low hot spot areas (12.7%) further confirmed the ecological niche conservation strategy (Table 3). This study was based on the Rabinowitz framework and classified 26 rare species into 7 rare types from three dimensions of geographic distribution, population abundance, and habitat specialization. The results showed that the distribution of species numbers was uneven

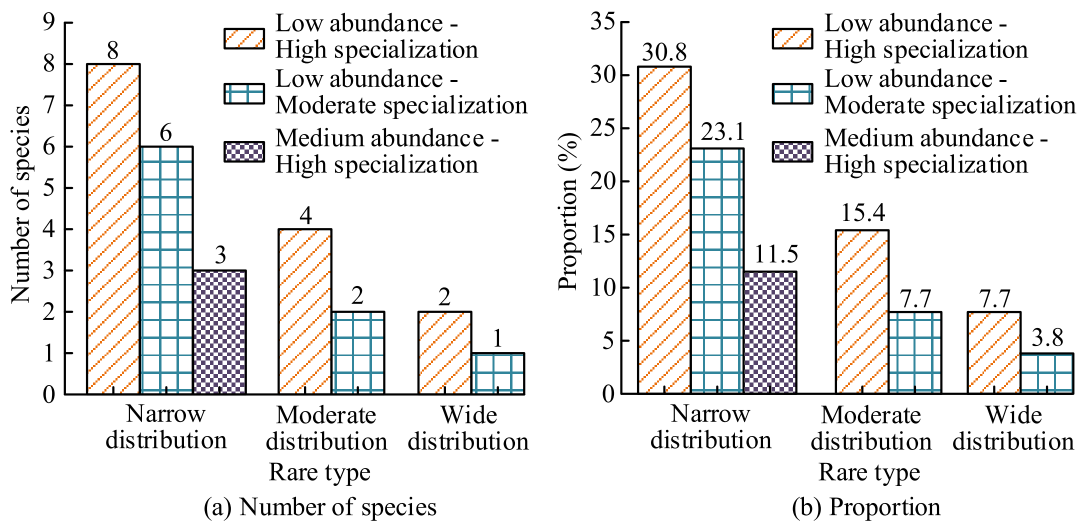

Figure 2. Classification of Rabinowitz rare types of rare species.

among the seven rare types. The type with "narrow geographical distribution - low abundance - high specialization" had the highest number of species with 8 species. The type of "widespread - low abundance - medium specialization" was the least with only one species. The overall trend decreased gradually from highly specialized and narrow distribution types to generalized and widely distributed types (Figure 2a). There was a significant difference in the proportion of each type. The type with "narrow geographical distribution - low abundance - high specialization" had the highest proportion, reaching 30.8%. The proportion of "widespread - low abundance - medium specialization" was the lowest, only 3.8%. The proportion of highly specialized and narrowly distributed types exceeded 60%, highlighting their dominant position among rare species (Figure 2b).

Spatial and temporal dynamic analysis of rare species diversity

In terms of temporal dynamic characteristics, this study collected all data from 2009 to 2022 and analyzed the changes in the Shannon-Wiener index (H) of rare species to explore the fluctuation patterns of rare species diversity over time. The Shannon-Wiener index was an indicator of community species diversity, which took into account both species' richness (number of species) and evenness (the degree of balance in the distribution of individual species). The higher the value, the richer the community diversity. The analysis results showed that the total H value of rare species demonstrated an overall downward trend from 2009 to 2022, dropping from 1.98 in 2009 to 1.05 in 2022. Among them, the H value reached its peak of 2.36 in 2010 due to sufficient precipitation and dropped to its lowest of 0.89 in 2021 due to extreme drought. Among different life forms, annual herbaceous plants had the most severe fluctuations in H values with coefficient of variation as 0.38, while shrubs had relatively stable H values with coefficient of variation as 0.12, reflecting the differences in adaptation to environmental changes among different life forms (Table 4). In terms of spatial dynamic characteristics, typical rare species were selected to clearly present the changing trend of the spatial distribution range of rare species, and the number and area changes of their distribution plots from 2009 to 2022 were statistically analyzed. The results showed that, from the number of distribution plots, the distribution range of all rare species showed a shrinking trend from 2009 to 2022. The number of *Gymnocarpos przewalskii* decreased the most significantly from 3 to 1 with a change rate of -66.7% and the

Table 4. Changes in Shannon-Wiener index of rare species in different years.

Year	Total H value	Annual herb H value	Perennial herb H value	Shrubs H value	Annual precipitation (mm)
2009	1.98	1.72	2.15	2.3	120
2010	2.36	2.05	2.41	2.52	152
2011	2.15	1.89	2.28	2.45	138
2012	1.87	1.63	2.01	2.32	115
2013	1.76	1.51	1.92	2.21	102
2014	1.68	1.43	1.85	2.15	98
2015	1.56	1.21	1.83	2.01	95
2016	1.42	1.1	1.67	1.93	85
2017	1.35	1.02	1.59	1.89	80
2018	1.3	0.97	1.52	1.86	78
2019	1.27	0.95	1.48	1.85	76
2020	1.23	0.98	1.45	1.87	82
2021	0.89	0.65	1.02	1.53	68
2022	1.05	0.82	1.21	1.68	75

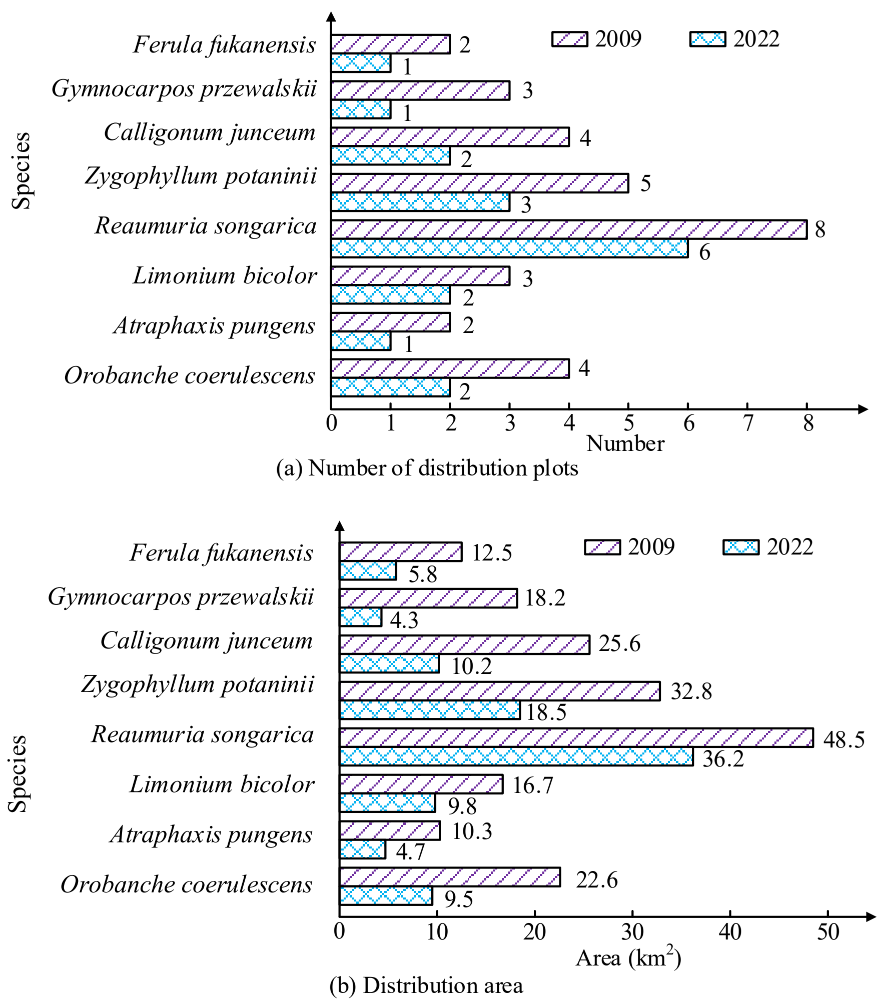

Figure 3. Changes in the number and area of rare species distribution plots.

largest shrinkage amplitude. *Reaumuria songarica* was relatively stable with a decrease in the number of plots from 8 to 6 with a change rate of -25.0%, making it the slowest shrinking species among all species. The contraction amplitude of widely distributed species such as *Reaumuria songarica* and *Tyrannosaurus rex* was relatively low, reflecting that species with a wider initial distribution range had a stronger tolerance to environmental changes (Figure 3a). The trend of changes in the distribution area was consistent with the number of plots, both showing a downward trend. The distribution area of naked fruit trees (*Gymnocarpos przewalskii*) had sharply decreased from 18.2 km^2 to 4.3 km^2 with a change rate of -76.4%, making it the species of the most severe area shrinkage. The area change of *Reaumuria songarica* was relatively gentle, decreasing from 48.5 km^2 to 36.2 km^2 with a change rate of -25.4%. In addition, the area shrinkage rates of species such as *Blue Leghorn* and *Thorny Ranunculus* were all over 50%, while the shrinkage rates of *Tyrannosaurus rex* and *Limonium bicolor* were between 40% and 50% (Figure 3b). The results further indicated that the distribution area of species was positively correlated with the number of plots, and the narrower the initial distribution of species, the more severe the area shrinkage and the higher the risk of endangerment.

Conclusion

This study aimed to reveal the spatiotemporal dynamic changes of RPD in the GutD. By using GIS spatial analysis technology and multidimensional classification theory, field survey data and multi-source environmental data from 2009 to 2022 were analyzed. During the research process, species information was recorded in detail by accurately setting sample bands and plots, and various types of data were strictly organized, statistically analyzed, and spatially visualized. The results demonstrated that rare plant species in the study area exhibited pronounced spatial heterogeneity and clear differentiation in rarity types, reflecting strong dependence on specific dune landforms and habitat conditions. Temporal analysis indicated an overall declining trend in RPD, accompanied by a continuous contraction of species distribution ranges, suggesting increasing ecological pressure under the combined influence of climate variability and environmental constraints. Species with initially narrow distributions and high habitat specialization were found to be particularly vulnerable, highlighting their elevated conservation risk. By combining spatial analytical techniques with a multidimensional rarity classification, this study provided an effective framework for identifying conservation priorities in desert ecosystems. The findings contributed to a deeper understanding of rare plant dynamics in arid environments and offered scientific support for targeted conservation planning and sustainable ecosystem management in desert regions.

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