Spatial Distribution Pattern of Plateau Zokor (Eospalax baileyi) Mounds and Its Spatial Association with Environmental Factors in the Eastern Qilian Mountains (Postprint)

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Date: 2018-02-01T00:00:00+00:00

Abstract

The mound-building behavior of plateau zokors has significant impacts on the production and ecological functions of alpine grassland ecosystems. Studying the spatial distribution patterns of plateau zokor mounds and their relationships with environmental factors can reveal the patterns of habitat utilization and selection by plateau zokors, providing a scientific basis for rational rodent control and protection of grassland biodiversity. In August 2014, a plateau zokor habitat measuring 140m×100m was selected in the eastern Qilian Mountains to eliminate heterogeneity in climate, topography, and soil caused by landscape-scale sampling. Using geostatistical methods, we analyzed the spatial distribution patterns of plateau zokor mounds and revealed their spatial relationships with environmental factors including soil bulk density, soil moisture, above- and below-ground plant biomass, root nutrient content (soluble sugars, crude protein, crude fat), and the richness of various functional groups (Gramineae, Cyperaceae, forbs). Semivariogram analysis and ordinary Kriging interpolation indicated that plateau zokor mounds exhibited moderate spatial variation and showed a clustered distribution, while all environmental factors displayed varying degrees of spatial heterogeneity. Cross-variogram analysis revealed that although plateau zokor distribution showed complex spatial associations (positive or negative) with various environmental factors at multiple scales, Mantel tests found that soil bulk density and Cyperaceae richness exhibited significant negative spatial associations with plateau zokor mound distribution, while forb richness and root crude fat content showed significant positive spatial associations with plateau zokor mound distribution. In summary, plateau zokors primarily inhabit and utilize areas with loose soil, lower Cyperaceae richness, higher forb abundance, and higher root crude fat content.

Full Text

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Abstract

The mound-building behavior of plateau zokor (Eospalax baileyi) significantly impacts the production and ecological functions of alpine grassland ecosystems. Investigating the spatial distribution patterns of zokor mounds and their relationships with environmental factors can reveal habitat utilization and selection patterns, providing a scientific basis for rational pest control and biodiversity conservation. In this study, we selected a 140 m × 100 m plateau zokor habitat in the eastern Qilian Mountains in July to eliminate climate heterogeneity associated with landscape-scale sampling. Using geostatistical methods including semivariogram analysis and ordinary kriging, we analyzed the spatial heterogeneity of zokor mounds and environmental factors including soil bulk density, moisture, aboveground biomass, underground biomass, root nutrients (water-soluble sugars, crude protein, crude fat), and functional group richness (grasses, sedges, forbs).

The results indicated that plateau zokor mounds exhibited a clumped distribution pattern with moderate spatial variation. All environmental factors showed varying degrees of spatial heterogeneity. Cross-variogram analysis revealed complex spatial associations between zokor distribution and environmental factors at multiple scales, showing either positive or negative correlations. Mantel tests identified significant negative spatial associations between mound distribution and soil bulk density and sedge richness, and significant positive spatial associations with forb richness and root crude fat content. In conclusion, plateau zokors primarily inhabit areas with loose soil, lower sedge richness, higher forb richness, and elevated root crude fat content.

Keywords: plateau zokor; spatial distribution; geostatistical analysis; environmental factors

Introduction

Population spatial distribution patterns result from long-term adaptation and selection to environmental conditions, and are crucial for understanding population characteristics, intra- and interspecific relationships, and population-environment interactions [1]. While numerous studies have investigated the spatial distribution of animal populations using classical statistical methods, these approaches have limitations. Classical statistics requires variables to be purely random and cannot clarify relationships between variables and geographic location, potentially leading to partial or erroneous results in population spatial distribution studies [2-4]. Because population spatial distribution is closely linked to ecological processes of habitat selection, and ecosystem components affect organism growth and development across different spatial scales [5], classical statistical methods ignore scale-dependent ecological phenomena.

Geographic Information Systems and geostatistical spatial analysis methods provide effective tools for determining population spatial distribution patterns and revealing spatial associations with environmental factors [6]. Compared with classical statistics, geostatistics emphasizes spatial processes of random variables and can reveal spatial patterns and relationships of one or two variables at different scales by examining differences between sampling points at various spatial intervals. Previous research on rodent spatial distribution in China has primarily focused on individual species using methods such as nearest neighbor analysis and negative binomial distribution [7-10]. However, these methods only determine distribution types without identifying specific locations and degrees of clustering, and they focus on temporal rather than spatial correlations, resulting in systematic errors and limited temporal scope.

Plateau zokor (Eospalax baileyi), endemic to the Tibetan Plateau, plays a unique role in alpine grassland ecosystem food webs and corresponding energy flow and material cycling [11-12]. As subterranean rodents, determining the spatial positions of all individuals within a population is difficult. However, surface mounds are easily identified and located, and their quantity and formation time can indirectly reflect population dynamics, making them an ideal proxy for studying population spatial distribution [13]. While previous studies have investigated zokor mound distribution at landscape scales [14], such scales inherently contain heterogeneity in climate, topography, and soil, which may not accurately reflect true relationships between zokor distribution and environmental factors. This study examines zokor mound spatial distribution patterns and their spatial associations with environmental factors at a small scale (140 m × 100 m) in alpine meadows of the eastern Qilian Mountains, providing scientific support for predicting zokor dispersal and protecting biodiversity.

1. Study Area

The study was conducted in Zhaxi Xiulong Township, Tianzhu Tibetan Autonomous County, Wuwei City, Gansu Province (37°12 N, 102°46 E, elevation 2937 m). The region has a cold, humid climate with strong solar radiation. Mean monthly temperature is -18.3°C in January and 12.7°C in July, with annual precipitation of 416 mm occurring mainly as topographic rainfall. The vegetation type is alpine meadow dominated by Poaceae species mixed with forbs, including Polygonum viviparum, Potentilla anserina, Kobresia humilis, Kobresia capillifolia, and Astragalus membranaceus [15], with vegetation cover reaching 90%. Elymus dahuricus is the dominant grass species. Plateau zokor is the main rodent species in this region [16].

2. Experimental Design

The study site was located in a winter alpine meadow pasture in the Tianzhu Jinqiang River area of the eastern Qilian Mountains. Plateau zokor is the only subterranean rodent species creating mounds in this area. A 140 m × 100 m plot was established and divided into 10 m × 10 m quadrats using wooden stakes at 10 m intervals. The average depth of zokor tunnels in the study area was 14.11 cm (n = 64), with 87.5% of tunnels distributed in the 10-20 cm soil layer.

3. Field Surveys

3.1 Mound Survey In July 2016, we used Real-Time Kinematic (RTK) GPS technology to record the latitude and longitude of each mound within the plot [17]. ArcGIS software was used to obtain the distribution and quantity of mounds in each quadrat.

3.2 Distribution Pattern Analysis The diffusion coefficient (s^2/m) was used as an index to determine the spatial distribution pattern of zokor mounds, where s^2 is variance and m is mean mound density [14].

3.3 Soil Bulk Density and Moisture Near the center of each quadrat, soil samples were collected at 10-20 cm depth using a cutting ring. Samples were placed in aluminum boxes and taken to the laboratory, where bulk density and moisture content were determined using the oven-drying method [18].

3.4 Aboveground Biomass Aboveground biomass was surveyed near the center of each quadrat using the Dry-Weight Rank (DWR) method [19].

3.5 Underground Biomass A root auger (diameter 7 cm) was used to collect root samples at 10-20 cm depth at each quadrat center. Soil attached to roots was washed away, roots were oven-dried, and biomass was determined.

3.6 Plant Functional Group Richness Botanical composition was surveyed at each sampling point using the DWR method [19]. Plants were classified into three functional groups: Poaceae (grasses), Cyperaceae (sedges), and forbs, with the proportion of each group calculated.

3.7 Root Nutrient Content Root samples collected at 10-20 cm depth were oven-dried. Soluble carbohydrates were measured using the anthrone method [20], crude protein by the Kjeldahl method [21], and crude fat by Soxhlet extraction [22].

4. Data Analysis

4.1 Semivariogram and Theoretical Model Fitting Semivariogram analysis was used to quantify spatial variation in zokor mounds and environmental factors. The semivariogram function (h) reflects variation between observations at different distances:

$$(h) = (1/2N(h))\ \Sigma[Z(xi) - Z(xi+h)]^2$$

where Z(xi) and Z(xi+h) are regional variable values at points xi and xi+h separated by distance h, and N(h) is the number of data pairs separated by distance h. Within a certain range, (h) increases with h. Model parameters were used to quantitatively describe spatial heterogeneity [23].

Key parameters include: - **Nugget (C)**: represents random variation from experimental error and variation at scales smaller than the minimum sampling interval (10 m) - **Sill (C + C)**: total variance - **Proportion [C /(C + C)]**: indicates spatial dependence degree - <25%: strong spatial autocorrelation (mainly structural factors) - 25-75%: moderate spatial autocorrelation (both random and structural factors) - >75%: weak spatial autocorrelation (mainly random factors) [24-25]

Models were selected based on maximum coefficient of determination and minimum residual sum of squares.

4.2 Ordinary Kriging Interpolation Using the structural components of semivariograms for mounds and environmental factors, ordinary kriging was applied for optimal unbiased estimation of regionalized variables at unsampled locations [23], and to map spatial distributions.

4.3 Cross-Variogram Analysis Cross-variogram analysis was used to examine spatial associations between mound patterns and environmental factor patterns [26-27]:

$$AB(h) = (1/2N(h))\ \Sigma[ZA(xi) - ZA(xi+h)][ZB(xi) - ZB(xi+h)]$$

where AB(h) is the cross-variogram value between variables A and B at distance h, ZA and ZB are values of the two variables, and N(h) is the number of point pairs separated by distance h.

Mantel tests were used to analyze significance of spatial relationships between mound distribution and environmental factors [6]. Semivariogram and cross-variogram analyses were performed in R (v3.1.2) using the "vegan" package, while kriging interpolation and Mantel tests were conducted in ArcGIS 10.0 and GS+ 10.0.

5. Results

5.1 Spatial Distribution Pattern and Heterogeneity of Zokor Mounds

The diffusion coefficient indicated a clumped distribution pattern ($s^2/m = 10.78 > 1$). The Gaussian model provided the best fit for mound spatial variation (Table 1). Mounds showed moderate spatial variation (C /(C + C) = 40.13%), with 59.96% of variation caused by spatial autocorrelation (mainly at scales <70.15

m) and 40.04% by random factors. Ordinary kriging interpolation revealed obvious patchiness in mound distribution [Figure 1: see original paper].

Table 1 Theoretical semivariogram models and parameters for plateau zokor mounds

Factor	Model	Nugget (C)	Sill (C +C)	Proportion [C /(C +C)]	Range
Mounds	Gaussian	0.02138	0.05328	40.13%	70.15 m

5.2 Spatial Heterogeneity of Environmental Factors Environmental factors including soil bulk density, moisture, aboveground biomass, underground biomass, root nutrients, and plant functional group richness could be fitted with Gaussian, spherical, or exponential models (Table 2). Root crude fat content and forb richness showed moderate spatial variation (25-75%), indicating joint control by random and structural factors. Other factors showed strong spatial variation (C /(C + C) < 25%), with variation mainly caused by structural factors. All environmental factors exhibited obvious patchiness [Figure 2: see original paper].

Table 2 Theoretical semivariogram models and parameters for environmental factors

Factor	Model	Nugget (C)	Sill (C +C)	Proportion	Range
Soil bulk density	Spherical	0.00027	0.0066	4.09%	3.11×10^{1}
Soil moisture	Exponential	0.00213	0.00427	49.88%	8.87×10^{1}
Underground biomass	Exponential	0.122	1.023	11.93%	2.57×10^{1}
Aboveground biomass	Spherical	0.0411	0.028	0.24%	4.74×10^{1}
Root crude fat	Gaussian	0.1242	0.00819	43.33%	1.84×10^{1}
Root crude protein	Spherical	0.0189	0.001	0.06%	1.10×10^{1}
Root water-soluble sugar	Spherical	0.0568	0.0023	0.64%	2.49×10^{1}
Grass richness	Gaussian	0.0411	0.028	5.60%	5.15×10^{1}

Factor	Model	Nugget (C)	Sill (C +C)	Proportion	Range
Sedge richness	Exponential	0.0189	0.001	7.14%	9.59×10^{1}
Forb richness	Exponential	0.1242	0.00819	45.73%	0.187

5.3 Spatial Associations Between Mound Distribution and Environmental Factors

Soil Physical Properties: Mound distribution showed positive spatial correlation with soil moisture at most scales (10.74-71.85 m) but negative correlation at 38.74-44.01 m. Negative spatial correlation with soil bulk density occurred across 10.74-71.85 m [Figure 3: see original paper].

Plant Biomass: Mound distribution showed positive spatial correlation with aboveground biomass at 10.74-30.82 m and 44.01-71.85 m, but negative correlation at 30.82-44.01 m. Positive correlation with underground biomass occurred at 10.74-71.85 m [Figure 4: see original paper].

Root Nutrients: Mound distribution showed positive spatial correlation with root crude protein at 10.74-17.37 m and 44.01-65.01 m, negative correlation at 17.37-44.01 m and 59.23-65.01 m. Positive correlation with root crude fat occurred at 10.74-44.01 m. Correlation with root soluble sugars was positive at 10.74-38.47 m and negative at 38.47-65.01 m [Figure 5: see original paper].

Plant Functional Groups: Mound distribution showed positive or negative spatial correlation with grass richness at multiple scales. Negative correlation with sedge richness occurred across 10.74-51.31 m, while positive correlation with forb richness occurred across all studied scales (10.74-71.85 m) [Figure 6: see original paper].

5.4 Significance Testing of Spatial Associations

Mantel test results showed that at the 95% confidence level ($P < 0.05$), mound distribution had significant negative spatial correlation with soil bulk density and sedge richness, and significant positive correlation with forb richness and root crude fat content. At the 90% confidence level ($P < 0.1$), only sedge and forb richness showed significant negative and positive associations, respectively .

Table 3 Mantel test results between mound distribution and environmental factors

Matrix	95% CI	P-value	90% CI	P-value
Mounds × Soil bulk density	-0.45	0.089	-0.089	0.175
Mounds × Soil moisture	-0.07	0.302	0.133	0.0601
Mounds × Aboveground biomass	0.068	0.0791	0.0589	0.0879
Mounds × Underground biomass	0.0731	0.0671	0.0658	0.0422
Mounds × Root crude fat	0.0465	0.0457	0.053	0.0617

Matrix	95% CI	P-value	90% CI	P-value
Mounds × Root water-soluble sugar	0.0564	0.044	0.065	0.0526
Mounds × Root crude protein	0.098	0.0347	0.0336	0.065
Mounds × Grass richness	-0.089	0.175	0.133	0.0601
Mounds × Sedge richness	-0.45	0.089**	-0.089	0.175**
Mounds × Forb richness	0.636	0.175**	0.175	0.0601**

Significant at P < 0.05; Significant at P < 0.1

6. Discussion

Research on rodent spatial distribution in China has a long history [7], but few studies have examined plateau zokor distribution and its relationship with environmental factors. This study used geostatistical analysis at a small scale (100 m × 140 m) to eliminate environmental heterogeneity from geographic differences, revealing that zokor populations exhibit clear heterogeneity and that environmental factors show varying degrees of spatial variation. Mantel tests indicated that zokors primarily inhabit areas with loose soil, lower sedge richness, higher forb richness, and elevated root crude fat content.

Traditional methods such as frequency comparison and distribution index analysis cannot identify specific locations and degrees of clustering, nor do they address spatial correlations [7]. Geostatistical methods are appropriate because rodent distributions are complex and structurally scale-dependent [28]. Our cross-variogram analysis revealed that mound distribution showed complex positive or negative spatial associations with environmental factors at different scales, indicating that relationships change with scale. This demonstrates the necessity of examining zokor distribution-environment relationships across multiple scales [35].

Semivariogram analysis showed moderate spatial variation in mound distribution, controlled by both random and structural factors. Random factors may include experimental error or variation at scales <10 m, while structural factors include abiotic and biotic influences. The clumped distribution pattern is consistent with previous studies [10,13]. Environmental factors also showed structural spatial heterogeneity, with underground biomass, root protein, root soluble sugars, grass richness, and sedge richness mainly controlled by structural factors.

At the 95% confidence level, mound distribution showed significant negative association with soil bulk density and sedge richness, and significant positive association with forb richness and root crude fat. Soil bulk density is a key factor affecting habitat selection [30], and zokors likely select loose soils to avoid high energy costs of burrowing, which can be 360-3400 times more expensive than locomotion for surface-dwelling rodents of similar body mass [32]. The significant positive association with root crude fat may reflect pre-hibernation food storage needs, as sampling occurred during the second peak of mound-building before winter. The positive association with forb richness and negative association with sedge richness align with dietary preferences, as forbs are primary food sources while sedges are rarely consumed [30,33-34].

7. Conclusion

At the studied scale (140 m × 100 m), the main abiotic factors influencing plateau zokor distribution were soil looseness, root crude fat content, and forb and sedge richness. Habitat utilization patterns are scale-dependent, and results from one scale cannot be extrapolated to others [35]. Therefore, multi-scale studies are essential for understanding zokor distribution-environment relationships.

Acknowledgments

We thank Wang Qiaoling for assistance with field surveys and sample analysis.

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Note: Figure translations are in progress. See original paper for figures.