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Influence of Environmental Factors on Species Richness and Diversity in a Semi-Arid Environment, South Africa

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Abstract: The Nama Karoo biome is one of the least well-studied biomes in the semi-arid region of South Africa, and essential baseline biodiversity data for this region are lacking. The aim of the present study was to examine the influence of environmental factors on the species diversity and richness of Mountain Zebra National Park, South Africa, which includes this vital biome. Vegetation data were obtained using the step-point method. Both species richness and diversity were unaffected by slope, aspect, coarse fragments, and soil texture. Multiple linear regression analyses indicated that a combination of four variables (nitrogen, clay, and sand contents, and longitude) should be included in the optimal model for species richness, and the optimal model for species diversity also revealed four influencing variables: soil organic carbon, clay and sand contents, and longitude. Overall, both species richness and diversity could be predicted by a combination of climatic, topographic, and soil properties. The findings of this study can be used as a reference for the effects of environmental factors on plant species richness and diversity in semi-arid environments.

Keywords: environmental factor; semi-arid; soil property; species richness; species diversity; vegetation

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1. Introduction

Vegetation plays a vital role in the lives of many organisms, as well as in natural preservation, and ecosystem balance [1]. Any impact on an ecosystem, such as pollution, development, grazing, fire, and drought, is first observed through changes in the vegetation. Detailed studies on the species and population dynamics of vegetation in an area are critical for developing scientifically sound management and conservation strategies [2]. Plant species richness and diversity patterns are the foundations of ecology and conservation biology research [3]. Local and regional plant community distribution patterns are influenced by environmental factors such as climate, topography, and soil physical and chemical properties [4]. Although several ecological studies have explored different aspects of vegetation within the Nama Karoo biome [5], there still exists a considerable knowledge gap regarding the driving factors that influence this vegetation. Soil is a vital environmental factor that influences ecosystem processes, and the distribution and characteristics of plant communities [5]. Soil properties affect the redistribution of rainwater, including runoff and infiltration [6]. The chemical, physical, and microbiological properties of soil influence the plant community structure, composition, distribution, and diversity [7]. In mountainous areas, elevation, slope, and aspect are the main topographic factors affecting plant species composition, diversity, and distribution patterns [8]. Vegetation monitoring is essential for understanding the vegetation structure and species composition over time [9]. However, few studies have investigated plant biodiversity patterns in the semi-arid Nama Karoo biome. Previous ecological research in the region has primarily focused on livestock grazing effects on the landscape [10,11], and several floristic studies have investigated species assemblages in some parts of the region [12]. However, there is a need to further explore how environmental drivers affect the vegetation in the region.

Bezuidenhout and Brown [9] divided Mountain Zebra National Park (MZNP) into 13 landscape units based on their geomorphological characteristics, land and soil types, and plant species composition. These landscape units serve as management units and provide an ideal opportunity to study the species richness and diversity across various topographical areas. MZNP was established to protect the threatened Cape Mountain Zebra. Since 1996, the Park has been enlarged with the incorporation of various farms alongside the northern boundaries. As a result, the park more than doubled in size, from 6536 ha to approximately 21,000 ha [13].

The Nama Karoo biome, the second largest biome in South Africa, is located on the central plateau area of the country. The biome is characterized by the dominance of dwarf shrubs and grasses on the lower-lying valley bottom areas and plateaus, with medium-sized shrubs along the moderate to steep mountain slopes [14,15]. The *Vachellia karroo* tree is prominent along drainage lines and streams. Although it is not as diverse as other biomes, the fauna and flora of the region are adapted to the arid and semi-arid environments within which they occur. In the past, the biome was characterized by vast herds of springbok that used to migrate to the area in search of grazing land and water [16]. With the settlement of humans in the area, most wild animals were destroyed, while the fencing of the farms effectively cut off any animal migratory routes [17]. The wild ungulates were replaced by sheep and angora goats that comprise the major agricultural activity of the area today [18]. The stocking of the area with domestic animals lead to the heavy overgrazing of large sections of the biome [14]. Foreign plants were also introduced into the area, which has resulted in the displacement of the natural vegetation of the biome in many areas [19,20]. Moreover, mining activities in some parts have contributed to the destruction of the natural vegetation and habitat of the biome [13]. To make scientifically justifiable decisions on the management of the remaining natural habitat, research on the vegetation of the area must be continued. This will not only provide an inventory of the biome, but also of the diversity of species present [13].

The main objective of the present study was to determine the effects of environmental factors on plant species richness and diversity in the study area. The following hypotheses were tested: (i) species diversity and richness vary across different landscape units, and (ii) plant species richness and diversity significantly correlate with soil parameters and topographic factors.

2. Materials and Methods

2.1. Study Area

The study was conducted in MZNP (Figure 1), which covers an area of approximately 28,412 ha and is in the Eastern Cape Province, South Africa (32°22′47′′ S; 25°47′8′′ E). The park comprises three biomes of South Africa: Karoo Escarpment Grassland (53%), Eastern Upper Karoo (37%), and Eastern Cape Escarpment Thicket (10%) [2]. The Eastern Upper Karoo is characterized by flat and gently sloping plains, interspersed with hills and rocky areas where the dominant flora are dwarf microphyllous shrubs (*Pentzia incana* and *Eriocephalus ericoides*) [21]. The Karoo Escarpment Grassland is characterized by low mountains and hills, with wiry tussock grasslands and mountain wire grass (*Merxmuellera disticha*) being the dominant flora. The Eastern Cape Escarpment Thicket is characterized by steeply sloping escarpment and mountain slopes with medium-high and semi-open to closed thicket, where the dominant flora are olive trees (*Olea europaea*) [2]. The park is located on the northern slopes of the Bankberg mountain range [21]. It is dominated by sedimentary rock types such as the sandstones, siltstones, and mudstones of the Beaufort Series [22]. Mountainous terrain with steep-sided drainage lines makes up the southern quarter of the park, where the highest point is found along Bankberg Mountain at 1957 m above sea level, with the lowest part of the park in the northern section only reaching 1000 m above sea level [22,23]. The soil in the park is predominantly shallow, with large areas of the park being rocky and having minimal or no topsoil [21,22]. The average monthly temperature in summer (September to March) varies between a minimum of 6 °C and a maximum of 28 °C, whereas in winter (April to August), the temperature often drops below 0 °C and reaches maximums of 20 °C [24]. Rainfall occurs regularly from December to April [24], and the average annual rainfall is 400 mm (Figure 2) [25]. The region experiences periodic light snow during the winter months, and frost is common between May and October [24].

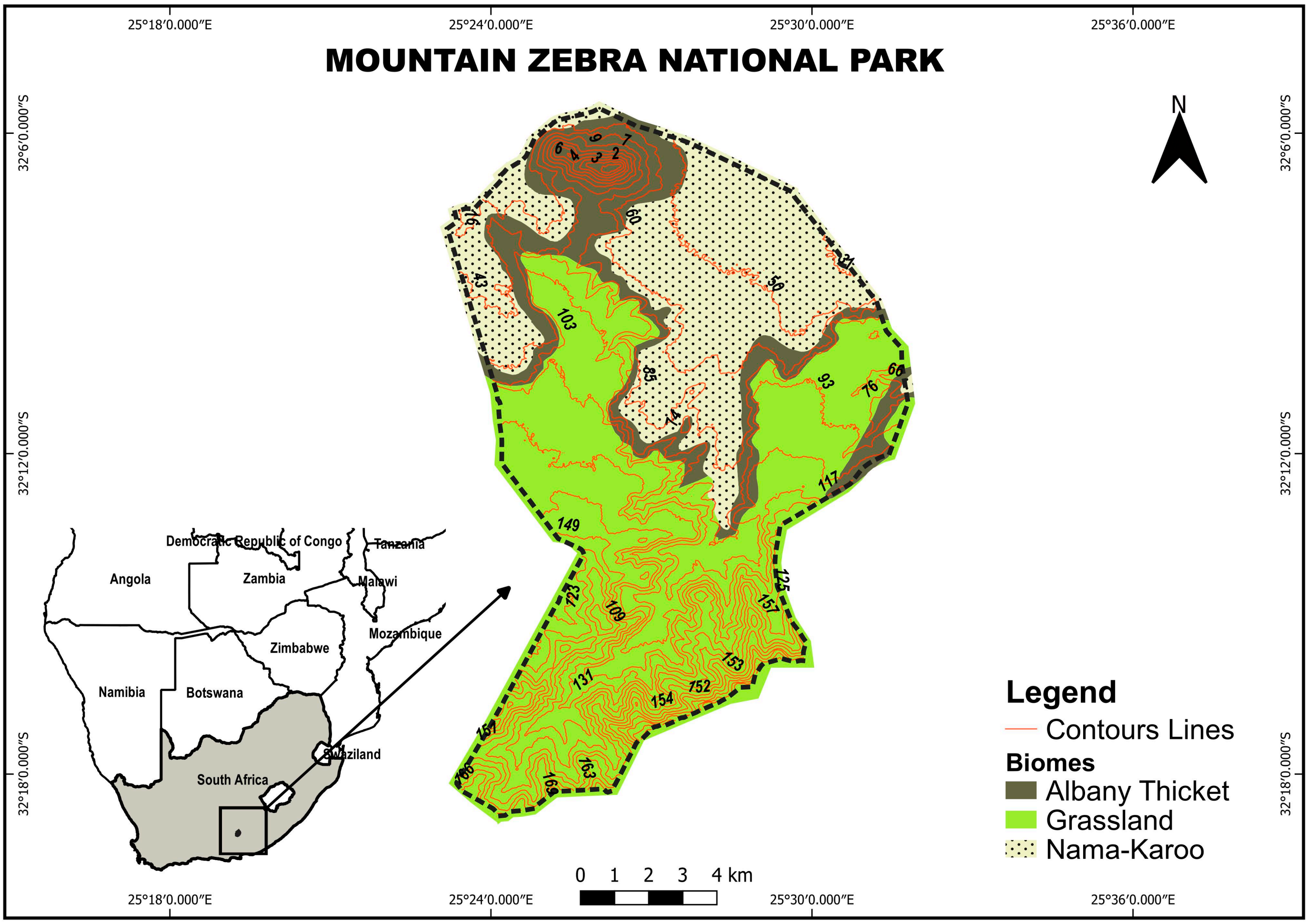

Figure 1. Location of Mountain Zebra National Park (MZNP) in South Africa and the three biomes in the study area in the park (contour interval = 10 m).

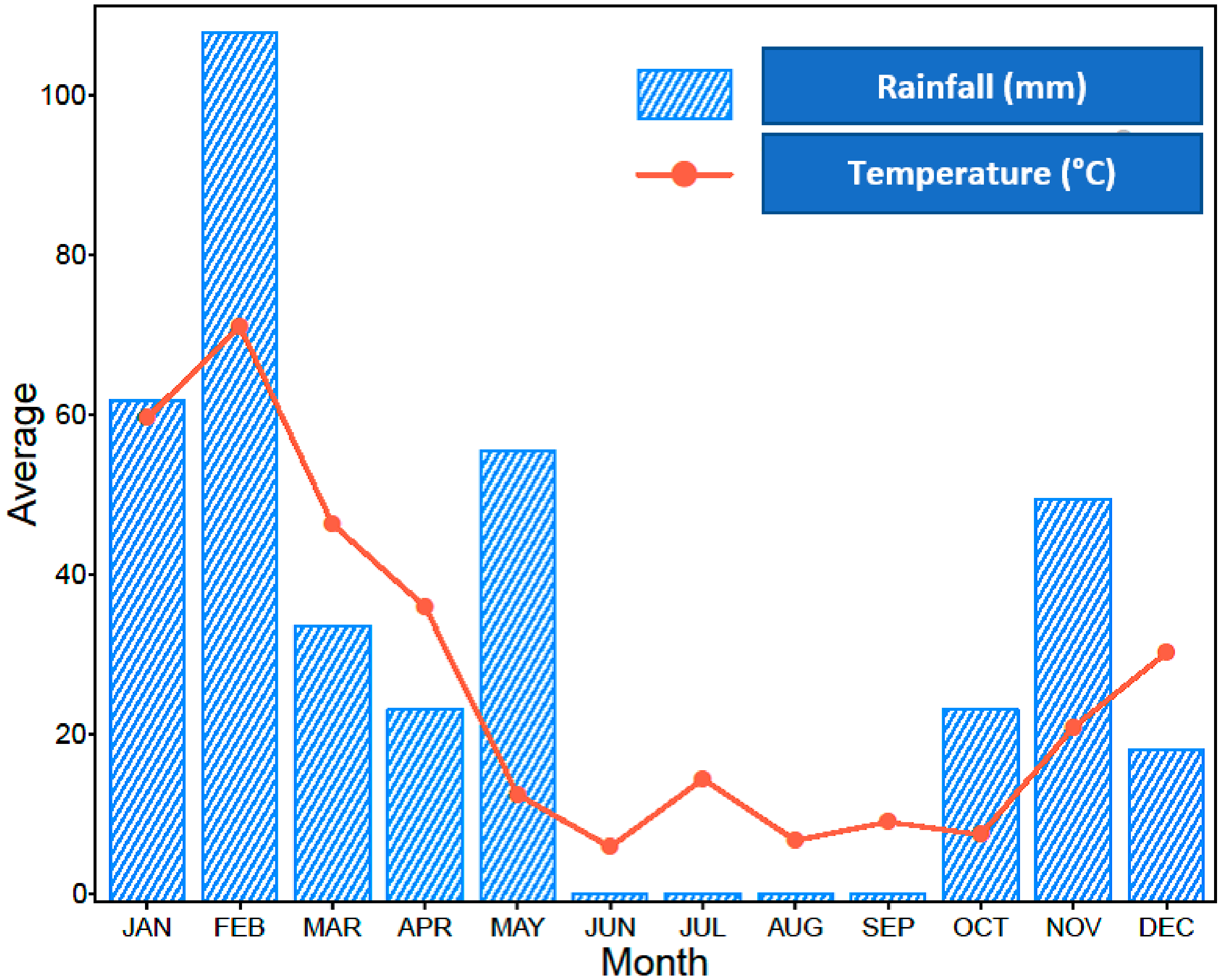

Figure 2. Climate and rainfall in Mountain Zebra National Park from 2019.

2.2. Field Data Collection: Plot-Based Method

Sampling was conducted using transects distributed across the different vegetation units in the park (Figure 3). Vegetation units are the categories of different portions in the park that are based on the dominant vegetation and the growth forms. Data were collected using the step-point method [26], using an approach based on a method reported previously [27]. In total, 50 transects were sampled across the eight management units. Several plots differed across the vegetation units. The transects were 50 m long, and observations were made at 1 m intervals, where the plant in contact with the meter stick was identified and recorded. All plants in the plots were identified to the species level. The geographical positioning system (GPS) coordinates were recorded using a Garmin GPSMAP 64s GPS device. The study was conducted during the growing season (January to February 2021) to facilitate easy plant species identification.

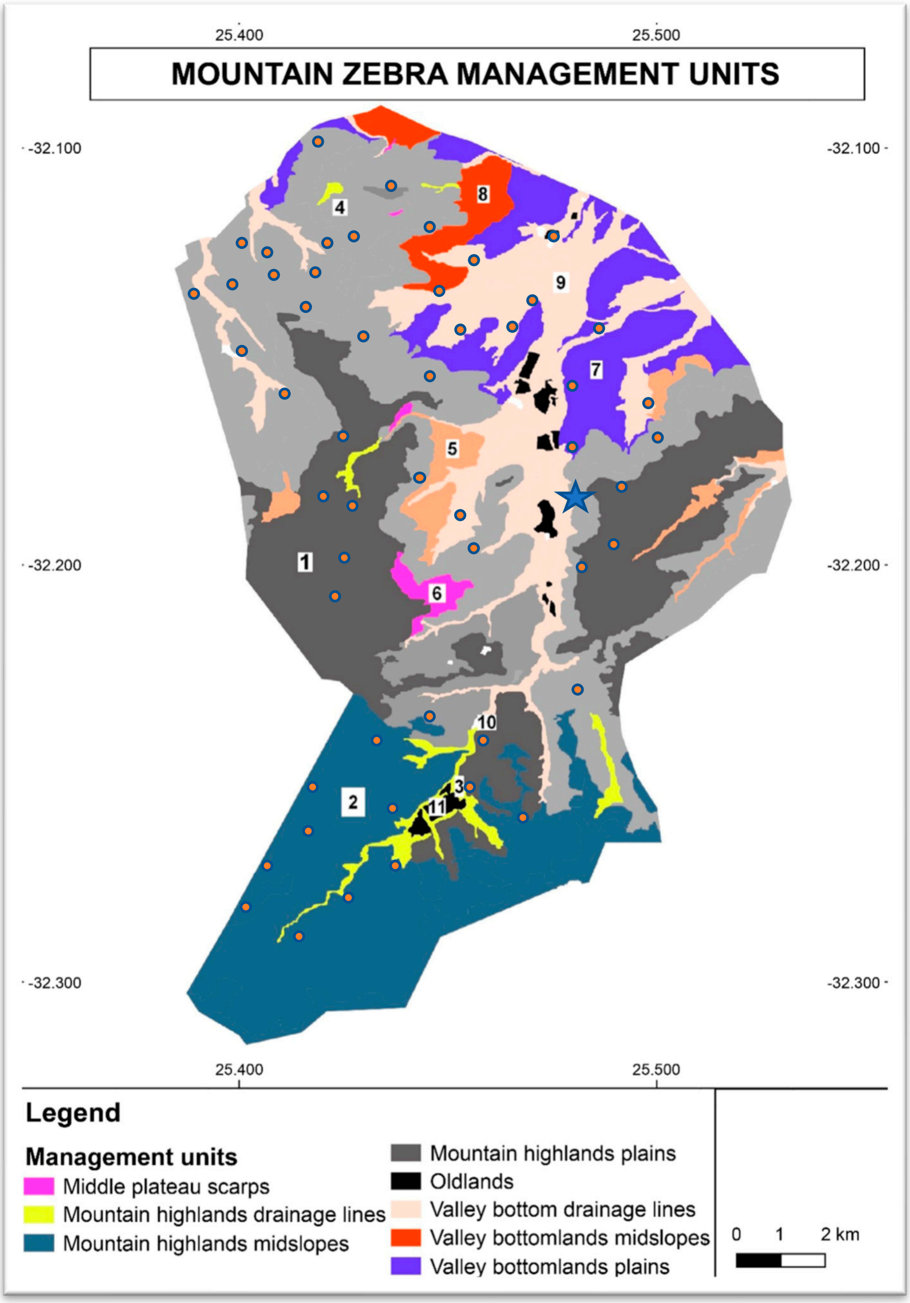

Figure 3. Location of the monitoring plots in the Mountain Zebra National Park management units. The star symbol on the map represents the location of the climatic weather station. Number 1 to 11 on the map are different vegetation unit.

2.3. Climate and Soil Data

Digital elevation model (DEM) data were obtained to compute the slope, and aspect data and environmental data, except the rainfall data, were extracted for each sample site using Quantum GIS (QGIS) 2.18.0 (Las Palmas de G.C.). All of the layers that were applied in QGIS used the geographic coordinate system WGS84 and EPSG:4326 as a spatial reference. This was completed using WorldClim, which allows for the extraction of raster values to points. The soil physical properties included organic matter content, sand, clay, coarse fragments, and silt, whereas the chemical properties included nitrogen and organic carbon (Table 1).

Table 1. Environmental variables used in the present study.

Class	Variables	Source	Scale/Resolution
Topography	Digital elevation model (DEM)	SRTM	30 m
	Slope	Derived from DEM	30 m
	Aspect	Derived from DEM	
Soil chemical properties	Nitrogen (cg/kg)	Soil grids	250 m
	pH	Soil grids	250 m
	Organic carbon (g/kg)	Soil grids	250 m
	Cation exchange capacity (mmol/kg)	Soil grids	250 m
Soil texture and physical properties	Silt (g/kg)	Soil grids	250 m
	Coarse fragments (cm^3/dm^3)	Soil grids	250 m
	Organic content (g/kg)	Soil grids	250 m
	Bulk density (cg/cm^3)	Soil grids	250 m
	Sandy (g/kg)	Soil grids	250 m
	Clay (g/kg)	Soil grids	250 m

2.4. Statistical Analyses

Statistical analyses were performed using R (R Development Core Team 2019) [28]. Two response variables were investigated: species richness and the normalized Shannon diversity index (NSDI). Species richness was calculated as the absolute number of unique species in the corresponding vegetation units. The NSDI (a fractional value that varies between zero and one) was implemented as an extension of the original proposal by Shannon [29]. The association between the response variables and different environmental variables was evaluated using appropriate visual and quantitative statistical tools. Geographic coordinates were also considered as predictor variables in the models. The GPS coordinates serve as proxies for the environmental gradient, meaning that the information added to the model by the longitude and latitude variables can be considered as an indicator of the positions of the plots on the map. Because of the limited size of the dataset used for the analyses, all of the *p*-values reported in this work were adjusted for multiple testing using the Benjamini–Hochberg technique [30], which minimizes the risk of incorrectly rejecting the null hypotheses verified with the statistical tests. Notably, all areas in each vegetation unit had similar richness and NSDI values, implying that the vegetation unit variable perfectly separated the response variables. Regression analyses were used to separate and evaluate the relationship between the overall species richness and the NSDI. These analyses required us to implicitly assume that the unobserved population data of the pairs of responses were normally distributed, depending on the predictors. Environmental variables were included as predictors in the models. The decisions regarding the parsimonious models relied on Akaike information criteria [30] and an analysis of variance (ANOVA). The NSDI was estimated, such that for each vegetation unit k, $NSDI_k = -\frac{1}{\log(S)}\sum_{i=1}^{S} p_i \log(p_i)$.

The notation is $p_i = n_i/\sum n_i$, where n_i is the number of times species i was observed in vegetation unit k and $S = 54$ denotes the total number of unique species observed across all the vegetation units. Normalization permits for unbiased comparisons among vegetation units.

3. Results

Both the species richness and the NSDI had low *p*-values (≈0.0003), indicating a statistically significant difference between richness and diversity across the vegetation units (Table 2). Unit 1 contained the highest number of species (34), whereas Unit 11 had more than five times fewer species (6). Subsequently, the degree of pairwise relationships between the vegetation unit response and each different environmental predictor was investigated using ANOVA and linear correlations.

Table 2. Species richness and the normalized Shannon diversity index (NSDI), summarized concerning the vegetation unit.

	Vegetation Unit									*p*-Value
	1	**2**	**3**	**4**	**5**	**7**	**8**	**9**	**11**	
Species richness	34	30	12	29	23	15	15	21	6	0.0003
NSDI	0.363	0.325	0.623	0.412	0.334	0.614	0.469	0.536	0.722	0.0003

The reported *p*-values obtained from the Chi-squared test of equal counts and proportions were adjusted for multiple testing.

The widths of the lines drawn in the graphical illustrations of continuous predictors were two times greater than those of the associated standard errors (Figure 4). The dots represent the positions of the corresponding average values. A statistically significant association was observed only between the vegetation units adopted here as a proxy for the NSDI and species richness. This inference was based on the corresponding low *p*-values (<0.05). The longitude coordinate, rainfall, and soil organic carbon content in Unit 2 appeared to be significantly higher than similar measurements in the other units.

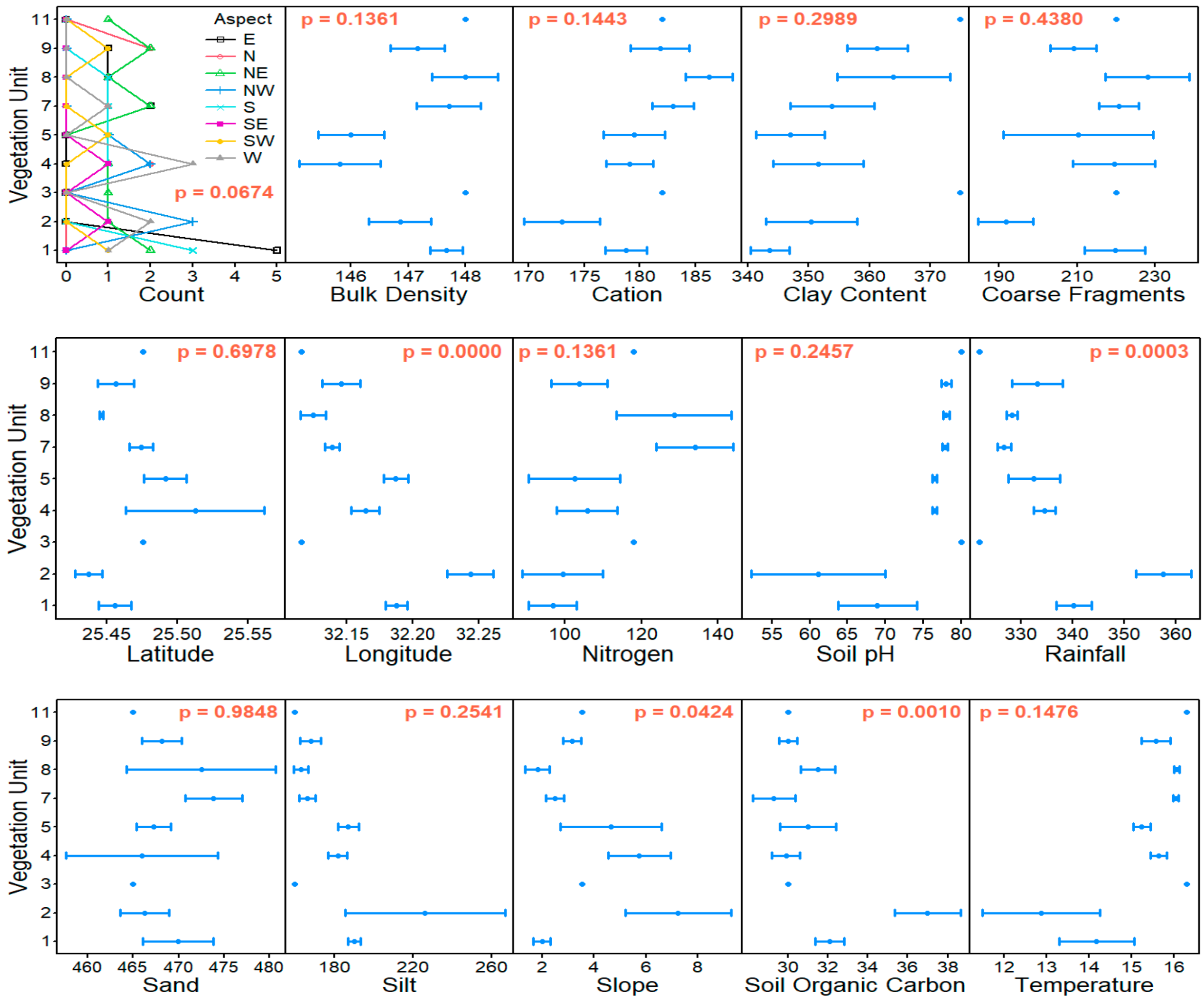

Figure 4. Pairwise comparison of the environmental and geographical predictor variables against the vegetation unit variable. The vegetation unit was used here as a proxy for the normalized Shannon diversity index and the species richness response variables. The reported adjusted *p*-values were obtained from appropriate Fisher tests of association.

Outputs from examining the magnitude and direction of the linear relationship between all pairs of continuous variables in the data are summarized in the correlation matrix (Figure 5). It is evident from the matrix that the coarse fragment variable had the lowest degree of linear correlation with the other continuous variables in the data. However, longitude appears to have the strongest linear relationship with the other variables. Sand exhibited the highest (approximately zero) pairwise linear correlation. These observations implied that: (1) the information provided by the longitude coordinates was similar to that provided by many of the other variables in the data, indicating that such "other" variables are likely to be redundant; (2) sand and coarse fragment variables are unlikely to be displaced from an optimal model, except if the quality of the information that they contribute is invaluable.

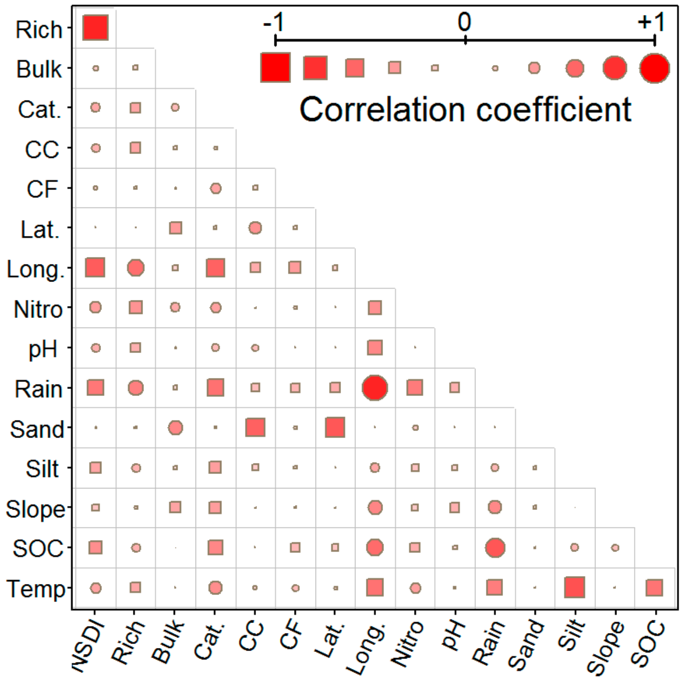

Figure 5. Pairwise linear correlation matrix for all the continuous variables in the analyzed data. The cells' color, size, and shape are proportional to the corresponding coefficients. NSDI = Normalized Shannon diversity index; Rich = Species richness; Bulk = Bulk density; Cat. = Cation; CC = Clay content; CF = Coarse fragments; Lat. = Latitude; Long. = Longitude; Nitro = Nitrogen; pH = soil pH Water; Rain = Rainfall; SOC = Soil organic carbon; Temp = Temperature.

The linear predictive equations for the NSDI and species richness, including all predictor variables in the dataset, are presented (Table 3). Note that the aspect categories were included in the model as dichotomous variables, with east being the reference category. Without a loss of generality, the East-Aspect category of vegetation units was adopted as the reference group for understanding the impact of Aspect on the response variables. The regression estimates from the regression model related to Aspect should be interpreted relative to the East-Aspect group. In addition, owing to its perfect portioning property, the vegetation unit variable was not included as a predictor variable. The degree of the observed variation in the response variable explained by the predictive models was measured by the adjusted correlation coefficient. The estimates were 38.13% and 33.43% for the NSDI and species richness, respectively. The regression coefficient estimated that eight of the predictors in the NSDI equal zero. This implied that the predictors did not affect the NSDI values in the presented full-model expression.

Table 3. Parsimonious multiple linear regression for the species richness response as inferred through implementation of all-subset variable selection analysis.

Species Richness = β_0 + β_1 × Clay Content + β_2 × Longitude + β_3 × Nitrogen + β_4 × Sand					
Coefficient	**Estimate**	**Std. Error**	***p*-Value**	**95% Confidence Interval**	
				Lower	**Upper**
β_0	−1528.7705	816.4972	0.0674	−3171.3511	113.8101
β_1	−0.2045	0.0778	0.0116	−0.3611	−0.0479
β_2	53.3856	25.5911	0.0424	1.9030	104.8682
β_3	−0.0715	0.0411	0.0885	−0.1541	0.0112
β_4	−0.1786	0.0891	0.0507	−0.3578	0.0006
Adjusted correlation coefficient: 43.53%					

Consequently, it is necessary to seek less complex models, i.e., those made up of fewer influential predictors, which are almost as effective as the full models.

The clay content, longitude, and sand predictor variables constituted the optimal models for both of the response variables (Tables 3 and 4). These three variables were also inferred to significantly influence the estimates of both the NSDI and the species richness. This claim was based on the corresponding low adjusted *p*-values (<0.05). The clay content and sand variables had positive impacts on the response values. In contrast, the longitude tended to be negatively associated with the NSDI, but positively associated with species richness. Two predictors, namely soil organic carbon for the NSDI, and nitrogen for species richness, were included in the final models, despite them not showing a statistically significant impact in determining the relative response value. This non-significance could result from the conservativeness related to the multiple test corrections or because these variables represent confounders. Thus, a pair of predictors could benefit from future interrogation with a larger dataset. The optimal models identified through all-subset variable selection analyses used to achieve the set objective are summarized in Tables 3 and 4 for the NSDI and species richness responses, respectively.

Table 4. Optimal linear regression model for the normalized Shannon diversity index (NSDI) response, as identified through implementation of all-subset variable selection analysis.

NSDI = β_0 + β_1 × Clay Content + β_2 × Longitude + β_3 × Sand + β_4 × Soil Organic Carbon					
Coefficient	**Estimate**	**Std. Error**	***p*-Value**	**95% Confidence Interval**	
				Lower	**Upper**
β_0	26.1353	13.1958	0.0053	−0.4113	52.6819
β_1	0.0026	0.0012	0.0279	0.0003	0.0049
β_2	−0.8593	0.4119	0.0424	−1.6880	−0.0306
β_3	0.0027	0.0013	0.0416	0.0001	0.0053

4. Discussion

The main findings indicate that the chemical properties of soil (nitrogen and soil organic carbon) significantly impacted on species richness and diversity, and that the clay and sand content (i.e., soil texture) positively affected species diversity. In contrast, the physical properties of soil (silt) did not affect plant species richness and diversity.

Furthermore, our results suggested that soil nitrogen content influences species richness, as the nitrogen content was inversely proportional to species richness. The negative relationship between species richness and soil nitrogen content in the present study was in accordance with the findings of [31,32], but it contradicted the "fertility effect" theory of Dybzinski et al. [33]. Duprè et al. [34] conducted a temporal analysis of species richness in grassland and found that species richness significantly declined relative to the estimated cumulative nitrogen deposition. According to Stevens et al. [35], a decrease in plant species richness is linked to long-term chronic nitrogen addition in acidic grasslands in Great Britain. However, other authors have contended that species richness increases with the increase in fertility [36,37]. The results of the present study supported the hypothesis that plant species richness, diversity, and soil parameters are correlated. Evaluating the factors controlling plant species richness and diversity distribution patterns is crucial to conclude the unresolved debate regarding the association between plant diversity and soil properties [38]. The relationship between the soil and plant response is vital for succession and competition dynamics [39]. Environmental factors such as soil properties positively and negatively influence species diversity and richness [40].

In the present study, clay and sand content (i.e., soil texture) positively affected species diversity. This finding differs from the observation of Abbasi-Kesbi et al. [40] that species diversity was negatively correlated with sand and clay content. In general, the effect of soil texture on the distribution of plant species is due to the influence of moisture on the soil. Similarly, species richness was negatively correlated with clay and nitrogen content in the present study, as previously observed by [41], who reported a negative correlation between species richness and soil clay content. This study also showed that longitude had a positive impact on species diversity and a negative effect on species richness.

5. Conclusions

The objectives of this study were to determine the effects of environmental factors on plant species richness and diversity in the study area. Nitrogen showed an inverse relationship with species richness. The results from this study add to an overall understanding of vegetation structure and distribution in relation to environmental factors in mountainous grassland regions. Future research should examine the influence of environmental factors on plant biomass. This will enhance our understanding of the structure of plant communities, and the relationships between environmental factors and plant species of semi-arid vegetation.

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Data Availability Statement: The data supporting this study's findings are available from the corresponding author (NM), upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

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