

PLANT DIVERSITY IN PROTECTED AREAS ALONG GEOGRAPHIC AND CLIMATIC GRADIENTS IN THE GRASSLAND BIOME OF SOUTH AFRICA

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Abstract. Grassland ecosystems globally are under enormous pressure brought about by anthropogenic activities such as agricultural intensification, habitat modification and destruction, and urban expansion. These anthropogenic pressures have resulted in the loss of biodiversity, and protected areas are seen as crucial ecological infrastructure that can assist in mitigating the process. The aim of the study was to analyse plant diversity in twelve protected areas across the Grassland Biome of South Africa, and to determine the environmental factors influencing diversity patterns. Plant diversity was determined as species richness (S), Shannon-Wiener diversity (H'), and Pielou evenness (J'), and interactions between environmental factors were analysed. The study area was characterised by an increase in mean annual rainfall with increasing longitude, and rainfall also increased along an elevation gradient. In addition, there was a monotonic decline in mean annual rainfall and temperature along latitudinal and altitudinal gradients, respectively. Plant diversity declined along latitudinal and altitudinal gradients. Protected areas located at lower elevations generally had higher local diversity but those with heterogeneous environments presented higher regional diversity. Insights on species diversity patterns in relation to environmental conditions are vital for developing effective conservation measures needed to arrest the current decline in biodiversity. Furthermore, knowledge of species diversity responses to latitudinal and altitudinal gradients is important, especially in light of the envisaged climate change perturbations. Protected areas, especially those at higher elevations and latitudes, are envisaged to play a crucial role as refugia for species migrating to escape the effects of climate change.

Keywords: *biodiversity conservation, elevation gradient, latitudinal gradient, local species richness, regional species richness*

Introduction

Global biodiversity assessments and projections reveal that the Earth's biodiversity is declining at an alarming rate (Barnosky et al., 2011; Ceballos et al., 2015). Although this dramatic decline cannot yet be regarded as a mass extinction event (Rull, 2022), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) warns that close to a million plant and animal species face extinction in the coming decades. The consequences of biodiversity loss are most likely to impact the delivery of important ecosystem functions and services (Cardinale et al., 2012; Newbold et al., 2015). Biodiversity is threatened by human pressures that include land-use changes, habitat conversions, agricultural intensification, and also climate change (Newbold et al., 2015; Maxwell et al., 2016). These threats are also pertinent in South Africa, and further include unsustainable resource use such as overharvesting of medicinal plants and overfishing, as well as habitat invasions by alien species (Government of South Africa, 2015).

There is no dispute that effective conservation measures are urgently needed in order to mitigate the loss of biodiversity (Barnosky et al., 2011; Ceballos et al., 2015; Rull, 2022). Areas that are set aside and formally designated for the protection and conservation

of biodiversity play a crucial role in mitigating the decline. According to the Convention on Biological Diversity (CBD), it is still possible to stop biodiversity loss and maybe even reverse it (Cooper and Noonan-Mooney, 2013) but that all depends on how effectively the Kunming-Montreal Biodiversity Targets for 2030 and beyond are implemented by respective countries. For the previous biodiversity targets, Aichi Biodiversity Target 11 clearly stipulated that 17% of terrestrial areas had to be conserved through effective, ecologically representative and well-connected systems of protected areas by 2020 (Cooper and Noonan-Mooney, 2013). To date, indications are that the world has met this target, with 16.64% of the global terrestrial and inland water areas reported to be protected by 2020 (UNEP-WCMC and IUCN, 2021) and 17.6% by 2024 (UNEP-WCMC and IUCN, 2024). However, although the global rush has been to increase the extent of protected areas within countries, there are cautionary calls to ensure that protected areas actually fulfil their purpose of conserving biodiversity (Barnes et al., 2015). Concerns still linger on the quality of these protected areas, especially with regard to how ecologically representative and well-connected they are, and whether they include key biodiversity spots (Heywood, 2019; IPBES, 2019; UNEP-WCMC and IUCN, 2021). There are also concerns around effective management, staffing and resourcing of the protected areas (Geldmann et al., 2018; Coad et al., 2019; Heywood, 2019), leading to acknowledgement that failure to address these concerns may not guarantee the effectiveness of protected areas in halting biodiversity loss (Geldmann et al., 2018).

South Africa has a network of protected areas which are managed for conservation of critical habitats and species, and most importantly to ensure that a representative portion of all ecosystems in the country is conserved (Government of South Africa, 2015). The country regards protected areas as terrestrial and oceanic areas that are protected according to the National Environmental Management: Protected Areas Act 57 of 2003 (Government of South Africa, 2004). The protected areas are officially distinguished into the following types: national parks, nature reserves, special nature reserves, marine protected areas and protected environments, forest nature reserves, forest wilderness areas, mountain catchment areas, and world heritage sites (Department of Environmental Affairs, 2016). Currently, 9.2% of land in South Africa has been declared as protected (Statistics South Africa, 2021) and three-quarters of the terrestrial types have some degree of representation in the protected area network. However, the protected area network has not evolved in a systematic manner that would ensure effective biodiversity conservation, mainly because some ecosystem types are well protected while others are not (Department of Environmental Affairs, 2016). In fact, the situation in South Africa is quite concerning because 22% of the country's terrestrial ecosystem types are threatened (Skowno et al., 2019).

Within the terrestrial ecosystems globally, plant species are numerically far more abundant than vertebrate species yet they are given less importance in biodiversity conservation and protected area establishment (Kier et al., 2005). In South Africa, many protected areas were historically established for maintaining mammalian wildlife species but the importance of conserving the country's flora has gradually come to the fore (Rouget et al., 2006). To that effect, the aim of the study was to determine patterns of plant diversity in selected protected areas (national parks and nature reserves), and to elucidate how diversity responds to environmental gradients in the Grassland Biome of South Africa. Environmental factors play a major role in the delimitation of South African grasslands, especially altitude and rainfall (Mucina et al., 2006). The Grassland Biome is rich in biodiversity with around 3800 plant species found in the biome (Bond and Parr,

2010; SANBI, 2013). It has the second highest plant diversity in the country, second only to the Fynbos Biome (SANBI, 2013). As pointed out by Bengtsson et al. (2019), grasslands in general are not only important for maintaining biodiversity, but are also vital for food production and for their effects on ecological processes such as water and climate regulation. Furthermore, grasslands in South Africa bear much needed economic benefits and provide the lifeline for many rural livelihoods (SANBI, 2013). But unfortunately, only 4.6% of the Grassland Biome land area is protected, making the biome the second least protected in South Africa (Statistics South Africa, 2021). To further highlight this concerning state of affairs, 40% of the biome has already been irreversibly transformed and 60% of the remaining grassland is regarded as threatened (SANBI, 2013). However, it is encouraging that efforts are continually being made to arrest this drastic transformation, by identifying suitable areas within the biome that can be protected (e.g., Prinsloo et al., 2021). The role of protected areas in the biome is indeed vital, and it is imperative that the protection and proper management of grasslands remains a priority.

Materials and methods

Study area

The study area comprised twelve protected areas (PAs) which differed in geographic (i.e., altitude, longitude, latitude) and climatic (i.e., temperature, rainfall) characteristics (*Table 1*). The PAs were mainly located within the Grassland Biome but there were a few that were located in Savanna and Nama-Karoo biomes; these PAs were included because they harbour isolated pockets of grassland vegetation. These pockets are maintained by environmental conditions conducive for grassland vegetation, mainly topographic and geological characteristics that can influence rainfall interception, soil depth, and moisture (O'Connor and Bredenkamp, 1997). The Grassland Biome is the second largest of the nine biomes in South Africa; it is mainly found on the Highveld, in KwaZulu-Natal and in the Eastern Cape Province (Mucina et al., 2006) at an altitude varying from 300 m to 2 850 m above sea level (Rutherford and Westfall, 1994). The climate of the biome is characterized by cold, dry winters with frequent occurrences of frost; summers are hot and rainfall occurs mainly during the summer season, with amounts varying spatially from 400 to 2 500 mm per annum (Mucina et al., 2006).

Five PAs occur in the northern part of the country, namely Verloren Valei Nature Reserve (VVNR henceforth), Blyde River Canyon Nature Reserve (BRCNR henceforth), Marakele National Park (MNP henceforth), Abe Bailey Nature Reserve (ABNR henceforth) and Boskop Dam Nature Reserve (BDNR henceforth). Although VVNR, BRCNR and MNP occur in the northern most part of the study area, they are found in areas of differing altitudes (*Figure 1*) that are characterised by vastly different climatic conditions. BRCNR and MNP are located in areas with high temperatures but annual rainfall at BRCNR is much higher than at MNP. Similar to BRCNR, VVNR also receives a high amount of annual rainfall but average temperatures are much lower due to its location at higher altitude. ABNR and BDNR are located at mid-altitudes in a region of mild temperatures and annual rainfall ranging between 600 and 800 mm.

The other four PAs are found in central South Africa, namely Soetdoring Nature Reserve (SNR henceforth), Willem Pretorius Nature Reserve (WPNR henceforth), Golden Gate Highlands National Park (GGHNP henceforth), and uKhahlamba-Drakensberg Park (UDP henceforth). All the PAs except UDP occur in the Free State

Province. SNR and WPNR are located in central Free State, where average annual rainfall ranges between 400 and 600mm per annum. GGHNP is found in eastern Free State, and this area of the province is at a higher altitude and is cooler and wetter than the central Free State where SNR and WPNR are located (*Figure 1*). To the east of GGHNP is the UDP which, together with Sehlabathebe National Park in the Kingdom of Lesotho, constitute a transboundary park known as the Maloti-Drakensberg Transboundary World Heritage Site (UNESCO, 2025). In this manuscript I am focusing on the South African side of the park i.e. the UDP in KwaZulu-Natal. Bokong Nature Reserve (BNR henceforth) is found slightly south of GGHNP, but in the Kingdom of Lesotho (shown as an enclave in *Figure 1*). UDP and BNR occur at high altitudes with low temperatures but high amounts of annual rainfall.

Table 1. Summary of altitude, mean annual temperature and mean annual rainfall for the protected areas, and the number of sample plots used for the present study

Protected Area	Province	Biome	Area (km ²) [^]	Altitude (m.a.s.l)	Temp (°C)	Rainfall (mm)	N
SNR	Free State	Grassland	62	1260	16.6	501	240(4) [*]
BNR	Lesotho [§]	Grassland	20	2773	6.8	956	65
VVNR	Mpumalanga	Grassland	59	2162	11.9	975	502
RNR	Northern Cape	Nama-Karoo [#]	52	1248	18.1	369	447
GGHNP	Free State	Grassland	328	1942	13.3	797	90
WPNR	Free State	Grassland	121	1393	16.3	599	386(8) [*]
UDP	KwaZulu-Natal	Grassland	2428	1990	12.7	970	90
MZNP	Eastern Cape	Nama-Karoo [#]	284	1278	14.7	444	115
BDNR	North-West	Grassland	32	1405	16.8	624	81
MNP	Limpopo	Savanna [#]	639	1363	18.2	634	145
ABNR	Gauteng	Grassland	42	1493	16.4	673	153(3) [*]
BRCNR	Mpumalanga	Grassland	269	1246	17.1	989	87

[§] Independent country, not part of South Africa. [^] Data sources: Bourquin (1973); Bredenkamp et al. (1994); Carbutt et al. (2011); Ferreira and Greaver (2016); Hrabar and Kerley (2013); Janecke et al. (2003); Jooste and Palmer (1982); Mpumalanga Tourism and Parks Agency (<http://www.mpumalanga.com>); Ndlovu (2016); Rademeyer and van Zyl (2014); SANParks 2013; Taylor and Atkinson (2012); Willis and Edge (2015). [#] Transition zone/ecotone with Grassland Biome. N is the number of sample plots. ^{*} The numbers in brackets indicate the number of sample plots with only one species, the plots were not included in data analysis

In the southern part of the country, the focus was on Rolfontein Nature Reserve (RNR henceforth) and Mountain Zebra National Park (MZNP henceforth). RNR is found in the south eastern part of Northern Cape Province near the border with Free State, in an arid area where average annual rainfall is less than 400 mm. MZNP occurs towards the north-western part of Eastern Cape Province, in a cool and arid region with average annual rainfall of approximately 400 mm (SANParks, 2016).

According to Rutherford and Westfall (1994), two major types of grassland can be distinguished within the Grassland Biome, namely moist grasslands receiving more than 600mm of annual rainfall and dry grasslands receiving less than 600 mm. BNR, VVNR, UDP, and GGHNP are dry grasslands, and these PAs also occur at high-altitudes above 1 500 m.a.s.l. The rest of the PAs are found at altitudes lower than 1 500 m.a.s.l and are dry grasslands.

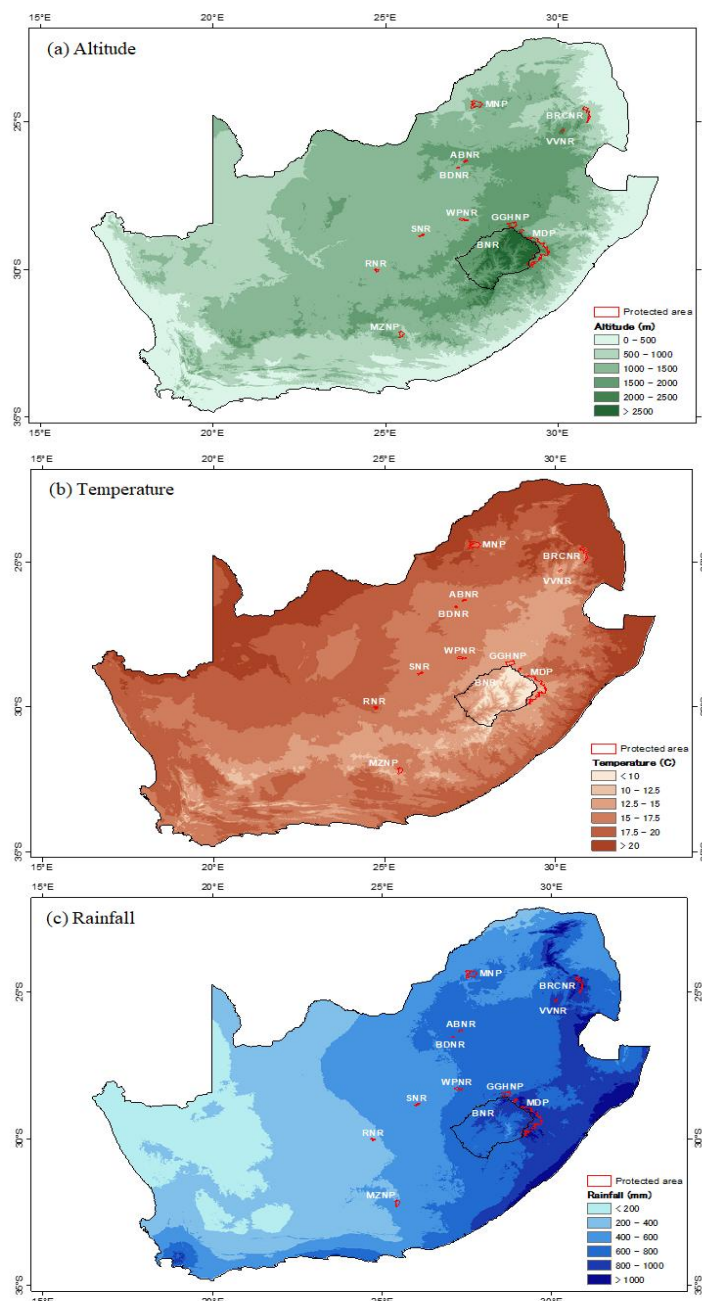


Figure 1. Maps of altitude, mean annual temperature and mean annual rainfall. Red lines indicate nature reserves and national parks. MDP is a transboundary park comprising Sehlabathebe National Park and uKhahlamba-Drakensberg Park (UDP), but only the latter is included in this study

Data acquisition

The vegetation dataset for the protected areas was acquired from the National Vegetation Database of South Africa (GIVD ID AF-ZA-001), which is under the custodianship of the South African National Biodiversity Institute (SANBI). The database contains floristic data mainly from South Africa and a few relevés from neighbouring countries (Mucina et al., 2000; Powrie et al., 2012). A total of 2416 relevés (i.e., sample

plot data) were extracted, containing floristic data, cover-abundance values and habitat data (Table 1). 15 relèves had only one species and were excluded from data analysis, bringing the total to 2401 relèves.

The boundaries of the protected areas were downloaded from the South African Protected Areas Database of the Department of Forestry, Fisheries and the Environment (<https://egis.environment.gov.za>) except for Abe Bailey Nature Reserve (ABNR), which was acquired from Google Earth. Altitude data was obtained from the Global Multi-resolution Terrain Elevation Data 2010 (Danielson and Gesch, 2011). 30 years (1970-2000) climate data was downloaded from WorldClim (<https://www.worldclim.org>); mean annual temperature and mean annual rainfall data in 30 arcsec grids (approximately 1 km²) of the WorldClim Version 2 (Fick and Hijmans, 2017) was used for the present study.

Data analysis

Two levels of diversity analysis were conducted i.e., local diversity and regional diversity analysis. Local or point diversity represented diversity at sample plot level, and it was determined as species richness (S), Shannon-Wiener diversity index (H'), and Pielou's evenness index (J'). The indices were determined according to Magurran (2010) and Kent (2012). Species richness was calculated as the number of species in a sample plot, while Shannon-Wiener and Pielou indices were based on the proportional abundance of species (Magurran, 2010).

The Shannon -Wiener diversity index was calculated as follows:

$$H' = \sum_{i=1}^s p_i \ln p_i \quad (\text{Eq.1})$$

where s is the number of species (richness) and p_i is the proportion of cover of the i -th species (Magurran, 2010). The cover values extracted from the National Vegetation Database were derived from the Braun-Blanquet cover-abundance scale (Van der Maarel, 2005; Kent, 2012), but for the current study they were transformed to median values of the cover categories, except category r & +. The median values were determined as follows: 1% for category r & +; 3 % for category 1 (1-5%); 15% for category 2 (6-25%); 38% for category 3 (26-50%); 63% for category 4 (51-75%); and 88% for category 5 (76-100%).

For species evenness, the Pielou's evenness index was calculated as:

$$J' = \frac{H'}{\ln S} \quad (\text{Eq.2})$$

Regional diversity was regarded as the total number of species (S_{Total}) recorded for each PA i.e., regional species richness. To determine the adequacy of sampling effort for each PA, incidence-based species accumulation curves were constructed according to Seaby and Henderson (2006).

Analysis of Variance (ANOVA) with a post hoc test (Games-Howell test) was conducted for comparisons of diversity indices between the protected areas. Pearson correlation analysis was conducted to determine the relationships of diversity indices with geographic (latitude, longitude, altitude) and climatic (temperature, rainfall) variables. The relationships were also determined using regression analysis, with latitude, longitude, altitude, temperature and rainfall as predictor variables and diversity indicators as

response variables. First, simple linear regression was conducted, followed by multiple regression. Prior to multiple regression analysis, collinearity check was conducted between the geographic and climatic variables through variance inflation factors (VIF) and Pearson correlations. The acceptable VIF limit was set at 10 (Neter et al., 1990); that for Pearson correlation coefficient was 0.7 which would indicate that the relationship between the variables would account for less than 50% of the variation in each variable (Freund, 1992; Snedecor and Cochran, 1996). There was high collinearity between longitude and rainfall (VIF = 11.926; $r = 0.957$, $p < 0.000$), and between altitude and temperature (VIF = 10.621; $r = -0.952$, $p < 0.000$). The diversity variables were therefore regressed with geographic and climatic variables separately. Finally, to determine the combined effects of both geographic and climatic variables, backward stepwise linear regression was conducted wherein all explanatory variables were included in the model and then sequentially removed until the best model fit was attained. All statistical analyses were conducted using SPSS® software version 19.

Results

Influence of altitude on temperature and rainfall, and the lateral effects of longitude and latitude

Linear regression revealed positive and significant association between latitude and longitude ($r = 0.588$, $p = 0.044$), while latitude and altitude were virtually uncorrelated ($r = -0.047$, $p = 0.884$). There was a positive correlation between altitude and longitude, although not significant ($r = 0.476$, $p = 0.118$). Specifically, there was a west-east gradient wherein altitude increased eastwards with increasing longitude, from the lower lying PAs of the Northern Cape (RNR) and Eastern Cape (MZNP) provinces and central Free State (SNR, WPNR) to those in the higher lying Drakensberg Escarpment in the east (GGHNP, UDP). The altitude however dropped further east beyond the escarpment to the lower lying BRCNR in the Lowveld of Mpumalanga (*Figures 1a and 2a*).

Temperature associated negatively but non-significantly with latitude ($r = -0.249$, $p = 0.436$) and longitude ($r = -0.390$, $p = 0.210$), but its relationship with altitude was strong and significant ($r = -0.952$, $p < 0.000$), in which there was a decreasing trend in temperature with increasing altitude (*Figure 2h*). According to the results of multiple regression analysis (*Table 2*), mean annual temperature of the PAs was strongly influenced by the combined effects of latitude, longitude and altitude ($r^2 = 0.957$, $p < 0.000$). With regard to mean annual rainfall, simple linear regression showed that rainfall was positively and significantly associated with longitude ($r = 0.957$, $p < 0.000$) and altitude ($r = 0.685$, $p = 0.014$) but negatively with latitude ($r = -0.440$, $p = 0.152$), wherein increase in longitude and altitude were accompanied by increase in annual rainfall but the rainfall declined with increasing latitude (*Figure 2c, f, i*). Jointly, all three geographical variables strongly influenced the rainfall patterns in the study area ($r^2 = 0.986$, $p < 0.000$) (*Table 2*). Rainfall and temperature were negatively and significantly correlated ($r = -0.612$, $p = 0.035$), wherein PAs with lower mean annual temperatures received the most annual rainfall and the rainfall trend decreased with increasing temperatures (*Figure 2g*).

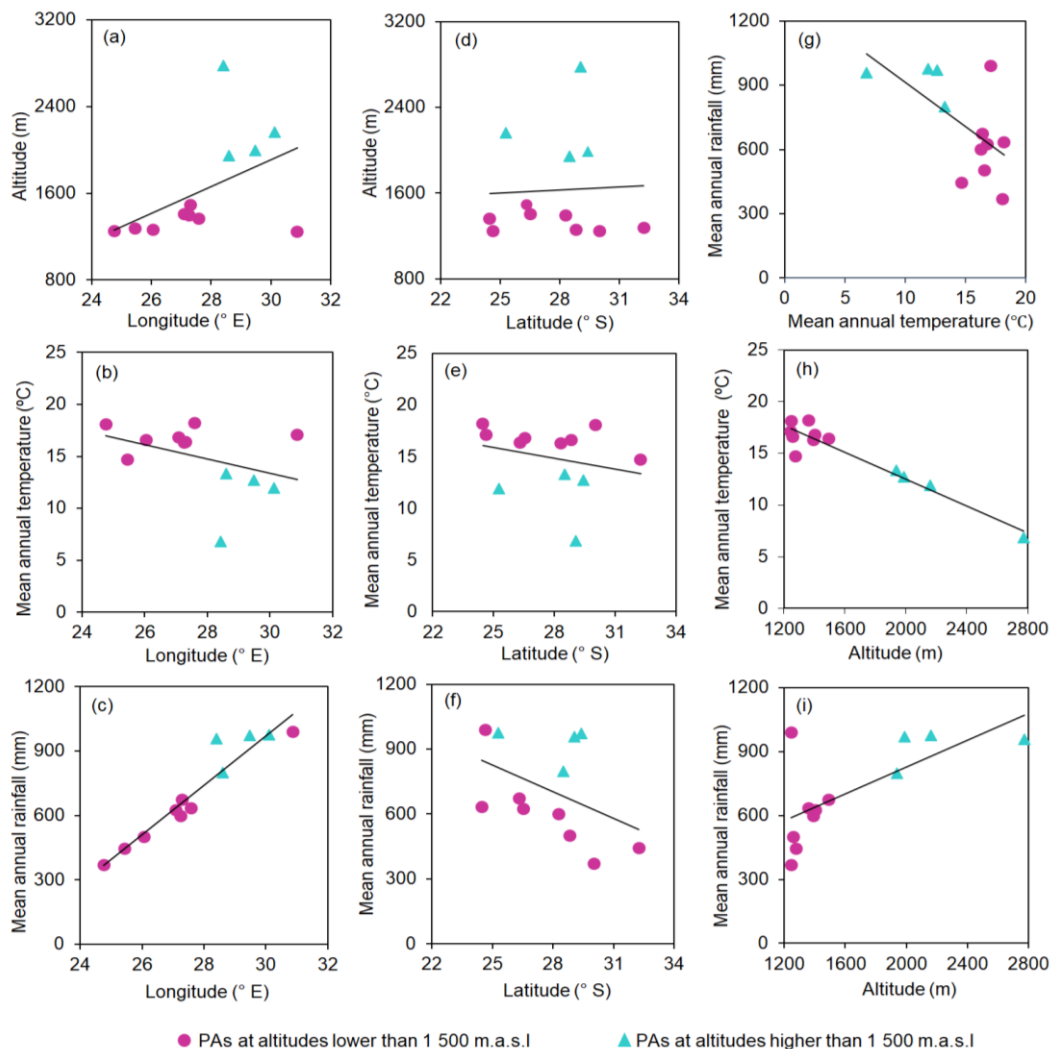


Figure 2. Relationships between the geographic and climatic variables of the study locations, with protected areas (PAs) distinguished into two elevation categories

Table 2. Results of multiple regression analysis with i) temperature and rainfall as dependent variables, latitude, longitude, and altitude as independent variables; and also, ii) diversity indices as dependent variables, temperature, rainfall, latitude, longitude, and altitude as independent variables

Diversity and climate variables	Prediction equations*	r^2	p
Temperature (T)	$T = 0.413\text{Lat} - 0.273\text{Lon} - 0.006\text{Alt} + 43.544$	0.957	0.000
Rainfall (R)	$R = 102.609\text{Lon} + 0.127\text{Alt} - 4.725\text{Lat} - 2474.446$	0.986	0.000
S	$S = 3.315T + 0.037R - 53.723$	0.580	0.020
	$S = 1.376\text{Lat} + 2.758\text{Lon} - 0.016\text{Alt} + 9.680$	0.613	0.046
H'	$H' = 0.180T + 0.002R - 1.615$	0.531	0.033
	$H' = 0.086\text{Lat} + 0.097\text{Lon} - 0.01\text{Alt} + 3.323$	0.515	0.107
J'	$J' = 0.023T + 0.000208R + 0.277$	0.441	0.073
	$J' = 0.013\text{Lat} + 0.007\text{Lon} - 0.000009\text{Alt} + 1.086$	0.386	0.249

* T : mean annual temperature; R : mean annual rainfall; Lat : latitude; Lon : longitude; Alt : altitude; S : Species richness; H' : Shannon-Wiener diversity; J' : Pielou evenness

Comparisons of plant diversity between protected areas

The diversity indices correlated strongly and positively with each other. There was high correlation between S and H' ($r = 0.953$, $p < 0.000$), and also between S and J' ($r = 0.824$, $p < 0.000$). H' correlated strongly with J' ($r = 0.948$, $p < 0.000$). BRCNR, MNP, BDNR, and ABNR had the highest S , H' and J' while the lowest diversity indices were recorded at RNR, SNR, VVNR, and BNR (Figure 3). ANOVA results showed that S differed significantly between many PAs, but H' and J' were not significantly different between many PAs (Table 3). When distinction was made between low-altitude ($< 1\,500$ m.a.s.l) and high-altitude ($> 1\,500$ m.a.s.l) PAs, there was no significant difference in S , H' , and J' between the two PA groups.

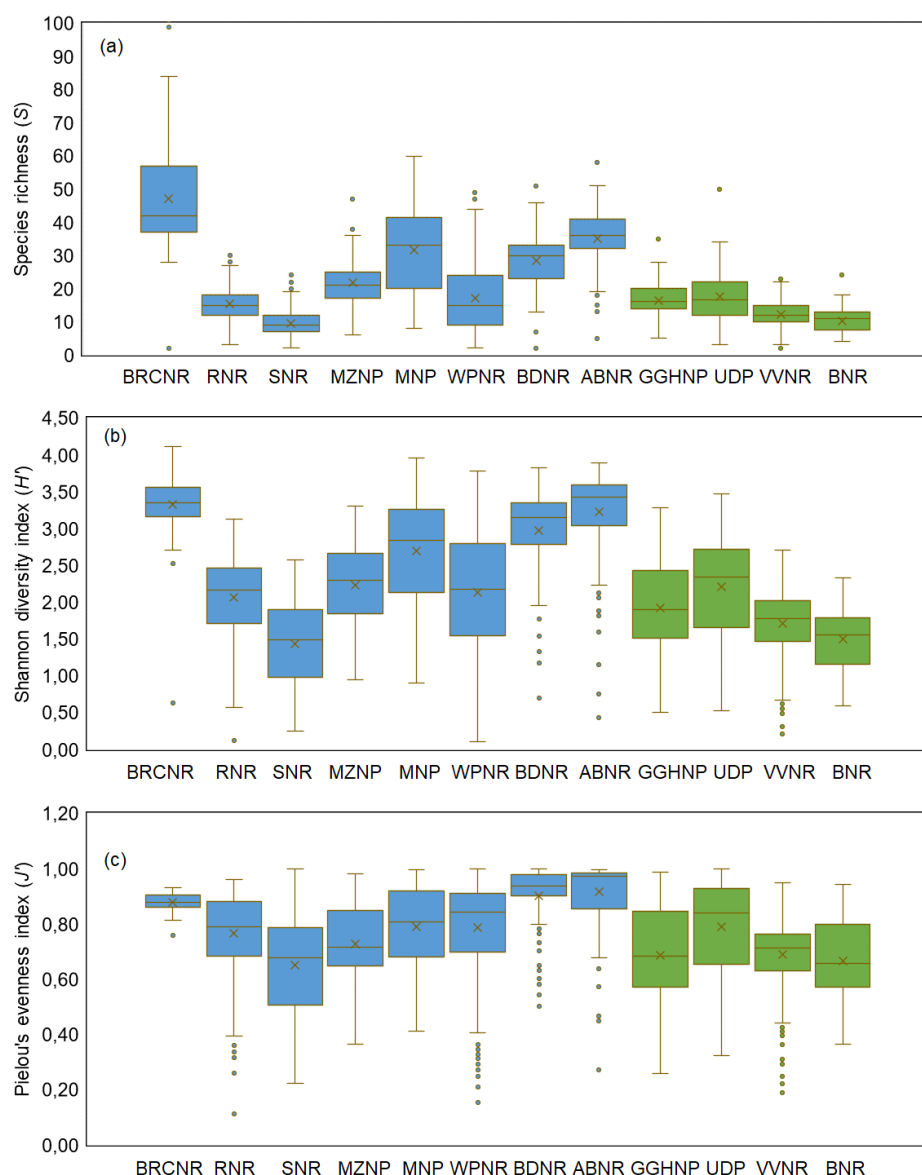


Figure 3. Box-Whisker plots for (a) species richness, (b) Shannon-Wiener diversity, and (c) Pielou evenness for each study location. Each box indicates the lower and upper quartiles, the horizontal line in the box represents the median, and the whiskers (vertical lines) denote the minimum and maximum values. Blue and green boxes denote low-altitude and high-altitude PAs, respectively

Table 3. Plant species richness, diversity and evenness in the protected areas, including ANOVA results with a post hoc test (Games-Howell test)

Location	Species richness (<i>S</i>)	Shannon-Wiener diversity index (<i>H'</i>)	Pielou evenness index (<i>J'</i>)
SNR	9.4 ± 3.9 a	1.43 ± 0.59 a	0.65 ± 0.19 a
BNR	10.2 ± 3.9 a	1.50 ± 0.44 a	0.67 ± 0.14 ab
VVNR	12.3 ± 3.9 b	1.71 ± 0.45 b	0.69 ± 0.13 ab
RNR	15.3 ± 5.2 c	2.07 ± 0.54 cd	0.77 ± 0.14 cd
GGHNP	16.5 ± 4.9 c	1.92 ± 0.62 bc	0.69 ± 0.18 ab
WPNR	17.1 ± 10.4 c	2.14 ± 0.83 cd	0.79 ± 0.17 d
UDP	17.5 ± 8.2 c	2.21 ± 0.71 cd	0.79 ± 0.16 cd
MZNP	21.7 ± 6.7 d	2.23 ± 0.56 d	0.73 ± 0.14 bc
BDNR	28.5 ± 8.3 e	2.98 ± 0.61 ef	0.90 ± 0.12 ef
MNP	31.7 ± 13.0 ef	2.69 ± 0.73 e	0.79 ± 0.14 d
ABNR	35.0 ± 9.1 f	3.23 ± 0.59 fg	0.92 ± 0.12 e
BRCNR	47.2 ± 15.4 g	3.33 ± 0.42 g	0.88 ± 0.03 f

Means ± standard deviations within columns followed by the same letters are not significantly different at $p \leq 0.05$

For regional diversity (S_{Total}), the PAs that had the highest local richness (S) also had the highest regional richness, except UDP which besides its moderate local diversity, showed the highest regional diversity of all PAs. High-altitude PAs in general had lower regional richness than lower-altitude PAs, with again the exception of UDP. Species accumulation curves (Figure 4) for MNP, WPNR, RNR, and VVNR reached an asymptote, showing that the sampling efforts for the four PAs were adequate. The relationship between local species richness (S) and regional richness (S_{Total}) revealed a significant hump-shaped curve ($r^2 = 0.499$, $p = 0.044$) (Figure 5), which was consistent even upon the exclusion of UDP ($r^2 = 0.575$, $p = 0.033$), which had very high S_{Total} and could be expected to distort the shape of the curve.

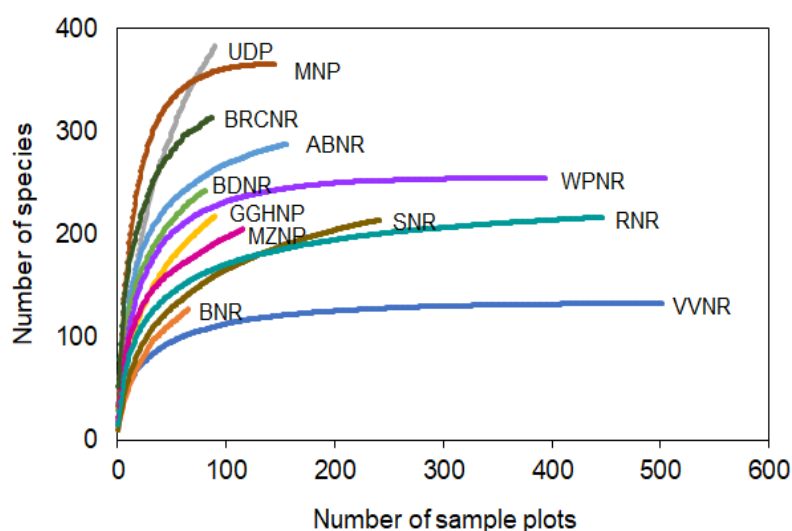


Figure 4. Species accumulation curves based on species presence/absence data for twelve protected areas

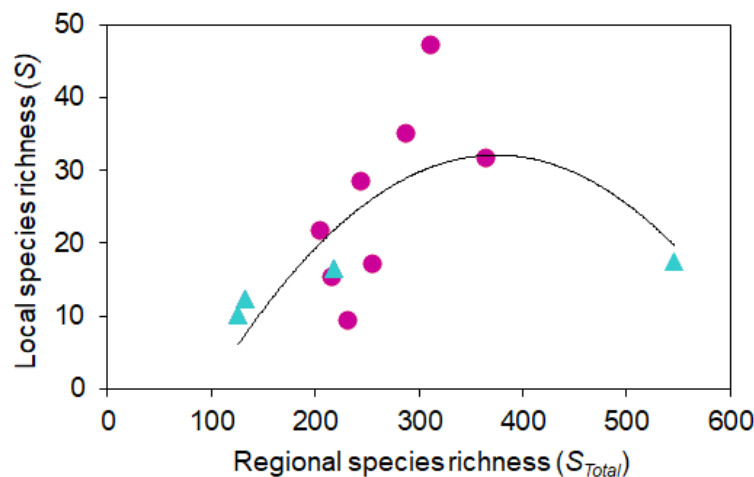


Figure 5. Relationship between regional (S_{Total}) and local species richness (S) for all protected areas. Circles and triangles denote plant diversity of protected areas located at altitude < 1500 m and altitude > 1500 m, respectively

Patterns of plant diversity in relation to geographical gradients

Longitude showed a very weak and non-significant association with S ($r = 0.291$, $p = 0.359$), H' ($r = 0.174$, $p = 0.588$), and J' ($r = 0.098$, $p = 0.762$) (Figure 6a-c). However, when simple regression analysis distinguished between low- and high-altitude PAs, S for low-altitude PAs showed a significant positive relationship with longitude ($r = 0.836$, $p = 0.010$), but no significant relationship was detected for high-altitude PAs. Latitude correlated significantly with S ($r = 0.577$, $p = 0.049$) but not with H' ($r = 0.511$, $p = 0.089$) and J' ($r = 0.439$, $p = 0.154$), and all the relationships were negative (Figure 6d-f). There were negative but non-significant associations between altitude and S ($r = -0.475$, $p = 0.119$), H' ($r = -0.495$, $p = 0.102$), and J' ($r = -0.450$, $p = 0.142$) (Figure 6g-i), wherein S , H' and J' were highest at PAs located at altitudes below 1500 m above sea level but declined as altitude increased.

Multiple regression analysis showed the combined effects of latitude, longitude, and altitude to be significant on S ($r^2 = 0.613$, $p = 0.046$), but not for H' ($r^2 = 0.515$, $p = 0.107$) and J' ($r^2 = 0.386$, $p = 0.249$) (Table 2). Regional diversity showed no relationship with the geographical variables but upon distinguishing between low-altitude and high-altitude PAs, there was a significant monotonic decline of regional diversity with increasing latitude for low-altitude PAs ($r^2 = 0.791$, $p = 0.003$). There was also an increase of regional diversity with increasing longitude for low-altitude PAs, though not significant ($r^2 = 0.470$, $p = 0.060$). The combined effects of latitude, longitude, and altitude were not significant in explaining the variation in regional diversity, as shown by multiple regression analysis ($r^2 = 0.243$, $p = 0.502$).

Relationships between plant diversity and climate

Temperature was positively but non-significantly associated with S ($r = 0.513$, $p = 0.088$), H' ($r = 0.556$, $p = 0.061$), and J' ($r = 0.530$, $p = 0.076$). In general, S was higher at PAs with higher temperatures which were located at lower altitudes (<1500 m) (Figure 7a); the same trends were observed for H' (Figure 7b) and J' (Figure 7c). In the main, PAs located at higher altitudes with the accompanying low mean annual

temperature had lower S , H' and J' . Rainfall had virtually no association with any of the diversity indices ($r = 0.131$, $p = 0.685$ for S ; $r = 0.033$, $p = 0.918$ for H' ; and $r = -0.007$, $p = 0.982$ for J'). However, simple linear regression conducted separately for lower and higher-altitude PAs indicated that at altitudes below 1500 m and lower rainfall below 750 mm, S ($r^2 = 0.751$, $p = 0.005$) and H' ($r^2 = 0.555$, $p = 0.034$) were positively and significantly related with rainfall. Although J' also tended to be positively associated with rainfall at those low altitudes, the relationship was not significant ($r^2 = 0.382$, $p = 0.103$). Overall, mean annual temperature and rainfall explained more than 50% of variation in S ($r^2 = 0.580$, $p = 0.020$) and H' ($r^2 = 0.531$, $p = 0.033$), but for J' even though the climate variables could partially explain the variation, no statistical significance was detected ($r^2 = 0.441$, $p = 0.073$) (Table 2). Neither temperature nor rainfall showed any relationship with regional diversity but for low-altitude PAs, there was a non-significant increase with increasing rainfall ($r^2 = 0.438$, $p = 0.074$). According to multiple regression analysis, temperature and rainfall combinedly could not significantly explain the variation in regional diversity ($r^2 = 0.284$, $p = 0.223$).

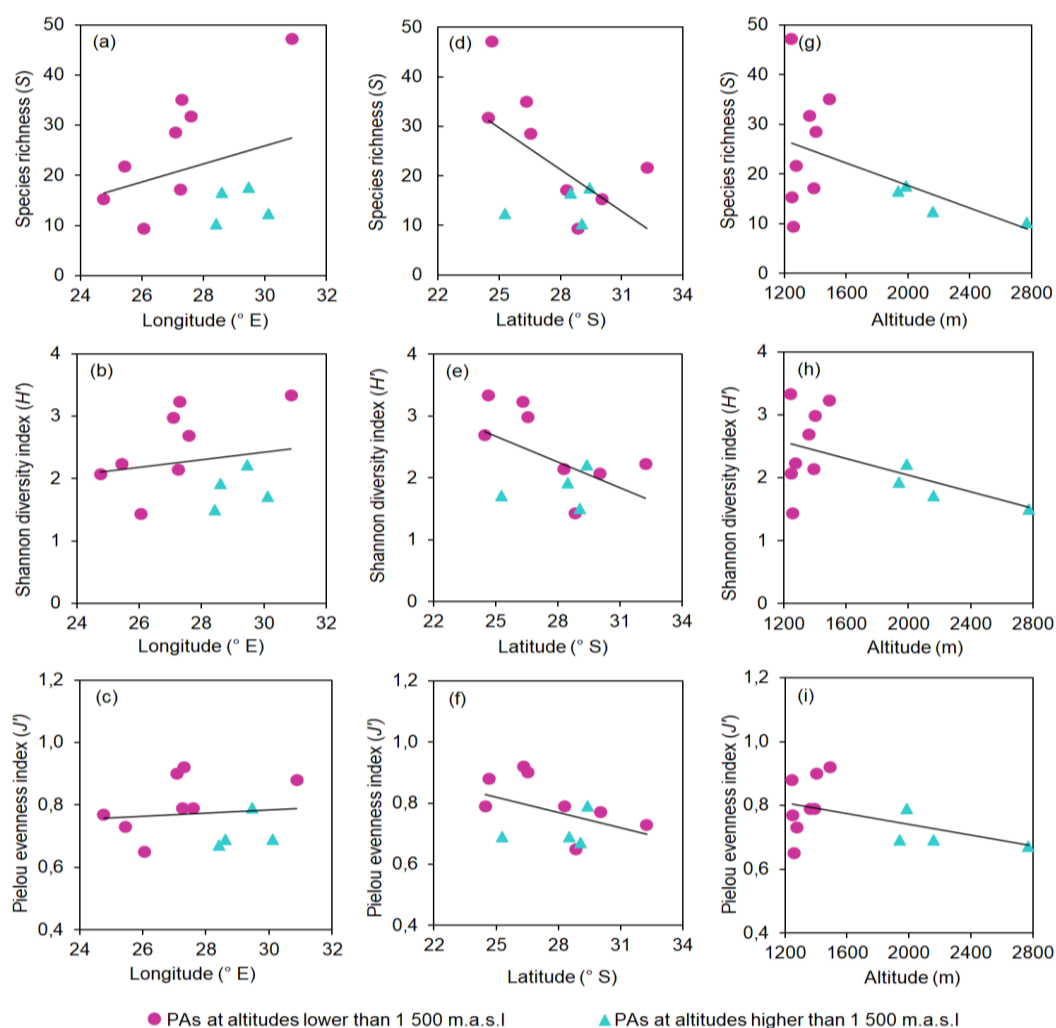


Figure 6. Relationships between plant diversity and the geographical variables of the study area

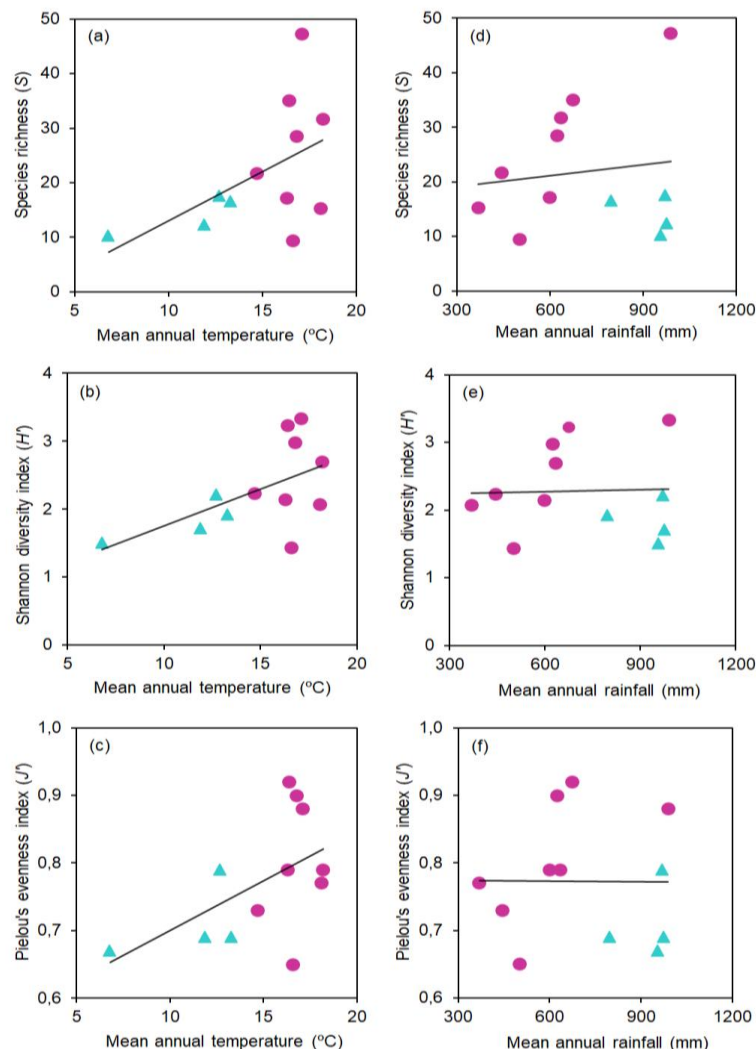


Figure 7. Relationships between plant diversity and climatic variables. Circles and triangles denote plant diversity of protected areas located at altitude < 1500 m and altitude > 1500 m, respectively

Combined effects of geographical and climatic variables on plant diversity

When the climatic and geographical variables were considered together, backward multiple regression analysis showed altitude and rainfall as best predictors for S ($F_{2,9} = 7.316$, $p = 0.013$). Both variables had significant influence but the influence of altitude was marginally stronger (and negative) ($\beta = -1.066$, $p = 0.004$) than that of rainfall ($\beta = 0.861$, $p = 0.014$), where β is the standardised beta coefficient. Similarly, altitude and rainfall were also the best predictors for H' ($F_{2,9} = 4.634$, $p = 0.041$) but altitude had the strongest (negative) and significant influence ($\beta = -0.977$, $p = 0.014$) on H' than rainfall ($\beta = 0.703$, $p = 0.056$). For J' , most of the models fitted poorly but the best performing model indicated temperature and rainfall to be the best predictors of J' ($F_{2,9} = 3.550$, $p = 0.073$). Temperature exerted the strongest and significant influence on J' ($\beta = 0.839$, $p = 0.026$) than rainfall ($\beta = 0.506$, $p = 0.143$), implying that overall temperature was relatively the best predictor of J' . Jointly, the five variables could not significantly predict regional diversity ($r^2 = 0.687$, $p = 0.135$).

Discussion

Plant diversity patterns along geographic gradients

Latitudinal and altitudinal gradients influence patterns of plant species richness and the richness response to these gradients is one of the most fundamental and well-reported patterns in ecology. However, latitude and altitude are regarded as indirect variables because they do not have a direct influence on plant growth or the availability of resources important for plant growth (Pausas and Austin, 2001). Instead, these variables have an effect on climatic conditions (*Figure 2*), which in turn directly influence plant growth and diversity. Globally, the general species richness trends along the latitudinal gradient reflect a decrease in richness with increasing latitude, and this is evident across various taxa and biomes (Willig et al., 2003; Rahbek, 2005). This is also evident in the current study, wherein S showed a strong and significant decline with latitude and even though the relations of H' and J' on the other hand were weak, they still showed a somewhat negative trend with increasing latitude (*Figure 6*). There was also a decline in regional richness with latitude, but only at low elevations.

A multitude of theories have been proposed to explain this latitudinal pattern and one of them is the productivity hypothesis, which suggests that the combination of warm temperatures and adequate rainfall in the tropics and lower latitudes provides ideal growth conditions for species (Gurevitch et al., 2006), which leads to higher net primary production and higher species abundance or number of individuals (Lomolino et al., 2010). Consequently, as suggested by the “more individuals hypothesis”, the number of species increases with increasing number of individuals (Scheiner and Willig, 2005). The highest species richness was recorded in PAs at latitudes lower than 27 °S (*Figure 1*), which were BRCNR, ABNR, MNP, and BDNr (*Table 3*). Species richness decreases when moving further from the tropics because conditions for growth may be unfavourable and physiologically limiting for some species (Gurevitch et al., 2006), and this pattern is consistent with the low richness of the higher latitude PAs such as SNR and RNR. On the contrary, although MZNP is located at the highest latitude (> 30 °S), it had high species diversity which Pond et al. (2002) attributed to heterogeneity of the environment. This high diversity of habitats is also regarded as one of the plausible drivers of the high species richness in the tropics (Gurevitch et al., 2006).

In contrast, species richness response to the altitudinal gradient is not as consistent as its response to the latitudinal gradient. However, the most reported pattern is a hump-shaped model (e.g., Bhattarai and Vetaas, 2003; Sánchez-González and López-Mata, 2005; Rahbek, 2005). In the current study, species diversity declined with increasing altitude (*Figure 6*) and similar monotonic declines have been reported in other studies (e.g., Zhang et al., 2016; Di Musciano et al., 2021). According to Rahbek (2005) and Lomolino et al. (2010), this monotonic decline may be regarded as an artefact of short gradients that do not include the lower elevations. Similar to the latitudinal gradient, the decline in species richness along an increasing altitudinal gradient may be due to unfavourable growth conditions for plant growth (Gurevitch et al., 2006), which include declines in temperature and precipitation (Sunqvist et al., 2013). Species diversity along elevational gradients is typically higher at mid-elevations than at low or highest elevations (Gurevitch et al., 2006; Lomolino et al., 2010). Local and regional richness were highest for PAs at elevations between 1200 and 1500 m above sea level and this can be regarded as mid-elevation, given the elevation range of the Grassland Biome that runs from 300 to 2 850 m above sea level (Rutherford and Westfall, 1994). The reason for the peak in

species richness at mid-elevations is that ideal environmental conditions for plant growth can be expected at mid-altitudes where temperature and rainfall stress are expected to be relatively low (Wang et al., 2002), and this is where generally the combined effects of environmental factors and species interactions promote co-existence of a high number of species (Lomolino, 2001).

Diversity patterns along climatic gradients

Global analyses of species richness have indicated that climatic (water-energy) variables are largely the best predictors of species diversity gradients across large spatial extents and taxonomic groups (Hawkins et al., 2003; Field et al., 2009). The general idea is that climate influences the productivity of a habitat and hence its ability to support individuals (and species) i.e., the productivity hypothesis (Wright, 1983; Wright et al., 1993). Both water and energy are essential for plant growth and physiological processes, and therefore these variables have direct effects on plant abundance and diversity but their influence varies across geographical locations (Wright et al., 1993; Hawkins et al., 2003). Water variables (i.e., rainfall and precipitation) are a major factor constraining plant richness in warm areas while in colder areas plant richness is limited by water-energy inputs (i.e., actual evapotranspiration and productivity) (Hawkins et al., 2003). In South Africa, similar variables have been reported as strong predictors of species diversity patterns across various biomes, in both arid and mesic regions. For example, in the Grassland Biome studies have reported species diversity patterns that were mostly driven by mean annual precipitation and energy variables such as potential evapotranspiration and primary productivity (Cowling et al., 1997; Thuiller et al., 2006; Hoare, 2009). These water and energy variables were also reported as important drivers of species richness in relatively drier biomes, such as the Nama-Karoo Biome (Hoffman et al., 1994; Petersen et al., 2020).

In the current study, mean annual temperature showed a positive though non-significant influence on plant diversity but mean annual rainfall showed no relationship. According to Hawkins et al. (2003), single climatic variables are at times unable to explain species diversity patterns but upon considering multiple climatic variables, they can have strong predictive power of species diversity. This is especially true for temperature and rainfall, which have interactive effects and are therefore ideal when considered together (Pausas and Austin, 2001). Indeed, this was evident in the current study because when considered jointly, mean annual temperature and rainfall were strong predictors of plant diversity in the study area, accounting for 58%, 53%, and 44% variance in S , H' , and J' , respectively (*Table 2*). The results of this study further indicate that plant diversity is generally high at PAs occurring at lower or mid-altitudes with consequent mild average temperatures and relatively high rainfall (*Table 1* and *Figure 3*), except for RNR and SNR where mean annual rainfall is low. Plant diversity is relatively low at GGHNP, UDP, VVNR, and BNR because even though the PAs receive high annual rainfall, their location at high altitudes is accompanied by lower temperatures which restrict species diversity.

There are however anomalies to the climate effects (in association with altitude) on plant diversity and the most obvious are BRCNR and MZNP. BRCNR is not a high-altitude PA but it receives a high amount of rainfall annually, with high average annual temperature. These climatic conditions are most favourable for plant growth and diversity, and this is reflected in the high species richness recorded for the PA, which is the highest of all the PAs (*Table 3*). This positive climatic effect is consistent with the

findings of O'Brien (1993), who reported highest species richness, albeit for woody species, under conditions of optimum energy and maximum moisture. MZNP on the other hand is located at the transition zone between the Grassland Biome and the Nama-Karoo Biome where there is high rainfall variability (Pond et al., 2002). The PA receives the second lowest average amount of rainfall annually but has higher species diversity than most of the other PAs. Pond et al. (2002) attribute this high diversity to environmental heterogeneity characterised by extreme variations in features such as microclimate, geology and altitude.

Local and regional drivers of plant diversity in the Grassland Biome

Factors influencing species diversity differ with the scale at which diversity is being investigated because, for example, processes determining species diversity patterns at local scale may differ with those operating at regional scale (Huston, 1999). Regional patterns of species diversity may be determined by climatic and geologic factors, as well as evolutionary and historical processes related to speciation, species dispersal, and immigration (Partel et al., 1996; Gaston, 2000; Hillebrand and Bleckner, 2002). One of the most important factors influencing plant diversity at regional scale is environmental heterogeneity. The variables commonly used to quantify environmental heterogeneity at broad geographical scales include spatial heterogeneity in climatic variables such as precipitation and temperature ranges; soil variables such as nutrients, soil types and soil pH; and also topographic features such as elevation range (Stein et al., 2014; Stein and Kreft, 2015; Udy et al., 2021). Cowling et al. (1997) have reported heterogeneity variables (i.e., gradients of mean annual rainfall and temperature) as strong determinants of regional species richness in the Grassland Biome of South Africa, but also highlighted energy variables which included potential evapotranspiration, primary production, and duration of the growing season as significant correlates with species richness. Environmental heterogeneity can explain the high regional richness of UDP reported in the current study, given the size of the PA and its location at high altitude (*Table 1*). The Drakensberg area, and especially UDP, is characterised by extreme variations in topography, altitude, climate and geology, resulting in various habitat types that have sustained a high level of species diversity and endemism (Zunckel, 2012).

Montane regions generally have high habitat heterogeneity and are species-rich, with a high number of endemics (Rahbek et al., 2019; Chang et al., 2023). Numerous studies globally have reported that environments which are highly heterogeneous have higher species richness than more homogeneous ones, and this has been reported for various taxonomic groups including plants, bats, birds. and various invertebrates (Stein et al., 2014; López-González et al., 2014; Yang et al., 2015; Cooper et al., 2020). However, this positive effect on species richness has not been detected in some semi-arid and arid environments (e.g., Cramer and Willig, 2005; Ahmed et al., 2022). According to the environmental heterogeneity hypothesis (Palmer, 2007), heterogeneous environments provide more niche space and a higher diversity and partitioning of resources, thereby allowing species to co-exist and consequently leading to high species richness (Udy et al., 2021; Thomsen et al., 2022). The effect of environmental heterogeneity is influenced by scale of observation (Stein et al., 2014; Chang et al., 2023), mainly because heterogeneity of the environment generally increases with spatial scale (Palmer, 2007). Environmental heterogeneity can thus influence species richness patterns more prominently at large (e.g., regional) spatial scales than at local scale (Pausas and Austin, 2001; Chang et al., 2023).

At the local scale, patterns of species diversity may be regulated by factors that include species competition for niche space and environmental resources, and environmental (micro) heterogeneity related to habitat disturbance and resource diversity (Huston, 1999; Partel and Zobel, 1999). In South Africa, although species diversity may be influenced by local-scale processes already mentioned, these effects may be modulated by climatic factors (especially rainfall) in regions where moisture may be limiting for plant growth. For example, experimental studies conducted by Ward et al. (2020) in the mesic grasslands of KwaZulu-Natal have indicated that local species coexistence and diversity were mainly determined by local, niche-based processes of both competition and facilitation. This is consistent with the findings of Hoare (2009) from a study of the grasslands of the Eastern Cape, which confirmed that facilitative or competitive species interactions, which are generally regarded as local processes, were important determinants of the diversity patterns of mesic grassland communities.

On the other hand, environmental variables (including rainfall) were important factors limiting species diversity in semi-arid grasslands in the same study by Hoare (2009). Similarly, Cowling et al. (1994) reported a strong association of local species richness with climatic variables (rainfall and temperature), albeit for arid and semi-arid localities that were not within the Grassland Biome. In the main, these studies suggest that factors considered important for regional richness may at times drive local richness, and vice versa, depending on climatic conditions. It is therefore plausible that for the current study, regional species richness of mesic high-altitude grasslands (i.e., BNR, VVNR, and GGHNP) was not only restricted by large-scale processes, such as low temperatures associated with high elevations, but may also be modulated by local processes including competitive species interactions. For the dry low-altitude grasslands, especially SNR, RNR, and MZNP, regional processes pertaining to climatic factors such as rainfall and temperature may be important in regulating local species diversity of the PAs.

There was a strong relationship between local species richness of the PAs and regional richness (*Figure 5*). In concurrence, various studies have shown that local and regional species richness are related but there is no consensus, or at least an understanding, of how local-scale and regional-scale processes interact to determine local and regional patterns in species diversity (e.g., Ricklefs, 1987; Hillebrand and Bleckner, 2002; Gurevitch et al., 2006). The contentious issue about this relationship particularly pertains to community saturation i.e., whether there is a density-dependent limit to the number of species or individuals that can co-exist within local communities, driven by intra- and inter-specific competition (Cornell and Lawton, 1992; Ricklefs, 2004). Two types of relationships have been reported by numerous studies. Type I relationships are positively linear, indicating that local species richness is determined by the size of the regional species pool and is independent of biotic interactions within a habitat; type II relationships show a humped curve wherein local richness is limited by local processes and therefore an increase in regional species pool does not influence local richness (Cornell and Lawton, 1992; Gurevitch et al., 2006).

Global meta-analyses have documented linear relationships (i.e., type I) across various taxa and scales (e.g., Caley and Schluter, 1997; Gaston, 2000). In concurrence, Cowling et al. (1997) have reported that local and regional species richness in South Africa are positively related, indicating the strong influence of the regional species pool on local species richness. This is contrary to the findings of the current study because a hump-shaped relationship was detected for all PAs (*Figure 5*). These conflicting observations might suggest that the relationship falls between type I and type II, which according to

Cornell and Lawton (1992), is characteristic of many plant communities. The other possible explanation for the discrepancy could be the scale-dependence of this relationship, with linear patterns generally expected with increasing extent and intensity of sampling (Caley and Schluter, 1997).

Importance of protected areas in safeguarding biodiversity

Current and future climate change is expected to impact global species diversity and distribution, and in the study area, protected areas such as UDP and BNR have been identified as key to safeguarding plant diversity in the Grassland Biome against envisaged climate change perturbations (Rutherford et al., 2000; Bentley et al., 2019). Loarie et al. (2009) have derived an index of the velocities of temperature change and the consequent number of years that suitable climates (in terms of temperature) are expected to remain resident in global biomes. According to the authors, mountainous ecosystems are projected to have the lowest temperature change velocities and species in such montane landscapes (such as UDP in South Africa and BNR in Lesotho) may require the slowest species velocities to keep pace with the changing climate, and such regions may shelter many species thereby spurring their future survival. Loarie et al. (2009) further suggest that protected areas globally will play a crucial role in mitigating biodiversity loss because of their unfragmented nature, and also because of their protection from land-cover change which the authors highlight as a major impediment to species movement. However, for South Africa, Rutherford et al. (1999) have cautioned that the protected area network of the country may not sustain species through the changing climate, at least in the arid and semi-arid parts of the country, where significant local species extinctions are envisaged. Furthermore, Bentley et al. (2019) have projected that the ranges of plant species in South Africa and Lesotho (Drakensberg) will contract to higher elevations and the size of suitable area for plant diversity will also decrease under the changing climate.

This is consistent with the findings of an earlier study by Rutherford et al. (2000), which assessed the vulnerability of plant diversity to climate change in South Africa, and suggested that there will be significant warming and aridification trends within the country. According to that study, the extent of the Grassland Biome is consequently expected to decline considerably, with the biome ultimately being confined to the high-altitude area of the Drakensberg. Rutherford et al. (2000) signaled that the predicted change in climate is envisaged to induce change in species composition of the Grassland Biome and other biomes as well, a phenomenon termed bioclimatic shift. Mountainous terrain and topographic diversity can protect against this bioclimatic shift to a certain degree and as such the Drakensberg region (which includes UDP) is seen as better buffered against climate change and will be least affected (Rutherford et al., 2000). This region and the Maloti highlands of Lesotho (which include BNR) will become refugia for migrating species and accordingly the two regions are projected to show increased trends of species richness (Bentley et al., 2019). Species that are envisaged to survive in the biome are those with wide climatic tolerances, while those that are adapted to cold climates might suffer reductions in their distribution ranges (Rutherford et al., 2000).

In the Drakensberg region, C₃ grasses are characteristic of cooler high altitudes, and their distribution is associated with temperature (O'Connor and Bredenkamp, 1997). According to Bentley and O'Connor (2018), in scenarios of increasing temperature due to climate change, the distributional ranges of these C₃ grasses will likely shrink with consequent shifts of the grasses to higher altitudes and latitudes where temperatures would be cooler. These authors warn that a distributional shift in C₃ or C₄ grasses in the

Drakensberg is likely to have adverse ecological and hydrological impacts, given the importance of the region as a biodiversity hotspot and a major water catchment area supplying good quality water to many regions of the country (Zunckel, 2003). Grasses and accompanying forb species play a crucial role in water regulation within the Drakensberg region because they protect the soil from rainfall erosion and ensure proper water absorption into the soil, ultimately regulating its release into the catchment system (Zunckel, 2012).

The Grassland Biome has five centres of plant endemism (CEs) and those that occur within the study area are the Drakensberg Alpine (BNR, UDP) (Mucina et al., 2006), as well as Wolkberg (BRCNR) and Lydenburg (VVNR) (MTPA, 2014). The three CEs are found at high altitudes and interestingly most of the grasses and herbs endemic to the biome are found in the high-altitude montane grasslands (Steenkamp et al., 2002; Mucina et al., 2006; MTPA, 2014). Mountainous regions have provided crucial refuge to species during past climatic fluctuations, thus producing the high number of endemics and preserving plant evolutionary history (Bentley et al., 2019; Di Musciano et al., 2021). During the envisaged climate change scenario, the Drakensberg region as previously indicated, is expected to act as refugia for species migrating away from the predicted warming and aridification trends in the country (Rutherford et al., 2000; Bentley et al., 2019). Globally, endemic-rich areas have previously been least affected by global climate change and are predicted to continue being less affected by future climate change than endemic-poor ones (Jansson, 2003).

Conclusions

Protected areas globally are regarded as a key defense against habitat destruction and biodiversity loss. A network of protected areas, whether at global scale or within individual countries, is important because it allows for ecological enquiry into the spatial patterns of diversity and the causal mechanisms behind the observed patterns. The current study has indicated a decrease in plant diversity in selected protected areas in the Grassland Biome of South Africa, in response to latitudinal and altitudinal gradients. The species diversity patterns were also associated with temperature and rainfall gradients. Studies providing insights on species diversity response to climatic, elevational, and latitudinal gradients are important for conservation purposes, especially given the impending threat of climate change. The impact of climate change is expected to influence global biodiversity distributions and protected areas, especially those in montane regions such as UDP and BNR, are expected to play a crucial role as refugia for species migrating to escape the effects of climate change.

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APPENDIX

Table A1. Families represented across all the PAs and the number of species per family

Family	Number of species	Family	Number of species
Asteraceae	305	Hypoxidaceae	14
Poaceae	229	Brassicaceae	13
Fabaceae	170	Polygonaceae	13
Cyperaceae	71	Thymelaeaceae	13
Scrophulariaceae	66	Amaryllidaceae	12
Rubiaceae	52	Aspleniaceae	12
Iridaceae	51	Ebenaceae	12
Malvaceae	49	Polygalaceae	12
Lamiaceae	48	Caryophyllaceae	11
Euphorbiaceae	39	Cucurbitaceae	10
Apocynaceae	37	Ericaceae	10
Crassulaceae	33	Juncaceae	10
Acanthaceae	32	Oleaceae	10
Asphodelaceae	32	Proteaceae	10
Amaranthaceae	29	Salicaceae	10
Anacardiaceae	29	Dryopteridaceae	9
Hyacinthaceae	27	Oxalidaceae	9
Geraniaceae	25	Rhamnaceae	9
Aizoaceae	23	Boraginaceae	8
Solanaceae	21	Combretaceae	8
Apiaceae	20	Commelinaceae	8
Convolvulaceae	20	Gentianaceae	8
Asparagaceae	18	Lobeliaceae	8
Orobanchaceae	18	Phyllanthaceae	8
Pteridaceae	18	Myrtaceae	7
Rosaceae	18	Onagraceae	7
Orchidaceae	17	Araliaceae	6
Santalaceae	17	Hymenophyllaceae	6
Campanulaceae	15	Rutaceae	6
Verbenaceae	15	Vitaceae	6
Celastraceae	14	Blechnaceae	5

Table A1. continued

Family	Number of species	Family	Number of species
Capparaceae	5	Passifloraceae	2
Lauraceae	5	Rhizophoraceae	2
Ochnaceae	5	Selaginellaceae	2
Polypodiaceae	5	Stilbaceae	2
Ranunculaceae	5	Xyridaceae	2
Agavaceae	4	Annonaceae	1
Buddlejaceae	4	Aponogetonaceae	1
Dioscoreaceae	4	Aquifoliaceae	1
Dipsacaceae	4	Athyriaceae	1
Molluginaceae	4	Begoniaceae	1
Moraceae	4	Burseraceae	1
Myrsinaceae	4	Buxaceae	1
Piperaceae	4	Connaraceae	1
Ruscaceae	4	Corbichoniaceae	1
Sapindaceae	4	Cupressaceae	1
Sapotaceae	4	Curtisiaceae	1
Agapanthaceae	3	Equisetaceae	1
Alliaceae	3	Erythroxylaceae	1
Anacampserotaceae	3	Flacourtiaceae	1
Araceae	3	Frankeniaceae	1
Cactaceae	3	Fumariaceae	1
Colchicaceae	3	Gisekiaceae	1
Gesneriaceae	3	Gunneraceae	1
Hypericaceae	3	Hamamelidaceae	1
Icacinaceae	3	Heteropyxidaceae	1
Limeaceae	3	Kirkiaceae	1
Loganiaceae	3	Lentibulariaceae	1
Lycopodiaceae	3	Linderniaceae	1
Meliaceae	3	Lonchitidaceae	1
Melianthaceae	3	Lythraceae	1
Myricaceae	3	Maesaceae	1
Nyctaginaceae	3	Malpighiaceae	1
Osmundaceae	3	Marattiaceae	1
Plantaginaceae	3	Melastomataceae	1
Podocarpaceae	3	Ophioglossaceae	1
Portulacaceae	3	Pedaliaceae	1
Thelypteridaceae	3	Phytolaccaceae	1
Velloziaceae	3	Pittosporaceae	1
Achariaceae	2	Primulaceae	1
Anemiaceae	2	Smilacaceae	1
Balsaminaceae	2	Tecophilaeaceae	1
Bignoniaceae	2	Tectariaceae	1
Bryaceae	2	Thuidiaceae	1
Chrysobalanaceae	2	Typhaceae	1
Cleomaceae	2	Ulmaceae	1
Cyatheaceae	2	Urticaceae	1
Dennstaedtiaceae	2	Vahliaceae	1
Droseraceae	2	Valerianaceae	1
Eriocaulaceae	2	Viscaceae	1
Linaceae	2	Zamiaceae	1
Menispermaceae	2	Zygophyllaceae	1
Oliniaceae	2		
Papaveraceae	2	Total = 166	Total = 2069

Table A2. *The largest families per PA and the number of species per family*

Protected area	Family	Number of species	Protected area	Family	Number of species
BRCNR	Poaceae	28	BDNR	Poaceae	64
	Rubiaceae	19		Asteraceae	31
	Asteraceae	17		Fabaceae	23
	Fabaceae	15		Malvaceae	11
	Aspleniaceae	11		Rubiaceae	8
RNR	Poaceae	51	ABNR	Poaceae	60
	Asteraceae	33		Asteraceae	37
	Fabaceae	13		Fabaceae	18
	Scrophulariaceae	12		Apocynaceae	10
	Amaranthaceae	10		Malvaceae	10
	Malvaceae	10	GGHNP	Asteraceae	50
SNR	Poaceae	57		Poaceae	42
	Asteraceae	36		Cyperaceae	10
	Fabaceae	11		Scrophulariaceae	10
	Amaranthaceae	10		Fabaceae	9
	Malvaceae	9	UDP	Asteraceae	172
MZNP	Asteraceae	39		Poaceae	116
	Poaceae	27		Fabaceae	87
	Scrophulariaceae	18		Cyperaceae	44
	Geraniaceae	9		Iridaceae	26
	Fabaceae	8	VVNR	Poaceae	27
	Lamiaceae	8		Asteraceae	24
MNP	Poaceae	67		Cyperaceae	9
	Fabaceae	39		Iridaceae	9
	Asteraceae	35		Scrophulariaceae	7
	Rubiaceae	15	BNR	Asteraceae	34
	Cyperaceae	14		Poaceae	23
WPNR	Poaceae	70		Cyperaceae	8
	Asteraceae	36		Scrophulariaceae	6
	Amaranthaceae	11		Fabaceae	5
	Fabaceae	11			
	Malvaceae	10			

Table A3. *List of references used as data sources for Table 1*

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