Assessing the regional endemism centres using species distribution modelling and biodiversity measurement matrices in Nilgiri Biosphere Reserve, Western Ghats, India

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Abstract: Endemism centres are the cradle of rich biodiversity around the globe. Surprisingly, a significant proportion of protected areas are not concordant with endemic hotspots. Nilgiri Biosphere Reserve is the largest continuous protected area in the WesternGhats. Due to the high endemism and species richness, it is a hotspot for rich flora and fauna. It constitutes a priority protected area network such as National Park, Tiger reserve, Wildlife sanctuary, and Reserve Forest. The research sought to investigate the regional hotspot inside the Nilgiri Biosphere Reserve, evaluate the dichotomy of regional endemic centres and delineated priority protected area networks, and assess the relationship between overall biodiversity-rich surrogates and avifaunal richness in the region. This study also investigated the relationship between environmental predictors and endemisms. The biodiversity measuring matrix and ecological niche modelling, as well as the citizen science database, were employed in the study. The Maxent technique was applied to estimate the potential distribution of a species by integrating macro environment and covariates from a variety of open-source platform. Four Centres of Endemism have been found in the southern part of the Nilgiri Biosphere Reserve, however the majority of priority protected areas are in the northern block. Analysis suggests that the regional endemism centres are congruent with the vascular plant richness. However, endemism centres support species-rich surrogates except at the edge of the forest boundary. Ecological predictors and the biodiversity measurement matrix have been identified as having a significant link. Isolating a hotspot within a hotspot has a generic implication on the fast biodiversity contracting scenario, because a similar pattern could be studied and observed in other biodiversity hotspots all across the planet. As a result of the gap analysis, the research recommends a higher degree of protection existing reserves should receive and assimilate the adjacent ecologically sensitive region.

Keywords: Biodiversity Hotspot, Conservation Priority, Nilgiri Biosphere Reserve, Regional Endemism Centres, Species-richsurrogates

1. Introduction

Climate change and human-induced biodiversity loss have witnessed an exponential rise in the past few decades, and therefore the deplorable situation demands accelerated conservation efforts (Das *et al.,* 2006; Gaucherel *et al*., 2016;Noroozi *et al., 2019*). Various researchers (Linder, 2001; Das *et al*., 2006; Smith *et al*., 2008; Kougioumoutzis *et al.,* 2021), have emphasised the need to protect endemic species-rich surrogates and biodiversity hotspot as it serves as a refuge insustaining biodiversity (Gaucherel *et al*., 2016; Noroozi *et al.,* 2019). Anthropogenic-driven climate change, in sync with forest encroachment, are, expediting the process of biodiversity loss (Newbold, 2018; Hidasi-Neto *et al*., 2019; Bolpagni, 2021), therefore elevating the risk of species extinction (Urban, 2015; Gray, 2019) and decreased ecosystem services (Grodsky & Hernandez, 2020). To address the rapidly declining trend, Conservation of Biological Diversity (CBD) developed an innovative strategy such as the 'Aichi target', which aims to preserve a portion of the biodiversity-rich cluster such as biodiversity hotspots (CBD, 2021a).

In the past, prioritisation efforts in India have focused on conserving 'flagship species' such as top predators under the 'Project Tiger' and large Carnivores under 'Project Elephant' (Sankhala, 1978; Venkataraman *et al.,* 2002), thereby snubbing the surrogates that host a range of endemic taxa (Das *et al*., 2006,). This predominant practice of 'emergency room conservation' (Scott et al., 1987) is ineffective in protecting species-richsurrogates (CBD, 2021b). It is time to optimise resource allocation and adopt an efficacious conservation scheme (Lamoreux *et al.,* 2006; Arponen, 2012; Reece & Noss, 2014). The existing research on conservation modelling is too coarse (Crisp *et al.,* 2001; Das *et al.,* 2006; Gaucherel *et al.,* 2016). Thus, fine-scale endemic zonation at a local or regional scale, such as 'hotspot within hotspot' is essential (Murray-Smith *et al.,* 2009; Cañadas *et al.,* 2014). Identifying the regional biodiversity hotspot, i.e., hotspot within the hotspot (Cañadas *et al*., 2014) and endemic centres, i.e., areas of high native taxa relative to the adjoining region, could be the potential solution. It is decisive to aim at conserving regional hotspots in the Anthropocene era, serving as the last resort for fast plummeting biodiversity. Protecting the remaining biodiversity must be expedited (Reid, 1998; Myers*et al.,* 2000; Mittermeier *et al.,* 2005; Brooks *et al.,* 2006).

The Center of Endemism is a biogeographic location with a high number of native species in comparison to the surrounding landscape (Crisp *et al*., 2001; Linder, 2001), which aidsin conservation priorities (Crosby, 1994; Ceballos *et al*., 1998; Myers *et al*., 2000; Noroozi*et al*., 2019). Identifying the 'centre of endemism' within biodiversity hotspots is an appropriate strategy for accomplishing these goals (Mittermeier *et al*., 2005; Orme *et al*., 2005). Overgrazing, forest fires, encroachment, timber extraction, and the replacement of naturally occurring woody species with monoculture plantations are all common in the forest's buffer zone (Kodandapani *et al.*, 2008; Baskaran *et al*., 2012). Severe ecological disturbances engulfed a significant proportion of the original WG and NBR natural habitat(Satish *et al.,* 2014).

The NBR reserve forest area in the southern block is under such ecological disturbances (Das *et al.,* 2006). The possibility of minimising such interference and conserving the remaining biodiversity surrogates is to narrow the scope of interest to the most critical ecological landscape, i.e., hotspot-within hotspot (Cañadas *et al.,* 2014; Noroozi *et al*., 2019). Hotspot endemic species have a narrow geographical niche (Wulff *et al.,* 2013) confined to particular biogeographic regions. Therefore, identifying those clusters is critical to effective management. Range-restricted species are more sensitive to climate change and anthropogenic interference (Gaston, 1998; Kougioumoutzis *et al.,* 2021). In synergy with land-use change, anthropogenic-driven climate change has caused immense pressure on biodiversity-rich resources (Newbold, 2018). Therefore, it is high time to identify the priority conservation gap in the biodiversity hotspot (Noroozi *et al.,* 2019). Citizen science data repositories in a digital platform such as the Global biodiversity information facility, iNaturalist, eBird, India biodiversity information portal, or published occurrence records are valuable sources for exploring biogeography research using GIS (Varela *et al.,* 2015). Using GIS to identify endemism patterns is a scale-dependent process(Crisp *et al.*, 2001); biodiversity measurement matrices such as species richness, weightedendemism, and centred weighted endemism use grid cells to identify gaps and prioritise the protected area network (Kier and Barthlott, 2001). (Myers, 1988; Scott *et al.*, 1993).

In the global arena, research on endemic biogeography has been conducted on coarse-scale(Crisp *et al.,* 2001; Linder, 2001; Goodman & Benstead, 2005; Pascual *et al.,* 2011; Kougioumoutzis *et al*., 2021). Advancements in frontier biogeography and macroecology have attempted to address the Wallacean shortfall in India (Das *et al.,* 2006; Shrestha *et al.,* 2021; Srinivasulu *et al.,* 2021; Jins *et al.,* 2022). Significant research has previously been conducted in tropical hotspots such as the Western Ghats to identify regions with high conservation values (Gadgil & Meher-Homji, 1986; Ullas Karanth, 1994; Daniels *etal*., 1991; Joshi *et al.*, 2017). Later, Ramesh *et al.* (1997b) and Prasad *et al*. (1998) used GIS to identify biodiversity hotspots. The conservative technique lacks SDM algorithm- based analysis, but modern GIS-based time-series gap analysis is scalable (Das *et al*., 2006). SDM-based methods in prioritising sites are species-specific (Sen *et al.,* 2016; Sumangala *et al.,* 2017); few adopted the surrogate-based SDM approach in the Western Ghats (Prasad *et al.,* 1998; Gaucherel *et al.,* 2016; Srinivasulu *et al.,* 2021). Nevertheless,none of the studies addressed the regional hotspot within biodiversity hotspot at a fine scale.

Hence, this study aims to isolate the endemic hotspot within the biodiversity hotspot, usinga combination of ecological niche modelling and biodiversity measurement matrices by (i) Identifying the regional biodiversity hotspot at a fine-scale based on endemism centres and species richness matrix, (ii) Assessing whether the endemic centres concomitantly supportbiodiversity-rich surrogates and avian richness, and (iii) Identifying the environmental factors responsible for determining the regional endemic hotspot.

2. Materials and Methods

2.1 Study Area

Nilgiri Biosphere Reserve (NBR) (10.83°-12.16° N and 76°-77.15° E) is a biodiversity- rich protected area in the Western Ghats – a globally recognised biodiversity hotspot established under the UNESCO Man and Biosphere programme (Satish *et al.*, 2016), which makes it ideal for our regional endemism investigations. NBR is one of India's earliest (1986) and largest continuously protected biosphere reserves, spread over 5520 km^2. The protected area network (PAN) such as Bandipur National Park (NP), Rajiv Gandhi National Park (or Nagarhole NP), Mukurthy National Park (NP), Silent Valley National Park (NP), Wayanad Wildlife Sanctuary (WLS), and Mudumalai National Park (NP), which are clearly delineated per Satish *et al*. (2014). Figure 1 depicts Sathyamangalam WLS (11.60°N and 76.08°E), Karimphuza WLS, which was NewAmarambalam reserve forest (11.26°N and 76.45°E) (Owen, 2013), Booluvampatti range (10.94 °N and 76.65°E), Vavul mala range (11.45°N and 11.15°E), and other Reserve Forest (RF). The NBR is located at the confluence of three southern Indian states: Karnataka, Kerala, and Tamil Nadu.The hill's altitude ranges vary between 300 and 2637 m asl (Krishnamoorthy *et al.,* 2013). Satish *et al.* (2014) classified the NBR vegetation and land use into the following classes: Wet-evergreen, Semi-evergreen, Moist deciduous, Dry deciduous, Riverine Forest, Shola, Savannah, Scrubland, Grassland, Wetland, Plantation areas, Agriculture, Barren land and settlements.

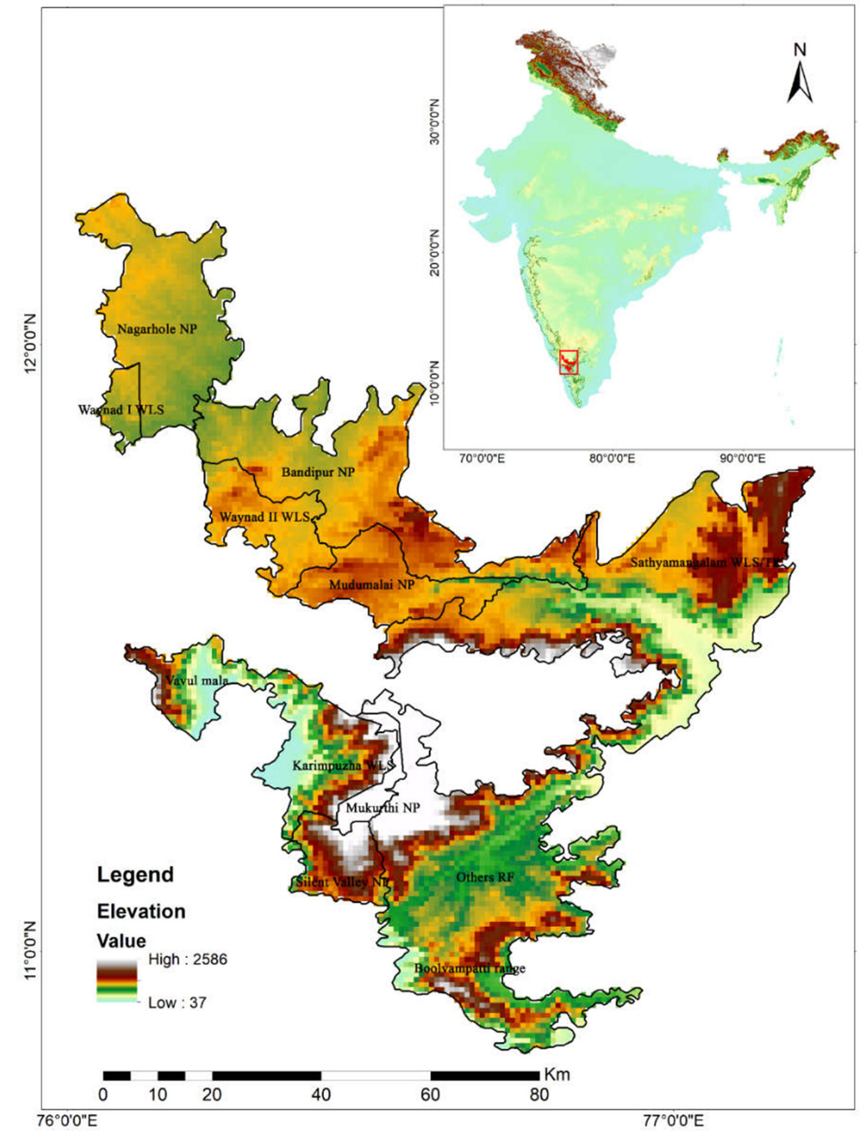

Fig. 1 Study area map of Nilgiri Biosphere Reserve, Western Ghats, India

2.2 Prevalence Records and Taxon Assortment

The biodiversity prevalence data were collated from various sources such as the Global Biodiversity Information Facility (GBIF), India's Biodiversity Information Portal (IBIP), and Atlas of Endemic Tracheophytes (Ramesh & Pascal, 1997a). Filtering was applied in GBIF to collect the available biodiversity dataset of phyla such as Tracheophyte, Chordata, Arthropoda, Basidiomycota, and Mollusca. Georeferencing was done using QGIS 3.14 to extract the prevalence records. The georeferencing residual value of <0.001 was considered as it has low uncertainty and high accuracy (Oniga *et al.,* 2017).

2.3 Environmental Variables and Covariates

Environmental variables constitute 19 bioclimatic variables obtained from worldclim2.0 (Hijmans *et al.,* 2005). Topographical variables such as slope and aspect were derived using a digital elevation model (DEM) from Databasin (https://databasin.org/datasets/). The associated covariates, such as the Normalised Difference Vegetation Index (NDVI), were obtained from the Indian Space Research Organization (ISRO) Bhuvan portal (https://bhuvan- app3.nrsc.gov.in/data/download/index.php), land soil from Soilgrids database (https://soilgrids.org/), Potentio-evapotranspiration (PET), and aridity obtained from CGIAR-CSI Portal (https://cgiarcsi.community/category/data/). The acquired environmental variables and covariates are resampled to a consistent resolution of 30 arc sec (1 km) using the resampling tool in ArcGIS 10.3. Annual mean temperature, mean diurnal range, isothermality, temperature seasonality, annual precipitation, driest month precipitation, temperature seasonality, seasonal variations in precipitation, precipitation in the warmest and coldest quarters, slope, aspect, potential Evapotranspiration, aridity, and the vegetation index (NDVI) are among the significant predictors that did not suffer fromcollinearity problems (Pearson correlation coefficient, $r < 0.7$) (Dormann *et al.*, 2013).

2.4 Sampling Artefacts

Occurrence localities were obtained from open-access portals and published databases. It is obvious to have sampling bias (Beck *et al.,* 2014; Rocha-Ortega *et al.,* 2021). Two methods have been used to eliminate sampling artefacts, including the roadmap effect and prevalence cluster: (i) data curation by selecting prevalence records with low uncertainty and (ii) geographic thinning of occurrence localities using the rarefying tool in ArcGIS 10.3. (Boria *et al*., 2014).

2.5 Species Distribution Modelling and Validation

Open-source Maximum Entropy (Maxent 3.4.1) (https://biodiversityinformatics.amnh.org/open_source/maxent/) algorithm was considered for modelling the potential distribution of the species (Phillips *et al.,* 2006). Maxent algorithm was preferred because it requires presence-only data, and training data (<5 points) is sufficient to simulate the model (Phillips *et al.,* 2006; Van Proosdij *et al.,* 2016). The environmental predictors were of various raster formats such as .img or .tiff; therefore, variables were converted into maxent supported (.ascii) format using the raster conversion tool in sdmtoolbox2.0 (Brown *et al.,* 2017). Data were partitioned into 30 % random test data and 70 % training data (Araújo *et al.,* 2005); Multiple replications (10 times) and the iteration default value of 500 was incremented to 5000 to reduce uncertaintyand provide sufficient time for convergence (Young *et al.,* 2011). The maxent default Receiving operating characteristics (ROC)/Area Under Curve (AUC) value above 0.95 was considered for Biodiversity measurement.

2.6 Biodiversity Measurements

The modelling output was changed into a binary raster using the "reclassify to binary" toolwith a threshold value of 0.5 because the maxent raw outcome could not be utilized for Biodiversity measurement. Biodiversity matrix such as species richness (SR), weighted endemism (WE), and corrected weighted endemism (CWE) was used. The binary raster was cropped to a specific study area and was fed into the ‘biodiverse measurement tool’ executed in ArcGIS 10.3 (Crisp *et al.,* 2001; Laffan *et al.,* 2003; Kougioumoutzis *et al.,* 2021). Modelling the potential suitability requires a minimum number of occurrence data(Van Proosdij *et al.,* 2016), species that lack a sufficient number of prevalence datasets forthe model building were separately fed as point vectors.

The biodiversity matrix was obtained using the following equations,Species Richness (SR) = N,

Weighted Endemism (WE) = $\sum 1/G$,

Corrected weighted endemism (CWE) = WE/N,

G is the total number of grid cells that hold particular endemic species, and N is the total number of species in a grid cell.

Species richness for Biodiversity Dataset is represented as SR_{biodiv}, endemic species datasetas SR_{end} and Avian dataset as SR_{aves}. Similarly, WE and CWE for endemic plants datasetsare designed as WE_{end} and CWE_{end}, respectively.

2.7 Species Richness Association with Environmental Parameters

Species richness model output was extracted using a ‘point sampling tool’ in Quantum GIS(QGIS). The numerical data extract was correlated with Ecological input variables using the Pearson Correlation coefficient (r) in R studio. Ecological covariates comprise topographical variables such as slope, surface elevation, and aspects ratio; and environmental variables such as Normalized Difference Vegetation Index (NDVI), Potential Evapotranspiration (PET), Aridity, Landcover, and Soil. The association was further verified using multivariate regression to ascertain the validity of the relationship.

3. Results

The analysis focused mainly on the NBR, the Western Ghats' largest continuous protected biosphere reserve. The sampling grid presented 2417 hexagonal polygons of ~2.25 km diameter, out of which 456 dummy grids with zero value lie on the boundary of the study area—elimination of dummy grids and retention of 1961 grid samples with unique values.Model output included records of 1007 species and 244 family-level taxa.

3.1 Biodiversity Species Richness

The species diversity was estimated using a biodiversity assessment method, and the analysed data are displayed in Figure 2. Observations indicate that the biodiversity speciesrichness (SRbiodiv) ranges from 636 to 1007. The species diversity Raster output was divided into seven classes based on natural breaks (Jenks) to classify pixels based on spatial congruency (Singh *et al.*, 2019). The lowest to maximum species richness in green to red spectral range displays the lowest to highest species richness.

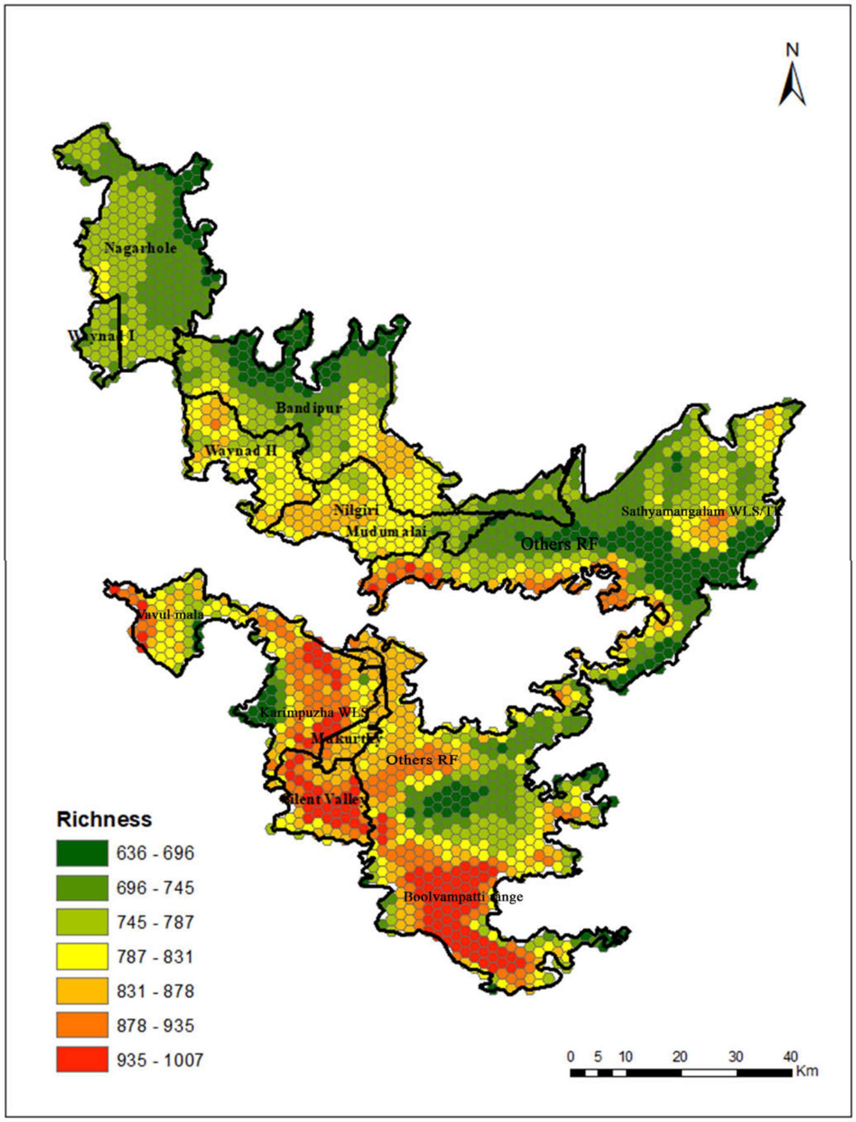

Fig. 2 Biodiversity species richness (SR_{biodiv}) in Nilgiri Biosphere Reserve (NBR)

Fig. 3 presents the species richness of endemic vascular plant distribution in NBR, whererichness was grouped into low (green), moderate (yellow), and high (red) richness grid cells. It was observed that high SR_{end} concentrated in and around endemic zones at four centres, such as Vavul Mala, Karimphuza WLS, Silent valley NP, and the Booluvampatti range. In contrast, Mudumalai NP, Bandipur NP, Wayanad II WLS, Sathyamangalam WLS, Nagarhole, and Wayanad I WLS hold low vascular plant richness. It was also observed that the high-richness grid cells are prevalent in the southern compartment, whereas northern sections have relatively low-richness grid cells.

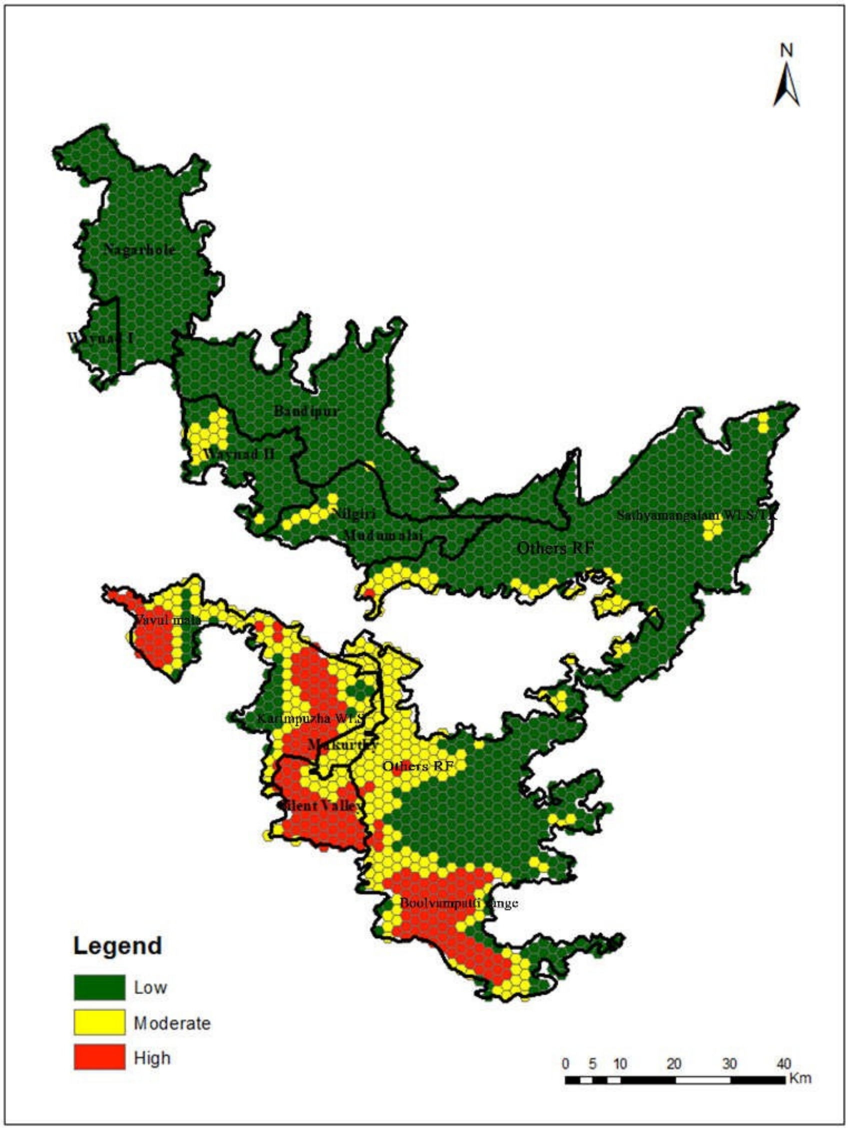

Fig. 3 **Species richness (SR_{end}) of endemic vascular plant in Nilgiri BiosphereReserve**

Fig. 4 presents the avian richness (SR_{aves}) in Nilgiri Biosphere Reserve. High and moderate richness were evenly distributed all over the biosphere. Karimphuza WLS, Silent valley NP, and Boolvampatti range offered high richness (SR_{aves}) clusters in the southern compartments. Mudumalai NP, Waynad II WLS, lower Bandipore NP, and Sathyamangalam NP presented avian-rich zones in the northern chamber of NBR.

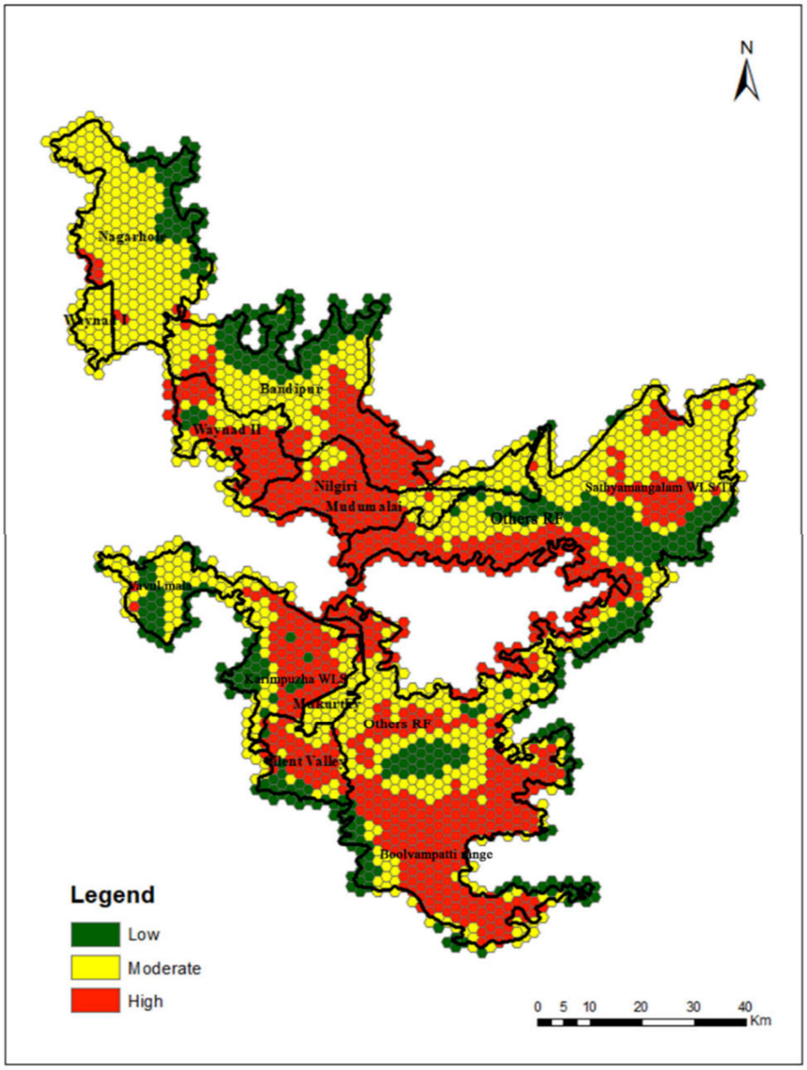

Fig. 4: Richness of avian species (SRaves) in the Nilgiri Biosphere Reserve

Moderate avian richness was observed in Nagarhole NP, upper Bandipur NP, upper Sathyamangalam NP, and upper Boolvampatti range in the reserve forests area. North- Eastern edges of Nagarhole NP, Bandipur NP, and western flanks present low richness.

3.2 Regional Endemism Centres

This research effectively identified the ‘regional endemism centres’ which support high species richness. Cañadas *et al.* (2014) acknowledged this process as prioritising ‘hotspots-within-hotspot’; this is the efficacious and cost-effective conservation and management method. Regional endemism centres in Nilgiri Biosphere Reserves are determined using biodiversity measurement matrices such as Weighted endemism (WE_{end}) and Centered Weighted endemism (CWE_{end}).

The analytical results of weighted endemism are illustrated in Figure 5. Utilizing the dataset of endemic plant species, WE_{end} was determined. We found that endemic tracheophytes had a weighted endemism (WE_{end}) value that ranges from a minimum of 0.1163 to a maximum of 0.2125. The corrected weighted endemism (CWE) value, on the other hand, ranges from a minimum of 0.443×10^{-3} to a maximum of 0.449×10^{-3}. We were able to divide the CWE_{end} in the study region into three distinct ranges: low, moderate, and high by examining the locations of the natural Jenks (breaks) (Fig. 6).

Nagarhole National Park, Bandipore National Park, Waynad I, and II National Park, Mudumalai National Park, and Sathyamangalam Wildlife Sanctuary were all found to have poor endemism grid cells in the Northern Compartment. Three PAs—Silent Valley NP, Mukurthy NP, and Karimphuza WLS—and the remaining reserve forests make up the southern compartment's high-endemic grid cell. The rest of the high-endemic grid cells are in reserve forests. It was observed that the Silent Valley NP and Karimphuza WLS exceptionally host the highest number of such endemic-rich grid cells. Additionally, two more Centres lie at the forest boundary's edge, such as the Vavul mala and Booluvampattiranges.

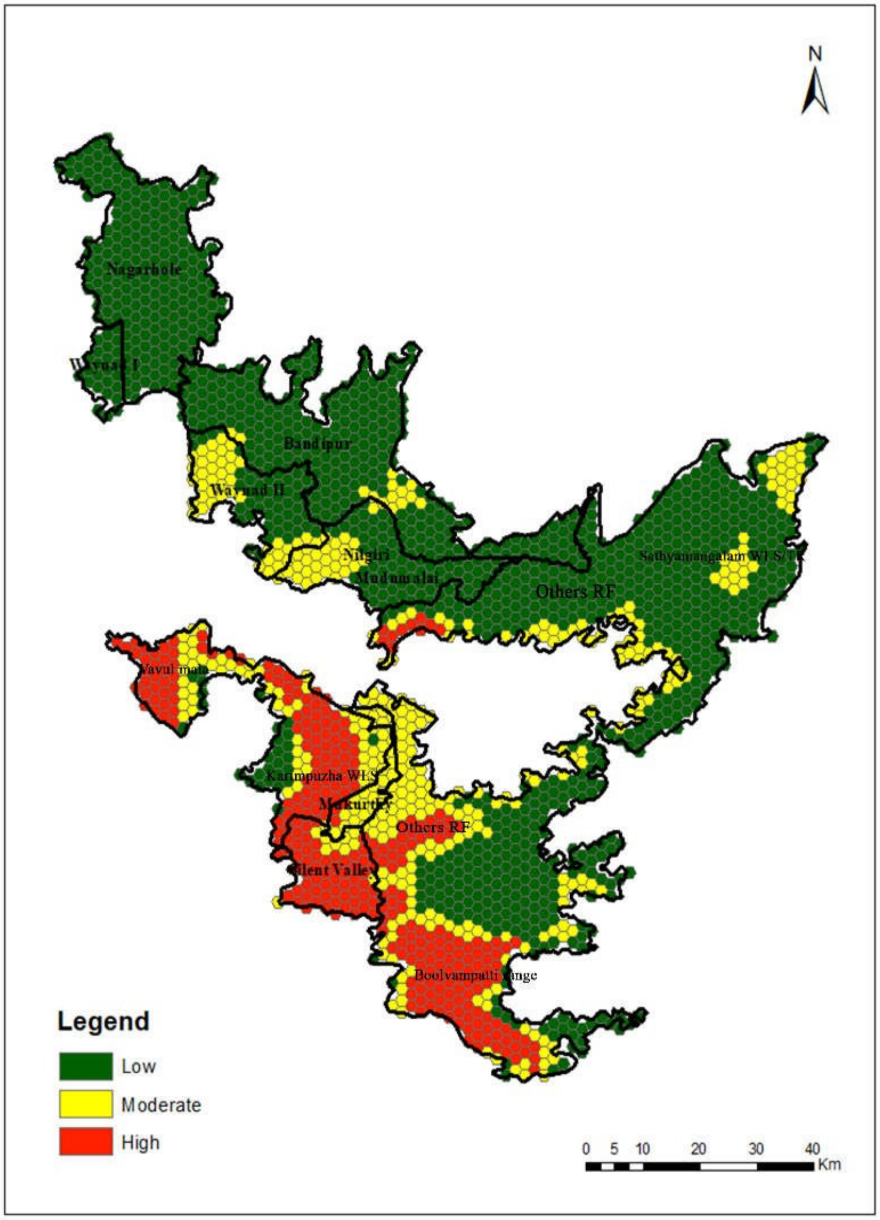

Fig. 5 Weighted Endemism (WE_{end}) in Nilgiri Biosphere Reserve

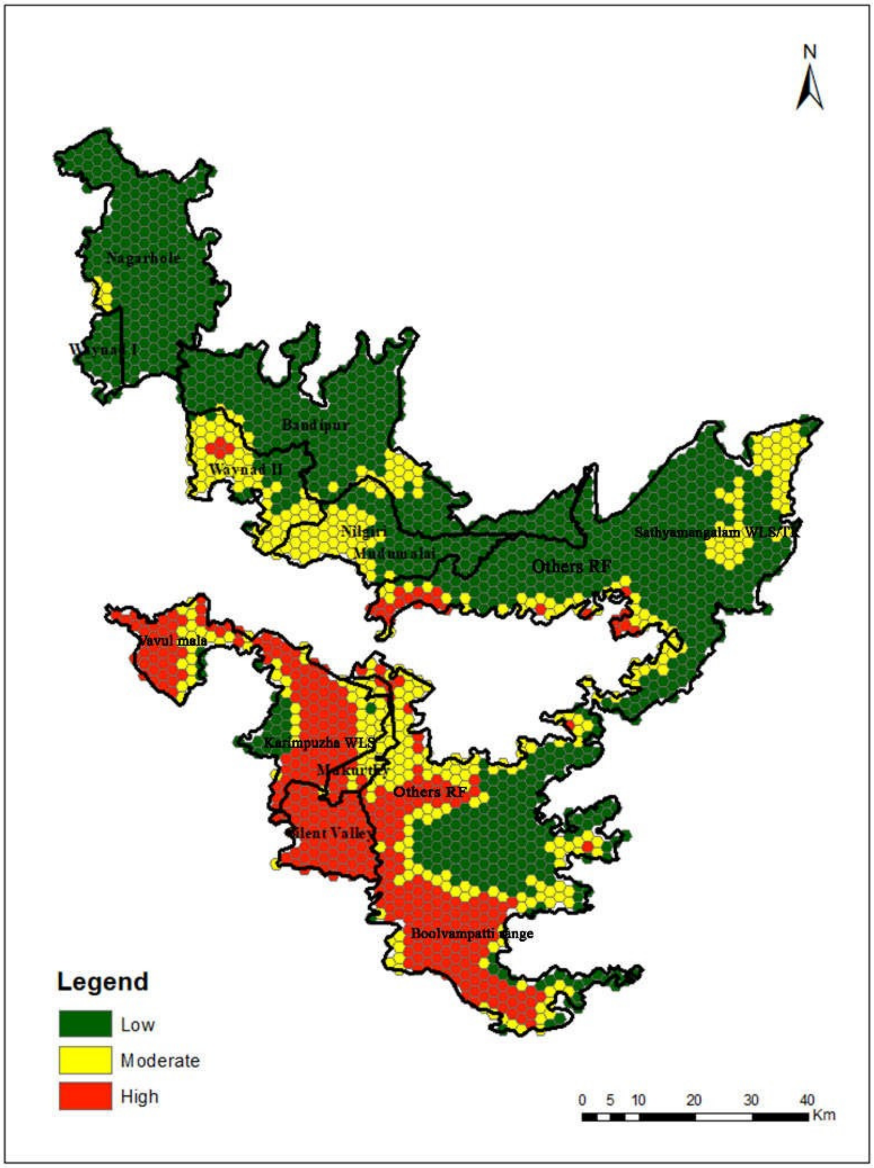

Fig. 6 Centered Weighted Endemism (CWE) in Nilgiri Biosphere Reserve

In consistent with the results of WE_{end}, the highest values of the Centered weighted endemism (CWE_{end}) grid were found in four different centres in the southern half of the NBR, facing southwest. In the northern compartment, the CWE_{end} grid was mostlymoderate and low, but there were a few high CWE_{end} grid cells in Waynad II WLS and at the bottom of Mudumalai NP. Protected areas such as Nagarhole NP (Rajiv Gandhi NP), Bandipore NP, and Waynad I WLS presented low-endemic vascular plant grids. Moderate CWE_{end} grids are present in western Mudumalai NP, Sathyamangalam WLS (Fig. 6).

3.3 Endemism and Richness Association

To assess the association of endemism and richness, the Pearson correlation was analysed and presented in Table 1. From the analysis, it was found that WE_{end} was perfectly correlated with SR_{end} (r=1.0). SR_{biodiv} and SR_{aves} shows high (r = 0.87) and low (r = 0.36) correlation with significance p-value <0.001.

Table 1 Pearson correlation among biodiversity measurement matrix

	WE_{end}	SR_{end}	SR_{biod}	SR_{aves}
WE_{end}	1			
SR_{end}	1^{***}	1		
SR_{biod}	0.87^{***}	0.87^{***}	1	
SR_{aves}	0.36^{***}	0.36^{***}	0.73^{***}	1

***= p<0.001

3.4 Endemism and Ecological Variable Association

Pearson correlation of WE_{end} with environmental variables are presented in Fig. 7. Ecological significant variables such as Isothermality (bio 03), Annual Precipitation (bio 12), Aridity, and Vegetation Index (NDVI) are positively correlated. At the same time, Annual Mean Temperature (bio 01), Mean Diurnal range (bio 02), Temperature Seasonality (bio 04), and Potential-evapotranspiration (PET) are negatively correlated.

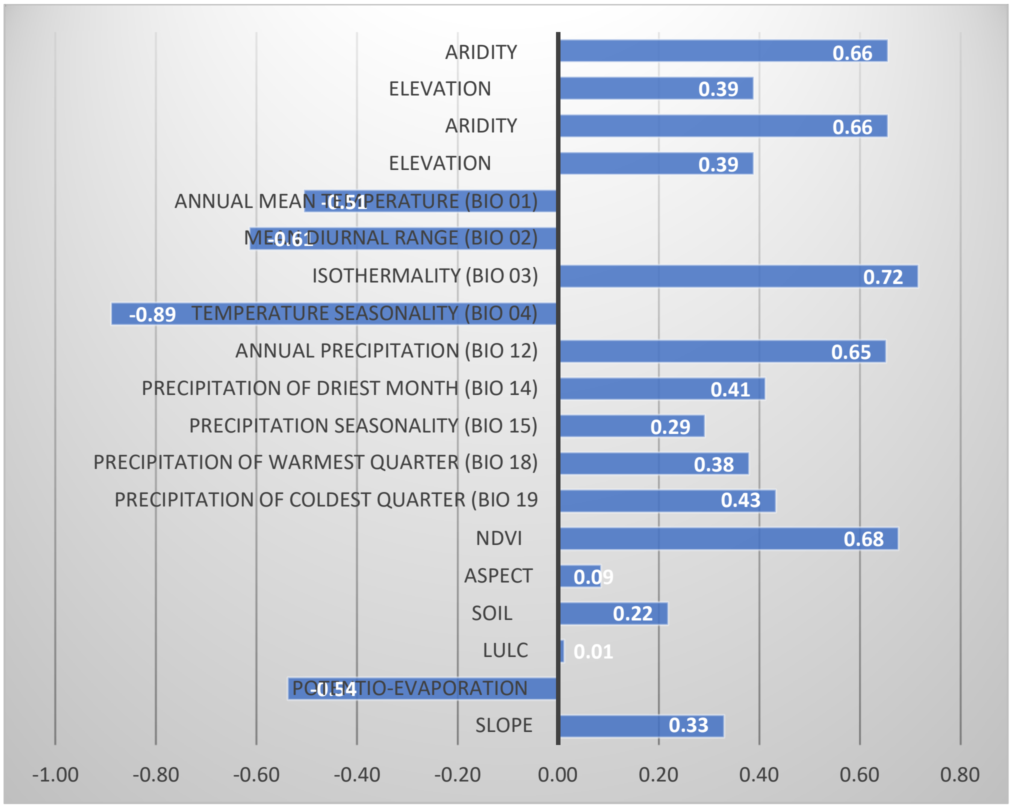

Fig. 7 Environmental variables contribution in determining the endemism (WE_{end}) with significant p value<0.001 except landuse and landcover (LULC).

On further regression analysis (Table 2), endemism (WE_{end}) was found to be significantly associated with all variables except Annual Mean Temperature (bio 01) and NDVI. Amongst the significant ecological variables, endemism appeared to increase with increasing Slope, Potentio-evaporation (PET), Soil types, Precipitation of Coldest Quarter (bio 19), Precipitation of Warmest Quarter (bio 18), Precipitation Seasonality (bio 15), Precipitation of Driest Month (bio 14), Annual Precipitation (bio 12), Isothermality (bio 03) and Elevation. Contrarily, it was shown that endemism declined in the context of growing landcover, aspect, temperature seasonality (bio 04), mean diurnal range (bio 02), and aridity.

Table 2 Multivariate regression analysis of endemism (Y) with environmental variables (X)

Variables	**Coefficient**	**S.E**	**P-value**
Slope	0.03562000	0.00756900	***
Potentio-evaporation	0.00002202	0.00001024	*
LULC	-0.00003739	0.00000463	***
Soil	0.00004919	0.00002087	*
Aspect	-0.00001139	0.00000199	***
NDVI	-0.00000946	0.00002011	
Precipitation of Coldest Quarter (bio 19	0.00000145	0.00000062	*
Precipitation of Warmest Quarter (bio 18)	0.00002841	0.00000408	***
Precipitation Seasonality (bio 15)	0.00016090	0.00004101	***
Precipitation of Driest Month (bio 14)	0.00153300	0.00016890	***
Annual Precipitation (bio 12)	0.00000966	0.00000136	***
Temperature Seasonality (bio 04)	-0.00048330	0.00004102	***
Isothermality (bio 03)	0.00089370	0.00023620	***
Mean Diurnal Range (bio 02)	-0.00915500	0.00081510	***
Annual Mean Temperature (bio 01)	-0.00064130	0.00045730	
Elevation	0.00001589	0.00000307	***
Aridity	-0.00000211	0.00000015	***
Model fitness details			
Multiple R-squared: 0.8719, Adjusted R-squared: 0.8707 F-value =750.9 P of F- statistics = ***			

Signif. codes: 0 '*<0.001 '**' <0.01 '*' <0.05**

4. Discussion

Western Ghats (WGs), one of the richest biodiversity hotspots in the Tropical region of the Earth, have an uneven endemism pattern (Gaucherel *et al.,* 2016; Bose *et al.,* 2016). Similar erratic trends of species richness (Fig. 2, 3, and 4), and endemism centres (Fig. 5 and 6) were detected within the NBR. All three biodiversity measurement matrices, such as WE_{end}, CWE_{end}, and SR_{end}, indicated the same set of regional endemism centres in NBR. Four endemism centres are identified in NBR: Silent Valley National Park, Karimpuzha WLS, Vavul Mala, and the Boolvampatti range.

4.1 Species-rich Surrogates and Endemism Centres

Integrating the overall biodiversity species-rich surrogate map with the overlay elevation study area map (Fig. 1) revealed that Rapoport's rule was followed, i.e., locations with mid- altitudes and varied terrain maintained a high species richness. Noroozi *et al.* (2019) stated that the complex escarpment with rugged topography and intricate mountain massif promotes endemism, a characteristic of Nilgiri Biosphere Reserve.

Strips of low richness zones were observed in the lower Sathyamangalam WLS, patches in the eastern boundary of Nagarhole, Bandipore in the northern block, and other reserve forests in the southern block. This could be attributed to the fact that as per NBR vegetation classification by Satish *et al.* (2014), the poor richness in the low elevational topography collides with Dry deciduous vegetation, plantation, and scrubland. These lower planes are easily accessible to anthropogenic factors and prone to biodiversity erosion (Lo Seen *et al.,* 2010). Udhagamandalam (also known as Ooty; 11.41°N and 76.70°E), a popular tourist destination, flourished in the southern and northern block confluence. Its rapid expansion of buildups and decline in vegetation have negatively impacted biodiversity (Satish *et al.,* 2014). The narrow corridor connecting the northern and southern blocks presented low richness in the eastern and intermediate richness in the western boundary. It is attributed to elevation as the west edge ascends to the Udhagamandalam mountainous region (Fig. 2).

Mukurthy NP was found to accommodate intermediate tracheophytes richness. This could be due to its vegetation, predominantly a mosaic of shola forest grassland (Robin & Nandini, 2012). Priority Protected area networks (PANs) such as Nagarhole NP, Bandipore NP, Madumalai WLS, and Wayanad WLS I and II were observed to have low endemic vascular plant richness. The high-priority protected area networks lie in the rain shadow and moist deciduous regions (Satish *et al.,* 2016). Daniels (1992) reported the presence of endemic angiosperm at an altitude above 1700 m asl. A similar pattern of continuous endemic vascular plants is visible in Silent Valley from mid-range to higher elevation. Noroozi *et al.* (2019) stated in their Irano-Anatolian hotspot study that poor accessibility in the higher elevational terrains is the potential reason for conserved endemic tracheophytes richness. Wet evergreen and semi-evergreen forests in the higher mountains of the study area align with high endemic vascular plant richness. Vavulmala range, Karimphuzha WLS, Silent Valley NP, and Boolvampatti range are aligned in the same western descending mountain slopes (Fig. 3).

Avian richness indicates robust ecological health (Gregory & Van Strien, 2010). NBR- protected area networks and dense vegetation have served well in retaining the rich avian fauna (Fig. 4). Wet evergreen, Semi-evergreen, moist deciduous, and dry deciduous host high avian richness. Scrubland, barren land, and plantation zone presented poor richness. An edge effect perturbation is visible in all its outer boundaries. Das *et al.* (2006) reported that dense settlement and significant anthropogenic disturbances on the outside edge of protected area networks could be the reason for sparse avifauna on the outer boundary, especially in the protruding strip lands of Vavul mala, Nagarhole, and Bandipur's eastern edges. Satish *et al.* (2014) reported a drastic reduction in the Natural Forest in the southernNBR due to extensive agro-plantation, which could have led to poor avian richness in the dry and rain shadow region. Previous studies have presented spatial similarities between taxa such as avians and mammals, particularly in tropical areas such as Kerala (Prasad *et al.,* 1998). At the fine scale, avian surrogates emerged incongruent with vascular endemism but highly congruently with overall biodiversity richness, including mammalian surrogates. Since biodiversity richness constitutes the combined dataset of Tracheophyte, Chordata, Arthropoda, Basidiomycota, and Mollusca. Disproportionate dataset availability in the citizen science sphere pushed us to run a combined model for biodiversity species richness.

Weighted endemism (WE_{end}) results from altitude-driven isolation and peninsular effect (Kougioumoutzis *et al.,* 2021). In the previous studies, high mountains in the NBR regions,especially wet evergreen and semi-evergreen forests identified as a region of high vascular endemism (Das *et al*., 2006; Satish *et al.,* 2014; Gaucherel *et al*., 2016). Specifically, the endemic vascular plants are concentrated on the western slope of the Nilgiri massif (Fig. 5), a rain-fed area that caters to wet evergreen and semi-evergreen forests (Vijayakumar *etal.,* 2016). Altitudinally, these hotspot lies in mid-elevation to high elevation ranging between 1500-2200 m asl. Daniels (1992) reported a similar presence of endemic angiosperm above 1700 m asl. High isolated mountains massif supports endemism and canact as a climate refugia for many species (Bose *et al.,* 2016; Aradhya *et al.,* 2017), also a cradle for rich biodiversity (Steinbauer *et al.,* 2016).

Priority protection classifications such as National Park and Wildlife refuge offered an additional layer of protection, and as a result, the Silent Valley is recognized as a virgin forest (Singh *et al*., 1984). Recently, Karimpuzha WLS added to the beads of high protection status, which was earlier called the new Amarambalam reserve. Delayed the promotion of slackly protected reserve forests to WLS has eroded much of the diversity inthe region. Vavul mala and Boolvampatti reserve forests are examples of such biodiversityerosion.

Centred weighted endemism (CWE_{end}) is an effective index for detecting endemism centres and biodiversity hotspots. Beta diversity is also called a high gradient of change in the proximity of endemic centres (Noroozi *et al.,* 2019). Centred weighted endemism (Fig. 6) has played a supportive role in substantiating the biodiversity measurement of Weighted endemism (WE_{end}). Although the WE_{end}, $CWE_{end,}$ and SR_{end} of vascular plant species are strongly correlated (Table. 1), each biodiversity measurement index must be considered to draw a strong inference on the regional hotspot (Noroozi *et al.,* 2019). The fractional value of WE_{end} and CWE_{end} reported in this research of fine-scale grid cells and potential presence due to fundamental niche modelling of the species. Slender spatial vascular richness (SR_{end}) (Fig. 3), compared to WE_{end} and CWE_{end}, results from the edge effect. A cluster of endemic tracheophytes was found to be aligned in and around the wet evergreen and semi-evergreen forests. Das *et al.* (2006) asserted similar findings that vascular endemism is confined in an area rich in evergreen and semi-evergreen forests. The wet forest types coincidently lie in the rain-fed western slopes with high topographic heterogeneity. Other vegetation types, such as dry deciduous, shola, savanna, and scrub, support poor or nil vascular plants' endemism (Fig. 5 & 6).

The spatial distribution of Avian richness is clustered around endemic hotspots (Fig. 5. &6) but is also abundant in the forest with higher vegetation cover (Satish *et al.,* 2014). Therefore, this could explain the low correlation (r= 0.36) in the observed endemic vascular-rich region. Adjacent to mountain regions on the western flanks is the presence of anthropogenic buildups (Das *et al.,* 2006) and plantations (Satish *et al.,* 2014), which could be the potential reason for biodiversity contraction. Centred weighted endemism highlights the possibility of continuity in regional hotspots in historical time (Fig. 6). In contrast, WE and SR show fragmentation into four distinct centres. A narrow strip of connected landmass between Vavul mala and Karimpuzha could have acted as a corridor for species mobility. But, due to the anthropogenic settlement on all its three sides (Das *et al.,* 2016), much of the Vavul mala species richness is eroded.

High endemism has been observed in the southern block of NBR due to topographical heterogeneity in conjunction with stable microclimate, historical, ecological, and lesser homogenization of species in the past (Cañadas *et al*., 2014; Kougioumoutzis *et al*., 2021). (Fig. 5 & 6). Mountainous terrain may hinder or promote species dispersal depending on the ease of connectivity (Flantua *et al.,* 2020). Kougioumoutzis *et al.* (2021), explain this phenomenon through two hypotheses: (i) Mountain geobiodiversity hypothesis (MGH), Mountain uplift plays a significant role in enhancing speciation and noble microhabitat for refugia (López-Vinyallonga *et al.,* 2015; Steinbauer *et al.,* 2016). (ii) Flickering connectivity hypothesis (FCH) explains a similar phenomenon where species niche diversification occurs due to species dispersal ability and landscape connectivity (Flantua *et al.,* 2020).

4.2 Ecological and climate variables in shaping species richness and endemism centres

Several studies in the past have revealed a concrete relationship between endemism, species richness, and environmental variables (Crisp *et al.,* 2001; Linder, 2001; Kougioumoutzis *et al.,* 2021). Fotheringham *et al.* (2003) stated that endemism and climate data have localised correlations. Even though a correlation exists between weighted endemism (WE_{end}), Species richness (SR_{end}) of endemic vascular plants (Table 1), each index has its significance (Table 2). Anthropogenic-driven climate change conditions andspecies richness may be coincidental as speciation is a function of bioclimatic, biotic interaction and competition in the confined geographical space (Whittaker *et al.,* 2001).

Annual mean temperature (Bio 01) and Annual precipitation (Bio 12) are the critical determinants in vascular endemism. Temperature variation, except Temperature seasonality, was observed to affect vascular endemism negatively. The precipitation derivatives such as precipitation seasonality (Bio 15), Precipitation of the driest month (Bio 14), warmest (Bio 18), and coldest (Bio 19) quarters affect the endemism positively. The vegetation covariates such as NDVI have a far greater correlation than landcover in determining the richness and endemism of the region. However, the regression analysis suggests that the contribution of landcover is significant as compared to the vegetation index. Satish *et al.* (2014) NBR classification suggests a drastic decline in greenness in the last three decades, partly due to biodiversity erosion and climate change. However, the wet evergreen and semi-evergreen landcover classes significantly contribute more to determining vascular endemism. National Parks with greater aridity and lower vegetation,such as Nagarhole, Bandipur, and Sathyamangalam, presented low endemism. The easternflanks' aridity region in the northern compartment and partly in the southern chamber haspoor or no endemism (Fig 05 & 06).

The diurnal range (Bio 02) and temperature seasonality (Bio 04) negatively affect the vascular plant. The greater the range in day-to-night temperature, the lesser the vascular's tolerance capacity to cope with climate variation (O'Donnell & Ignizio, 2012). Whereas the diurnal range-dependent isothermality (Bio 03), which incorporates the annual variation in temperature, determines the aridity pattern, the arid part will have no endemism, whereas the wet part will bear high endemic vascular plants.

Topographical elevation and slope have a role in determining the endemism pattern as this topography variability insulates the mountain range from invasion, retaining the neovascular diversity (Fjeldsaå & Lovett, 1997; Gaucherel *et al*., 2016). More than land use and land cover (LULC), the vegetation variables are correlated with endemism. Edaphic factors such as soil humus have a minor role, but the other bioclimatic and environmental variables have dominated the variable contribution in the ecological niche modelling.

Temperature fluctuation, i.e., Diurnal range (bio 2), and temperature change over the year, as well as mean input temperature (bio 1), affect endemism significantly (Table 2). However, Crisp *et al.* (2001) reported little or insignificant relationship between endemism and temperature variables upon multivariate regression analysis on the Australian landscape. They further cited that the roadmap effect in the database, particularly in a remote location, is the reason for it. The potential-evapotranspiration is a precipitation associate variable; hence, PET is inversely proportional to aridity and directly proportional to annual Precipitation. The significant adjusted R square (0.8707) substantiates the variable importance in the model building.

4.3 Recommendation for Conservation and Management of Hotspots-within-Hotspot

Based on the ecological gap analysis, four regional centres of endemism are detected in the Nilgiri biosphere reserve. Due to their close proximity and high level of protection under the protected area networks (PAN), two centres, Karimpuzha WLS and Silent Valley NP, are still intact (Fig. 8). In contrast, the territory around the fence, including the Vavul mala and Boolvampatti area, was ravaged by anthropogenic disturbances. Due to continuity breaks, the fragmented centres are isolated, reducing gene flow and biodiversity erosion. The recommendation would be to prioritise the stretch of endemic zones based on weighted endemism (WE_{end}) and centred weighted endemism (CWE_{end}) and restore the degraded regional hotspot with neo-native vascular plant species. The restoration of habitat will balance and revamp ecosystem services. Traditional knowledge is the key to conservation and biodiversity measurement; hence its profound wisdom should be integrated into the management effort (Noroozi *et al.,* 2019).

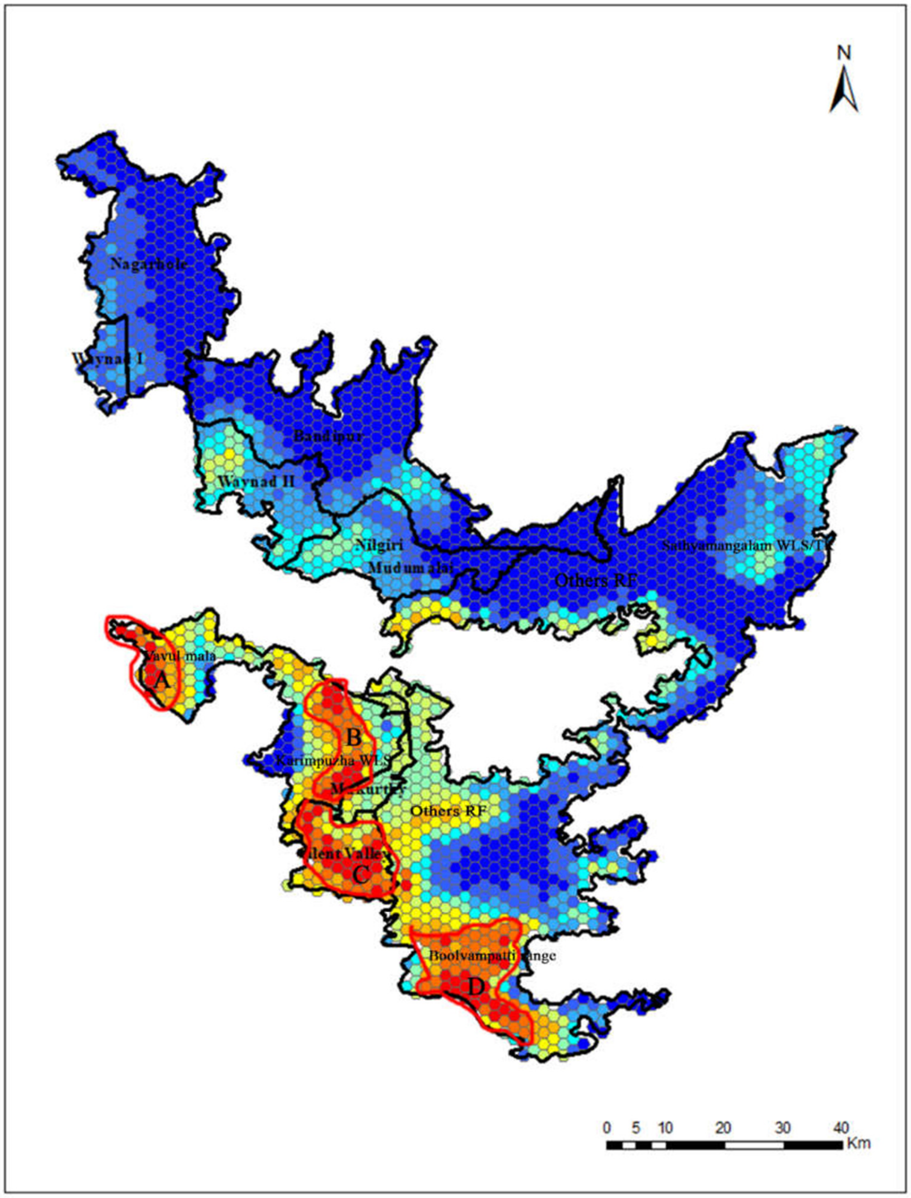

Fig. 8 **Demarcated 'center of endemism' for prioritising in Nilgiri BiosphereReserve**

5. Conclusion,

Ecological data analysis of NBR, suggests an apparent dichotomy between endemic species-rich surrogates and priority PANs; they are not concomitant. The priority endemism centres were successfully identified by combining ecoinformatics techniques such as species distribution modelling using the Maxent algorithm and biodiversity measuring matrix. Four regional endemism centres within the NBR study area, such as Vavul mala, Boolvampatti range, Silent Valley NP, and New Amarambalam WLS, are present in the southern block. Whereas, high priority PANs such as Nagarhole NP/TR, Bandipur NP/TR, Wayanad I and II WLS, Mudumalai NP, and Sathyamangalam TR in thenorthern block. The significant portions of the endemism grids lie in the slackly protectedreserve forest, such as the Vavul mala and Boolvampatti range, which are subjected to severe biodiversity erosion and demand special attention. Spatial analysis suggests low congruency among taxa, such as vascular endemism and avian richness. Yet, at endemic hotspots, patterns of global biodiversity surrogates coincide, as demonstrated by statisticalcorrelation and regression analysis. Further, restoration of eroded regional centers with neo-native species and upgrading the hotspot to higher priority status is recommended.

List of Abbreviations

AUC	Area Under Curve
Bio4	Temperature Seasonality
Bio5	Maximum temperature of the warmest month
Bio7	Temperature annual range
CBD	Conservation of Biological Diversity
CGIAR Consultative Group for International Agricultural ResearchCGIAR-CSI	CGIAR
Consortium for Spatial Information	
CWE	Corrected Weighted Endemism
CWE_{end} Corrected Weighted Endemism of Endemic species datasetDEM	Digital
Elevation Model	
ES	Ecosystem services
FCH	Flickering connectivity hypothesis
GBH	Global Biodiversity Hotspot
GBIF	Global Biodiversity Information Facility
GIS	Geographical Information System

IBIP	India’s Biodiversity Information Portal
ISRO	Indian Space Research Organization
MGH	Mountain geobiodiversity hypothesis
NBR	Nilgiri Biosphere Reserve
NDVI	Normalized Difference Vegetation Index
NP	National Park
PANs	Protected area networks
PET	Potentio-evapotranspiration
QGIS	Quantum Geographical Information System
RF	Reserve Forest
ROC	Receiving operating characteristics
SR	Species Richness
SR_{aves}	Species Richness of Avian dataset
SR_{Biodiv}	Species Richness of Biodiversity dataset
TR	Tiger Reserve
WE	Weighted Endemism
WE_{end}	Weighted Endemism of Endemic species dataset
WG	Western Ghats
WLS	Wildlife Sanctuary

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