Geodiversity and biodiversity in the Himalaya region: Quantifying spatial patterns and exploring linkages.

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Abstract

Geodiversity is the term that describes the variability of Earth's surface materials, forms, and physical processes. Conservation of geodiversity has become increasingly significant in recent decades since it has become apparent that geodiversity provides the abiotic preconditions for habitat development and maintenance and has a considerable influence on biodiversity. The Himalaya is one of the mountain systems showing the highest levels of geodiversity and biodiversity. The hypothesis for this research to be tested is that 'geodiversity can be a useful surrogate for biodiversity information in the Himalaya mountain system.' Jammu and Kashmir (J&K) and Sikkim, located in the subtropical western Himalaya and humid eastern Himalaya respectively, have been selected as two study areas within this global hotspot of biodiversity. To prove the hypothesis, the first approach of this research was to explore the geodiversity of Sikkim, J&K, and the Himalaya mountain systems, using topographical, pedological and climatological information, and to analyse the importance of geodiversity in the context of climate change and future conservation of natural resources. Quantification of geodiversity was followed by different methodologies in System for Automated Geoscientific Analyses (SAGA) open-source software. I used fuzzy logic to produce geodiversity information and a species richness map. A detailed database on species (flora) richness has been drawn from several studies. The total number of species in Sikkim is 5,087(in 7,096 km^2), and in J&K, it is 5,656 (in 1,38,992 km^2). The number of families is 245 in Sikkim and 266 in J&K, and the number of genera is 1,489 in Sikkim and 1,537 in J&K. The most dominant families in Sikkim are Asteraceae, Cyperaceae, Leguminosae, Rubiaceae, Rosaceae, Scrophulariaceae, Primulaceae, Gentianaceae, Euphorbiaceae, Ranunculaceae, and Lauraceae and the most dominant families in J&K are Asteraceae, Poaceae, Fabaceae, Cruciferae, Rosaceae, Labiatae, Cyperaceae, Ranunculaceae, Boraginaceae, and Caryophyllaceae.

The highest number of species (around 1,864 to 2,146 species) in Sikkim is at an elevation between 1,000 to 2,500 m above sea level (asl). The highest species richness (around 1,000 to 1,800 species) in J&K is at an altitude between 1,500 to 4,000 m asl. The subtropical forest and tropical broadleaved forest vegetation zones have the richest species diversity (more than 1,600 species) in Sikkim. The number of species in J&K is less than 200 in the subtropical forest.

Multiple regression analysis between species richness and other abiotic predictors showed very little difference in results for Sikkim and J&K. The generalised linear model (GLM) found that 68% and 67.6% of species richness can be predicted from the abiotic variables for Sikkim and J&K, respectively. The generalised additive model (GAM) with smoother function shows

better results than does GLM, and the deviance explained in the model is 69.8% in Sikkim and 66.9% in J&K. The model also found that temperature and slope (inclination) are the significant predictors in Sikkim, and precipitation and slope (inclination) are the most noteworthy variables in J&K. Model accuracy was evaluated using threshold-independent (Area Under the Curve) measures. The GLM and GAM models in the study areas showed a lesser model prediction error than the geodiversity vs. species richness model, and GAM was the most suitable model for prediction.

The quantified geodiversity index (GI) was 0.01–0.32 in Sikkim and 0–0.16 in J&K. The GI in the Himalaya range is 0.01–0.18, in which Sikkim has a relatively higher GI (0.05–0.18) than does J&K (0.01–0.12). This difference of geodiversity proves that hotspots in the eastern Himalaya have greater geodiversity than those in the western Himalaya. Lower elevation areas in Sikkim show low to moderate geodiversity, and temperate broadleaved forest and subalpine forest areas have high to very high GI (0.17–0.32). Vegetation cover in Kashmir Valley which has low geodiversity has low species richness. High to very high GI (0.08–0.16) and species richness exist in sub-alpine, and temperate zones in J&K. Moderate geodiversity in some parts of the Jammu division correlates with very high and medium species richness. Potential species richness compares the actual differences of the number of species per km^2 in both study areas, which shows higher richness in Sikkim than in J&K. Quantified geodiversity and species richness showed a positive relationship accurately, which proves geodiversity information can surrogate biodiversity information for the Himalaya. The present method to measure geodiversity using widely available data has the potential to be used as a conservation planning tool even in remote areas such as the Himalaya.

Zusammenfassung

Geodiversität ist der Begriff, der die Variabilität der Oberflächenmaterialien, Formen und physikalischen Prozesse der Erde beschreibt. Die Erhaltung der Geodiversität hat in den vergangenen Jahrzehnten zunehmend an Bedeutung gewonnen, da sich gezeigt hat, dass die Geodiversität die abiotischen Voraussetzungen für die Entwicklung und Erhaltung von Lebensräumen bietet und einen starken Einfluss auf die Biodiversität hat. Der Himalaya ist eines der Gebirgssysteme mit der höchsten Geo- und Biodiversität. Die Hypothese der vorliegenden Untersuchung lautet: ‚Geodiversität kann ein Ersatz für Informationen zur biologischen Vielfalt im Himalaya-Gebirgssystem sein.' Sikkim sowie Jammu und Kashmir (J & K) im feuchten östlichen bzw. subtropischen westlichen Himalaya wurden als zwei Untersuchungsgebiete innerhalb dieses globalen Hotspots der biologischen Vielfalt ausgewählt. Um die Hypothese zu überprüfen, bestand der erste Ansatz der Forschung darin, die Geodiversität von Sikkim, J & K und des Himalaya-Gebirgssystems unter Verwendung topografischer, pedologischer und klimatologischer Informationen zu untersuchen sowie die Bedeutung der Geodiversität im Kontext des Klimawandels und des zukünftigen Schutzes der natürlichen Ressourcen zu analysieren. Nach der Quantifizierung der Geodiversität und ihrer Validierung wurden verschiedene Verfahren in der Open-Source-GIS-Software SAGA durchgeführt. In dieser Arbeit wurde die Fuzzylogik verwendet, um Geodiversitätsinformationen und eine Karte des Artenreichtums zu erstellen. Eine detaillierte Datenbank zum Artenreichtum (Flora) wurde aus verschiedenen veröffentlichten Literaturstellen zusammengestellt. Die Gesamtzahl der Arten in Sikkim beträgt 5018 (im 7,096 km^2) und in J & K 5656 (im 1,38,992 km^2). Die Anzahl der Familien beträgt 245 in Sikkim und 266 in J & K, während sich die Anzahl der Gattungen in Sikkim auf 1489 und in J & K auf 1537 beläuft. Die dominantesten Familien in Sikkim sind Asteraceae, Cyperaceae, Leguminosae, Rubiaceae, Rosaceae, Scrophulariaceae, Primulaceae, Gentianaceae, Euphorbiaceae, Ranunculaceae und Lauraceae, während die dominantesten Familien in J & K Asteraceae, Poaceae, Fabaceae, Cruciferae, Rosaceae, Ranunculaceae, Boraginaceae und Caryophyllaceae sind.

Der höchste Artenreichtum (etwa 1864 bis 2146 Arten) in Sikkim liegt auf einer Höhe zwischen 1000 und 2500 m über dem Meeresspiegel (ü. M.), während im Höhenintervall zwischen 500 und 4000 m ü.M die Anzahl der Arten bei über 1000 liegt. Der höchste Artenreichtum (etwa 1000 bis 1800 Arten) in J & K liegt in einer Höhe zwischen 1500 und 4000 m ü. M. Die subtropischen Wälder und tropischen Laubwaldvegetationszonen weisen die reichste Artenvielfalt (mehr als 1600 Arten) in Sikkim auf. Die Artenzahl in J & K beträgt etwa 300 im tropischen Laubwald und weniger als 200 im subtropischen Wald.

Die multiple Regressionsanalyse zwischen dem Artenreichtum und anderen abiotischen Prädiktoren zeigte für Sikkim und J & K geringe Unterschiede in den Ergebnissen. Das Generalized Linear Model (GLM) ergab, dass 68 % und 67.6% des Artenreichtums aus den abiotischen Variablen für Sikkim bzw. J & K vorhergesagt werden können. Das generalisierte additive Modell (GAM) mit glatterer Funktion zeigt bessere Ergebnisse als das GLM, wobei die im Modell erläuterte Abweichung 69.8 % in Sikkim und 66.9 % in J & K beträgt. Durch das Modell wurde auch herausgefunden, dass Temperatur und Neigung die signifikanten Prädiktoren in Sikkim und Niederschlag und Neigung die bedeutendsten Variablen in J & K sind. Die Modellgenauigkeit wurde unter Verwendung von schwellenwertunabhängigen (Area Under the Curve) Messungen bewertet. Die GLM- und GAM-Modelle in den Untersuchungsgebieten

zeigten einen geringeren Modellvorhersagefehler als das Modell Geodiversität vs. Artenreichtum, wobei sich GAM als das am besten geeignete Modell für die Vorhersage herausgestellt hat.

Der quantifizierte Geodiversitätsindex (GI) betrug in Sikkim 0,01 bis 0,32 und in J & K 0 bis 0,16. Der GI im Himalaya-Bereich variiert zwischen 0,01 und 0,18, wobei Sikkim einen höheren GI (0,05 bis 0,18) aufweist als J & K (0,01 bis 0,12). Dieser Unterschied in der Geodiversität zeigt, dass Hotspots im östlichen Himalaya eine größere Geodiversität aufweisen als im westlichen Himalaya. Niedrigere Höhengebiete in Sikkim weisen eine geringe bis mäßige Geodiversität auf, während gemäßigte Laubwaldgebiete und subalpine Waldgebiete einen hohen bis sehr hohen GI aufweisen (0,17–0,32). Die Vegetation im Kashmir-Tal weist bei einer geringen Geodiversität einen geringen Artenreichtum auf, obwohl sie sich in der gemäßigten Zone befindet. In subalpinen, montanen und gemäßigten Zonen von J & K gibt es einen hohen bis sehr hohen GI (0,08–0,16) und Artenreichtum. Die mäßige Geodiversität in einigen Teilen der Jammu-Division korreliert mit einem einen sehr hohen und mittleren Artenreichtum. Der potentielle Artenreichtum vergleicht die tatsächlichen Unterschiede in der Anzahl der Arten pro km^2 in beiden Untersuchungsgebieten, was einen größeren Reichtum in Sikkim als in J&K zeigt. Quantifizierte Geodiversität und Artenreichtum zeigten eine positive Beziehung, was auf die Indikatorfunktion für Informationen zur biologischen Vielfalt im Himalaya hinweist.

Die hier angewandte Methode zur Messung der Geodiversität unter Verwendung der allgemein verfügbaren Daten kann auch in abgelegenen Gebieten wie dem Himalaya als Instrument zur Planung im Umwelt und Naturschutz eingesetzt werden.

Teilveröffentlichungen dieser Dissertation

Pre-published work related to this dissertation

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Offen I A, Bobrowski M, Jahan R, Jentsch A, Mal S, Schwab N & Schickhoff U (2021) Vegetation-environment relationships, species richness, and climate change impacts along the elevational gradient in the Sikkim Himalaya – General findings and preliminary results from a reconnaissance field trip. In: Hartmann, Barclay & Weipert (eds.): Biodiversität und Naturausstattung im Himalaya, pp. 9-40, VII. Erfurt.

Jahan R (2021) Altitudinal distribution and spatial pattern of species richness of the high mountain flora: A case study on Ladakh (Himalaya). The Jahangirnagar Review: Part II: Social Science, Vol. XLV, pp. 99-106.

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List of Abbreviations

BIS_ Biodiversity Information System

DEM_ Digital Elevation Model

GI_Geodiversity Index

GAM_ General Additive Model

GLM_ General Linear Model

IIRS_ Indian Institute of Remote Sensing

ISO data_ Interactive Self-Organizing Data

LP DAAC_ Land Processes Distributed Active Archive Center

MA_ Millennium Ecosystem Assessment

MBT_ Main Boundary Thrust

MCT_ Main Central Thrust

m a.s.l._ meter above sea level

NDVI_ Normalized Difference Vegetation Index

PET_ Potential evapotranspiration

SAGA_ System for Automated Geoscientific Analyses

SOC_Soil Organic Carbon

SRTM_ Shuttle Radar Topographic Mission

cf._ confer, approaching

Chapter One

Introduction

1.1 What is geodiversity, and what is biodiversity?

Geodiversity is now a pervasive aspect of physical geography and geology. Simply, it is defined as the heterogeneity of the geological, pedological, climatological, hydrological, and geomorphological properties of the Earth's surface (Nieto 2001, Gray 2004, and references therein, Kozłowski 2004, Carcavilla et al. 2007, Bruschi 2007, Serrano and Flano 2007, Panizza and Piacente 2008, Benito-Calvo et al. 2009). The importance of geodiversity has increased for the future monitoring of ecosystem services (Alahuhta et al. 2018), particularly in the context of climate change and rising sea levels, conservation, and sustainable management of environmental resources (Gordon & Barron 2012). Geodiversity has great significance for ecosystem services and economic development, and it has vital relevance to historical and cultural heritage (Gordon & Barron 2012, Alahuhta et al. 2018). Ecosystem services are typically grouped into four main categories, as set out in the Millennium Ecosystem Assessment (2005) framework: provisioning, regulating, and cultural services that directly affect people and supporting services needed to maintain the other services. Geodiversity provides necessary raw materials that affect ecosystem processes in freshwater, coastal, and upland systems (Gordon and Barron 2011, Gray 2011, 2012). For example, Scotland's organic soils play a significant role as a terrestrial sink of carbon, which is considered in climate change mitigation and adaptation (Bardgett et al. 2011, Smith et al. 2011). Soil processes (e.g., weathering and soil profile development) and soil as a growing medium that provides supporting services are two of the essential elements of geodiversity (Gray 2018). Soil is the interface between geodiversity and biodiversity, and it is crucial for maintaining agricultural systems, storing carbon, filtering water, and regulating the climate (GLNP 2016). Habitat provision (e.g., caves, salt marshes, and terrestrial habitats), land (e.g., building land), burial, and storage (e.g., landfill, oil, and gas reservoirs), and fossils are provided by soil and are integrated parts of geodiversity.

Geodiversity is an important parameter to be considered in the assessment and management of natural areas and a remarkable natural factor underpinning biological, cultural, and landscape diversity (IUCN 2008). UNESCO built the Global Geoparks Network and has highlighted the cultural and economic importance of geodiversity to promote geo-conservation as part of a more comprehensive strategy for regional sustainable socio-economic and cultural development to save the environment (Eder & Patzak 2004). Geodiversity has been widely valued, for instance, by the Nordic Council of Ministers (Johansson 2000) and by the Australian Natural Heritage Charter (Australian Heritage Commission 2002). Geodiversity includes geology, geomorphology, topography, hydrology, soils, and climate (Benio-Calvo et al. 2009, Parks and Mulligan 2010), and these six components are intimately linked with key abiotic drivers of biodiversity, such as energy, water, and nutrients (Richerson and Lum 1980). Geodiversity can also be defined as the combination of features from the geosphere (geology, geomorphology, and topography), pedosphere (soil physical and chemical properties), hydrosphere (e.g., streams and springs), and atmosphere (e.g., temperature and rainfall) and their spatial variation. By these means, geodiversity displays the heterogeneity of abiotic features of the Earth's surface (Hjort et al. 2012). As the same abiotic factors mainly govern biodiversity patterns, geodiversity may provide a useful surrogate for various aspects of biodiversity (Whittaker et al. 2001, Willis and Whittaker 2002, Hjort and Luoto 2010, Parks and Mulligan 2010). According to Gray (2018), geodiversity is a value-neutral term describing the variety of abiotic phenomena on Earth, which is the abiotic equivalent of biodiversity. He outlines the abiotic goods and services in five groups, which are provided by the Earth's geodiversity.

According to the 1992 UN Conference on Environment and Development in Rio de Janeiro (Convention on Biological Diversity, Article 2), the term 'biological diversity' means the variability among living organisms from all ecosystems, including, among others, terrestrial, marine and other aquatic ecosystems, and the ecological complexes that include diversity within species and between species in the ecosystems. This term is determined by internal biotic factors, extrinsic abiotic factors, or both (Huston 1994). Though the concepts of biodiversity are essential in many areas of biology, the term 'biodiversity' comes from conservation biology (Maclaurin and Sterelny 2008). In 1979, Norman Myers suggested that the Earth might be losing as many as 40,000 species a year. Similar predictions were made by Paul Ehrlich and Thomas Lovejoy (Maclaurin and Sterelny 2008). Following their predictions, Wilson (1992) speculated that extinction rates might be between 27,000 and 100,000 species per year. Biodiversity is sometimes thought of as a measure of what society wants to keep, but it is sometimes also thought of as a tool to measure an instrumentally valuable dimension of biological systems (Maclaurin and Sterelny 2008).

Species richness is the simplest way to describe community and regional diversity (Magurran 1988). Species richness or several species form the basis of many community structure ecological models (MacArthur and Wilson 1967, Connell 1978, Stevens 1989).

1.2 State of the art

Quantification of geodiversity had been the focus of natural scientists in nineteenth century. Cendrero (1996) made the first attempts to assess geological diversity and proposed that diversity of elements of geological interest and their intrinsic values, in particular, be one of the criteria to be considered for classifying geological heritage. He presented geological diversity on a scale from one to five, according to the number of different elements present in a study area. Durán et al. (1998) contended that geodiversity assessment should consider space and time, and Gray (2004) raised awareness of geodiversity values and outlined the need for a more holistic approach to nature conservation and land management.

Burnett et al. (1998) and Nichols et al. (1998) were the first authors who tried to assess geodiversity by employing a methodology based on the Shannon-Weaver diversity index (Shannon and Weaver 1963), which has been used by biologists in the assessment of biodiversity. These early studies showed that high values on the biodiversity index also characterised variation in terrain and soil properties (in areas of high geomorphological heterogeneity). Similar conclusions were made using the same abiotic variables (Silva 2004, Jačová and Romportl 2008).

Johansson et al. (1999), Nieto (2001), and Stanley (2001) described their idea of geodiversity, which were restricted to geological elements and processes. According to Kozłowski (2004), geodiversity includes surface water and considers the consequences of anthropogenic processes. He emphasized geomorphology and assessed five classes based on four main elements (relief, soils, surface, water, and landscape structure). The primary purpose of geodiversity quantifications is the conservation of the Earth's resources and the conservation of biological richness. The geodiversity index (GI) assessment formula had been established by Serrano and Ruiz-Flaño (2007) and followed by Serrano et al. (2009) on a rural landscape. They assumed that more elements mean greater geodiversity and the number of components and roughness affects the increase in geodiversity. They combined geological, geomorphological, hydrological, and pedological elements, then multiplied the sum by the coefficient of roughness and then divided the logarithmic surface area results. Their quantitative approach was enabled to establish useful results that identify very high to low geodiversity in their study sites. They did not include climate variables in their analyses, and they suggested following their method to assess biodiversity, but they did not draw any relationship between geodiversity and biodiversity from their research. Their approaches to geodiversity assessment were focused on geomorphology. This approach seems to have a bias as the concept of geodiversity cannot be developed only on geomorphological units. The determination of roughness coefficients presented is not compatible with the geodiversity assessment of large areas (Pereira et al. 2013). Their results for each geomorphological unit were semi-quantitative, involving five geodiversity values, from very low to very high.

Benito-Calvo et al. (2009) tested landscape diversity indices to assess regional geodiversity in the Iberian Peninsula using GIS techniques. Their terrain classification was generated from morphometric, geological, and morphoclimatic regional classifications, which were applied to compute richness, diversity, and evenness indices and to assess current regional geodiversity quantitatively among the central geological regions of Iberia. Costantini and L'Abate (2009) used Shannon's index to assess pedosite diversity in Italy, which could be a partial exploration of geodiversity assessment. Pedosite is defined as a georeferenced soil having a cultural heritage, which is a soil exposure or a soilscape where an extraordinary cultural interest has been recognised (Costantini 1999).

The quantification of geodiversity by a spatial grid system at a landscape scale was developed by Hjort and Luoto (2010), and they aimed to explore the relationship between topography and geodiversity, particularly for high-altitude and high-latitude areas. They included geology, geomorphology, and hydrology and excluded pedology and topography in their quantification method. They applied the GI formula from Serrano and Ruiz-Flaño (2007 a, b, and 2009) in their index computation.

Considering the source of data used for the assessment of geodiversity, Pellitero et al. (2014) divided two recognised methods. The direct method implies fieldwork to calculate the value of geodiversity for a specific component of the natural environment, which is considerably more expensive and whose scope is limited for large areas (Zwoliński et al. 2018). On the other hand, the indirect method performs calculations on raster or vector data within a GIS environment.

The concept of geodiversity has in recent years been put forward as a new alternative and potentially useful means to assess and model spatial biodiversity patterns (see Parks and Mulligan 2010, and the references therein). Biodiversity is the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of an ecosystem (Jeyamohan 2015). The term 'biodiversity' is now inextricably linked to a widening of focus in conservation efforts beyond preserving particular species of ecological or social significance and towards maintaining essential ecosystem functions and services (CICES 2018, Alahuhta et al. 2018) to embrace the challenge of conserving the global variety of species, the genes they contain, and the ecosystems in which they occur (Ferrier 2002). Geodiversity includes geology, geomorphology, pedology, topography, hydrology, and climate (Benito-Calvo et al. 2009, Parks and Mulligan 2010), which are meticulously linked with key abiotic drivers of biodiversity such as energy, water, and nutrients (Richerson and Lum 1980; Hjort et al. 2012). Geodiversity also provides essential supporting services for biodiversity as well as provides minerals, nutrients, landform mosaics, and geomorphological processes for habitat creation and maintenance. Hjort et al. (2012) quantified geodiversity for a boreal landscape in Finland, which was used to improve biodiversity models, and they followed the developed system by Hjort and Luoto (2010), Serrano and Ruiz-Flaño (2007), and Benito-Calvo et al. (2009). They showed the relationship between species richness and explanatory variables using a generalised linear model (GLM) and generalised additive model (GAM). According to their study, geological, geomorphological, and hydrological diversity appeared to be promising surrogates of biodiversity in mesoscale plant species richness models. GAMs were also used to indicate the positive relationships between forest carbon budgets and geodiversity and between forest carbon budgets and biodiversity in Finland (Alahuhta et al. 2018). Pereira et al. (2013) assessed the geodiversity of Paraná State in Brazil, and Silva et al. (2013) assessed the geodiversity of the Xingu drainage basin using geology, geomorphology, palaeontology, soils, and mineral occurrences. Their main aim of GI production was to use this as a tool in land use planning, particularly in identifying priority areas for conservation, management, and use of natural resources at the state level. Pellitero et al. (2014) calculated mid- and large-scale geodiversity using lithology, structures, geomorphology, hydrology, fossils, soils, and slope. Their approach was intended to promote geodiversity protection within an integrated environmental management system. However, their GI should not be used as a surrogate indicator of biodiversity, as climate data were not included in the calculations, while climate is a potential resource for biodiversity development (Parks and Mulligan 2010). Fragoso-Servón et al. (2015) calculated the geodiversity of the Yucatan Peninsula in south-eastern Mexico by considering geomorphology, geology, hydrology, and soil properties as components of geodiversity. They used a simple additive model of thematic diversity and assured from their results that a study with detailed information could provide valuable insights into the spatial distribution of biological diversity.

Earlier studies used the point bonitation (high-quality, means the evaluation of natural environment by points 1 to 4) method to assess the relief geodiversity of Polish lowlands and the Carpathian Mountains (Kostrzewski et al. 1998, Kot 2006, Kot and Szmidt 2010; Radwanek-Bąk and Laskowicz 2012, Kot 2015, Najwer et al. 2016). However, this research method (bonitation or high-quality method) was used implicitly in various studies with the number of different elements (Őrsi 2011, Pellitero et al. 2011), GI (Pereira et al. 2013, Silva et al. 2013), total diversity (Hjort and Luoto 2010), and categorisation and computation of landform geodiversity (Zwoliński 2009).

Manosso and Nóbrega (2015) identified and defined eight compartments or landscape units for a quantitative evaluation of geodiversity in a unit of the Cadeado Range, Paraná State. They made an integrated analysis of the set of elements of the geoecological structure, that is, geomorphological, geological, pedological, hydrologic, and socio-economic features, to understand the spatial distribution of geodiversity. Mauerhofer et al. (2017) contributed geomorphosite inventory to geoheritage knowledge in their research, which was followed by a direct method in a qualitative approach. Geoheritage conservation was their primary emphasis. Özşahin (2017) assessed geodiversity in the Mount Ganos following the methods of Serrano and Ruiz-Flaño (2009) using GIS data. He used the GI formula in his study area and applied one-sample statistics and descriptive statistics to show the relationship between habitats and geodiversity.

The altitudinal zonation of mountain flora has been investigated since the 18th century (e.g., Humboldt 1805-1834, Weberbauer 1911, Acosta-Solís 1968, Ellenberg 1975, Cleef et al. 1984). However, the detailed quantitative comparisons of an extensive floristic database (e.g., Brako and Zarucchi 1993, Clinebell et al. 1995, Terborgh and Andersen 1998, Jørgensen and León-Yánez 1999, Braun et al. 2002) with altitudinal gradients started in the last decade. Braun et al. (2002) quantified the geodiversity of Andean mountain regions based on climatic, soil, geographical, and topographical data. They found maximum geodiversity in the Colombian Andes, around 5° N latitude, and along the Peruvian and Bolivian Eastern Cordilleras. They related that those maxima coincide almost entirely with the Andean phytodiversity maxima shown in the global map of species numbers of vascular plants from Barthlott et al. (2000), but they did not measure statistical correlation. Jačkova and Romportl (2008) found a significant influence of abiotic heterogeneity on habitat richness in two protected areas in the Czech Republic. Jačkova and Romportl (2008) used geological, hydrological, and digital terrain models to determine abiotic heterogeneity, and GIS vector layers of habitat were used for the formation of habitat richness. They overlaid habitat richness and abiotic heterogeneity by the grid square method and generated a statistical regression model to show the relationship between geodiversity and habitat richness. They found more than 40% of the habitat richness variability from the heterogeneity of abiotic conditions. Parks and Mulligan (2010) determined a positive relationship between the resource-based measure of geodiversity and biodiversity patterns on a broader scale than others, and they included climate information with all other variables in their analysis. Their paper outlined potential data sets that could be used to represent geodiversity, and then they reviewed the theoretical links between each element of the proposed compound index of geodiversity. Räsänen et al. (2016) explained vascular plant species richness patterns in a fragmented landscape. According to their study, topography explained the majority of the variation, but the relative importance of topography and geodiversity was higher in explaining native species richness. They used gridded species richness data and used a GLM and GAM to analyse the relationship between species richness and explanatory variables.

Seijmonsbergen et al. (2018) presented two methods in their research to produce an index-based map for landscape planning. Their second approach was the evaluation of the relationship between geodiversity and biotopes. They followed indirect methods and used a tectonic map, geological formation, drainage, lakes, elevation, slope, and solar radiation in their GI assessment. As they used vector and raster data, they calculated several units for each independent variable in every grid and classified each layer in separate index maps. Finally, they added all index maps to compute the GI of their study area. They did a cross-tabulation analysis of the relationship between the areal coverage of biotope units and the morphogenetic types occurring within these biotopes. Boothroyed and McHenry (2019) presented a critical literature review of 299 academic journal articles on geodiversity. They found that 7.5% of the literature considered geodiversity concepts for exploring biodiversity. According to the literature, geodiversity can define an abundance of plants (Keith 2011, Sutherland 2011, Semeniuk and Brocx 2011, Bailey et al. 2017, Bailey et al. 2018, Stavi et al. 2018, Boothroyed and McHenry 2019), primarily in a qualitative sense. Geodiversity parameters such as soil textural variation and landform rugosity has been considered as a component of species and habitat distribution modelling in some recent studies (Robinson and Fordyce 2017, Tukiainen et al. 2017a and 2017b, Pereira and Bonetti 2018, Tracz et al. 2019, Boothroyed and McHenry 2019, Zarnetske et al. 2019). Supporting evidence for the geodiversity-biodiversity relationship is found primarily in European terrestrial ecosystems (Bailey et al. 2017, Tukiainen et al. 2017, Alahuhta et al. 2020).

1.3 Geodiversity and biodiversity of Sikkim and Jammu & Kashmir

The Greater Himalaya has much higher biodiversity values than the global average (Körner 2004); the eastern Himalaya has the highest plant diversity and richness within this mountain system (Xu and Wilkes 2004; Mutke and Barthlott 2005; Salick and Byg 2007). Mountains, especially in wet tropical latitudes, create the physical stage and bioclimatic gradients for species evolution, both in mountain areas and in adjacent valleys (Hoorn et al. 2013, Mattews 2014, Gordon 2018, Manríquez et al. 2019). An about 53,000 km^2 area has been declared a 'hotspot' in the tropical forest zone of Eastern Himalaya where the number of plant species in the original forest was 9,000, and the number of endemic species in the original forest was 3,500 (Myers 1988). The Himalaya is one of the youngest and richest ecosystems on Earth. This mountain system harbours nearly 8,000 species of flowering plants, of which 25.3% are endemic (Singh and Hajra 1996). Himalayan forests are considered to be among the world's most depleted forests (Schickhoff 1995). Myers (1988) described the species richness in the tropical forest zone of the eastern Himalaya. The total extent of tropical forest is 2,204,000 km^2, and the eastern Himalaya contains 340,000 km^2 of primeval forest and 9,000 plant species in the original forest. Myers (1988) also has mentioned entire India, which has 15,000 species, of which 33% are endemic. Hajra and Verma (1996) and Singh and Dash (2002) kept records of Sikkim's botanical explorations and described phytogeographical aspects, plant resources, species of horticultural importance, and other details, which is all an excellent contribution to the Botanical Survey of India. Grierson and Long (1983) recorded data on the flora of Bhutan in eight volumes and included the floral record from Sikkim.

Dhar and Kachroo (1983) wrote a book on the alpine flora of Kashmir and discussed the alpine habitat, geology, climate, and general vegetation of the Kashmir region. Dhar and Kachroo (1983) also provided a profile of vegetation stages according to altitude. They included *Pinus*, *Cedrus*, *Picea*, *Abies*, *Viburnum*, *Indigofera*, *Parrotiopsis*, *Cotoneaster*, *Isodon*, *Rhododendron*, *Salix*, *Betula*, *Juniperus*, and *Lonicera* species in their distributional diagram. The book contains chapters on phytogeographical assessment, floristic analysis, and distribution patterns of natural orders, and it discusses endemism and species composition and provides a database of alpine species of the Kashmir Himalaya. Blatter (1920, 1984) described the species of Kashmir, and his emphasis was on beautiful flowers. He published two volumes with more critical identification of the species, their genera, and their families. Seybold and Kull (1985) made observations of the vegetation and plant ecology in the Zanskar region. They studied 13 points from an altitude of 3,600 to 4,700 m and characterised the plants with precise locality information. Singh and Kachroo (1987) published a book on the forest flora of Srinagar, in which they described the topography, climate, and soils of Srinagar and recorded all species in that region. They also analysed the percentage of life forms, biotic influence, and succession trends of that area.

A study on the flora of the upper Liddar valleys was published by Sharma and Jamwal (1988), which covers 130 genera under 35 families with all vital species identification. Hartman (1999) presented floristic and vegetational studies on the real Ladakh range and included Pangong Tso and Tso Moriri. He divided plant communities in five elevation ranges: the semidesert with *Artemisia brevifolia* and/or *Tanacetum fruticulosus* (3,890–4,320 mNN), the alpine steppe with *Potentilla bifurca* and *Artemisia gmelinii* (4,440–4,780 mNN), the high alpine communities with *Poa attenuata* and *Potentilla sericea* (4,700–5,150 mNN), the mountain desert with *Stipa glareosa* and *Krascheninni kovia ceratoides* from the edges areas (4,100–4,700 mNN), and an alpine steppe with *Stipa purpurea* and/or *Carex moorcroftii* within the catchment basin of the Kiagar Tso (4,720–4,800 mNN).

Kala and Mathur (2002) studied vegetation distribution in eight landscape types in the Trans-Himalayan region of Ladakh and distinguished six plant communities by cluster analysis. They found 74 plant species in their sampling area. Miehe et al. (2002) recorded 79 species of vascular plants and 17 species of crustose lichens in an Aksai Chin plain's alpine desert. This area can be called a 'cold spot' as it falls into Diversity Zone 1 (<100 species per 10,000 km2). Miehe et al. (2002) analysed the life forms, phytogeography, and diversity of the species. According to the altitudinal gradient in Ladakh, life forms analysis was performed by Klimeš (2003), and he also presented species richness patterns in an alpine desert. He recorded 404 species of vascular plants in his study area and found a hump-shaped altitudinal distribution of species numbers.

Nagar and Singh (2007) analysed phyto-diversity in the Nubra Valley of Ladakh and found a high level of endemism, rarity, and fragility. They recorded 431 species in 251 genera. Khuroo et al. (2010) pioneered and updated a study of the native and alien woody flora of the Kashmir Himalaya with taxonomic composition, geographic distribution, and invasion status of alien species. According to their investigation, among 520 woody species, 322 species were native and 198 were alien. The most updated records on the floristic diversity of J&K have been made by Dar and Khuroo 2020, Haq et al. 2020, Ismail et al. 2020, Kumar et al. 2020, Dar and Dar 2020, Dar and Khuroo 2020, Ganie et al. 2020, Malik et al. 2020, Bhellum 2020, Sanjappa and Ambarish 2020, Ahmad et al. 2020, and Shukla and Srivastava 2020.

Biodiversity studies in the Himalaya include country-specific (e.g., Samant and Dhar 1997, Gairola et al. 2013) and species-specific studies (e.g., Grau et al. 2007, Srinivasan et al. 2014). Singh and Anand (2013) described the term 'geodiversity' according to the diversity of geological features and assessed India's geodiversity and the Himalayan range qualitatively. Rawat and Sharma (2012) described the geodiversity of the Dabka watershed in the Lesser

Himalaya for their geo-hydrological database modelling of a landslide susceptibility assessment. Their major geodiversity parameters were average slope, geology, geomorphology, soil types, land use, drainage density, and drainage frequency, and they expressed geodiversity as least-stressed, moderately-stressed, highly-stressed, and extremely stressed categories. They used these geodiversity categories to produce a landslide susceptibility index (LSI), but not a GI. All these previous studies touched on geodiversity issues of the Himalaya but did not quantify geodiversity and did not specify its relationship to biodiversity. Jahan et al. (2017) quantified the geodiversity of Sikkim through the indirect method and compared their GI with biological richness in different parts of Sikkim. Geology and soil parameters were not considered in their quantification. Thus, there is a significant deficit of quantified data about geodiversity for the Himalaya mountain ranges, of which Sikkim is only a small part. The spatial distribution of species richness has not been calculated yet for the species-rich areas in the Himalaya, and the comparative study of the relationship between geodiversity and biodiversity in the different sites of the Himalaya region is still missing.

1.4 Objectives

My research hypothesis is that: **The species-rich East Himalaya has a higher geodiversity than the western Himalaya.** This work has the aim of quantifying the geodiversity of the Himalayan mountain system and analysing the linkages between geodiversity and biodiversity in two subregions of contrasting biodiversity. This study will focus on the following objectives:

- Determine the pattern of species richness in the high biodiversity region (Sikkim) and in the low biodiversity region (J&K) at different elevational gradients of the Himalaya.
- Quantify the spatial pattern of geodiversity in Sikkim and J&K.
- Analyse the geodiversity pattern and make a correlation between GI and biodiversity for Sikkim and J&K.
- Perform model analyses on the spatial differences between species richness in Sikkim and that in J&K.
- Discuss the factors and reasons for diversified geodiversity and diversified biodiversity for both study areas.
- Quantify geodiversity for the Himalayan mountain system and compare GI differences for Sikkim and J&K.

By following these objectives, this research will be able to contribute to establishing the linkages between geodiversity and biodiversity in the Himalaya.

Chapter Two

Materials and Methods

2.1 Study areas

2.1.1 Sikkim

Sikkim is bounded by Nepal to the west, Bhutan to the southeast, Tibet to the north and northeast, and the West Bengal plains to the south. Sikkim is the least populous state in India, covering an area of 7,096 km^2. Sikkim is geographically diverse due to its location in the Himalayas; the climate ranges from subtropical to high alpine. Kangchenjunga, the world's third-highest peak, is located on Sikkim's border with Nepal.

Sikkim is one of the richest houses of plant diversity in the country because of its unique geographic position, high annual precipitation, a wide range of topography, and the presence of perennial streams and rivers (Singh and Dash, 2002). This region has a wide range of climatic conditions due to the varied topography and a great deal of altitudinal variation from ca. 200 m asl to 8,598 m asl (Fig. 2.1). There are 4,250 plant species, and 2,550 (60 percent) are endemic (Palliwall 1982).

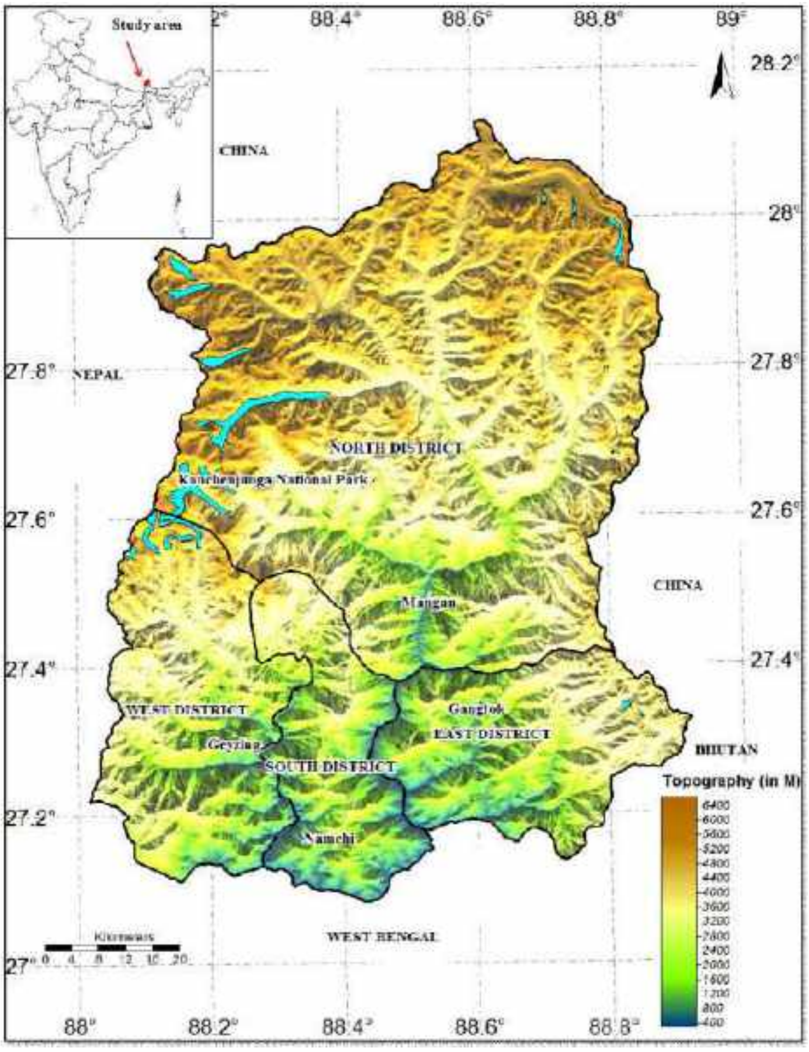


Figure 2.1: A topographic map of Sikkim (Source: Jahan et al. 2017).

2.1.2 Jammu and Kashmir (J&K)

The state of J&K is situated in the north of India and has an area of 138,992 km^2 (640 km north to south and 480 km east to west). The state is highly mountainous except for a short belt adjoining the Punjab plains and the valley of Kashmir. This state is distinctly divided into three biogeographic units: the Western Himalaya of Jammu, Northwest Himalaya of Kashmir, and Trans-Himalayan zone of Ladakh (Rodgers et al. 2002, Dar and Khuroo 2020; Figure 2.2, 2.3).

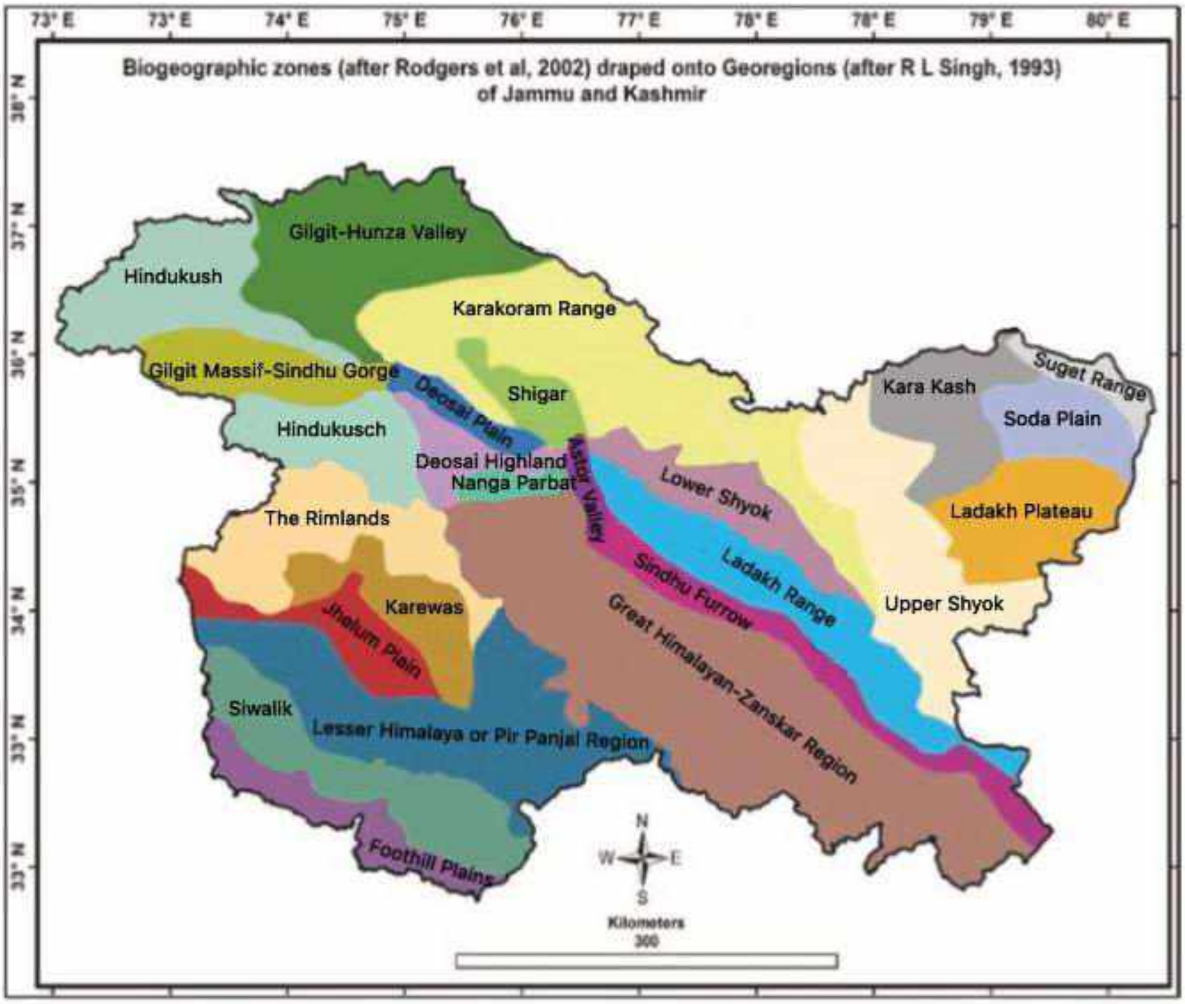


Fig. 6.11 Biogeographical zones and Geo-regions in the J&K state

Figure 2.2: Biogeographical zones and geo-regions in the J&K state (Source: modified from Romshoo et al. 2020).

The state lies between 32°27’ N to 35°5’ N latitude and 73°76’ E to 79°6’ E longitude. The stratified rock formations have resulted in a broad division of three main tectonic structural groups in the state, namely the Panjal, the Zanskar, and the Tertiary groups. The Panjal includes the outer hills, outer plains, and the middle mountains; the Zanskar is the whole of the eastern region from Spiti to Lahul to the lofty Karakoram in the north, and the Tertiary group is the valley of Kashmir and other river valleys (Singh and Kachroo 1987). A great physiographic and climatic variation is observed in the state. The altitude varies from 305 m asl (in the south) to 7,000 m asl (in the north) (Dhar and Kachroo 1983). Areas between 3,500- 3,600 m asl are treeline. Because of the large variation in climate and topography, the region supports rich biodiversity (Champion and Seth 1968).

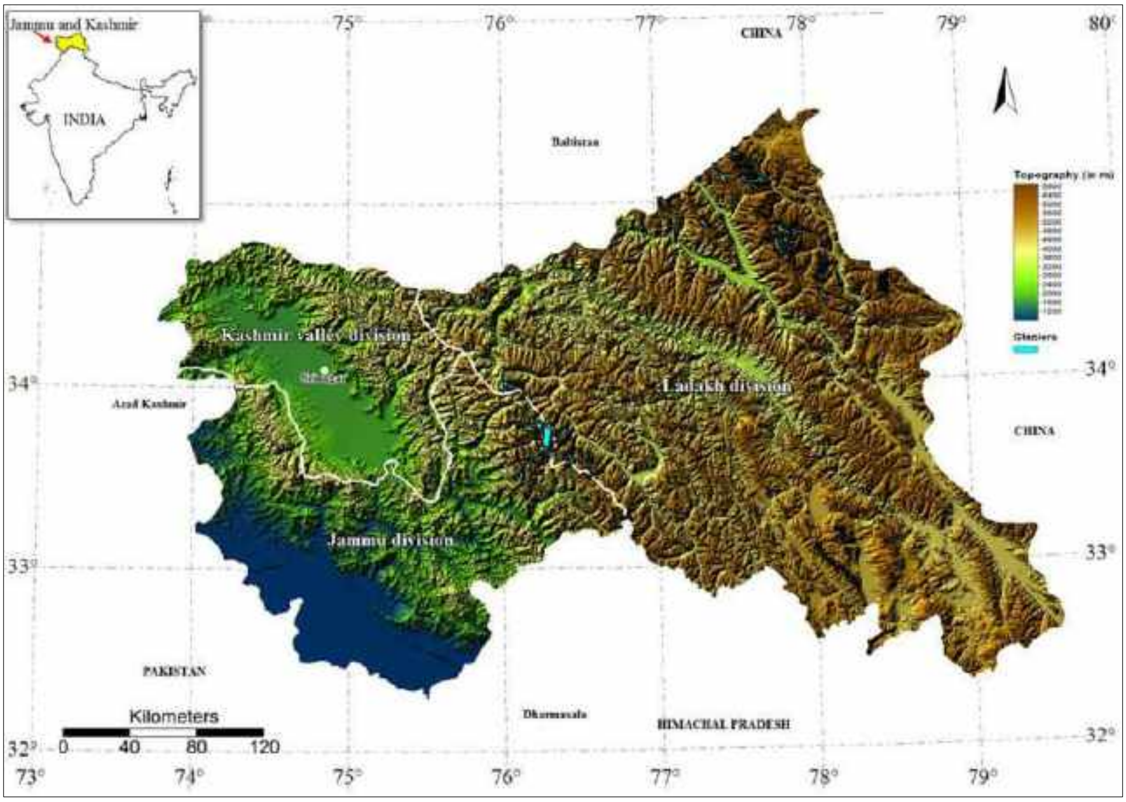


Figure 2.3: Topographic map of J&K (Source: Author 2022).

Kashmir Himalayas harbour a rich floristic diversity of immense scientific interest and supports about 12% of the state's total angiosperm flora and 3% of its endemics (Dar et al. 2012). Approximately 56% of the total area of J&K is covered by vegetation, and the dominant vegetation types are forest and grasslands (Romshoo et al. 2020). The entire forest cover of the state accounts for 19.95% of its total geographical area, and the Kashmir, Jammu, and Ladakh region have 40.17%, 59.64%, and 0.17% area under forest cover (Romshoo et al. 2020). This region represents a unique bio-region owing primarily to its varied topography and habitat heterogeneity along with a wide elevational range (Dar and Sundarapandian 2016).

Kashmir: This region falls into a temperate climate and extends from nearly 1,350 m asl to the upper altitude (around 4,600 m asl) of the plant life. The annual precipitation in Kashmir Valley is 1,050 mm, which falls as winter snow (Khuroo et al. 2010) and monsoonal precipitation. The seasonal distribution of rainfall in Kashmir Valley is 28%, 21%, 8%, and 43% for pre-monsoon, monsoon, post-monsoon, and winter season, respectively (Kumar and Jain 2010). This area shows three zonations of vegetation cover: 1. Mixed vegetation of broadleaved deciduous trees and conifers 2. Conifer forest zone 3.White birch zone dominated by perennial herbs (Singh and Kachroo 1987). The mountain ranges around the valley also have alpine and subnival vegetation.

Jammu: The subtropical and temperate belt of Jammu province is mostly dominated by broadleaved woody elements, with both deciduous forests at lower elevations (<300 m asl) and coniferous and evergreen forests at a higher elevation (Singh and Kachroo 1987, Khuroo et al. 2010, Khoshoo 1997, Dar and Khuroo 2020). The annual precipitation in Jammu is about 1,700 mm due to the Indian summer monsoon.

Ladakh: Ladakh is the coldest, loftiest, and remotest area of the Indian Union. Ladakh receives just about 100 mm of annual precipitation because of the high mountain ranges, which prevent rain clouds from reaching the interior valleys (Khuroo et al. 2010). This high-altitude desert is mostly dominated by xerophytic vegetation because of a lack of rainfall during the growth period. The natural tree elements are found mainly in humid regions of Nubra valleys and river valleys in the district.

2.1.3 The Himalaya

The geographical location of the Himalayan mountain ranges lies from Nanga Parbat (35° 14'N/74° 35'E) to Namcha Barwa (29° 38'N/95° 03'E), and the total extent is 2,500 km from NW to SE (Miehe 2004). The Himalayan range was formed by the tectonic movement of the Indo-Australian Plate and the Eurasian Plate, converging along their borders deep underneath the surface of the Earth. The Himalayan range is the tallest and one of the youngest mountain ranges in the world. The Himalayan range is traditionally divided into four major tectonic zones (Searle 2015), which are bounded by large-scale faults (Fig. 2.4).

The Tibetan Himalaya or **Tethyan Himalaya** lies south of the suture zone and comprise folded and thrusted sedimentary rocks of the Indian plate upper crust. Stratigraphically these rocks include Neo-Proterozoic, Palaeozoic, Mesozoic, and Lower Tertiary rocks spanning over 500 million years of deposition along the northern margin of the Indian plate; the youngest marine rocks in this zone are limestones.

The Greater Himalaya or **High Himalaya** lie south of the Tethyan Himalaya and mainly are composed of once-profoundly buried metamorphic rocks and granite that form many of the highest peaks such as Kanchenjunga, Manaslu, Ganesh, and Nuptse. The southern boundary of the Great Himalayan zone is the Main Central Thrust, arked by a zone of inverted metamorphic isograds with higher-grade, more deeply buried sillimanite and kyanite-grade gneisses thrust structurally above lower-grade schists.

The Lesser Himalaya (Midlands or Midhills) lying south of the Main Central Thrust comprise metamorphosed rocks that formed the upper-crust levels of the Indian plate (Searle

2015). These rocks are mainly Neo-Proterozoic or Palaeozoic in age and include sedimentary rocks such as shales, sandstones, quartzites, and turbidites, with prominent series of Cambrian-Ordovician granites formed around 500 Ma. The Lesser Himalayan zone's southern boundary is the Main Boundary Thrust, a north-dipping, low-angle thrust fault that is the presently active margin of the Himalaya. South of the Main Boundary Thrust, there is the Sub-Himalayan Zone, which currently is the active boundary of the Himalaya.

The Himalayan range is made up of three smaller mountain ranges running very close to each other: the Siwalik Hills, the Lesser Himalaya, and the Greater Himalaya. Some of the range’s top peaks include Mount Everest (at 8,849 m asl) Kanchenjunga, Makalu, Dhaulagiri, Nanga Parbat, and Annapurna. It has an extensive altitude range (300–8,000 m asl) and rich diversity of habitats providing varied macroclimates and ecological niches for both plants and humans. The vegetation of this region includes subtropical, temperate, sub-alpine, and alpine vegetation types.

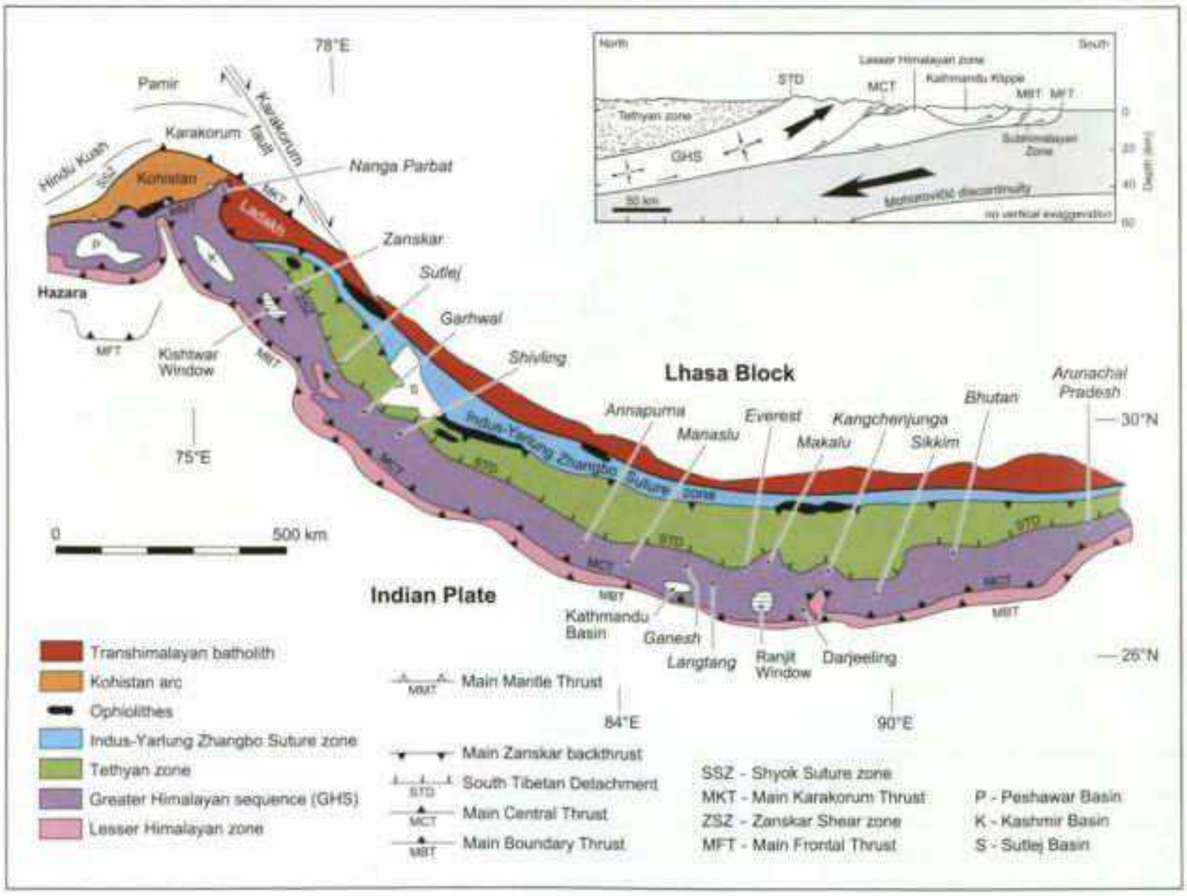


Figure 2.4: General geological map of the Himalaya and simplified cross-section, after Hodges (2000). The arrows indicate the southward thrusting of the Himalaya relative to the northward under-thrusting of the lower Indian crust. Source: Searle (2015).

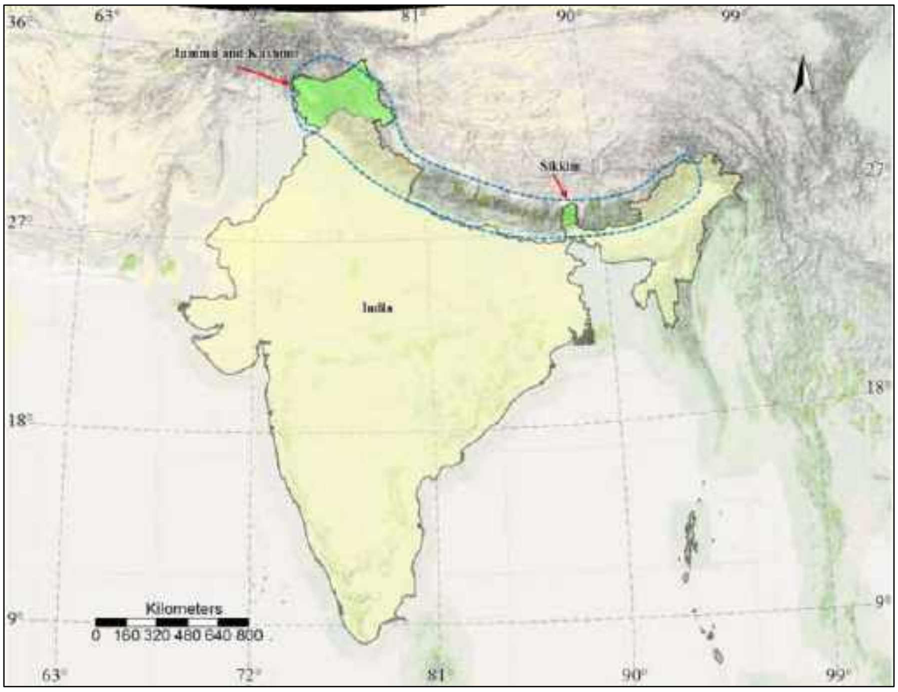


Figure 2.5: The Himalaya and the location of the present study areas. The blue dashed line shows the extent of the Himalayan mountain ranges (Source: Author 2022).

Most of the climate observation centers in the Himalaya are in the Pir Panjal, the Siwalik, and the Mahabharat Ranges. Rainfall decreases above the elevation of 3,000 m asl, and the eastern Himalaya receives more annual rainfall (around 400 cm) than do the western Himalaya (less than 200 cm; Rao 1976). The entire humid mountain terrain has summer precipitation from July to September in the northwest and May to October in the southeast. Monsoonal precipitation is most pronounced in the S-slope, and Jammu (75° E) has one-third of winter precipitation.

2.2 Materials

Species richness assessment from fieldwork is very time consuming and expensive and requires a large network of sampling stations. There are several factors, viz. vegetation type, slope, aspect, edaphic factors, and altitude (Sharma et al. 2009, 2010; Gairola et al. 2011) that determine the community composition, structure, and distribution pattern of diversity in mountain vegetation (Kessler 2001, Schmidt et al. 2006). The indirect method of data gathering and the assessment of geodiversity are the only ways to cover the whole mountain systems. Spatial scale and approach are the main determinates to quantify the geodiversity of the Himalaya. Validation of the data is the most important part of scientific research. To validate the results, two study areas have been chosen, one from a high geodiversity area in the east Himalaya Sikkim, and the second study area has been chosen in the J&K in the western Himalaya. Species richness data is a good source of data for validation, which is possible to produce from published sources. Species richness data is challenging to produce for the

Himalayan mountain ranges because of their vast spatial extent. I choose an unsupervised method to quantify the geodiversity for Sikkim and J&K. If these two study areas show a good correlation with biodiversity, then the approach can be used to produce a geodiversity map of the Himalaya mountain ranges.

2.2.1 Species richness data

Databases of species richness in Sikkim and J&K have been produced from published floras of Bhutan, Sikkim, and J&K. A database of 5,087vascular plant species in Sikkim, including information on family, habitat, location according to altitude and district, and community affiliation, has been prepared using published sources (Hajra and Verma 1996, Grierson and Long 1983, Singh and Dash 2002). J&K has experienced more botanical exploration than Sikkim. A database of 5,660 vascular plant species, including information on family, habitat, and location according to altitude, has been prepared using published sources (Sharma and Kachroo 1981, Dhar and Kachroo 1983, Blatter 1984, Singh and Kachroo 1987, Sharma and Jamwal 1988, 1998, Hartmann 1999, Dickore et al. 2000, Kala 2005, Malik et al. 2015, Khuroo et al. 2007, 2010, 2011, FRLHT 2010, Tali et al. 2014, Dvorský et al. 2018, Dar & Dar 2020, Dar and Khuroo 2020, Kumar et al. 2020, Shukla and Srivastawa 2020). Among 5,660 species, 2,394 species have no data on elevation and spatial location, and that is why those species (2,394 in number) were excluded from the altitudinal distribution of the J&K region. In this database, the same species were found from different sources; in that case, duplicate names were removed. Some species have a diverse altitudinal range in various sources. To solve this problem, the elevations of the same species were combined together. As field based data collection was not in this methodical approach, secondary species richness data have been used according to each species' altitudinal distribution. The number of species for every 500 m asl interval has been calculated for both study areas, and a species richness map has been produced by the tool 'change grid values' in Shuttle Radar Topographic Mission (SRTM) elevation data.

I produced a species richness map from the information of the total number of species in each elevational range. J&K has plain landform at high altitudes (e.g., Kashmir Valley), and this valley is used primarily for agricultural activity. The slope inclination is the main parameter that affects land-use patterns and species occurrences in J&K. A fuzzy logic approach (intersection AND) has been used to model a species richness map by the combination of fuzzified species numbers and a fuzzified slope. In the subsequent analysis, the total number of vascular plant species recorded in each grid cell was used as a measure of biodiversity. A database of species richness for the Himalayan mountain system was challenging to prepare as several country boundaries fall on the whole mountain system.

2.2.2 Explanatory variables

In this study, I compiled a total of six topographic and climate-based variables and one soil variable (Table 2.1) to cover the most commonly used abiotic resource factors affecting the vascular plant species richness at different resolutions of my study areas. I avoided qualitative data like geology and soil types in my analyses to avoid distortion of the output maps. Number of geological classes or soil types for small scale analysis (e.g. 500 m or 1000 m grid size) is able to produce good results but in this analyses/scale this kind of maps will produce only 0 or 1 types in each grid and lead to destruction for the final result. I calculated all explanatory variables inside 90 m^2 grid cells. To quantify geodiversity, I fuzzified all the variables separately and this method normalizes data according to expert's opinion. This classification was elaborated using GIS techniques (SAGA 6.3.0), which involved morphometric and morphoclimatic classification together. The spatial analysis in SAGA GIS is a cross-platform open-source GIS software developed by the Departments of Physical Geography in Göttingen and Hamburg (Conrad 2007, Conrad et al. 2015). Morphometric variables were obtained from the SRTM digital elevation model (DEM; NASA). Temperature and rainfall data were collected from the CHELSA Database (Karger et al. 2017). I selected the DEM-based topographical variables elevation, slope, topographic wetness index (TWI), terrain ruggedness index (TRI), and climatological variables (temperature and precipitation) to quantify the geodiversity map. SRTM data had been pre-processed using fill-sinks (Wang Liu) of primary DEMs before my calibration was started. The terrain ruggedness index provides an objective quantitative measure of topographic heterogeneity in a geographical information system (Rilley et al. 1999). This algorithm is appropriate with broad area habitat analysis where sources of error in DEMs will not particularly affect the biological interpretation of the data and is applicable for smaller areas with higher quality data or corrected DEMs (Rilley et al. 1999). TWI (Sørensen et al. 2006, Gruber and Peckham 2009) is a tool to indicate areas accumulating water flow, often with seasonality and permanently waterlogged ground. Variation of geomorphological processes (e.g., erosion, transportation, solution of Earth materials) is higher in wet areas than it is in dry regions associated with high geodiversity. Soil moisture is one of the most critical determinants of vegetation composition, and DEM-based TWI is the most popular proxies of soil moisture for ecologists (Kopecký et al. 2010).

Table 2.1: Explanatory variables used in GIS analyses.

Variables	Type of variable
Precipitation	Continuous (in mm)
Temperature	Continuous (in °C)
Altitude	Continuous (in m)
Slope	Continuous (in degrees)
Topographic ruggedness index (TRI)	Continuous
Topographic wetness index (TWI)	Continuous
Soil organic carbon (SOC)	Continuous (g/kg)

Pedological and climatological data are the crucial variables for association with topographical variables to determine geodiversity (Nieto 2001, Gray 2004, and references therein, Kozłowski 2004, Carcavilla et al. 2007, Bruschi 2007, Serrano and Flano 2007, Panizza and Piacente 2008, Benito-Calvo et al. 2009, Ibáñez and Brevik 2019). Soil organic carbon (SOC) content contributes to soil fertility by contributing other nutrients and by increasing both cation exchange and water-holding capacity (Brady and Weil 1999, Laughlin et al. 2007), and it is strong evidence to represent biological richness for an area (Jobbágy and Jackson 2000, Bobbink et al. 1998, Laughlin et al. 2007). SOC content data was acquired from SoilGrids – global gridded soil information (ftp.soilgrids.org/data/recent/, Hengl et al. 2017), which is based on remote sensing data sources. SOC has significant importance in different depths of soil. In this analysis, I considered SOC content at 0.05 m depth. The SoilGrids1km: ORCDRC_M_sl2: SOC (fine earth fraction) in g per kg at depth 0.05 m was downloaded for the whole mountain system.

Soil parent material or geology had a significant effect on topsoil organic carbon (Barré et al. 2016) and was an important driver of SOC at the regional scale (Heckman et al. 2009, Baritz et al. 2010, Wilson et al. 2011, Wiesmeier et al. 2013, Prietzel and Christophel 2014, Johnson et al. 2015, De Vos et al. 2015, Barré et al. 2016). In the analysis, I preferred SOC, for my method.

2.2.3 Methods in GIS and statistical analysis

Fuzzy logic has been used in this study to quantify the geodiversity of the Himalaya. In this method, elevation, slope, TWI, TRI, SOC, temperature, and precipitation were fuzzified as an individual layer. The respective suitability cell values in all fuzzified layers range from 0 (not suitable at all) to 1 (very suitable). In this fuzzy logic, ‘increase and decrease’ methods were used to fuzzify elevation and slope, and only the ‘increase’ method to fuzzify TWI, TRI, SOC, precipitation, and temperature layers. The six fuzzified data sets were then combined using the

'AND Intersection' algorithm with the min-operator in the fuzzy logic module of SAGA GIS (Fig. 2.6). This algorithm assigns the lowest cell value from the seven different inputs, and potential geodiversity can be only as high as the worst constraining factor at a specific location (Weinzierl and Heider 2015). The data are continuous, and fuzzy logic makes data suitable for non-suitable ranges.

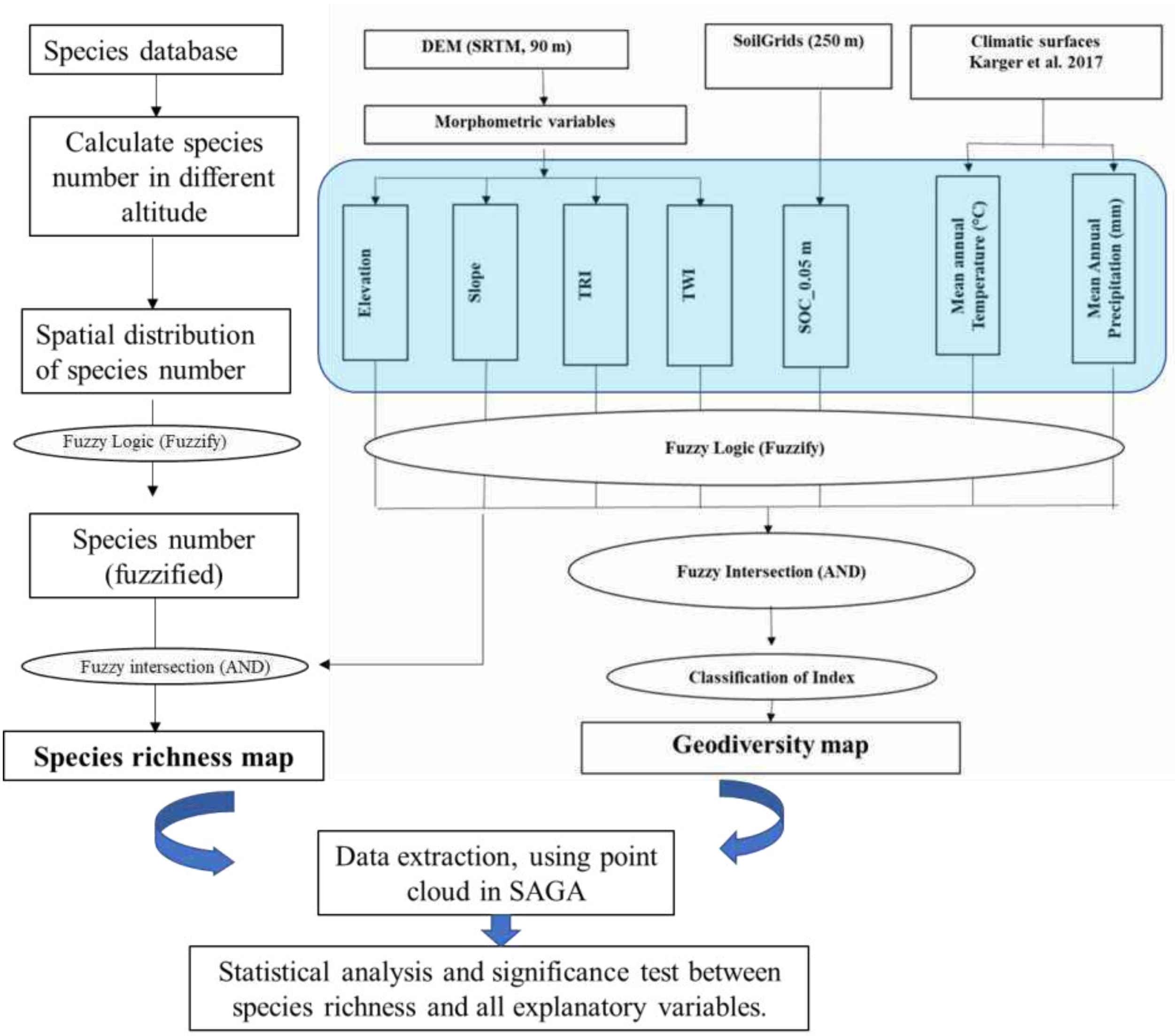


Figure 2.6: The workflow of quantifying geodiversity and species richness.

Other studies (Benito-Calvo et al. 2009) have calculated several classification maps (e.g., morphometric map, 10 classes; morphoclimatic map, five classes; and geological map, 15 classes) to finalise their geodiversity indices. In this study, the SOC map, all the data of SRTM, and climatic variables from CHELSA have been analysed together.

After producing the final geodiversity map and species richness map, the raster data were extracted as point cloud data in SAGA and prepared for regression analysis. The extracted values of the geodiversity map and all the variables were analysed in statistical tool R. To correlate geodiversity data with the independent variables, multiple regression and stepAIC (Akaike 1973) have been used. The Akaike information criterion (or AIC) is an estimator of the relative quality of the statistical models for a given set of data. The stepwise regression (or stepwise selection) consists of iteratively adding and removing predictors, in the predictive model, to find the subset of variables in the data set, resulting in the best performing model, which is a model that lowers prediction error. Stepwise selection models were chosen in these analyses, which is a combination of forward and backward selections (James et al. 2014, Bruce and Bruce 2017). The analysis starts with no predictors. Then it sequentially adds the most contributing predictors (such as forward selection). After adding each new variable, one removes any variables that no longer provide an improvement for the model fit (such as backward selection).

I used two approaches to the analyses. Using GLMs (Nelder and Wedderburn 1972) and GAMs (Hastie and Tibshirani 1986), I examined the relative importance of different variables in models (Räsänen et al. 2016). I tested if the independent variables explain a more substantial proportion of the variation in species richness than do the GLMs and if there are non-linear dependencies between explanatory variables and dependent variables (Räsänen et al. 2016). In these models, the dependence between a dependent variable and explanatory variables is modeled in a gaussian family with an identity link. Smoother functions have been used in GAMs. GLMs (Lopatin et al. 2016, Bobrowski and Schickhoff 2017) and GAMs are among the most widely used statistical techniques in species distribution models (e.g., Guisan et al. 2002, Guisan and Thuiller 2005, Lopatin et al. 2016, Räsänen et al. 2016, Bobrowski and Schickhoff 2017). For model validation, all data sets were split into training and testing data samples with a ratio of 80% to 20% using random stratified sampling (Kuhn and Johnson 2013). I calculated pseudo R^2 in the GLM to account for the explained variance in the data set (Nagelkerke 1991). I chose the area under the curve of the receiver operating characteristics curve (Fielding and Bell 1997, Elith and Burgmann 2002) as a threshold-independent evaluation metric.

The relative importance of the predictors refers to the quantification of an individual regressor's contribution to a multiple regression model. I used the Lindeman, Merenda, and Gold methods in my model. In addition, in this study, all statistical analyses were performed using the programming language R (R Core Team, 2015, version: 3.6.1).

Chapter Three

Results

3.1 Relationship between geodiversity and biodiversity in Sikkim

3.1.1 Floristic analysis

All the vital forest types of eastern Himalaya such as sub-Himalayan wet mixed forests, subtropical hill forests, Himalayan subtropical pine forests, wet temperate forests, mixed coniferous forests, eastern Oak-Hemlock forests, Oak-fir forests are found in Sikkim (Champion 1936, Singh and Dash 2002, Miehe et al. 2015). Pure chir pine forests are the dominating feature in small pockets in dry valleys of south Sikkim, and Sal forests are found up to around 900 m asl in altitude along the valleys of Rangeet and Teesta. Hazra and Verma 1996, Miehe et al. 2015 and Offen et al. 2021 have classified the vegetation cover of Sikkim according to altitudinal distribution (Fig. 3.1.1), which is summarised in Table 3.1.1.

Table 3.1. 1: Elevational zonation of vegetation in Sikkim (Source: Hazra and Verma 1996, Miehe et al. 2015 and Offen et al. 2021).

Vegetation	Elevational zone	Characteristic species
Tropical deciduous / evergreen forests	Hill; up to 900-1000 m	*Shorea robusta, Dillenia pentagyna, Lagerstroemia parviflora, Bombax ceiba, Terminalia tomentosa, Bauhinia variegata, Cedrela toona, Stereospermum tetragonum, Adina cordifolia*
Subtropical deciduous / evergreen forests	Submontane; 1000–2000 m	*Schima wallichii, Castanopsis tribuloides, Castanopsis indica, Engelhardia spicata, Phoebe hainesiana, Macaranga pustulata, Machilus odoratissima, Quercus glauca, Toona ciliata, Alnus nepalensis*
Warm/cool temperate deciduous / evergreen forests (lower/ middle cloud forests)	Lower montane; 2000-3000 m	*Quercus lamellosa, Lithocarpus pachyphylla, Ilex dipyrena, Rhododendron arboreum, Magnolia doltsopa, Castanopsis tribuloides, Betula alnoides, Acer campbellii, Quercus semecarpifolia, Tsuga dumosa*
Cold temperate	Upper montane (subalpine);	*Abies densa, Rhododendron hodgsonii, Betula utilis, Acer caudatum, Rhododendron campanulatum,*

deciduous / evergreen forests (upper cloud forests)	3000-4000 m	*Rhododendron wightii, Prunus rufa, Juniperus indica, Larix griffithiana*
Alpine dwarf thickets and grasslands	Alpine/subnival ; above 4000 m	*Rhododendron setosum, Rhododendron anthopogon, Cassiope fastigiata, Kobresia nepalensis, Bistorta vivipara, Bistorta macrophylla, Rhodiola spp., Potentilla spp., Carex spp., Primula spp.*

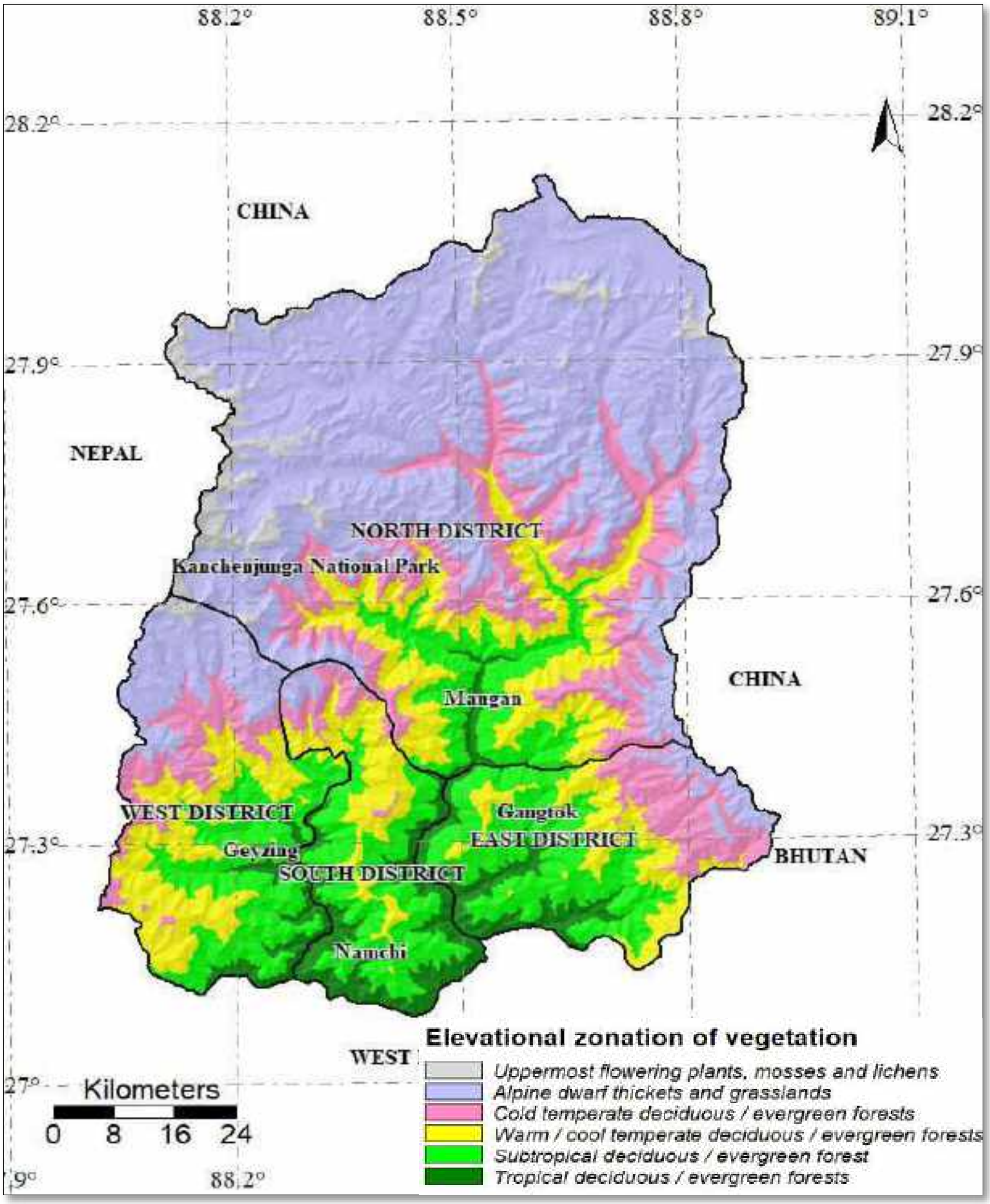


Figure 3.1.1: Elevational zonation of vegetation map of Sikkim (map prepared according to the information in Table 3.1.1) (Source: Author 2022).

The vegetation classification with relief information of the Himalaya was prepared in 1957 (Schweinfurth 1957). The elevational zonation map of Sikkim can be compared with Schweinfurth's vegetation distribution map (1957) of the Himalaya (Fig. A.1), where the tropical, moist deciduous forest was mentioned as a tropical, dry winter-frosty deciduous forest and where the subtropical forest was referred to as a tropical evergreen mountain forest. The distribution of subalpine forests has similarities in both maps, and Schweinfurth showed a forest of *Betula* species in the subalpine forest of the eastern corner of the East District. The alpine steppe and steppe forests of *Juniperus* species were shown at the edges of the subalpine forest in the North Districts in Schweinfurth's map. The distribution of temperate broadleaved forest and mixed coniferous temperate forest are almost the same for these two maps.

A database has been prepared on the flora of Sikkim from different published sources. There are 5,087species from 245 families in Sikkim, in which the most dominant families are Orchidaceae, Poaceae, Asteraceae, Cyperaceae, Fabaceae, Rubiaceae, Rosaceae, Scrophulariaceae, Primulaceae, Gentianaceae, Euphorbiaceae, Ranunculaceae, and Lauraceae. Figure 3.1.2 shows the total number of species found in the most dominant families in Sikkim. The number of genera in this region is 1,489, and the most prevalent genera are shown in Figure 3.1.3. Carex (Cyperaceae) and Primula (Primulaceae) are the most species-rich genera, followed by Saxifraga (Saxifragaceae), Juncus (Juncaceae), and Pedicularis (Orobanchaceae).

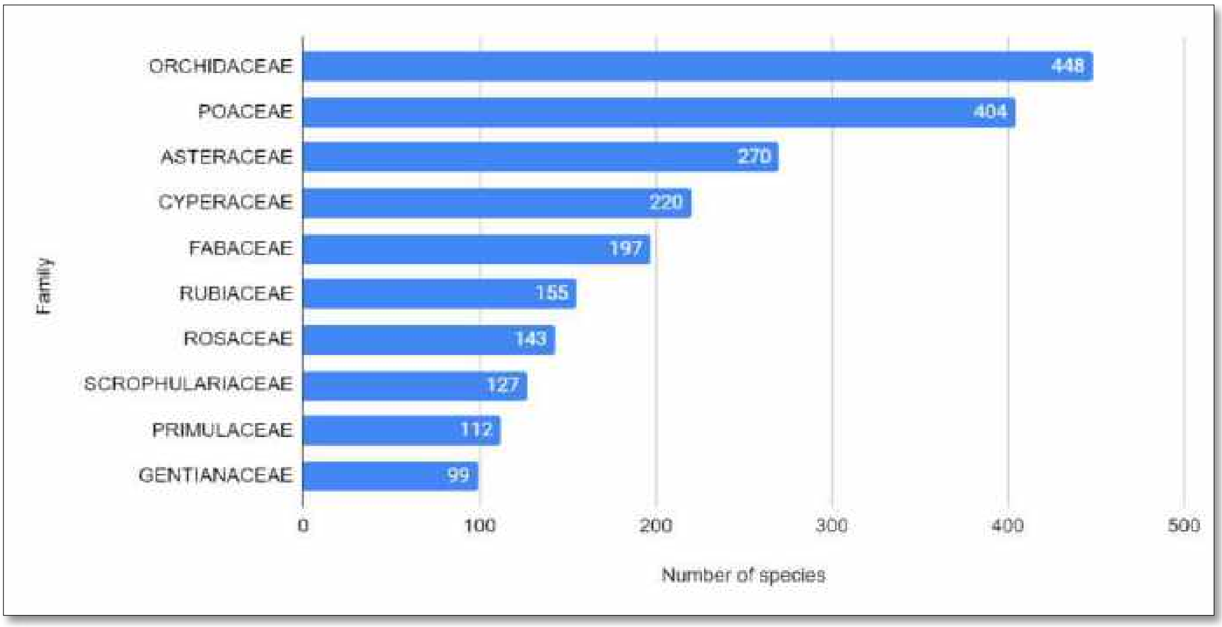


Figure 3.1.2: Dominant families of the Sikkim flora (Source: Author 2022).

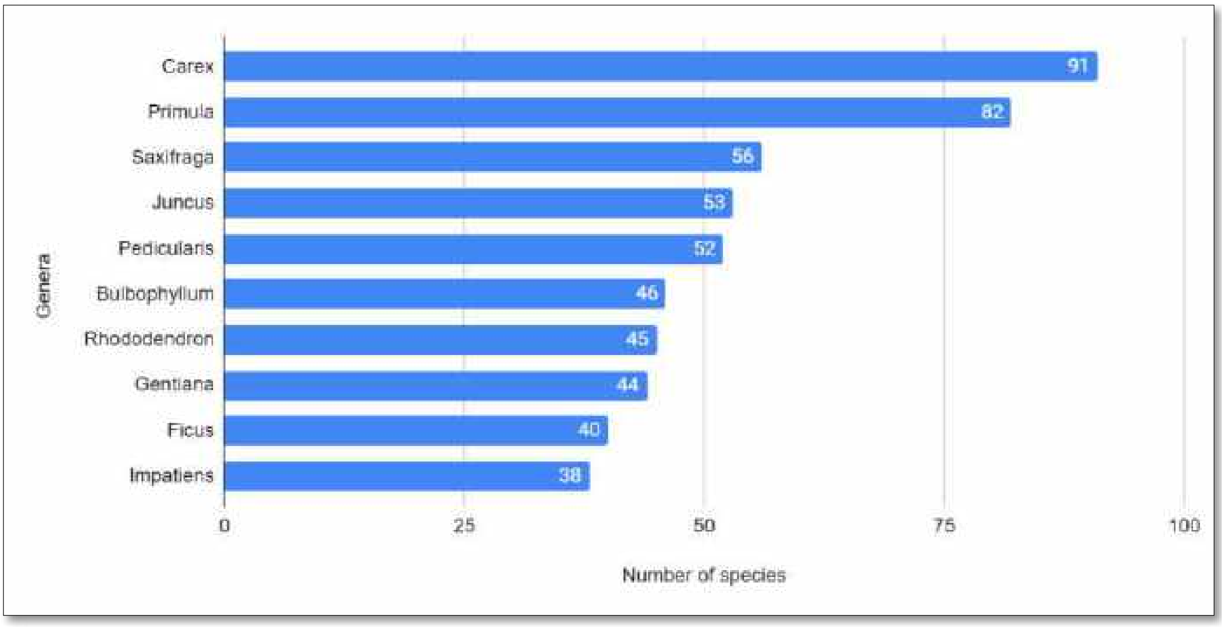


Figure 3.1.3: Dominant genera of the Sikkim flora (Source: Author 2022).

3.1.2 Spatial analysis

Altogether there were 431 species for which information on altitude was missing. Thus, 4,587 species were used to show their distribution. The results show that the highest species diversity (around 1442 in number at 1200 m asl) can be found in the elevational range between 1,000 and 2,000 m asl (Fig. 3.1.4). The number of species is around 1,384 in between 200 and 1000 m asl; from 1,000 to 2,000 m asl, the total number of species is 2147, and the number of species starts to decrease above 2,000 m asl. There are only 125 species between 5,000–6,000 m asl altitude in the Sikkim Himalayan range. Higher elevations show a decrease in species diversity, in particular above 5,000 m.

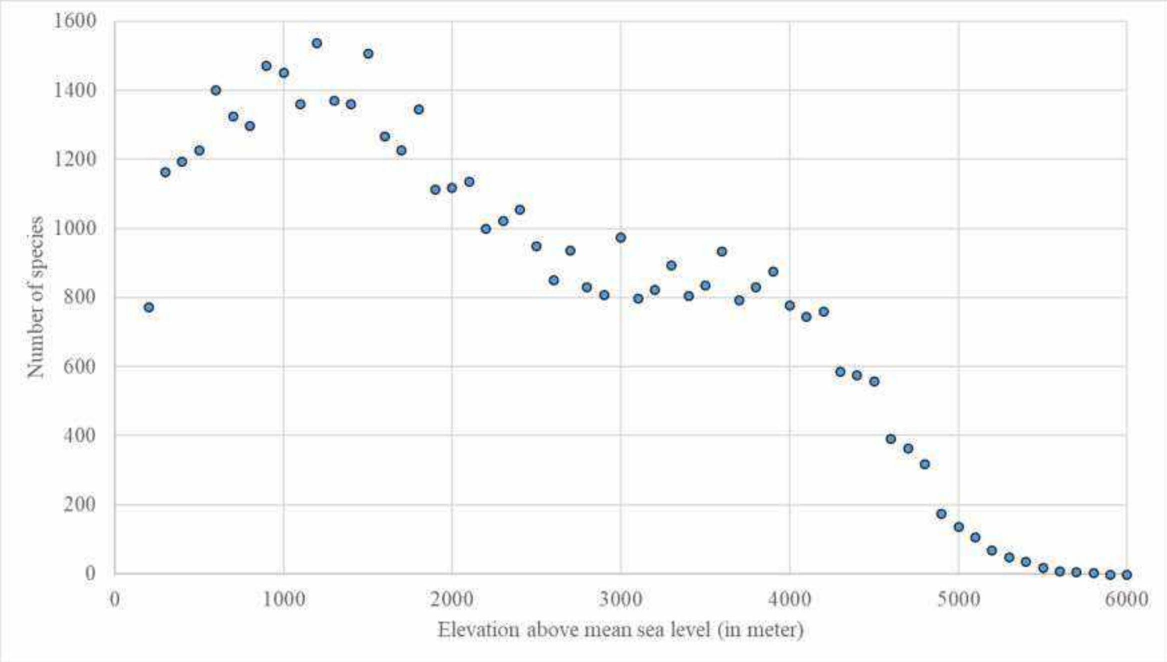


Figure 3.1.4: Elevational species richness based on all vascular plant species in Sikkim (Source: Author 2022).

Table 3.1.2: Distribution of species numbers of the most species-rich families along the elevational gradient in Sikkim (*Scrophulariaceae* not splitted up). (Source: Author 2022).

No.	Family	Elevation above sea level (in meter)					
		<=1000	1001-2000	2001-3000	3001-4000	4001-5000	5001-6000
1	ORCHIDACEAE	158	205	85	42	5	0
2	POACEAE	107	142	107	72	55	15
3	FABACEAE	91	74	36	19	12	0
4	RUBIACEAE	91	89	40	16	3	0
5	CYPERACEAE	76	83	85	96	55	14
6	ASTERACEAE	72	104	96	120	100	28
7	EUPHORBIACEAE	72	45	9	3	1	0
8	ASCLEPIADACEAE	41	36	18	2	0	0
9	SCROPHULARIACEAE	39	36	44	59	57	8
10	ROSACEAE	11	35	87	69	39	2
11	PRIMULACEAE	5	17	32	75	66	1
12	LAMIACEAE	11	17	15	13	10	2
13	GENTIANACEAE	5	15	24	60	58	14
14	BORAGINACEAE	12	17	17	23	22	9
15	RANUNCULACEAE	4	13	29	48	37	1

Species richness can be categorised from Table 3.1.2, and species richness ranging from high to very high richness is found at altitudes from <1,000 m asl to 2,000 m asl. The most dominant families of species for this area are Orchidaceae, Poaceae, Asteraceae, Rubiaceae, Cyperaceae, Leguminosae, Urticaceae, Lauraceae, Euphorbiaceae, Scrophulariaceae, Verbenaceae, and Acanthaceae. Moderate species richness can be found at altitudes between 2001 and 4,000 m asl, and the most dominant species families are Asteraceae, Poaceae, Cyperaceae, Rosaceae, Primulaceae, Scrophulariaceae, Ericaceae, Rubiaceae, Gentianaceae, Umbelliferae, Ranunculaceae, Leguminosae, and Primulaceae. Low species richness is found at altitudes between 4,001 and 5,000 m asl, and families with a high number of species are Asteraceae, Primulaceae, Gentianaceae, Scrophulariaceae, Cyperaceae, Poaceae, Saxifragaceae, Rosaceae, Ranunculaceae, and Cruciferae. There are 125 species in elevation between 5,000 and 6,000 m asl, and the most dominant species are Asteraceae, Poaceae, Cyperaceae, Gentianaceae, Boraginaceae, Scrophulariaceae, Caryophyllaceae, Umbelliferae, and very few species from other families.

The number of species at each elevation represents the spatial distribution of species richness (Table 3.1.3). Figure 3.1.5 shows the spatial distribution of species richness according to altitude. This map is generated by converting grid values (elevation) into species number values, and other topographic variables have not been considered here.

Table 3.1.3: Number of species in Sikkim (at 200 m intervals) (Source: Author 2022).

Altitude (m)	Number of species	Altitude (m)	Number of species
<200	490	3200-3400	920
200-400	1208	3400-3600	840
400-600	1274	3600-3800	940
600-800	1454	3800-4000	917
800-1000	1483	4000-4200	795
1000-1200	1456	4200-4400	763
1200-1400	1576	4400-4600	617
1400-1600	1534	4600-4800	402
1600-1800	1291	4800-5000	330
1800-2000	1371	5000-5200	147
2000-2200	1248	5200-5400	78
2200-2400	1055	5400-5600	42
2400-2600	1097	5600-5800	12
2600-2800	971	5800-6000	6
2800-3000	848	6000<	2
3000-3200	970		

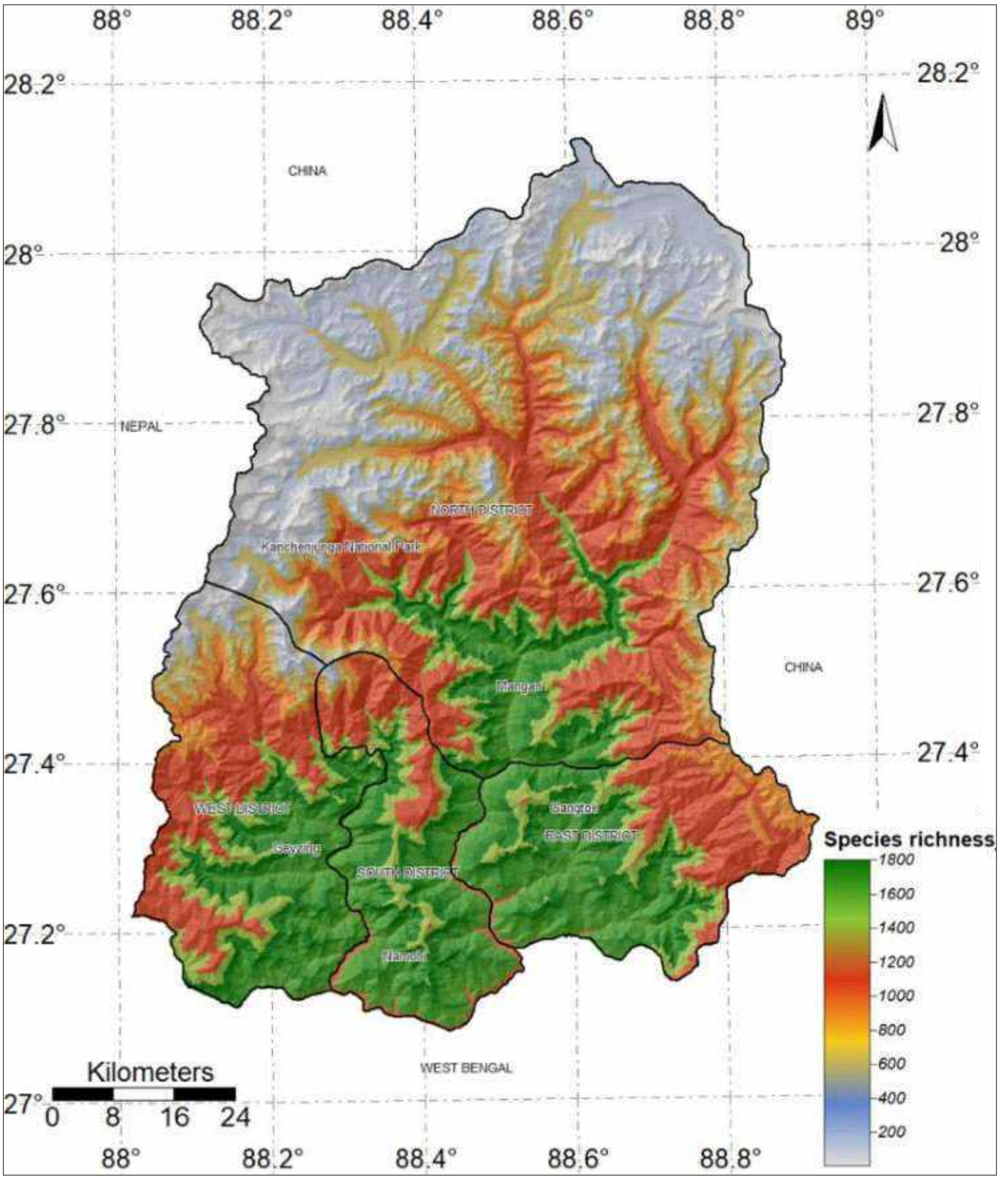


Figure 3.1.5: Spatial distribution of species richness in Sikkim (Source: Author 2022).

3.1.3 Quantification of geodiversity

The geodiversity of Sikkim has been quantified, and the index values range from 0.01 to 0.32. The index values are classified as five classes with equal intervals using GIS option. In this classification the index values range from 0.25 < 0.33 (very high), values from 0.21 < 0.25 (high), values from 0.15 < 0.21 (moderate), values from 0.08 < 0.15 (low), and values from 0.02 < 0.08 (very low; Fig. 3.1.6). In the case of Sikkim, geodiversity is low to moderate in the urban areas of Mangan, Geyzing, Namchi, and Gangtok. The Kanchenjunga National Park area is mainly covered by several glaciers, snowfields, and rocky wastes. Zemu Glacier, Nepal Gap Glacier, Tent Peak Glacier, and Hidden Glacier are the nearest to Kanchenjunga peak, and also are places of tourist interest. There are other glaciers scattered in the Kanchenjunga National Park, for instance, Chungsang Glacier, Lhonak North, and Lhonak South Glaciers in the northern part and Talung Glacier and Zumthul Phuk Glacier in the southern part. The forest of the northwestern part of Mangan city (in the north district, mixed coniferous temperate forest and subalpine forest; Fig. 3.1.1) has a higher GI. Near the eastern border of Sikkim, the area from east district to north district (Fig. 3.1.1; temperate broadleaved forest and subalpine forest) has a very high GI in the produced map (cf. Fig. 3.1.6).

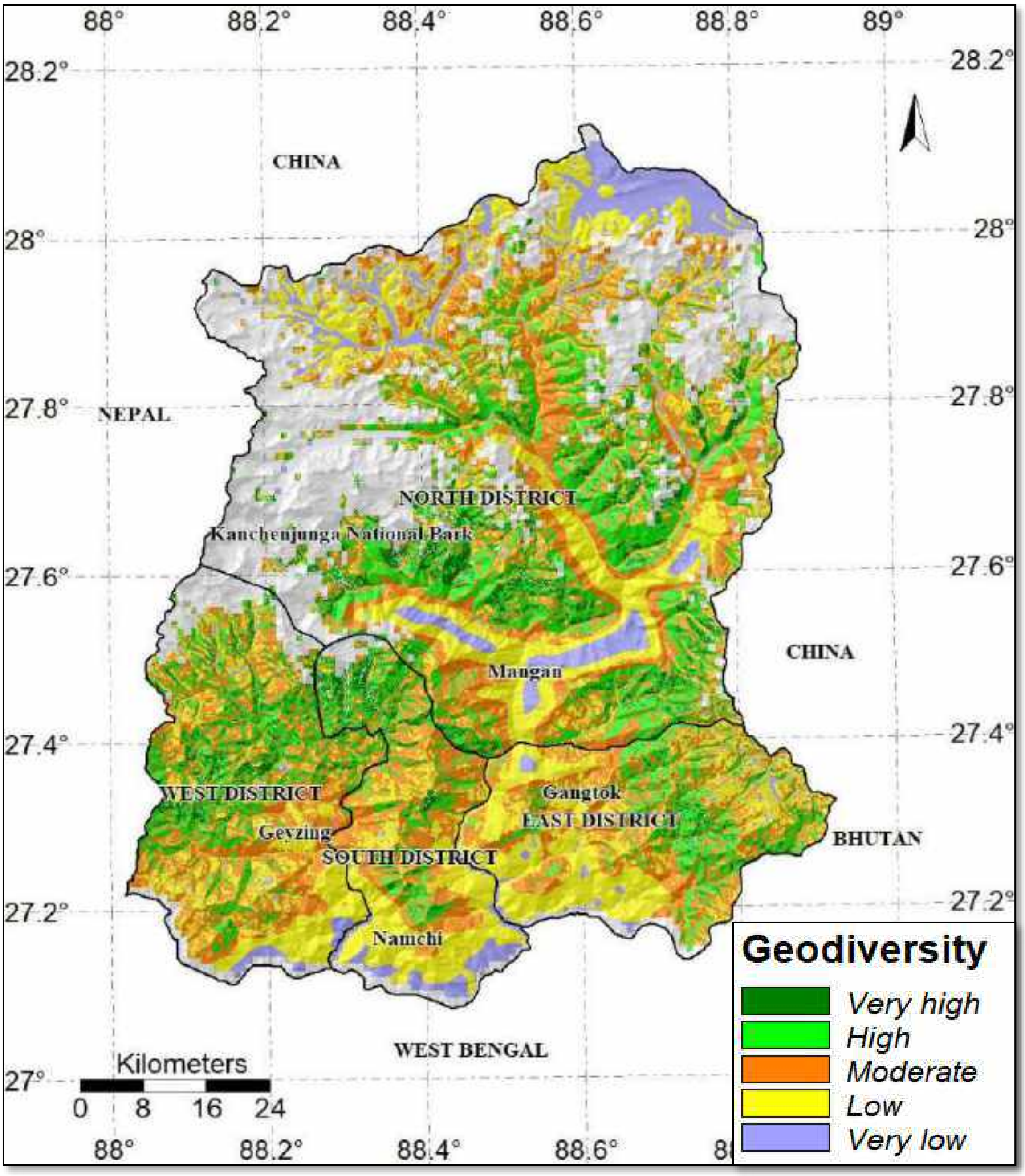


Figure 3.1.6: Geodiversity of Sikkim (Source: Author 2022).

The mixed coniferous forest and broadleaved forest (Fig. 3.1.1) in the west district and south district have high to very high geodiversity. The temperate broadleaved forest to subalpine forest areas (at an altitude between 1,700 and 3,000 m asl; Fig. 3.1.1) have high geodiversity as well as high species richness. This area of high species richness consists of forest cover, alpine scrub, grass and scrub, glacial moraines, and screes. In the middle of the East district, the city of Gangtok, which is the main urban settlement surrounded by agricultural fields, shows low to moderate geodiversity (Fig. 3.1.6). In the west district of Sikkim, the northern areas have high to very high species richness, and the GI is also shown as high to very high on the map.

3.1.3 Statistical analysis

Several statistical analyses have been performed to find the relationship between species richness and geodiversity and also with other predicted variables. Multiple linear models and stepAIC were performed to improve model performance. The Akaike information criterion was used to simplify the model and to quantify the amount of information loss due to this simplification. In this algorithm, the sequential replacement of the variables made a combination of forward and backward selections. This method starts with no predictors and then sequentially adds the most contributing predictors.

Spearman's rank correlation showed a positive relationship between species richness and geodiversity, mean annual temperature (temperature hereafter), slope, and TRI, and it showed a negative relationship with mean annual precipitation (precipitation hereafter), SOC, altitude, and TWI (Fig. 3.1.7). The correlation coefficient reveals +0.50 between geodiversity and species richness, which means that the quantified geodiversity explains 50% of species richness in Sikkim. Temperature, slope, and SOC are highly significant with species richness ($p < 0.005$). Precipitation data has no significance with other variables. Temperature and slope have a higher relationship with species richness. Altitude is highly correlated with temperature, and TRI and TWI have been calibrated from altitude and slope variables. To avoid collinearity in the model, altitude, TRI, and TWI were not included as explanatory variables.

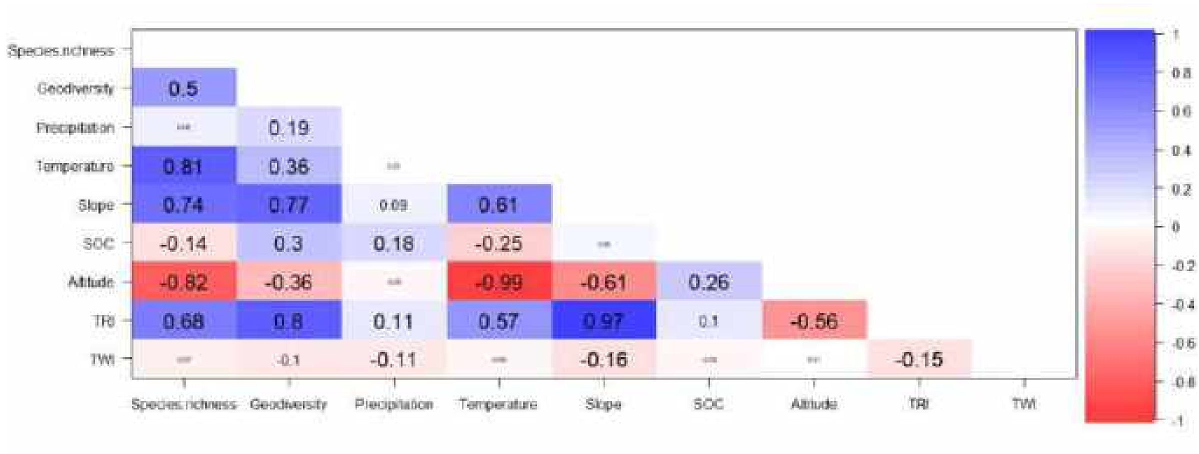


Figure 3.1.7: Correlation among different variables in Sikkim (Source: Author 2022).

Multiple regression analysis between species richness and predictors shows a good correlation (R^2 values around 68% in GLM and 69.8% in GAM). These models quantify the relationship between species richness and all individual predictors separately. The mean annual temperature and slope are the main predictors for analysing species richness in Sikkim (Fig. 3.1.8). This model produces correlation in different steps according to their fitness to the dependent variable. SOC has minimal impact to relate species richness compared to temperature and slope. The relative importance of explanatory variables showed different responses at the district level of Sikkim. The north and the west districts have the same pattern of variable importance, whereas the south and the east region showed different patterns of variable importance. Temperature, slope, and SOC are the crucial variables in Sikkim's north and west districts. On the other hand, the slope is the essential variable in the south and east districts, followed by temperature and SOC.

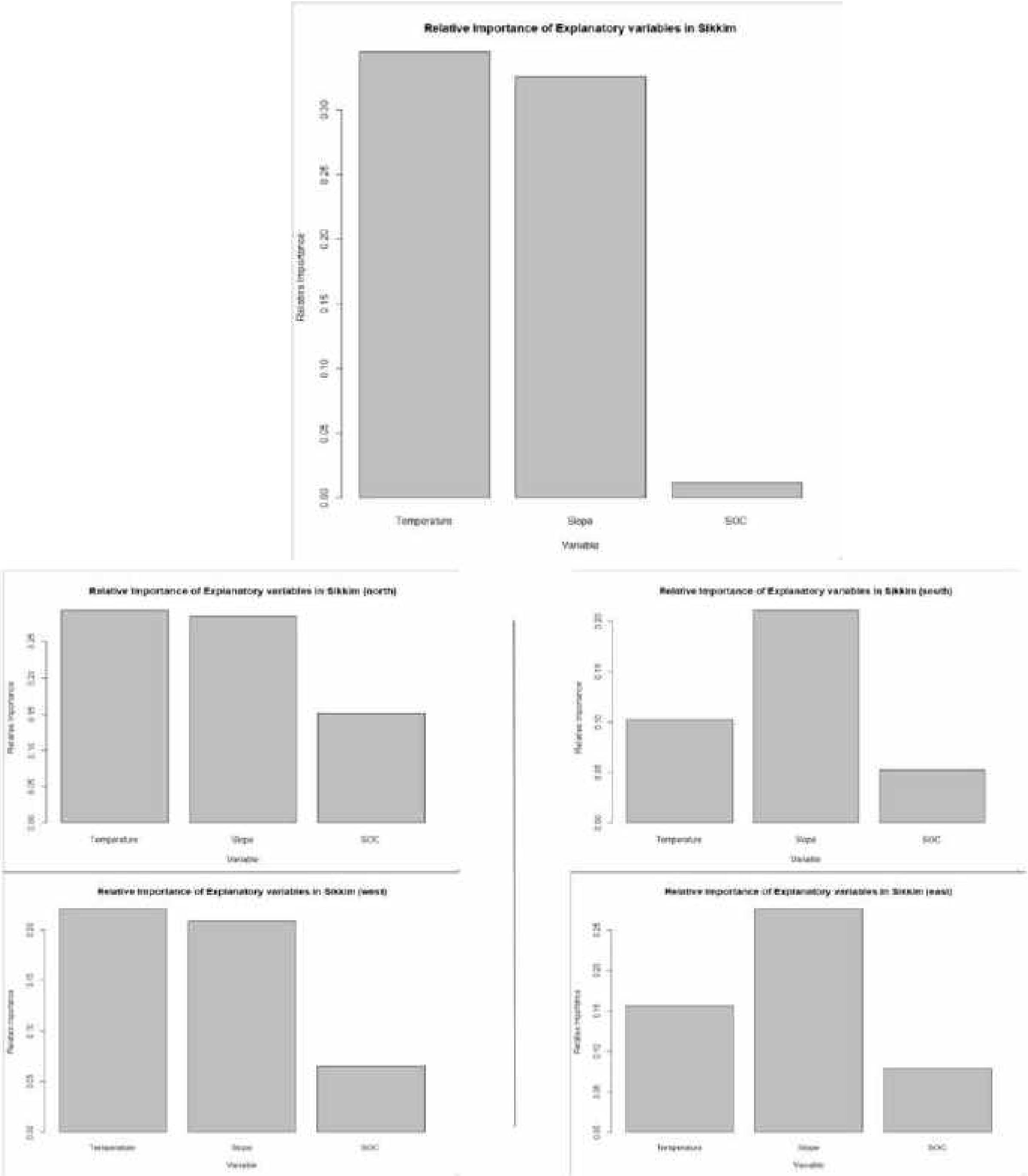


Figure 3.1.8: Relative importance of explanatory variables in Sikkim and its four districts (Source: Author 2022).

The response curves of selected explanatory variables showed no distinctive differences for most of the variables in GLM and GAM (Fig. 3.1.9). In GLM, the variable SOC showed concave curves, whereas response types differed. The slope has approximately linear response curves in both models. The mean annual temperature has the highest relative importance, and the response curve is also linear.

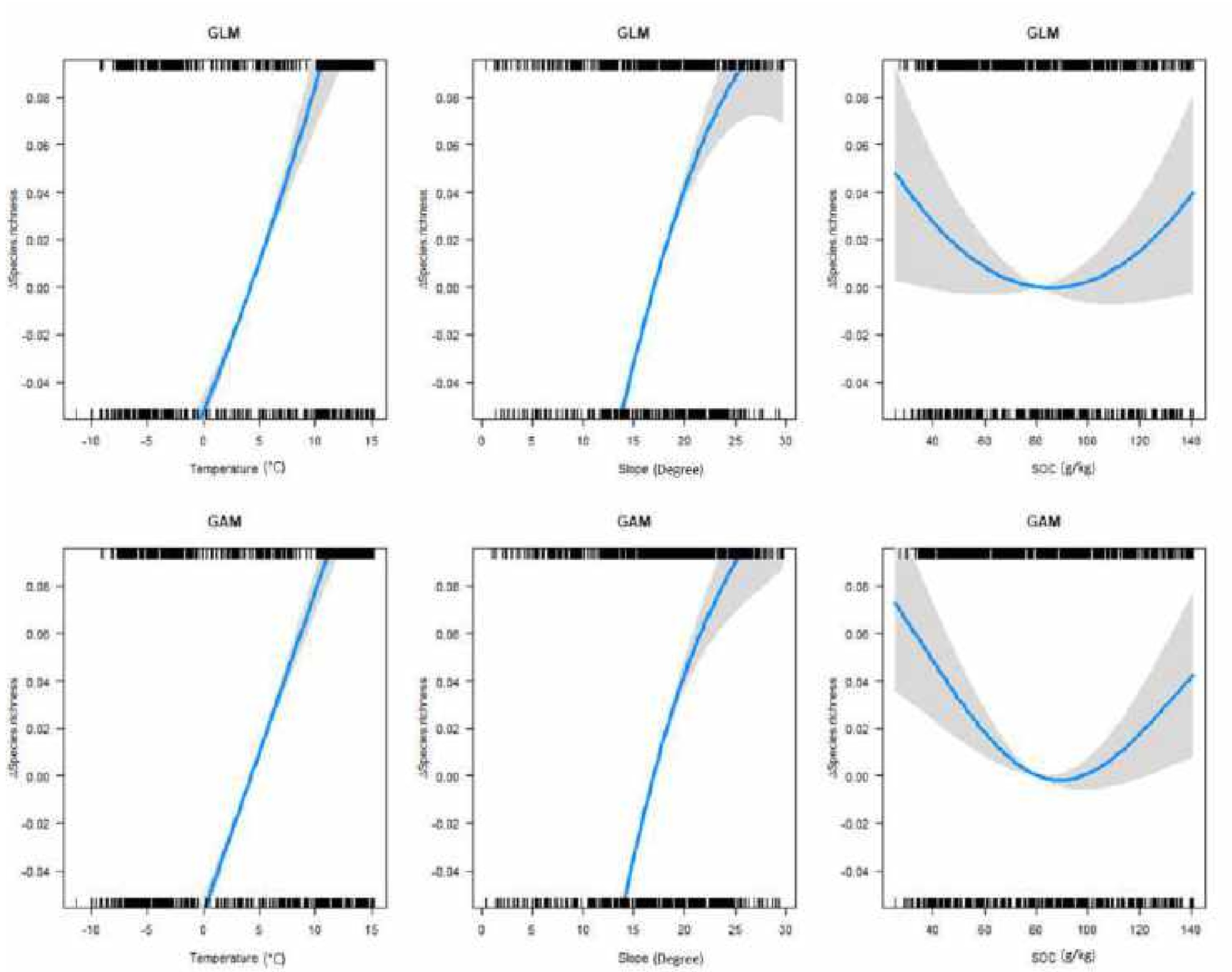


Figure 3.1.9: Response curves for the explanatory variables in Sikkim (GLM: upper; GAM: lower). Gray-shaded areas represent the confidence interval of the predicted probabilities. Response curves do not account for interactions between the variables (Source: Author 2022).

Evaluation of the non-binary responses is more straightforward that evaluating models based on binary data (Fletcher and Fortin 2018). The root mean square error (RMSE) and the coefficient of determination (R^2) focus on how well models are calibrated (Potts and Elith 2006, Fletcher and Fortin 2018). The response between species richness and explained variables in Sikkim and its four districts have a positive coefficient of determination, and RMSE values for all models were also low (Table: 3.1.4). The north Sikkim district had the highest coefficient of determination (in GLM: R^2 = 71; in GAM: R^2 = 74.8) in both models and showed less RMSE, and the south Sikkim district has the lowest R^2 value among all models (in GLM: R^2 = 33.4; in GAM: R^2 = 43.9). The east Sikkim district and west Sikkim district showed average (R^2 = approximately 50) and lower RMSE values. The lower RMSE values represent the higher accuracy of the models.

Table 3.1.4: Comparison of R^2 and RMSE values obtained from GLM and GAM in Sikkim and its four districts (Source: Author 2022).

Study areas	**GLM**		**GAM**	
	R_sqr	RMSE	R_sqr	RMSE
Sikkim	68	0.14	69.8	0.136
Sikkim (north)	71	0.115	74.8	0.105
Sikkim (south)	33.4	0.178	43.9	0.167
Sikkim (east)	51	0.135	51.6	0.131
Sikkim (west)	49.4	0.140	48.6	0.138

The model accuracy plots (Fig. 3.1.10) from the actual and predicted values showed good accuracy for the GLM (R^2 = 0.68) and GAM (R^2 = 0.69). The model relating to geodiversity and species richness showed weak accuracy (R^2 = 0.20). The mean absolute prediction error (MAPE) and mean square prediction error (MSPE) values represent the validation capacity of the models (Table: 3.1.5). These two values are almost the same for the GLM and GAM in Sikkim and showed very low values. Lower values indicate a better model fit, and it is also used to find the best model. As GAM has the lowest value of MAPE and MSPE, this model performed as the best model for this area.

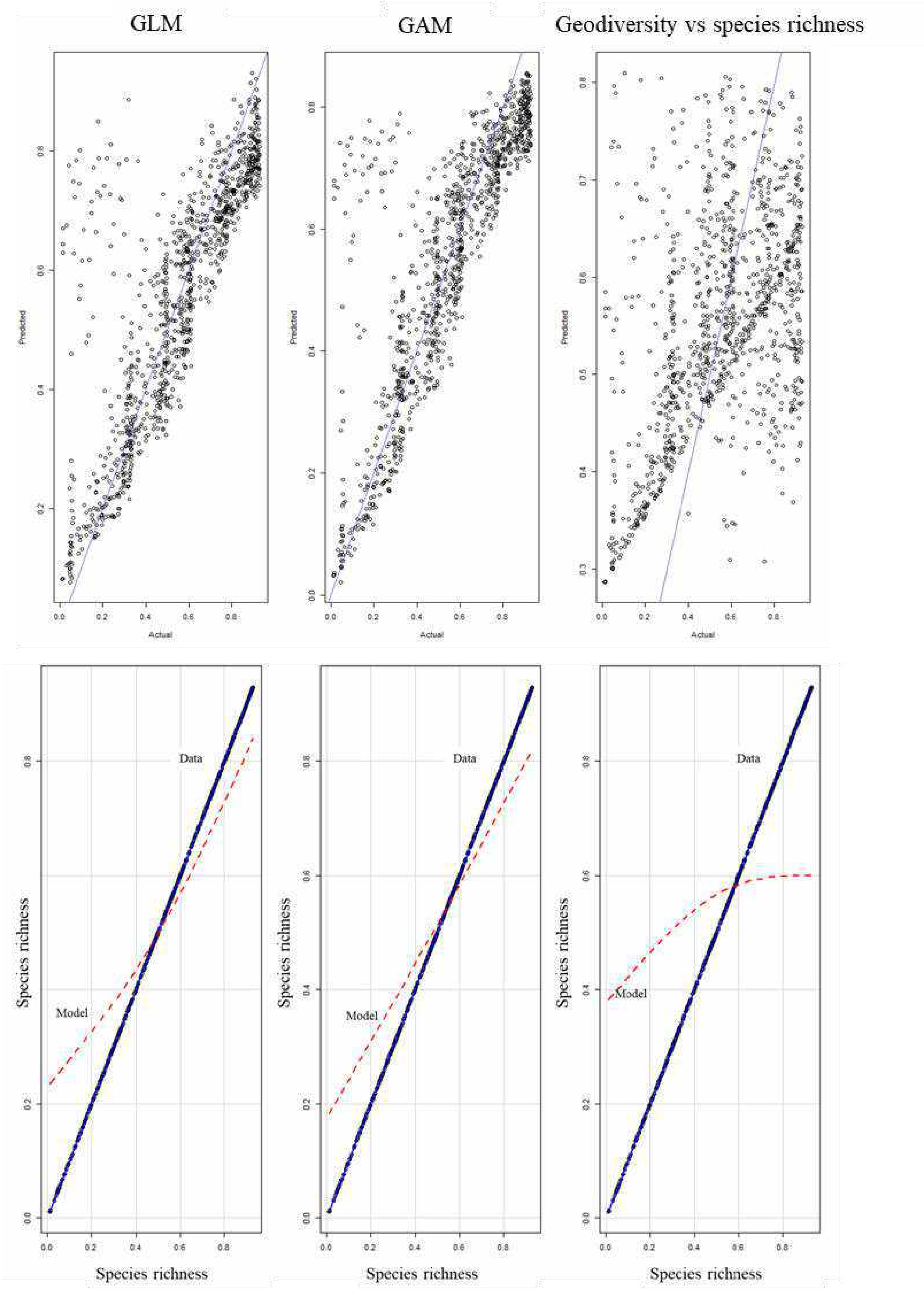


Figure 3.1.10: Model accuracy in Sikkim (Source: Author 2022).

Table 3.1. 5: Comparison of mean absolute prediction error and mean square prediction error values obtained from different models in Sikkim (Source: Author 2022).

Model	Mean Absolute Prediction Error (MAPE)	Mean Square Prediction Error (MSPE)
GLM	0.091	0.019
GAM	0.088	0.018
Geodiversity vs. species richness	0.179	0.487

Table 3.1.6 shows the mean value of all predictors for each category of geodiversity. The mean value of precipitation, slope, TRI, and SOC increases with the increase of geodiversity. Low geodiversity and less species richness are found at low altitudes as well as very high altitudes, and this is the reason why mean altitude is higher (3,454 m asl) in this geodiversity region (see Table A1 in Appendix A). Low geodiversity at low altitudes results from the presence of plain land and settlements (human impact). In contrast, low temperature at high altitudes is the result of remote areas and permafrost. Mean species richness and mean temperature are higher in areas of moderate geodiversity than they are in areas of high and very high geodiversity.

Table 3.1.6: Comparison of geodiversity and mean value of the other predicted variables.

Geodiversity	Species richness	Temperature (°C)	Precipitation (mm)	Altitude (m)	SOC (g/kg)	Slope (degrees)	TRI	TWI
Low	0.46	0.51	1523	3454	66.26	15.15	18.93	15.28
Moderate	0.58	3.01	1708	2995	84.82	22.02	27.83	14.7
High	0.57	1.87	1909	3223	104.3	28.69	36.95	14.48
Very high	0.56	1.55	2102	3299	116.9	36.7	49.6	14.57

For a better comparison of the geodiversity values with the values of other variables, I highlight 20 random locations in Sikkim (Fig. 3.1.11). I extracted all the variable's values regarding the GI and made a bar plot (Fig. 3.1.12) to show their differences. Point IDs 1 to 5 represent a very high GI, and species richness varies from 0.61 to 0.94 (Table A2 in Appendix A). Among these five-point locations, points 2, 4, and 5 have relatively higher precipitation (from 2,207 mm to 2,925 mm). Point 3 in the north district has a high mean annual temperature

(12.8°C) as well as high species richness (0.94). Very high geodiversity in point 1 is found at an altitude of 2,089 m asl, which has a relatively lower mean annual temperature (6.94°C) and precipitation (1,909 mm). Exceptional output was revealed at point 5 in the west district, where temperature, precipitation, and other variables are relatively higher, but species richness is low (only 0.01)

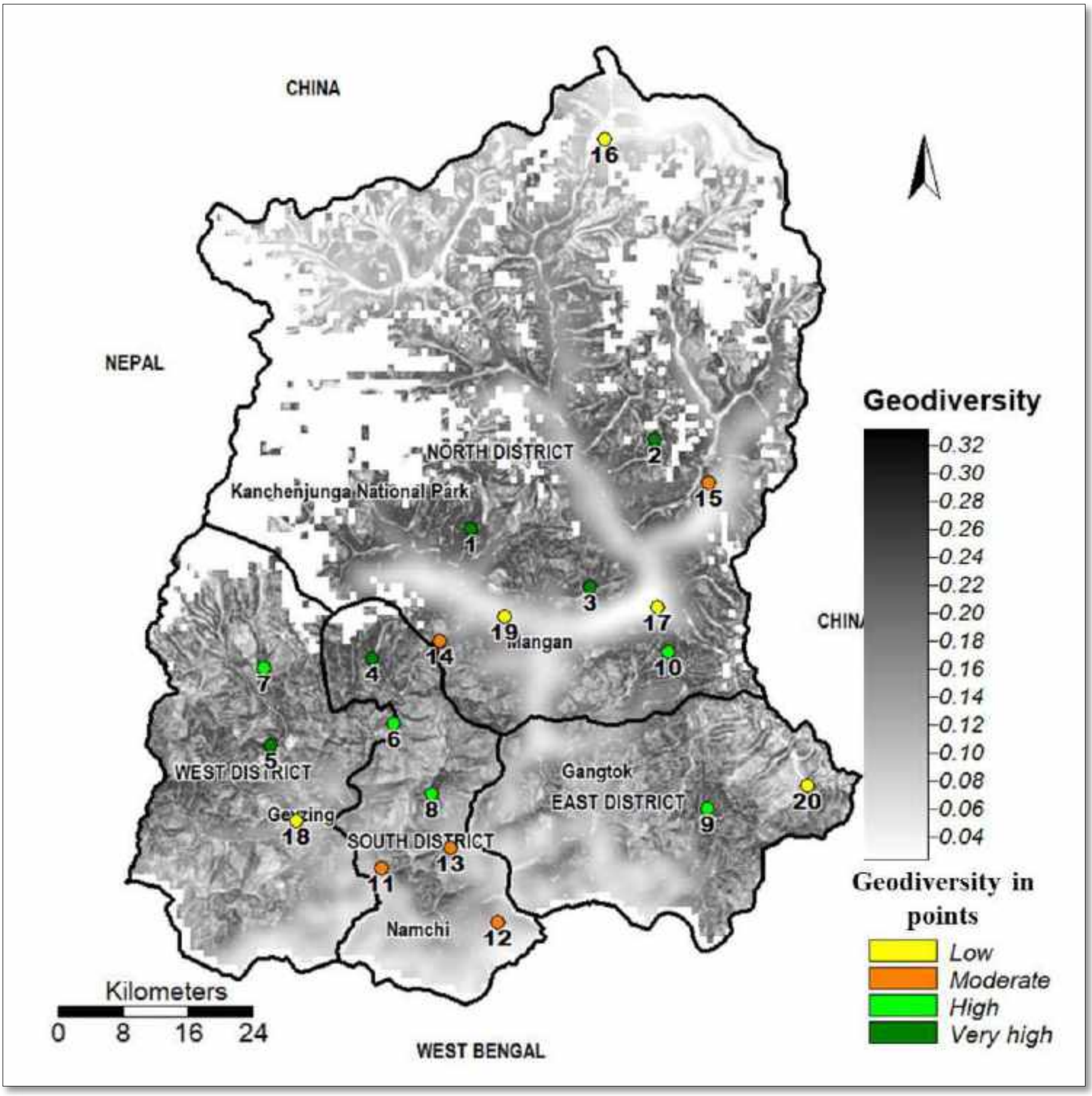


Figure 3.1.11: Geodiversity in Sikkim (20 point locations) (Source: Author 2022).

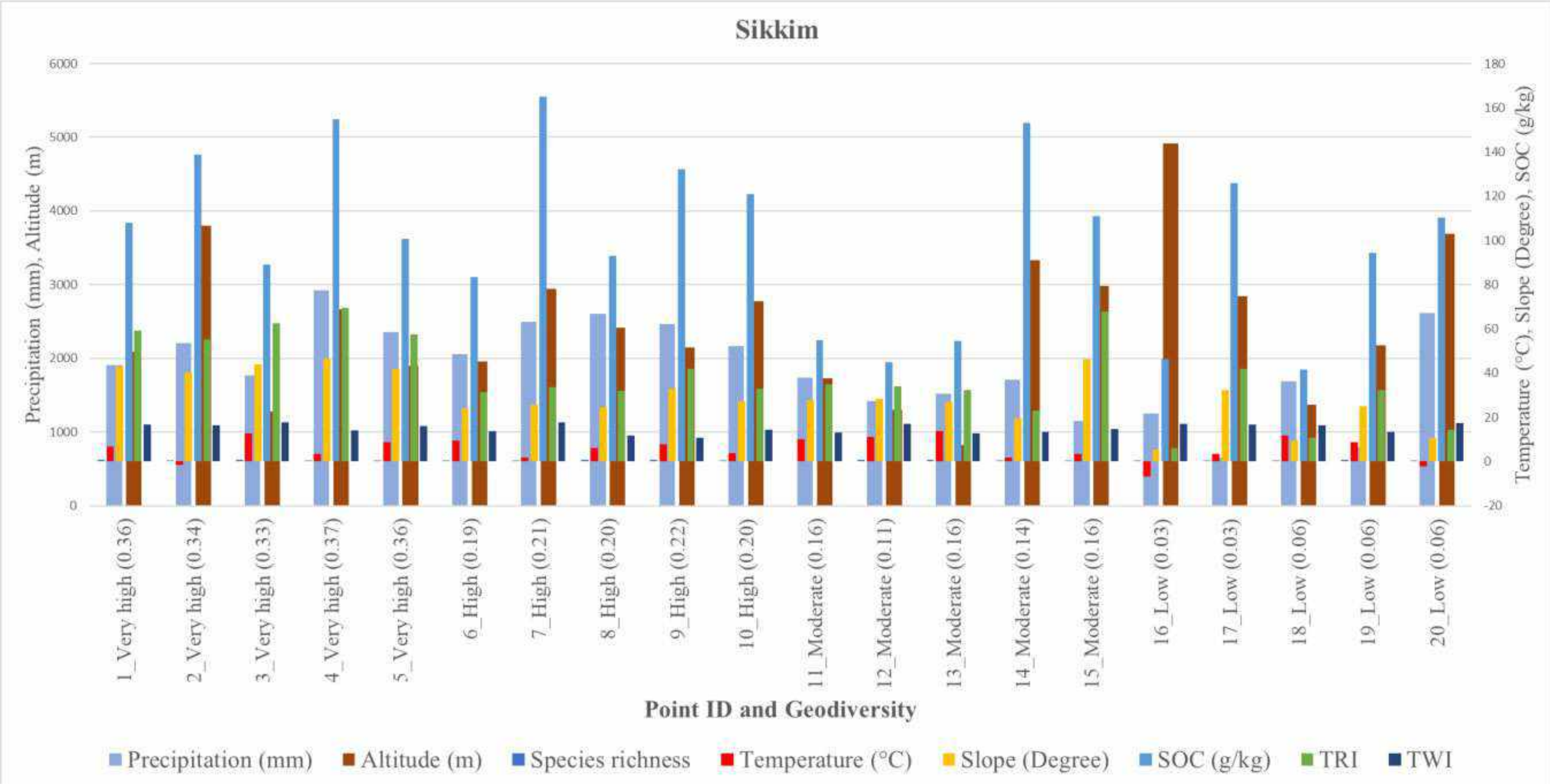


Figure 3.1.12: Comparison of geodiversity and other variables in Sikkim (20 point locations). The left y-axis shows the parameters for precipitation and altitude; the right y-axis represents the parameters for temperature, slope, SOC, TRI, and TWI (Source: Author 2022).

High geodiversity areas are shown between point locations from 6 to 10. A high geodiversity area at point 6 has a high temperature (9.49°C) and precipitation (2,056 mm asl). A high geodiversity area at points 7 and 10, located in the west district and north district, respectively, has a high precipitation, but relatively low mean annual temperature (1.75°C at point 7 and 3.66°C at point 10). Points 8 and 9 have high geodiversity, high species richness, as well as high values in annual mean precipitation and temperature. There were two locations (points 12 and 13) with high species richness in moderate geodiversity areas. These points are located in the south district in Sikkim and have a high temperature (11–13.7°C) and precipitation (1,425–1,520 mm). Moderate geodiversity with moderate species richness was found at points 14 and 15. The mean annual temperature of these locations is relatively lower (1.7–3.5°C). The most exceptional result was found for point 11 in the south district. This location has moderate geodiversity, temperature, and precipitation, but species richness was found to be 0. Low geodiversity areas are located at points 16-20; and points 16 and 20 are in glaciated regions of the north district and the east district. These two regions have a very low mean annual temperature (-6.7°C and -2.1°C). Points 17 and 19 are located near Mangan City in the north district and have low geodiversity but higher species richness (0.61 and 0.74). Geodiversity at Geyzing (point 18) in the west district was low, with a high temperature (11.8°C).

Though TRI has significantly less impact on species richness, a higher TRI value (55.1–69.45) represents very high geodiversity areas (points 1–5). Point 15 has high TRI (67.7) but moderate geodiversity. Low geodiversity areas (points 16, 18, 20, and 19) have low TRI values (6.2–32.5). TRI values between 23 and 42 can be seen in high, moderate, and low-geodiversity areas. There was no significant relation between geodiversity and TWI in Sikkim. Higher TWI (17–17.69) can be seen in moderate (point 12), low (point 20), high (point 7), and very high (point 3) geodiversity areas. Low TWI is also present in high geodiversity areas (points 8 and 9). SOC also showed a very irregular pattern in its relationship with geodiversity. A higher slope range between 42 and 46.5 degrees represents very high geodiversity areas, and a lower slope range (between 5 and 11 degrees) represents low geodiversity areas (points 16, 18, and 20). A slope range between 19 and 33 degrees shows high, moderate, and low geodiversity areas (points 6–12 and 13, 14, and 17).

3.2 Relationship between geodiversity and biodiversity in J&K

3.2.1 Floristic Analysis

J&K is a land of high biodiversity in the western part and low biodiversity in the eastern part. The altitudinal zones of this region can be divided into five specific vegetation zones. These include semi-evergreen monsoon forests, mixed forests with deciduous broadleaved and coniferous trees, coniferous forests, scrub vegetation, and alpine grasslands. These vegetation zones are listed with altitudes in Table 3.2.1, and Figure 3.2.1 shows the spatial distribution of different vegetation zones of J&K. Altitudinal zonation of vegetation for some location in the Himalaya was established by Troll in 1937, and this was later followed by producing a large-scale vegetation map of the entire mountain system by Schweinfurth (1957). The vegetation distribution map consists of altitudinal information that had some blank parts where data collection was not possible (Fig. A.2). The temperate mixed coniferous forest in Schweinfurth's map is located as surrounding the Kashmir Valley, which is shown as a montane zone in Figure 3.2.1. The subtropical zone in Figure 3.2.1 consists of *Pinus roxburghii* forest, subtropical steppe forest, and subtropical evergreen-deciduous forest on Schweinfurth's map. Subalpine forests of *Betula utilis* are found in subalpine zones of J&K divisions. Mixed steppe and steppe vegetation of *Juniperus spp.* and Kashmir bush are located in the alpine vegetation zones of the northern part of the Kashmir border. Ladakh is dominated by subalpine and alpine vegetation zones, which are covered with *Artemisien steppe*, and alpine steppe.

Remote sensing and GIS techniques are now able to quantify the diversity parameters of remote areas as well as conflicted area (Rashid et al. 2015, Roy et al. 2015). Rashid et al. (2015) delineated nine types of land cover in J&K and measured different vegetation types: shrubland with 33.62%, forests with 16.69%, and grasslands with 5.89% (Fig. A.4). They also mentioned the dominant species of this region; for example, *Berberis lyceum, Viburnum grandiflorum, Indigofera heterantha, Parrotiopsis jacquemontiana* are the dominant shrubland species in the areas with an elevation of less than 3,000 m asl. The alpine shrubland areas comprise of *Juniperus squamata, Rhododendron campanulatum*, and *Rosa webbiana*. The forest species include *Pinus wallichiana, Pinus roxburghii, Pinus gerardiana, Cedrus deodara, Abies pindrow, Quercus semecarpifolia, Quercus leucotrichophora, Olea cuspidata*, and *Ulmus wallichiana*. Grasslands were dominated by *Cynodon dactylon, Stipa sibirica, Poa alpina*, and *Poa annua* (Rashid et al. 2013).

Table 3.2 1: Main vegetation zones of Kashmir Himalaya (Source: Dar et al. 2002).

Altitudes (m)	Zone	Characteristic Vegetation
500–1,200	Subtropical	Semi-evergreen monsoon forests
1,200–1,800	Temperate	Mixed forests with deciduous broadleaved and coniferous trees
1,800–2,800	Montane	Coniferous forest
2,800–3,400	Sub-alpine	Scrub vegetation
3,400–4,600	Alpine	Alpine grasslands

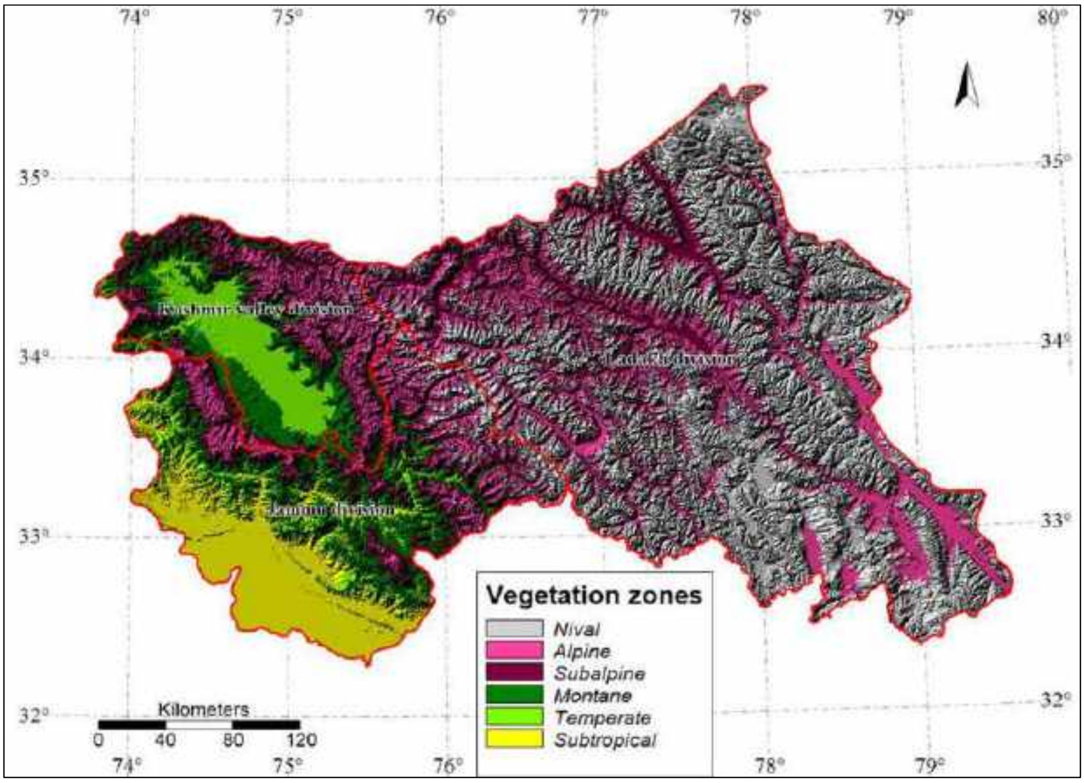


Figure 3.2.1: Spatial distribution of vegetation zonation in J&K (using the information from Table 3.2.1) (Source: Author 2022).

I prepared a database on the flora of J&K from different published sources and found 266 families. The most dominant families are Asteraceae, Poaceae, Fabaceae, Rosaceae, Cruciferae, Ranunculaceae, and Labiatae (Fig. 3.2.2). All of these families are from the angiosperm group. There are 1,537 genera found in the region, and the most dominant 10 genera are listed in Figure 3.2.3.

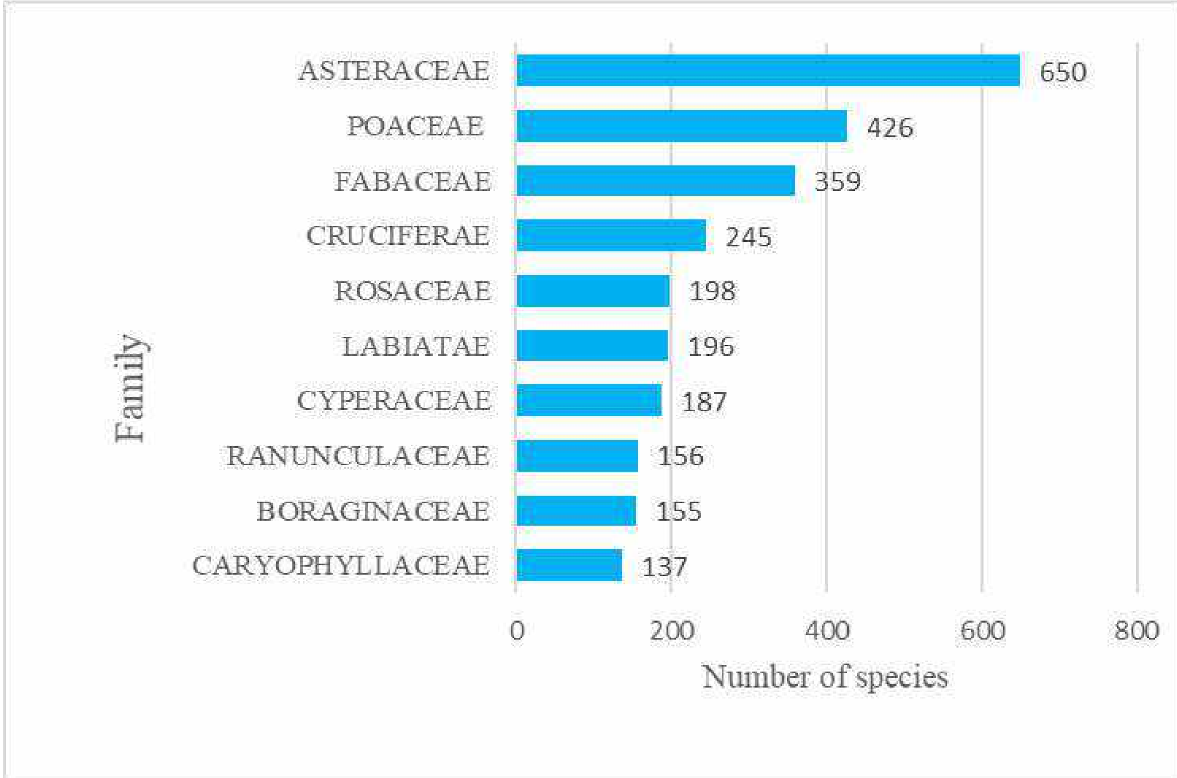


Figure 3.2.2: Most dominant families of species in J&K (Source: Author 2022).

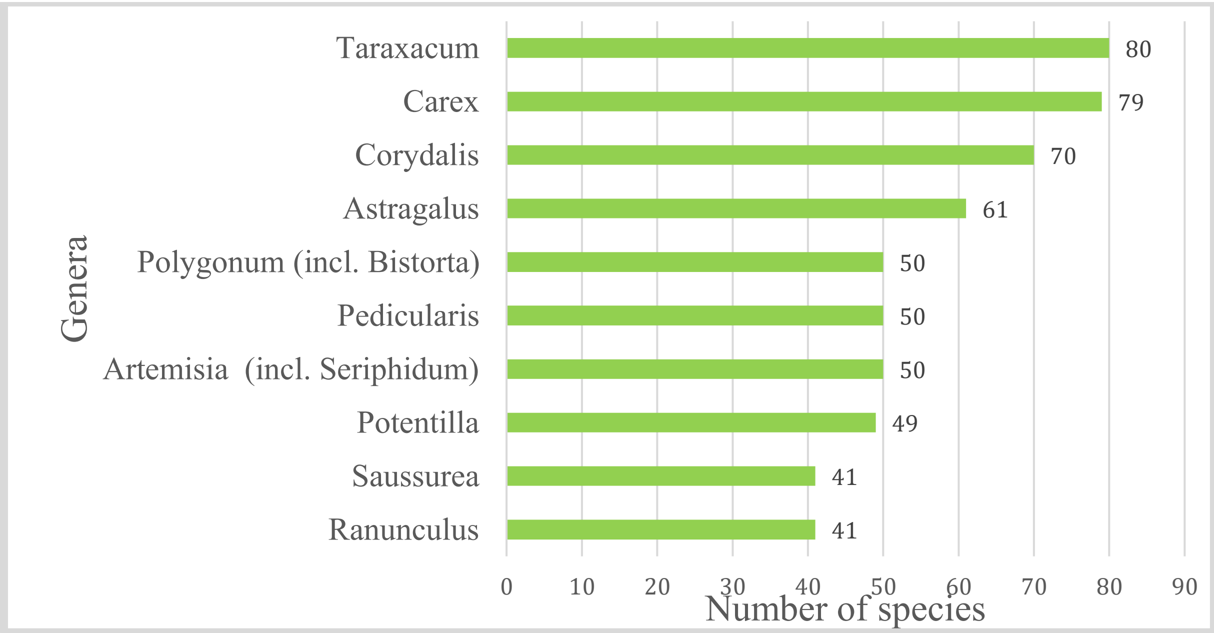


Figure 3.2.3: Most dominant genera of species in J&K (Source: Author 2022).

3.2.2 Spatial analysis

The analysis of published data on flora revealed a total number of species of 5,660. Two thousand nine hundred seventy species have information about their distribution range or their appearance in vegetation zones. Among those 2,970 species, 26% exist in Kashmir, 29% in Ladakh, 21% in Jammu, 7% in J&K, 11% in Kashmir and Ladakh, 2% in Jammu and Ladakh, and only 4% of the species are standard in these three districts (Fig. 3.2.4). There were 2,400 species for which information on altitude was missing. Thus, 3,266 species were used for showing their distribution (Fig. 3.2.5) according to a different elevation. The result shows that the highest species richness can be found in the altitudinal range between 2,500 and 3,400 m asl. A sharp increase in the number of species has been found between 1,000 and 3,100 m asl. There is a slight declining trend in the number of species from 3,000 to 4,000 m asl. The number of species crosses 1,200 at the elevation of 3,100 m asl. There is a continuous decline in species number from 4,000 to 6,000 m asl. The relationship between height and species number is polynomial, and the number of species increases with increasing altitude. Above 3,400-3,600 m, the alpine environment starts, which causes a decrease of the species number chronologically until 6,000 m asl. At an elevation of 3,100 m asl, the highest number of species is found (1,256). The elevation range between 4,000 and 5,000 m has 805 species, and the elevation range between 5,000 and 6,000 m also has 242 species. Higher altitudes show a decreasing number of species diversity, in particular above 5,000 m asl.

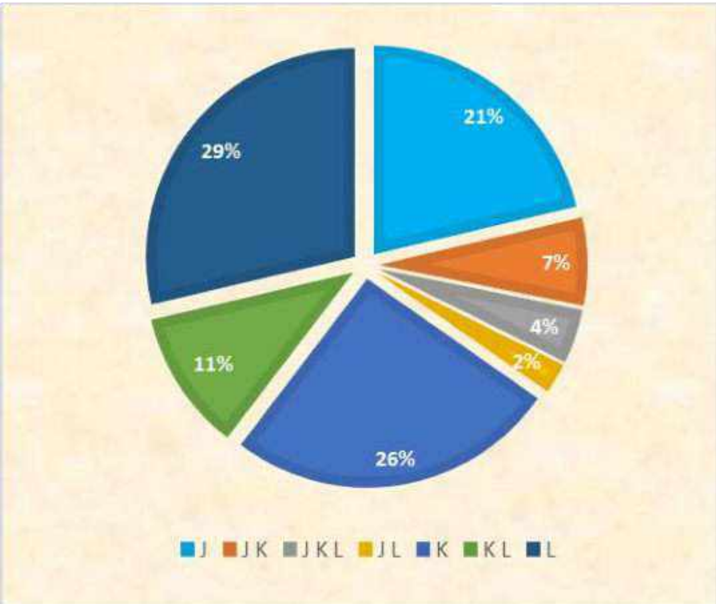


Figure 3.2.4: Chorological spectrum of J&K flora. J = Jammu, K= Kashmir, and L= Ladakh (Source: Author 2022).

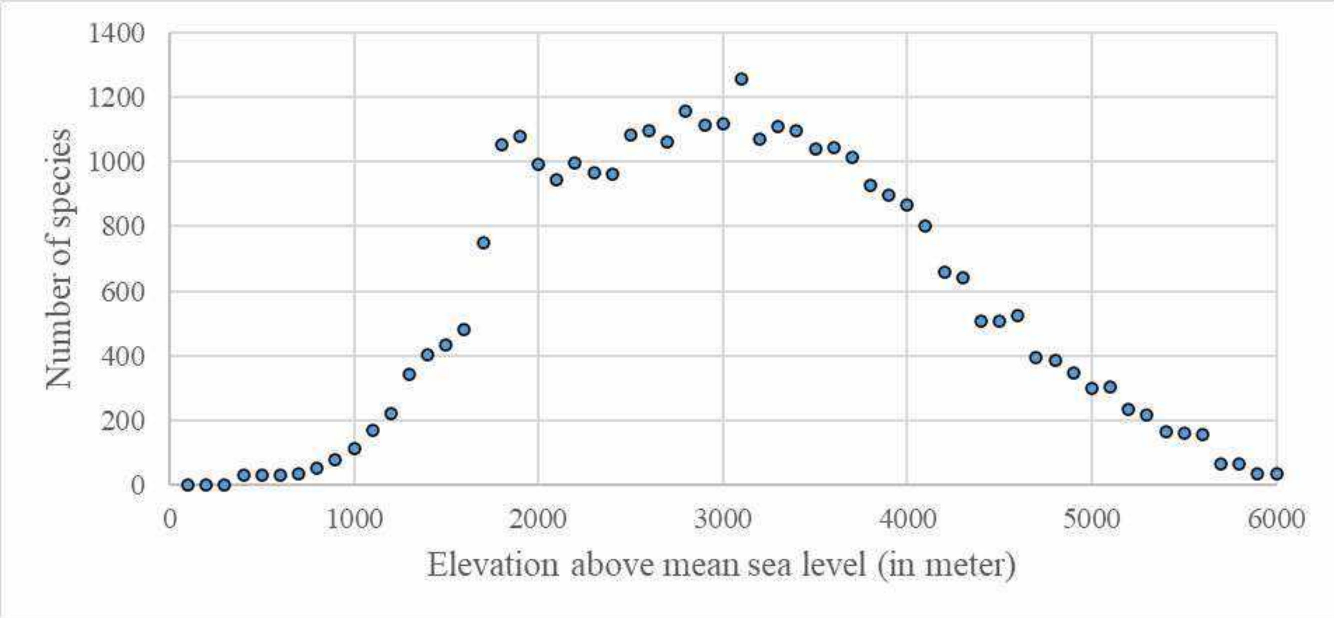


Figure 3.2.5: Species richness according to different altitudes in J&K (Source: Author 2022).

Table 3.2 2: The most dominant families and their species numbers at different altitudes in J&K.

No.	Family	J&K Elevation above sea level (in meter)					
		<=1000	1001-2000	2001-3000	3001-4000	4001-5000	5001-6000
1	POACEAE	2	91	129	113	63	29
2	FABACEAE	25	102	122	86	46	23
3	CYPERACEAE	0	29	36	39	29	21
4	ASTERACEAE	6	127	231	228	102	12
5	SCROPHULARIACEAE	3	27	67	67	34	11
6	ROSACEAE	1	77	101	72	36	15
7	LAMIACEAE	8	64	89	53	24	8
8	GENTIANACEAE	1	13	42	68	48	16
9	BORAGINACEAE	4	31	61	60	23	0
10	RANUNCULACEAE	3	36	75	86	48	15
12	CRUCIFERAE/ BRASSICACEAE	1	49	86	80	53	12
13	UMBELLIFERAE/ APIACEAE	0	28	67	58	18	2

Species richness has been vertically divided according to the 1,000 m interval in Table 3.2.2. The most dominating families in high to very high species-rich areas (elevation between 1,800 to 3,500 m asl) families are Asteraceae, Fabaceae, Poaceae, Rosaceae, Ranunculaceae, Labiatae, Cruciferae, Boraginaceae, Umbelliferae, and Scrophulariaceae. Species numbers are found to be very high for Asteraceae (more than 200), Poaceae (more than 100), and Fabaceae (around 102-122) in this part. Moderate species-rich area (elevation between 4,001-5,000 m asl) comprise Asteraceae, Cruciferae, Poaceae, Fabaceae, Ranunculaceae, Gentianaceae, Boraginaceae, Scrophulariaceae, Rosaceae, and Labiatae, and overlapped families have a lower number of species than do families in the high to very high species richness areas. Low species richness areas (5,001 to 6,000 m asl) include Poaceae, Fabaceae, Cyperaceae, Asteraceae, Gentianaceae, Ranunculaceae, Rosaceae, Scrophulariaceae, Composite, Cruciferae, and Labiatae.

Figure 3.2.6 shows the spatial distribution of species richness in the study area. According to this distribution, the highest number of species are found in the Kashmir Valley Division and Jammu Division. The northern part of Ladakh also has high species diversity, mainly at an altitude between 2,500 and 3,500 m asl. This high to very high species richness belongs to temperate and montane vegetation zones (Fig. 3.2.1 and 3.2.6). The moderate species richness is distributed in alpine and subalpine vegetation zones of Kashmir Valley, Jammu, and the western part of the Ladakh division. The subtropical zone of the western part of the Jammu division has very low species richness, and the altitude above 5,000 m asl also has the same low species richness.

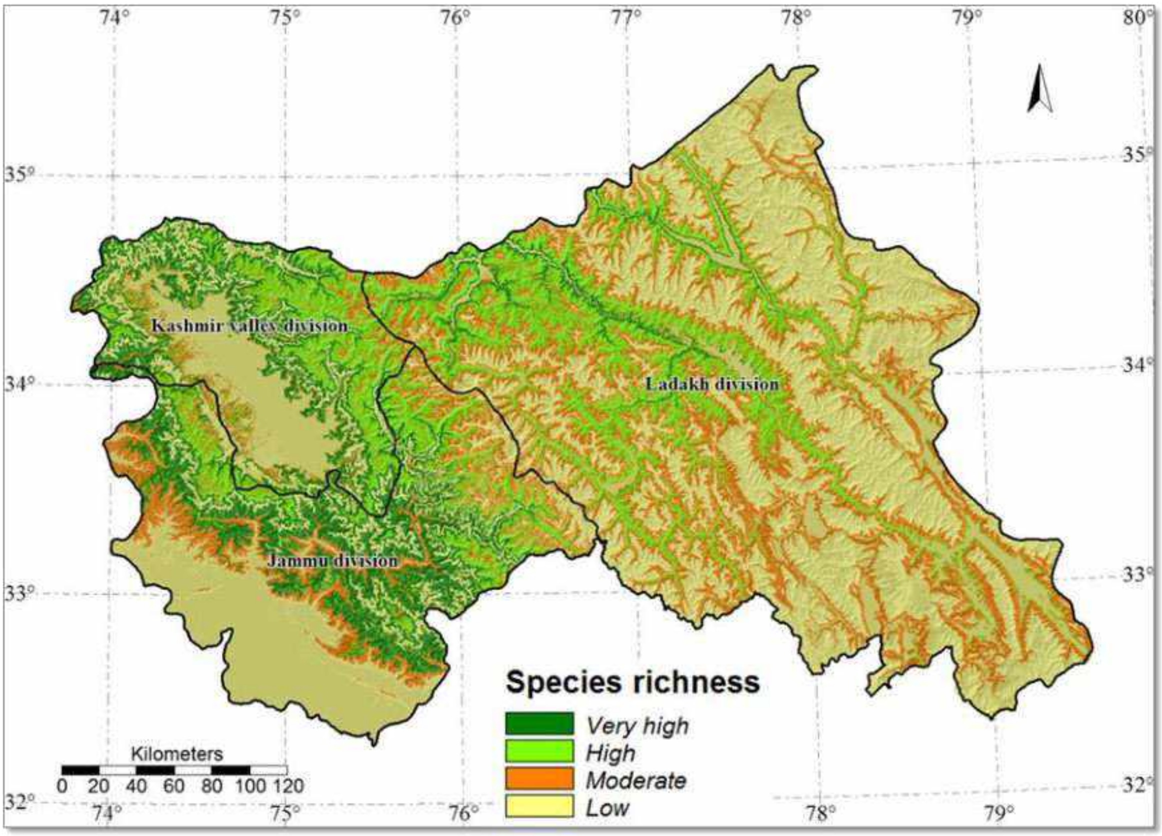


Figure 3.2.6: Species richness in J&K (Source: Author 2022).

3.2.3 Quantification of geodiversity

The geodiversity map produced from all abiotic variables in fuzzy logic (AND operator) and the index value is classified into four groups. The index value was classified according to equal interval in GIS and the classes are, 0.12 < 0.16 (very high geodiversity), 0.08 < 0.12 (high geodiversity), 0.04 < 0.08 (moderate geodiversity), and 0 < 0.04 (low geodiversity; Fig. 3.2.7). The geodiversity pattern in the Kashmir division is almost similar to the species richness pattern. In the Jammu division, moderate geodiversity areas have moderate to very high species richness. In the Ladakh division, the moderate to high geodiversity area represents moderate to high species richness. Very high geodiversity of the western Ladakh has high to very high species richness.

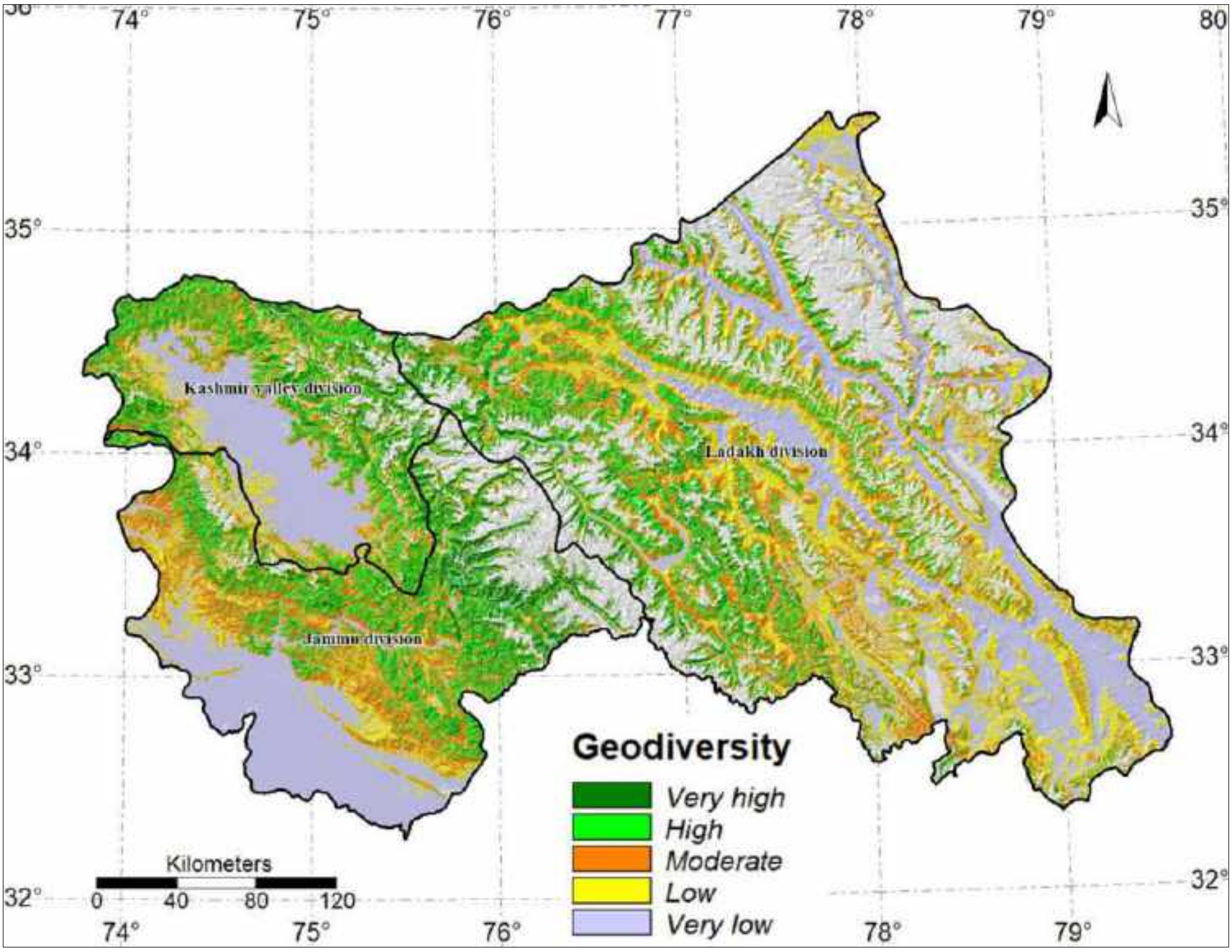


Figure 3.2.7: Geodiversity of J&K (Source: Author 2022).

The National Natural Resources Management System, ISRO, (2014) in India has produced the land use/land cover map of J&K (Fig. 3.2.8). The very low geodiversity and unclassified areas in Figure 3.2.7 are mainly agricultural land (in J&K; Fig. 3.2.8) and barren rocky parts of Ladakh. These unclassified areas also had low measures of geodiversity in analysed maps. Kashmir has a predominantly temperate flora with a temperate climate (Fig. 3.2.1). The altitude of Kashmir Valley is around 1,700 m asl, and the altitude range includes a low geodiversity region while this area is used as agricultural land. This area shows a low species richness and low geodiversity (Fig. 3.2.6 and 3.2.7) region. The species richness pattern and geodiversity pattern surrounding the Kashmir Valley also have similarities. Though very high biological diversity patterns do not match precisely with the very high geodiversity patterns, the overall patterns match each other for three districts. Jammu has a different spatial pattern of species richness, geodiversity, and biological richness. The moderate geodiversity region in Jammu shows very high species richness (cf. Fig 3.2.6 and 3.2.7). The northern part of Ladakh from these figures shows almost the same pattern of species richness and of geodiversity.

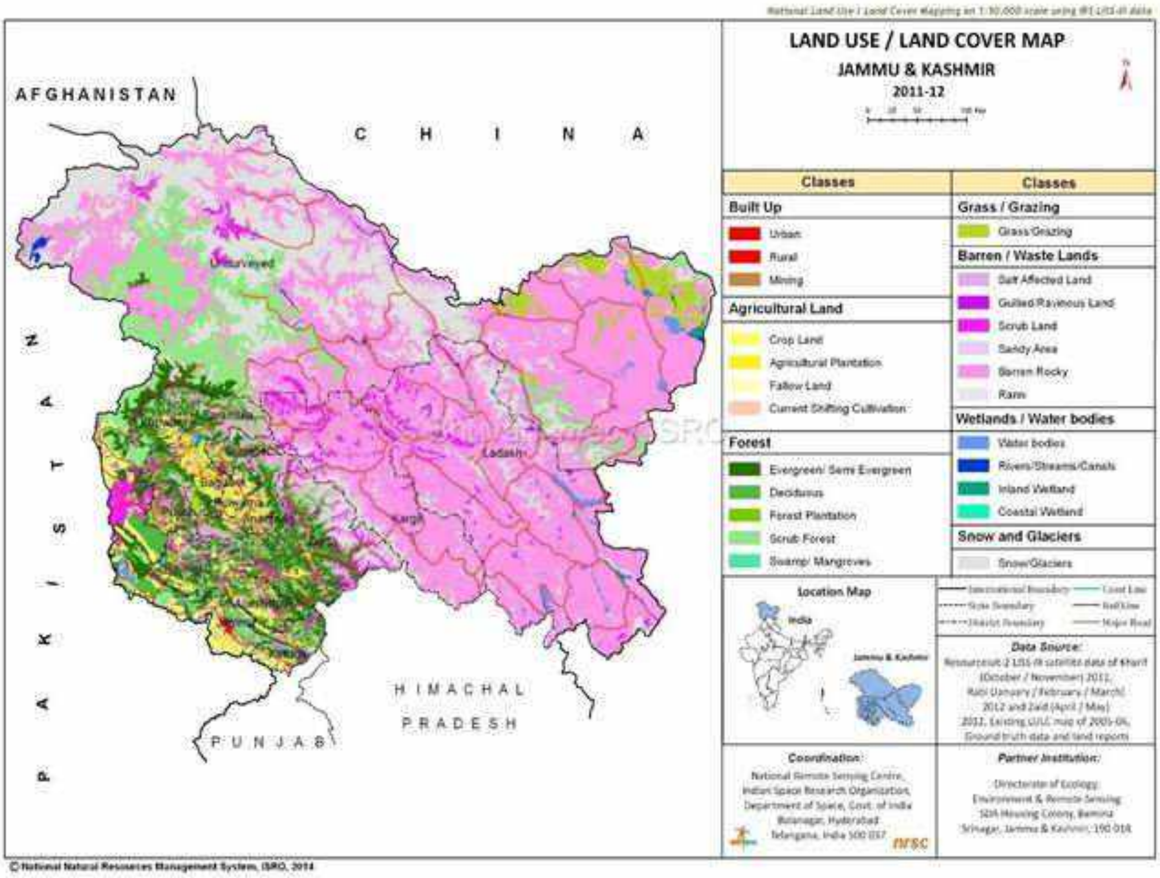


Figure 3.2.8: Land use/land cover map of J&K, 2011–2012. (Source: National Natural Resources Management System, ISRO, 2014).

3.2.3 Statistical analysis

Spearman's rho correlation showed a positive relationship between species richness and all the variables except altitude and TWI (Fig. 3.2.9). The positive relationship between geodiversity and species richness revealed 0.56, which means geodiversity values can surrogate 56% of the species richness pattern in J&K. The mean annual precipitation (precipitation hereafter) is highly correlated with species richness (r = +0.63) as well as the mean annual temperature (r = +0.55; temperature hereafter). Still, the slope showed an average relationship (r = +0.47) with species richness. Slope and TRI are highly correlated (r = 0.99) with geodiversity and showed an average relationship (r = +0.48) with species richness. The SOC showed a weak correlation (r = +0.26) with species richness and an average correlation (r = +0.54) with geodiversity. Altitude is highly negatively correlated with the mean annual temperature (r = -0.99). To avoid the autocorrelation between the variable in a model, I avoided altitude, TRI, and TWI in GLMs and GAMs.

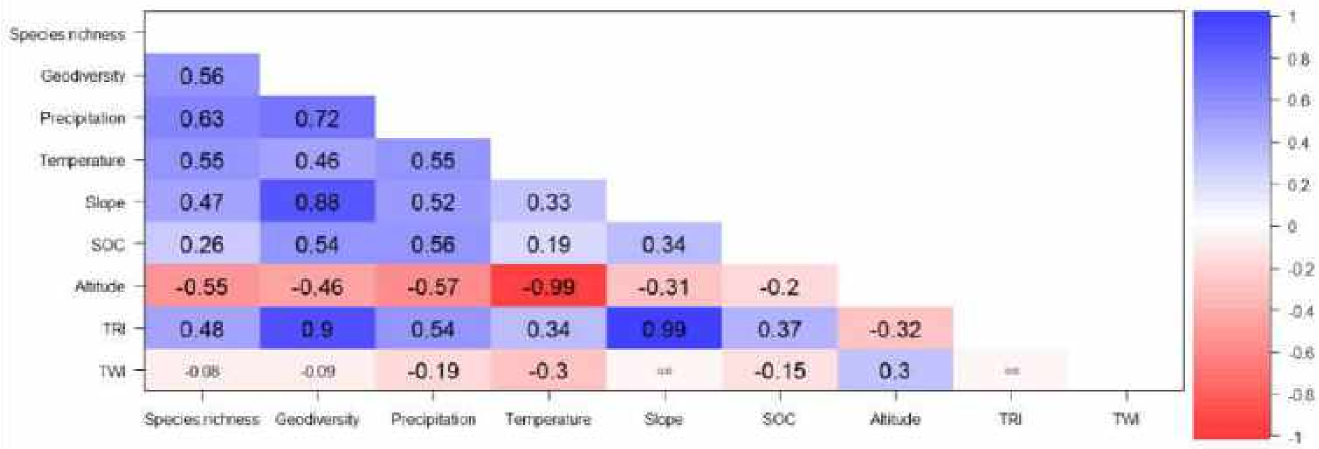


Figure 3.2.9: Correlation among different variables (Source: Author 2022).

Four regressors (precipitation, temperature, SOC, and slope) were used in GLM, and 67% (Pseudo R^2, Nagelkerke) of the variance was explained in this model. GAM shows almost the same ($R^2 = 66.9\%$) results as does GLM. Precipitation is the most crucial variable, and slope and temperature are the second and third most essential predictors in this model (Fig. 3.2.10). The three districts inside the J&K state showed different patterns of the relative importance of the explanatory variables. The slope was the most crucial variable in Kashmir and Jammu districts, and temperature was the most important variable in Ladakh and Jammu to explain species richness. Though precipitation is the most vital variable in J&K, it has less importance for the models in individual districts.

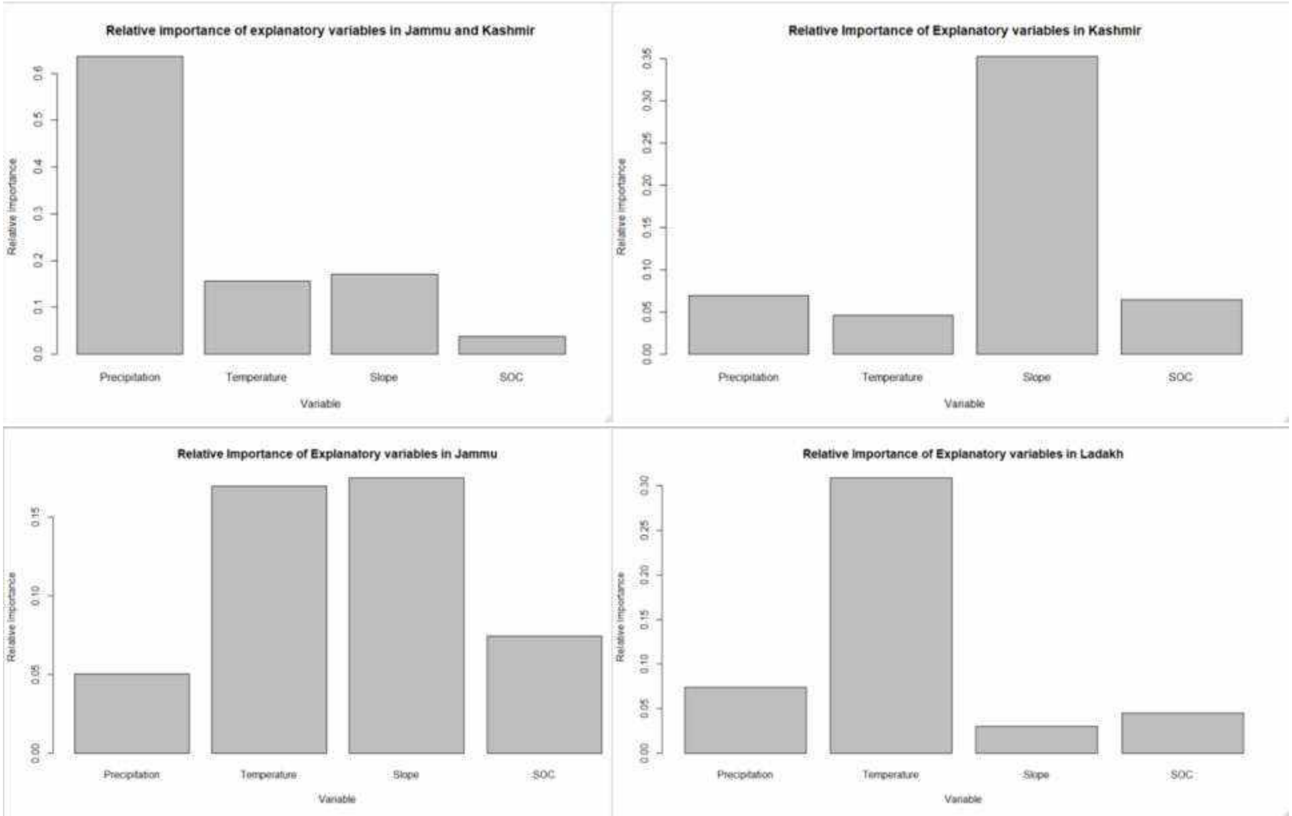


Figure 3.2.10: Relative importance of explanatory variables in J&K and its three districts (Source: Author 2022).

Figure 3.2.11 shows the response curve of selected explanatory variables in GLM and GAM. In both models, the variable slope shows concave positive slopes, whereas response types differed. The mean annual temperature has unimodal response curves in both models. The mean annual precipitation has the highest relative importance, and the response curve is almost linear. The lowest variable importance was found for SOC, which was excluded by GLM because of its lower importance.

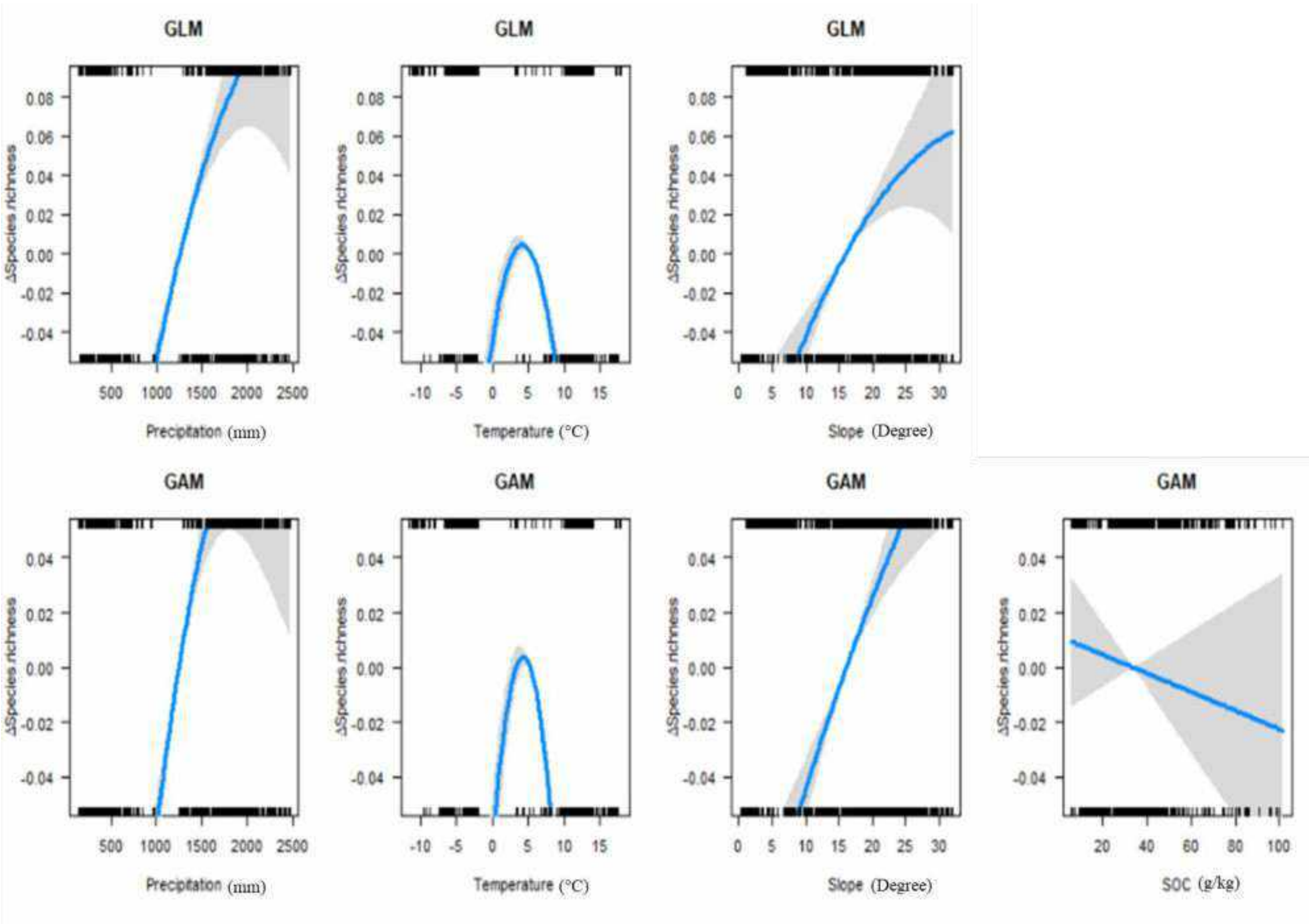


Figure 3.2.11: Response curves for the explanatory variables in J&K (GLM: upper; GAM: lower). Gray-shaded areas represent the confidence interval of the predicted probabilities. Response curves do not account for interactions between the variables (Source: Author 2022).

Table 3.2.3 shows the coefficient of determination and RMSE results from J&K state and Kashmir, Jammu, and Ladakh separately. GLM and GAM results showed no significant difference between them. Kashmir had the best value of R^2 among all regions, and low RMSE value represents that the model prediction is reasonable. Jammu and Ladakh districts showed more than 50% of deviance that is explained with species richness in the models, and RMSE values derived from these models are less than 0.5, which proved that the models are good for prediction also.

Scatter plots of different levels of model accuracy (Fig. 3.2.12) show the dispersion of data is higher and excellent prediction cannot be considered from these models. The Efron R^2 revealed 0.56 in GLM, 0.66 in GAM, and only 0.37 in the geodiversity vs. species richness model.

Table 3.2 3: Comparison of R^2 and RMSE values obtained from GLM and GAM in J&K and its three districts (Source: Author 2022).

Study areas	GLM		GAM	
	R_sqr	RMSE	R_sqr	RMSE
Jammu and Kashmir	67.6	0.204	66.9	0.177
Kashmir	70.5	0.207	71.1	0.163
Jammu	55.8	0.237	55.7	0.216
Ladakh	57.9	0.054	57.5	0.047

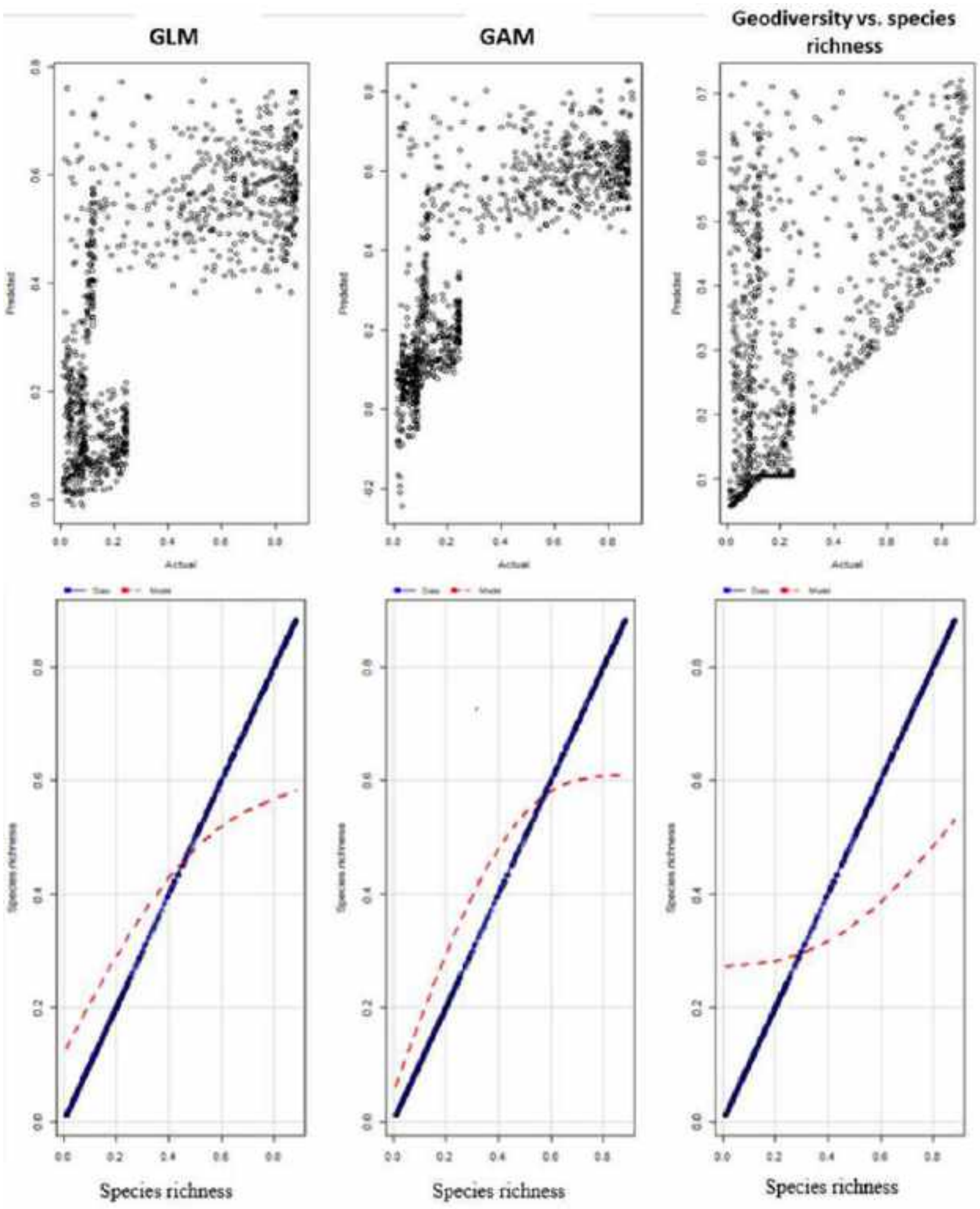


Figure 3.2.12: Model accuracy in J&K (Source: Author 2022).

MAPE and MSPE can compare the predictability of the model, and Table 3.2.4 shows the MAPE and MSPE resulted from the GLM, GAM, and geodiversity vs. species richness models. Lower MAPE values represent better model fits, and GLM and GAM showed better model prediction than did the geodiversity vs. species richness model. If I want to compare the best model for J&K region, it would be GAM, as this model has the lowest value of MAPE and MSPE.

Table 3.2 4: Comparison of mean absolute prediction error (MAPE) and mean square prediction error (MSPE) values obtained from the GLM, GAM, and geodiversity vs. species richness model in J&K.

Model	Mean Absolute Prediction Error	Mean Square Prediction Error
GLM	0.162	0.041
GAM	0.121	0.028
Geodiversity vs. Species richness	0.201	0.064

Table 3.2.5 shows the mean value of all predictors for each category of geodiversity. The mean value of species richness, precipitation, SOC, TRI, and slope increases with the increase of geodiversity. Species richness shows an increasing trend with a rise in geodiversity values. Mean annual temperature prevails low in moderate geodiversity regions; however, relatively higher temperature prevails in high and very high geodiversity regions. In J&K, low geodiversity areas are agricultural fields (plain landscape) and the cold deserts of Ladakh (at higher altitudes). Altitude and TWI do not have a clear trend with geodiversity values, but TRI has a positive relationship with geodiversity in J&K (for details, see Table A3 in Appendix A).

Table 3.2 5: Comparison of geodiversity and mean value of the other predicted variables.

Geodiversity	Species richness	Temperature (°C)	Precipitation (mm)	Altitude (m)	SOC (g/kg)	Slope (degrees)	TRI	TWI
Low	0.06	2.6	673	3485	28	8.06	10.12	10.92
Moderate	0.102	0.72	887.5	3742	37	15.36	19.24	11.25
High	0.21	3.99	1315	3139	49.8	21.54	27.91	11.26
Very high	0.34	3.74	1648	3142	68.58	26.47	35.17	11.36

I selected 20 point locations in J&K and compared the extracted values of all variables in each geodiversity area (Fig. 3.2.13, Fig. 3.2.14, and Table A4 in Appendix). Point IDs 1–5 represent a very high GI, and species richness varies from 0.53 to 0.90. The highest species richness is located at point 2, where temperature and precipitation are moderate. Points 3, 4, and 5 have relatively higher precipitation (2,131–2,623 mm). Point 4 in the Jammu division is located at a higher elevation (3,894 m) and has the lowest mean annual temperature (-2.3°C). Species richness varies from 0.082 to 0.79 at points 6–9. Point 10 is located in the Kashmir division and has high geodiversity, but has low species richness (0.004). In moderate geodiversity areas (points 11–15), species richness varies from 0.08 to 0.57. Point locations 11 and 12 have a negative temperature (-2.42°C and -6.8°C, respectively) and are located at higher altitudes (3,944 m and 4,666 m asl, respectively) in the Ladakh division. Point 15 is in the Jammu division and has a higher temperature (11°C) and precipitation (2,201 mm). Species richness in low geodiversity areas (points 16–19) vary from 0.06 to 0.54. Points 18 and 19 have temperatures of -0.5°C and -4.2°C and are located in the higher altitude zone of Ladakh. In contrast, low geodiversity at point 20 is located in the north Ladakh and has high species richness (0.91).

The slope was the second most crucial variable in the GLM, and from the selected points, low geodiversity areas (location 16–19) are located on less steep slopes (6.9–4.9 degrees), and very high geodiversity areas are located on steeper slopes (29–42 degrees). High geodiversity areas belong to 23–26-degrees slope areas. The TRI value varies from 8.7 to 19 in low geodiversity areas (points 6–9), and a higher TRI value (41–64) belongs to very high geodiversity areas (points 1–5). There is no significant relationship between geodiversity and TWI values.

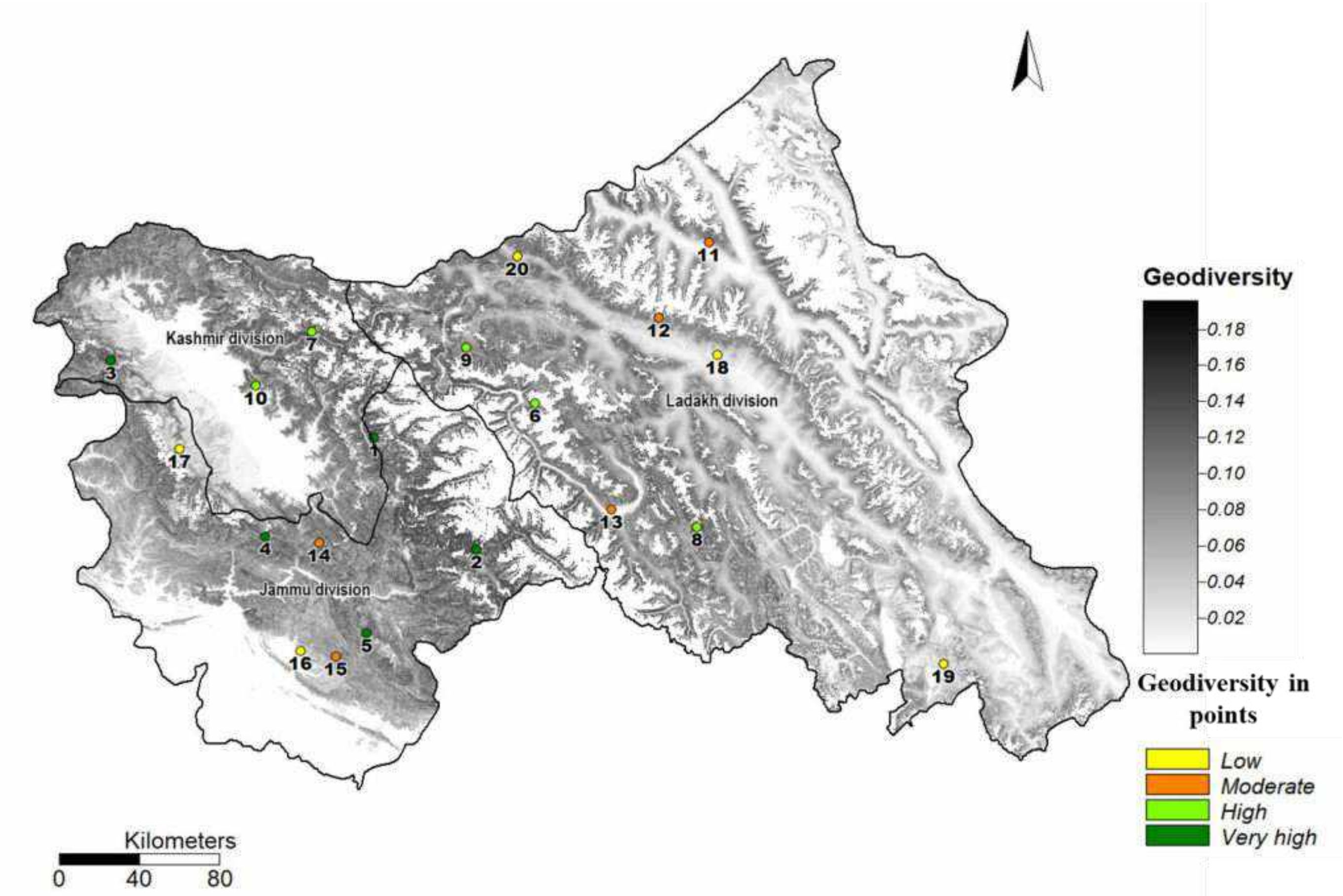


Figure 3.2.13: Geodiversity in Jammu and Kashmir (20 point locations) (Source: Author 2022).

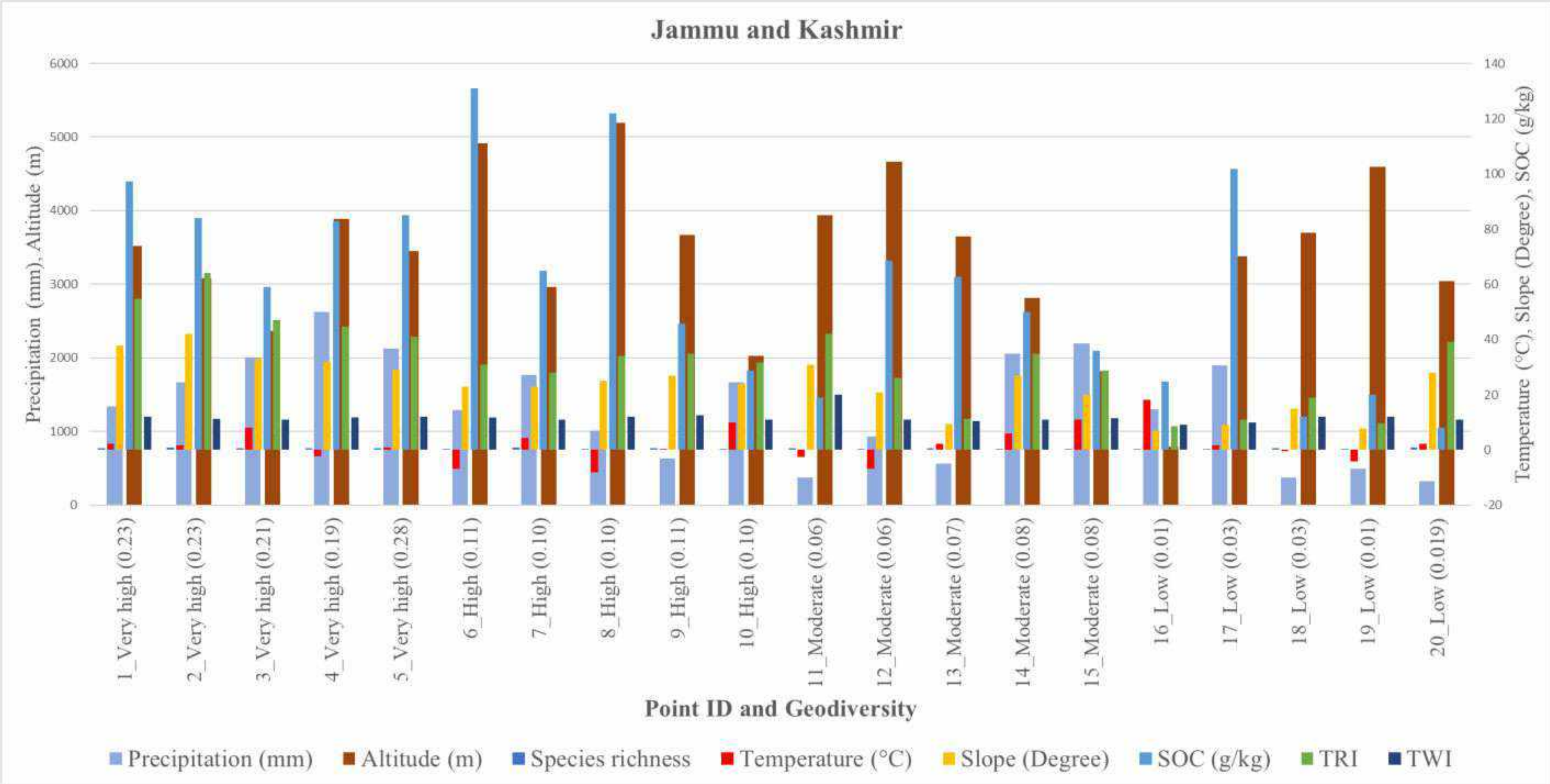


Figure 3.2.14: Comparison of geodiversity and other variables in J&K (20 point locations) (Source: Author 2022).

3.3 Geodiversity of the Himalaya mountain system

GIS and remote sensing data can quantify large-scale geodiversity mapping in the high mountain regions (Braun et al. 2002). I used fuzzy logic to combine all topographical, climatological, and SOC content layers with the operation 'Intersection' in GIS. The GI of the Himalaya quantified from 0.00 to 0.18. After that, these values were classified into five classes from very low to very high categories (Fig. 3.3.1). The extent of the Himalaya mountain system corresponds to the delimitation of Schweinfurth's (1957) map (Fig. 3.3.3). As the species richness studies for the Himalaya do not exist in large scale, the only comparison of the geodiversity pattern could be done by comparison with the vegetation distribution map by Schweinfurth (1957). Though the vegetation distribution map has many void areas, especially along the Nepal and Bhutan boundaries, the map covered the parts in India and Pakistan.

The geodiversity map of the whole Himalaya does not show a detailed classification as the geodiversity map of Sikkim or J&K. Still, it can compare the regions of very high geodiversity to very low geodiversity. It is visible that the middle mountain ranges (1,700–3.000 m asl) have high to very high geodiversity and mixed vegetation distribution on Schweinfurth's map. In the western Himalayan subalpine forest, temperate coniferous forests and subtropical evergreen forests have high to very high geodiversity, and alpine steppe (*Pinus gerardiana, Juniperus spp.*) vegetation cover has moderate to low geodiversity (cf. Fig. 3.3.1 and Fig. 3.3.3). A biodiversity hotspot in the Himalaya starts from the middle part of the Himalaya (from Nepal) and ends at Namcha Barwa (in China), where the highest number of species (vascular plants) are found and which has been ranked the highest diversified zone (Barthlott et al. 1996, 1999; Mutke & Barthlott 2005). Among all abiotic factors, high to moderate precipitation and high to moderate temperature zones have high to very high geodiversity (Fig. A.6).

The geodiversity map is clipped for two study areas, and the results show a significant difference in index values in Sikkim and J&K. GI values in Sikkim range from 0.05 to 0.18, and in J&K, it ranges from 0.01 to 0.12 (Fig. 3.3.2). Though Sikkim has a smaller geographical area than J&K, it has higher geodiversity than J&K. Here, the highest index value of 0.18 is visible in Sikkim at its highest diversified neighborhoods, and in J&K, the highest geodiversity reaches an index value of 0.12.

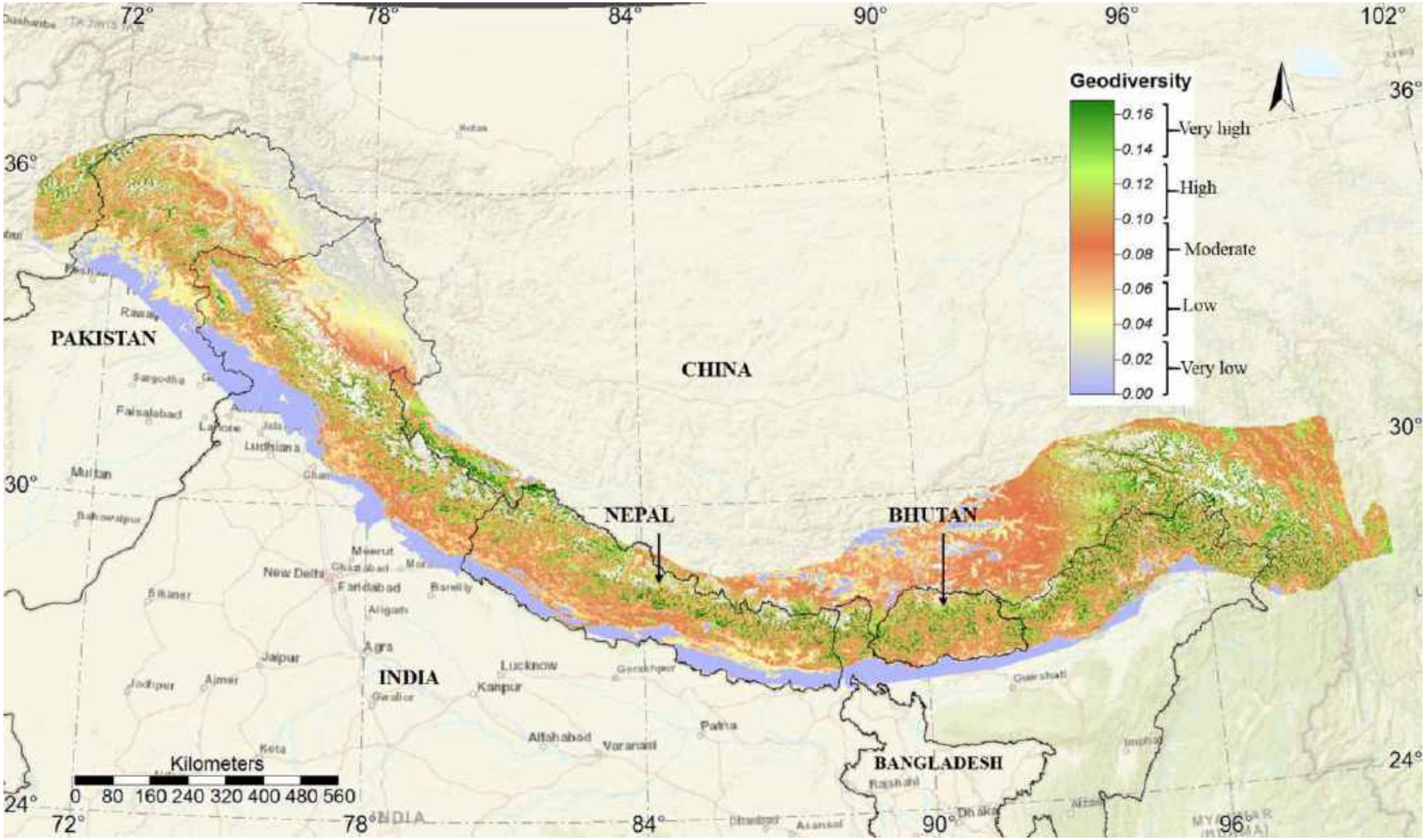


Figure 3.3.1: Geodiversity of the Himalaya mountain system (Source: Author 2022).

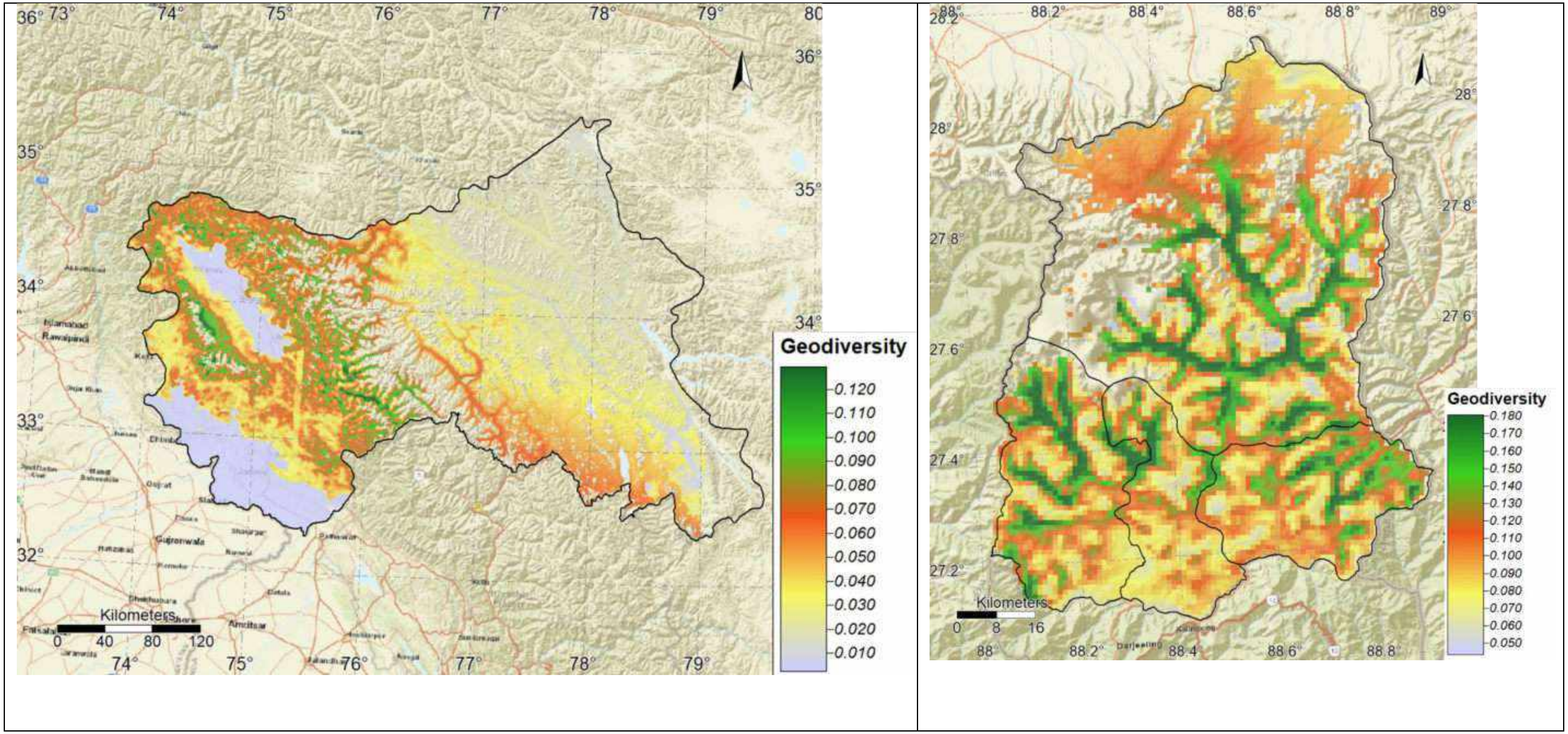


Figure 3.3.2: Geodiversity maps clipped for J&K (left) and for Sikkim (right) to compare geodiversity index values (Source: Author 2022).

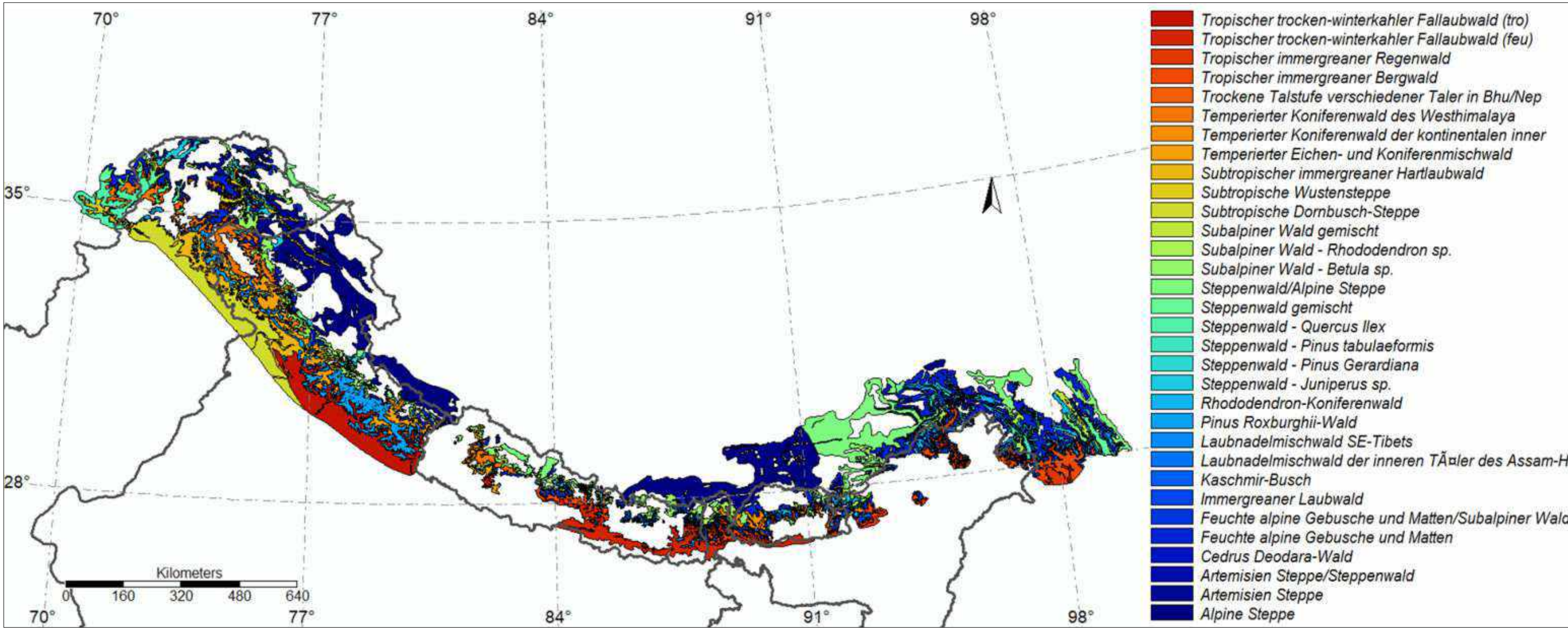


Figure 3.3.3: Vegetation distribution in the Himalaya (Schweinfurth 1957, regenerated by Kim Stolle).

The steppe vegetation cover has low to moderate geodiversity in J&K and markedly so in the Tibetan plateau. Temperate coniferous forest (Temperierter Koniferenwald des Westhimalaya) in western Himalaya has moderate to high geodiversity. *Pinus roxburghii* forest in the west of the Himalaya, associated with temperate oak and mixed coniferous forest (Temperierter Eichen- und Koniferenmischwald), has been marked as having moderate to high and very high geodiversity. Temperate coniferous forest of the inner continent (Temperierter Koniferenwald der kontinentalen inneren Täler), associated with various dry valleys of various thaler (Trockene Talstufe verschiedener Täler in Bhutan/Nepal), has been revealed as having high to very high geodiversity.

Chapter Four

Discussion

4.1 Species richness

The number of species in dominant families in Sikkim and J&K are not the same (Fig. 4.1). The most dominant family in Sikkim is Orchidaceae, which has a deficient species number in J&K. Orchidaceae is the 3rd largest family of the Indian flowering plants and grows in the tropical and subtropical forests (Dar and Khuroo 2020, Singh P 2020). Asteraceae, Poaceae, and Fabaceae are the most species-rich families in J&K and Sikkim, though the species richness differs. In general, J&K has a more significant number of species in each family (nine dominant families) than Sikkim. Seven dominant families have a higher number of species in Sikkim than in J&K, and the differences are significantly high. Scrophulariaceae and Gentianaceae have approximately the same number of species in both states. Thus, the diversity of dominant species is high in J&K rather than in Sikkim.

The most dominant genus is *Carex* in both study areas. *Taraxacum* (80 species) is another prevalent genus in J&K (as it is native to the temperate zone), but very few species from this genus are found in Sikkim. *Pedicularis* and *Gentiana* have almost the same number of species in both states. The genera *Primula*, *Saxifraga*, *Juncus*, *Rhododendron*, *Ficus*, and *Impatiens* have a significant difference, showing higher species richness in Sikkim than in J&K. In addition, *Taraxacum*, *Astragalus*, *Artemesia*, *Potentilla*, *Polygonum*, and *Ranunculus* have a significant difference, showing higher species richness in J&K than in Sikkim.

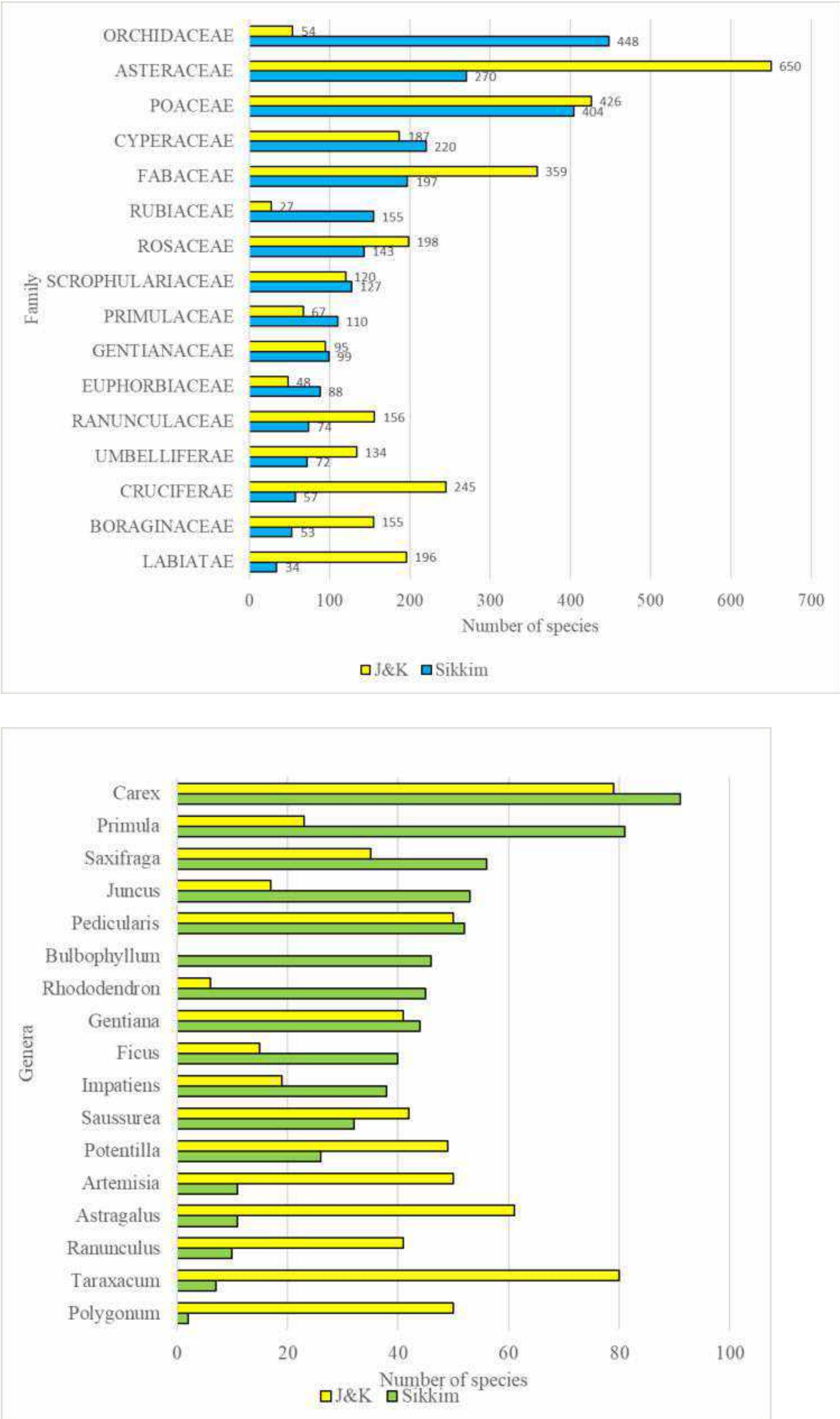


Figure 4.1: Comparison of the dominant family and genera between Sikkim and J&K (Source: Author 2022).

4.2 Comparison of altitude and vegetation zones

Sikkim and J&K are both in high mountainous regions and vegetation zonation differs in these two regions. Sikkim has one more vegetation zone that extends from the bottom of the elevation range up to 900 m asl (Fig. 4.2). This vegetation zone is a tropical moist deciduous forest. The elevation range of subtropical forest in Sikkim is from 900 m to around 1,700 m asl, and in J&K, this forest zone starts from 500 m and ends around 1,200 m asl. These zones are also known as the hill belt/tropical and submontane belt or subtropical range (Miehe et al. 2015). The altitudinal range between 2,000 and 4,000 m asl is known as the montane zone, (Miehe et al. 2015) which includes several vegetation zones and has moderate warmth and higher humidity. Temperate broadleaved forest has a broader distribution in Sikkim (1,700–2,700 m asl), and in J&K, this vegetation range is around 1,200–1,800 m asl.

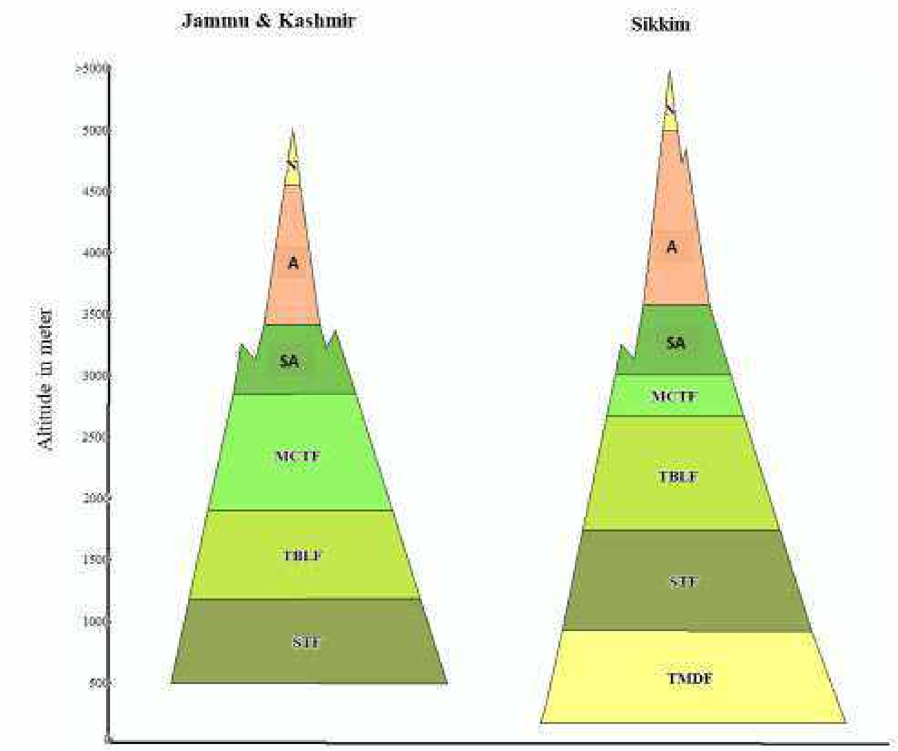
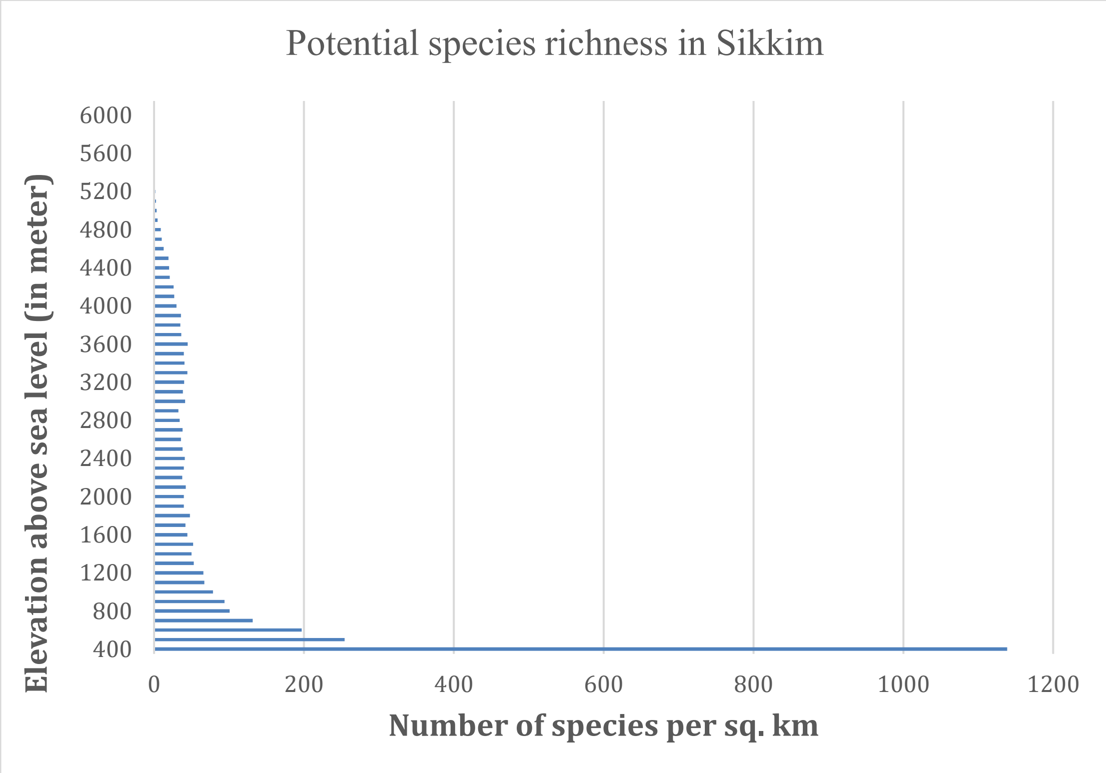


Figure 4.2: Comparison of altitude and vegetation zonation between Sikkim and J&K. These two areas have almost the same vegetation zonation, and the name of the different vegetation zones are TMDF = Tropical Moist Deciduous Forest, STF = Subtropical Forest, TBLF = Temperate Broadleaved Forest, MCTF = Mixed Coniferous Temperate Forest, SA = Sub-Alpine, A = Alpine, and N = Nival/No vegetation (Source: Author 2022**).**

The mixed coniferous temperate forest zone extends from 2,700 to 3000 m asl in Sikkim and from 1,800 to 2,800 m asl in J&K. This vegetation zone is much more widely distributed in the western part of the Himalaya. The subalpine ranges between 3,000 to 3600 m asl in Sikkim and between 2,800 and 3,400 m asl in J&K. This vegetation zone has almost the same width for these two regions. The topmost vegetation zone above the upper limit of trees and taller shrubs on humid slopes is alpine, which is distributed between 3,600 and 5,000 m asl in Sikkim and between 3,400 and 4,600 m asl in J&K. There are some vegetation (nival zone; free gelifluction belt) found at 4,600 m asl in J&K, and the same zone in Sikkim found at 5,000 m asl.

4.3 Comparison between altitude and potential species richness

Species diversity in the Himalaya is challenging to calculate. The published sources have helped document the number of species in my study areas. The high biodiversity areas of Sikkim and J&K are situated in two different latitudinal zones. When I wanted to compare the species diversity patterns between them, I found that the patterns vary at the same altitude. Figure 4.3 shows the altitudinal distribution of potential species richness per square km for 100 m intervals in Sikkim and J&K. Two study areas have considerable differences in areal extent and to compare the species richness, species number per square kilometer has been calculated. Potential species richness in Sikkim is 0.70 per square km, and in J&K, it is 0.040 per square km. The altitude range in Sikkim varies from 200 to 8,000 m asl, and the number of species is also high, up to 1000 m asl. The peak of the potential species-rich elevation for Sikkim is between 200 and 400 m asl (more than 1100 species per sq. km). It belongs to the mixed zone of tropical moist deciduous forest. A higher number of potential species richness is also found compared to J&K, between >1,000 m and 4,000 m asl in Sikkim. In this altitude range, the potential species richness varies approximately from 6 to 20. The possible potential species richness was found almost the same in the elevation range between 2,000 and 4,000 m asl, and at an altitude above 5,000 m asl, the potential species richness started to decrease.



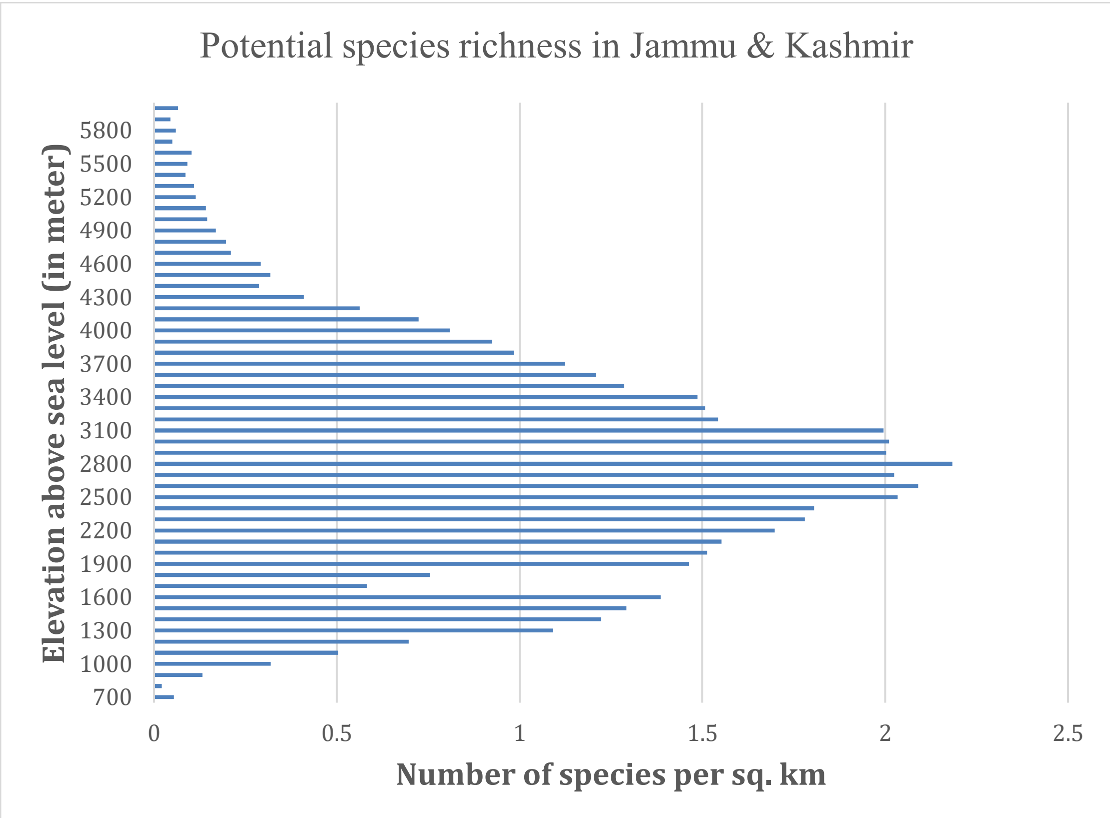


Figure 4.3: Comparison of potential species richness per km^2 along the elevational gradient between Sikkim and J&K (Source: Author 2022).

According to the same altitude, J&K has very poor potential species richness compared to Sikkim (Fig. 4.3). The highest species richness was found at elevations between 2,500 and 3,100 m asl, and the number varies from 2 to 2.18 per square km. This elevation range falls in the temperate broadleaved forest, mixed coniferous temperate forest, and subalpine forest zones. The species richness starts to decrease in elevations above 2,800 m asl. J&K has significantly less potential species richness per sq. km than Sikkim at elevations between 1,000 and 5,000 m. At elevations between 5,000 and 6,000 m asl, the species richness is approximately the same in Sikkim and J&K.

Sikkim has the advantage of the tropical region, and the bottom vegetation zone (tropical moist deciduous forest) consists of more than 1,400 species, which is absent in J&K. The altitudinal extents of each vegetation zone are also different in these two study areas. The highest species richness is located in the subtropical forest and tropical broadleaved forest (altitude between 1,000 and 2,000 m asl) in Sikkim. In J&K, the highest number of species (around 1,200) is found at altitudes between 1,800 and 3,700 m asl, which is significantly less than in Sikkim. The species richness pattern exhibits a hump-shaped pattern in J&K, which is a usual elevational pattern in the Himalayan region (Grytnes and Vetaas 2002, Bhattarai and Vetaas 2003, Tripathi et al. 2004, Oommen and Shanker 2005, Carpenter 2005, Roy and Behera 2005, Grau et al. 2007, Behera and Kushwaha 2007, Acharya et al. 2011, Sharma et al. 2019). Sikkim has decreased potential species richness pattern along the elevation gradient observed in the eastern Himalaya (Saikia et al. 2017, Shooner et al. 2018). The hump-shaped curve was relatively flat in Sikkim, and the species richness curve in J&K was more pronounced. That difference explains that the spatial distribution of these two study areas influences plant richness patterns along the elevation gradient. The species richness pattern is almost bimodal in Sikkim, and the highest peak is at 1,200 m asl. In J&K, the richness pattern was unimodal, with the highest peak at 3,100 m asl.

I found the species richness peak between 900 and 1,500 m asl in Sikkim and between 2,800 and 3,100 m asl in J&K. Tropical deciduous forest in Sikkim has the highest species richness, which is also true for Bhutan (Rana et al. 2019). According to climate reconstructions, the East's lowest elevations of the Himalaya have been climatically stable over millions of years, and the temperate climate in the high elevations (north-west Himalaya) is facing turnover (changing) in harsh environments (Rana et al. 2019). Vascular plant richness in the Nepal Himalaya has peaks between 1,000 and 2,500 m asl, and between 2,500 and 4,000 m asl, there was a gentle decrease in species richness (Vetaas and Grytnes 2002). Behera and Kushwaha (2007) observed the decrease in alpha diversity with two elevation peaks, from 601–1,000 m asl and 1,601–1,800 m asl, while their observation was limited to 200–2,200 m asl. Acharya et al. (2011) demonstrated peaks in species richness (among orchids) at around 1,600 m asl in the eastern part of the

Himalaya. Namgail et al. (2012) found a unimodal pattern of plant richness, with a maximum between 3,500 and 4,000 m asl in Ladakh. The decrease of species richness above 4,000 m asl is related to the timberline and hard environmental boundaries such as glaciation limits (Colwell & Lees 2000, Vetaas and Grytnes 2002).

4.4 The importance of explanatory variables

Geodiversity calculation for Sikkim is satisfactory because the variance explained (R^2) between predictors and species richness is almost 68% in the GLM and 69.8% in the GAM. The climate variable is more noteworthy than are the morphometric variables for Sikkim. The temperature has significant control in the eastern Himalaya (Sharma et al. 2019). As altitude and temperature are highly correlated variables in a model, altitude has been removed to avoid auto-correlation in the model. However, other studies (Kharkwal et al. 2005) have shown that plant species richness depends on elevation and climatic variations in the central Himalaya. Among all variables of geodiversity, climatic variables seem to be most important for explaining species richness pattern with elevation (Odland & Birks 1999, Hawkins et al. 2003, Fossa 2004, Sanders et al. 2007, Acharya et al. 2011); however, the importance of the variables differs by the topographical or spatial variations of the study areas.

Temperatures decrease by an average of approximately 0.6°C for each 100 m increase in elevation (Barry 2008). This moist adiabatic lapse rate varies depending on the latitude, size, shape, and prevailing weather patterns on the mountain from 0.4°C to 0.7°C for every 100 m increase in elevation (Barry 2008). The mean annual temperature range from Chelsa data in Sikkim is from 18.6°C to -17.88°C. The mean summer temperature in Sikkim is as high as 38°C in hot valleys, and the mean winter temperature goes down to -30°C at higher altitudes (Singh and Dash 2002). A temperature distribution map or isotherm maps of the study areas show optimum temperature for affluent vegetation areas. The temperature trend can be seen from 5° to 15° C at elevations between 500 and 3,000 m asl in Sikkim (Fig. 4.4), and the highest species richness is between 1,000 and 2,200 m asl where the predicted temperature range is 14–17°C (Acharya et al. 2011).

In J&K, the mean annual temperature range is between 19.15°C and -21.41°C, and the average favourable temperature for the forests (5–15°C) prevails between the elevations of 1,000 and 3000 m asl (Fig. 4.5). The temperature (5°C) in high-latitude regions is found at a higher elevation than in the lower-latitude regions. Tropical mountains, due to higher temperatures at low latitudes, have warmer temperatures at their base (McCain 2010) than do subtropical mountains. The topmost vegetation zone is alpine scrub and is distributed between 3,600 and

5000 m asl in Sikkim (Singh and Dash 2002) and between 3,400 and 4,600 m asl in J&K (Dar et al. 2002). Thus, the isotherm line of 0°C is distributed on the zone of these altitude ranges of these two sites. The nival zone starts at 4,600 m asl in J&K and at 5,000 m asl in Sikkim, which has an average temperature range between -5°C and -10°C. Multiple regression analysis between species richness and other predictors shows high variability of species richness according to temperature in Sikkim and shows more moderate importance of temperature for J&K than other predictors for both study areas. In Sikkim, the temperature distribution showed unpredictable temperature ranges for different levels of geodiversity (Table 3.1.5). Still, there was a weak positive trend (r = 36%) between geodiversity and temperature (Fig. 3.1.7). The better results are visible in multiple regression analysis in the J&K region. The temperature in J&K has an average correlation with species richness of r = 55% and geodiversity of r = 46% (Fig. 3.2.9).

In broader Asia, the temperature range is marginally the strongest predictor and have a negative effect on species richness (Antonelli et al. 2018). The mean value of precipitation, slope, TRI, and SOC increases with the increase of Sikkim's geodiversity. The randomly sampled points in Sikkim show higher species richness in higher geodiversity areas (in most cases), and topographic variables like TRI and slope have an irregular pattern of a relationship with geodiversity and species richness.

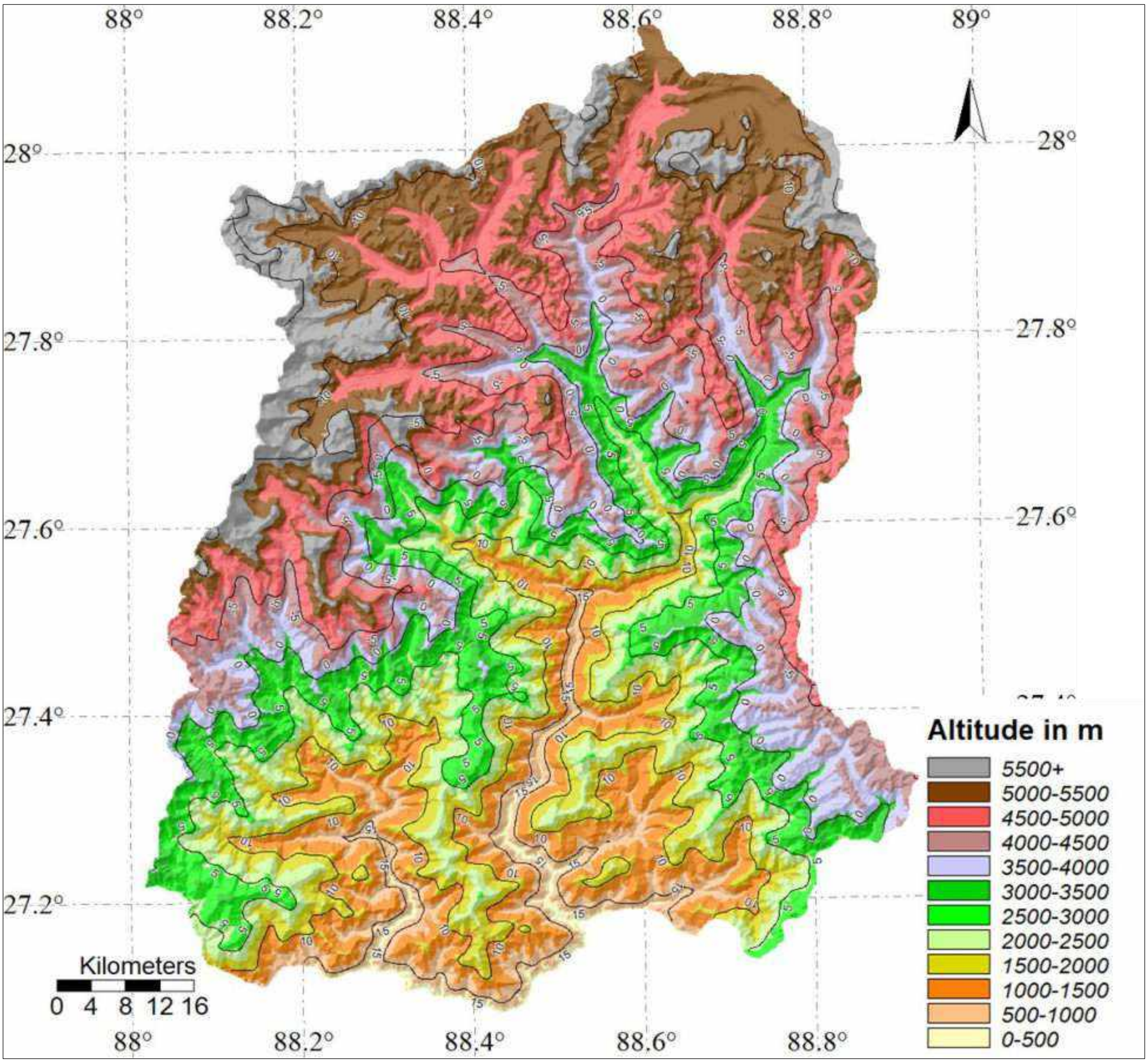


Figure 4.4: Isothermal map of Sikkim (Source: Author 2022).

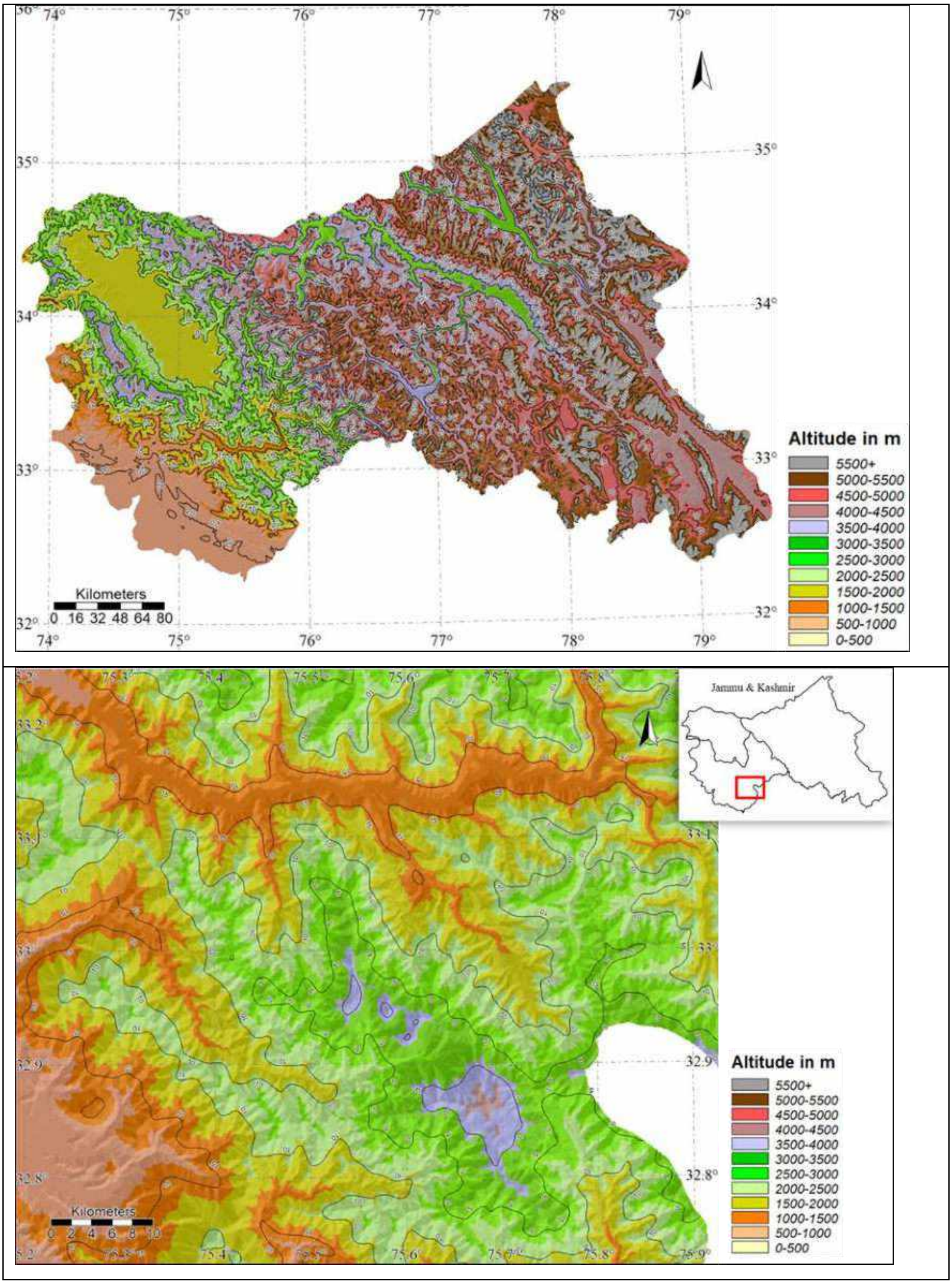


Figure 4.5: Isothermal map of J&K (Source: Author 2022).

Precipitation is an important climatic and abiotic factor, which varies along montane gradients and shows a complicated relationship to elevation (Barry 2008). Precipitation can be in the form of rain, snow, and condensation from clouds (e.g., horizontal precipitation in a cloud forest; McCain 2010). The most common elevation pattern is increasing precipitation with increasing elevation (McCain 2010). This pattern predominates on mountains at temperate latitudes and in arid regions regardless of latitude (Barry 2008). Tropical mountains show a more variable pattern and display decreasing trends, increasing trends, unimodal trends, or bimodal trends with the highest precipitation at middle elevations (McCain 2010). The precipitation trend increases with altitude in both of the study areas. According to the Chelsa database, the mean annual precipitation range in Sikkim is about 734–3,012 mm, and in J&K, it is around 96–2,162 mm. The isohyet map shows that the mean precipitation at the lower altitude in Sikkim is 800 mm and at the higher altitude is 2,800 mm (Fig. 4.6). Sikkim receives heavy to moderate rainfall from both south-east and south-west monsoons (Singh and Dash 2002). The southern part of Sikkim has a subtropical climate, and towards the interior, the weather becomes temperate and cold. Though monsoon precipitation is significant for tropical and subtropical forests, multiple regression analysis between species richness and predictors in Sikkim shows a very low correlation (r = 0.06%) between species richness and precipitation (Fig. 3.1.7).

High and very high geodiversity areas have a relatively higher range of precipitation (Table 3.1.5). The isohyet map of J&K shows the same increasing pattern for the Kashmir and Jammu region, but it is different in Ladakh (Fig. 4.7). The altitude range of Kashmir Valley is 1,500–2,000 m asl, and the mean annual precipitation is around 800 mm. In the southwestern part of Jammu (in the lower altitude region), the mean precipitation range varies from 1,200 to 1,600 mm. The mean annual precipitation increases up to 2,400 mm according to altitude until 4,000 m asl in the Kashmir and Jammu region. Multiple regression analysis proved precipitation to be the most significant variable for species richness assessment in J&K (Fig. 3.2.10; Table 3.2.4). Geodiversity in J&K shows a positive trend (r = 72%) with precipitation from low to high, and precipitation is one of the most significant variables among all predictors. Precipitation revealed an important factor for species richness in J&K because the variation of the intensity of it is very markable (e.g. higher number of species in high rainfall areas and fewer species in dry areas), but in Sikkim, the small areal extension with high potential species richness has a very low variation of precipitations.

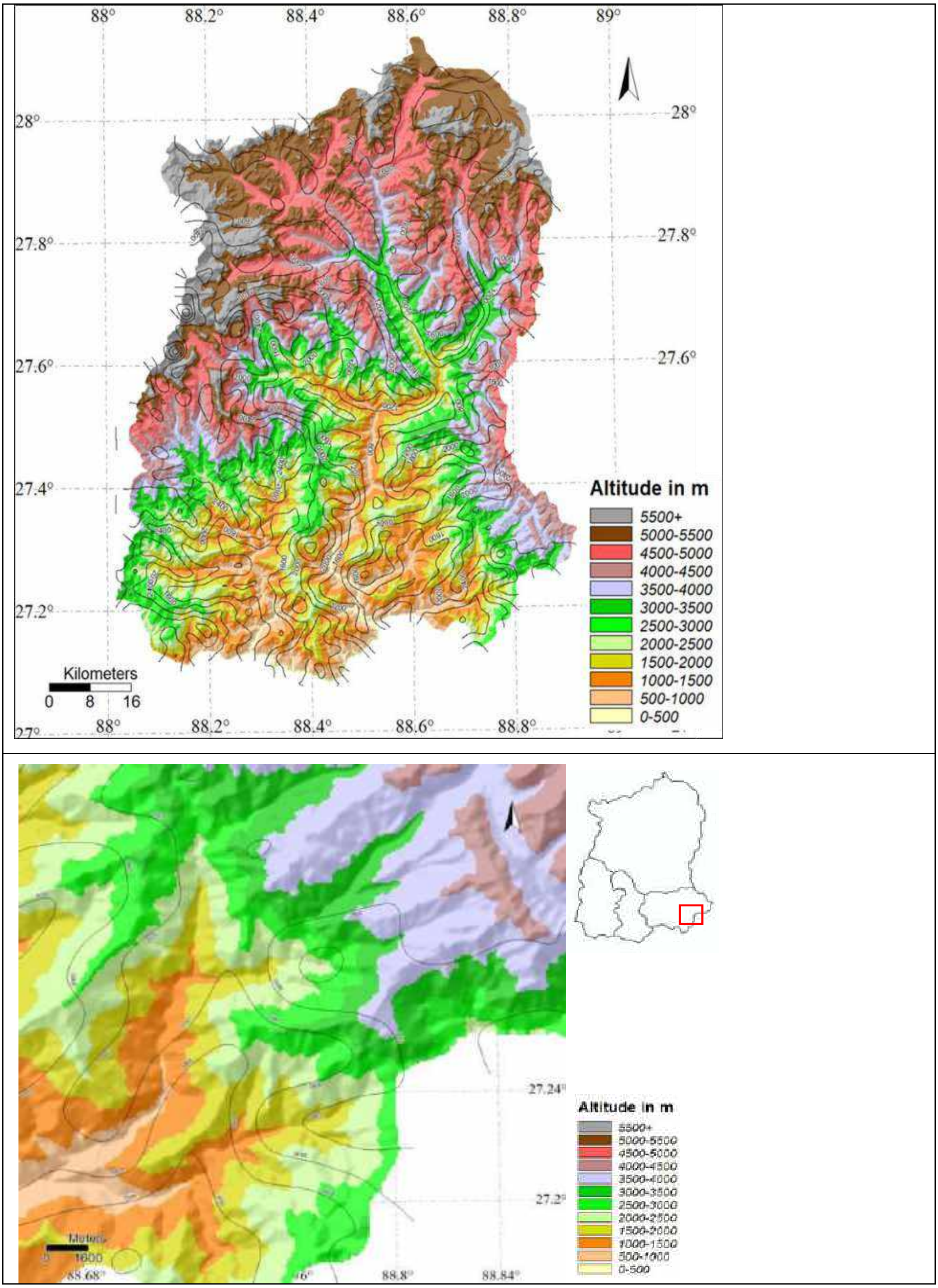


Figure 4.6: Isohyet map of Sikkim (Source: Author 2022).

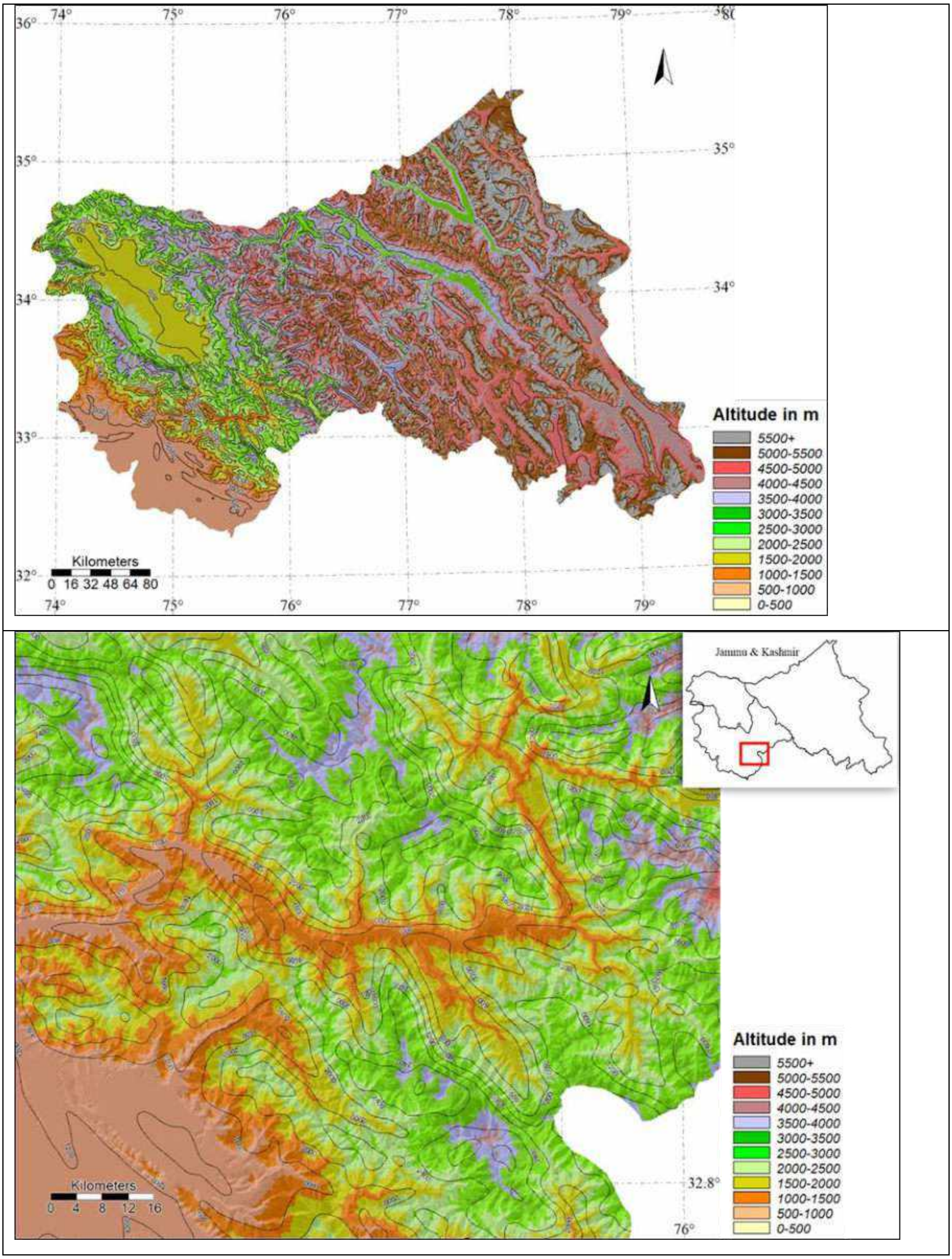


Figure 4.7: Isohyet map of J&K (Source: Author 2022).

The coefficient of variance between predictors and species richness in J&K is around 67.6% in the GLM and about 66.9% in the GAM. A different picture emerges for the relative importance of explanatory variables in J&K. In this model, precipitation has the highest significance, and temperature, slope, and SOC have relatively lower influence. Climate variables are the most important explanatory variables in both study areas, and the slope has a stronger control on species richness in Sikkim than in J&K.

The mean value of species richness, precipitation, SOC, TRI, and slope increases with the increase of geodiversity in J&K. Altitude and TWI do not have a clear trend with geodiversity values and topographic variable like TRI, has a positive relationship with geodiversity in J&K. Randomly sampled geodiversity points show irregular pattern of relationship between geodiversity and other variables.

Other assessments of geodiversity have used geomorphological, geological, and soil features (Serrano and Ruiz-Flaño 2007b) or have used geology, geomorphology, and hydrology but omitted soils and topography in their assessment (Hjort and Luoto 2010). Some studies compiled climate- and topography-based variables with geological, geomorphological, and hydrological features (Parks and Mulligan 2010; Hjort, Heikkinen and Luoto 2012), but all of them followed the same formula (Serrano and Ruiz-Flaño 2007b) to obtain the geodiversity of their study areas. Benito-Calvo et al. (2009) calculated several classification maps (e.g., morphometric map, 10 classes; morphoclimatic map, five classes; geological map, 15 classes) to finalise their geodiversity indices, but in my method, I used all data of SRTM, soil data, and CHELSA data together to produce one geodiversity map. Most of the studies followed a number of different features (e.g., number of soil classes) in grids and finally added all grids together to generate their geodiversity maps and used both vector and raster data in their analyses (cf. Pellitero et al. 2014 for information on methodologies and formulae used for geodiversity calculations to date). Their method is not able to produce realistic results for the large-scale study area. Other studies used a cell size of 500 m or 1km, and their cell size covered at least one or more than one class of diversified features (e.g. soil classes or geological classes). Still, my raster cell size will mostly cover one or two features that will destroy my analytical results as this method uses min value of the cells. I used raster data, which has unique values in every cell, and fuzzy logic helped me to normalise each layer of data separately. Most of the studies followed more complex classifications and required higher computation capacity and expert opinion for classified layers. It is comparatively easier and more logical to count the worst constraining factor (as 'AND Intersection' in fuzzy logic works with the min-operator) to produce a GI using my automated method.

The quantification of geodiversity in J&K has a realistic observation for me. The geodiversity of Leh (Ladakh) is low to very low because of its high altitude, low temperature, and little precipitation. Picture 4.1 shows the sparse vegetation cover and bare mountains of the Ladakh region. Haplic Calcisols, Luvic calcisols, Haplic cryosols, and Haplic leptosols are the main soil groups that dominate the Ladakh region (Hengl et al. 2017). The presence of rivers or channels has positive effects on species occurrence, but Picture 4.1 (right) shows that the soil of the mountains has a Calcic property and is not suitable for vegetation growth because of a lack of precipitation. Species presence increases towards Kargil (near Kashmir), and temperature and precipitation increase along this route. This part of the soil (in Kargil) is mainly Haplic Chernozems (Hengl et al. 2017), which is more fertile than the soils of Leh and supports vegetation growth. Figure Pictures 4.2 shows the humid mountains near Kargil, on the way to Kashmir. Accordingly, geodiversity shifts from low to high and very high towards Kashmir and then to Jammu regions (Fig. 3.2.7).


Picture 4.1: Nubra Valley (left) and conjunction of Indus and Zanskar rivers (right) in Ladakh (Source: Author 2018).


Picture 4.2: Soil and vegetation near Kargil (elevation around 2,600 m asl)(Source: Author 2018).

Picture 4.3: Mixed coniferous forest in Sonamarg (elevation around 2,800 m asl) (Source: Author 2018).

Picture 4.3 shows the mixed coniferous forest in Sonamarg, which is situated 87 km north-east of Srinagar. The geodiversity map of this part shows a high index value, and vegetation cover is also higher than in Ladakh and Kargil.

Fuzzy logic is a new approach to quantify and combine different data sets to produce geodiversity maps for the Himalayan mountain system. This fuzzy logic has been used for modeling future agricultural conditions (Heider et al. 2018) in the Nepal Himalaya and used by the scientific community to handle uncertainties, incomplete information, and class memberships that are approximate (Malczewski 2006, Chadded et al. 2009, Delgado et al. 2009, Keshvarzi et al. 2010, Elaalem et al. 2011, Elaalem 20012, Weinzierl and Heider 2015). Fuzzy logic requires only moderate computing resources and can reproduce the continuous transitions found in nature (Weinzierl and Heider 2015). Though this logic had been introduced to the revised FAO land evaluation framework (FAO 2007), this method has been criticised by a number of authors (Burrough 1989, Baja 2001, Delgado et al. 2009, Keshavarzi et al. 2010). This method has not been used so far to quantify geodiversity, and like every model, it is still an idealisation of reality. Apparently, this geodiversity pattern is statistically correlated with species richness in Sikkim and J&K. Braun et al. (2002) quantified geodiversity of the Andean mountain ranges, and they used soil texture, DEM (1 km), temperature, and precipitation. My method includes more morphometric variables such as slope, TWI, and TRI, and I preferred SOC rather than soil texture.

My approach's limitations are that results produced from this method are entirely dependent on the quality of data that has been used. Reliable data sources can deliver reliable results in an indirect approach. Data gaps in one layer diminish the data results of other layers in that gap. SOC had many void parts in the Himalaya's remote areas, which caused void parts in the final geodiversity maps. Assessment of species richness from secondary data sources is also problematic as all the sources are not available online. Remote sensing (RS) techniques provide a pathway towards cost-effective, comprehensive, repeatable as well as standardised monitoring of continuous geodiversity on the local to global scale (Lausch et al. 2019), but we need biodiversity information from secondary or primary data to relate them in a scientific manner. This method quantified geodiversity and showed around 50% of positive correlation with species richness.

Sikkim and J&K should be considered for the management of natural resources. As these areas are India's great tourist spots, geo-tourism should also be focused on high-geodiversity areas. Hjort et al. (2012) and references therein have suggested the conservation of high-geodiversity areas as a means to long-term biodiversity preservation, because a diverse geomorphological landscape consisting of various abiotic habitats provides a setting for a more extensive number of niches available for species to occupy (Pellitero et al. 2014).

Chapter Five

Conclusions and Outlook

Mountains are the last refuge for many threatened and endangered species (Lomolino 2001). The Himalayan region encompasses a large fraction of global climate diversity (Rana et al. 2019). Wet and warm regions in the eastern low elevations have higher species richness suggests that climatic control can play an important role in the establishment of plants. Though climatic variables have higher relative importance in species richness; the topographic variable is significantly important in the western Himalaya. Scale is the most crucial factor in comparing the geodiversity index; the geodiversity map (with coarser resolution) for the whole Himalaya is a generalised geodiversity pattern that reflects the high to low geodiversity of the Himalayan Arc. The conservation of high-altitude environments is necessary while alpine vegetation is threatened by global warming (Gottfried et al. 2012, Miehe et al. 2011). Telwala et al. 2013 studied climate-induced elevational range shifts in the two alpine valleys of Sikkim, where they found that the ongoing warming in the alpine Sikkim Himalaya has transformed the plant assemblages. According to their results, warming-driven geographical range shifts have resulted in increased species richness in the upper alpine zone, compared to that in the 19th century, which can cause species extinctions, particularly at mountain tops. Thus, species conservation requires proper monitoring through species richness data in these mountain systems. Ecosystem resilience and adaptation to climate change also require a definitive reconciliation between human-induced disturbances and the natural processes that support life on Earth (Manríquez 2019).

Geodiversity contributes to understanding the drivers and effects of environmental change (e.g., climate change, sea-level rise, and carbon dynamics in organic soils). Changes in geomorphological processes make changes in habitats; sometimes, it becomes more dynamic and challenging for species to adapt.

For example, some environmental hazards, flash floods, or landslides, occur more frequently in some places, and it becomes mandatory to have strategic planning for those areas. If sufficient geodiversity information is available for those areas, it is possible to take proper action for sustainable development, risk management, and geodiversity maintenance. Paleoenvironmental archives and geomorphological records can provide long-term perspectives on trends, rates of change, and future trajectories in ecosystems (Dearing et al. 2010). Geodiversity has significant value for informing about the past condition of habitats, species, and ecosystems and the speed of their changes. Geo-conservation has been part of statutory nature conservation in the UK for more than 60 years, and the primary intention is to conserve and enhance geological, geomorphological, or soil features, processes, sites, and specimens. Such conservation includes associated promotional and awareness-raising activities (Brown et al. 2012).

It is well-time and essential that biogeographers, ecologists, and evolutionary biologists should take up the challenge of describing and understanding patterns of biological diversity of mountain ecosystems.

5.1 Summary of findings

Sikkim is one of the most species-rich areas in the Himalayas and has a higher altitude variation within only 7,096 km^2 area. DEM (SRTM) data were used to derive morphometric variables, and Chelsa data were used to obtain climatic variables. The geodiversity map of Sikkim was compared with the species richness map produced from secondary data, and it showed similarities in their spatial distribution patterns.

J&K has an area of 138,992.1 km^2, which is almost 19.5 times greater (according to the area) than is Sikkim, and is located in the western part of the Himalayas. I applied the same methodology and used the same morphometric and climatic variables to quantify geodiversity for all three study areas. GIs for smaller regions can provide more detailed information than the vast fields. Still, the geodiversity map of the whole Himalaya is handy to compare the diversity index of different areas.

A database of 5,087 vascular plant species from Sikkim and 5,660 vascular plant species from J&K has been recorded to analyse species richness in different elevation gradients. The most dominating species families in Sikkim are Orchidaceae, Asteraceae, and Poaceae, and the most dominating species families in J&K are Asteraceae, Poaceae, Fabaceae, and Rosaceae. The genera that belong to a higher number of species in Sikkim are *Carex*, *Primula*, *Saxifraga*, and *Juncus,* and in J&K they are *Taraxacum Carex*, *Corydalis*, *Astragalus*, *Polygonum*, *Pedicularis*, and *Potentilla*.

Species richness reached around 1,400 at the elevation gradient of 1,000 to 2,000 m asl in Sikkim, but at the same altitude gradient in J&K, the number of species was calculated to be 1,078. The highest species richness (around 1,000 to 1,256 in number) in J&K has been estimated at the elevational range between 1,800 and 36,00 m asl. The potential species richness was assessed in Sikkim is 0.70 per km^2 and in J&K it is 0.042 per km^2 . Sikkim has the highest potential species richness at the elevation between 200 and 400 m asl and a sharp decline of species number till 1000 m asl. In J&K, the potential species richness increased to slightly more than 0.05 to per km^2. At an elevation above 3,000 m asl, the potential species richness was significantly reduced in J&K. Potential species richness shows the density of the species for these two study areas.

Fuzzy logic has been introduced as a new approach to quantify the geodiversity of the Himalayas. The morphometric variables for quantifying geodiversity of the Himalayas were elevation, slope, TWI, TRI, SOC, and the climatic variables were temperature and precipitation. Using that approach showed the considerable spatial distribution of very high to very low geodiversity patterns, which can be used as a surrogate for biodiversity patterns of the Himalayas.

5.2 Perspectives

-**Nature conservation**: Geodiversity information provides the spatial distribution of the richness of abiotic elements or diversity of aspects in a mountain system. Understanding these richness patterns can offer support for land management, more sustainable exploitation of resources, and also the definition of priority areas for nature conservation (Pellitero et al. 2014). Nature conservation is only possible when both biotic and abiotic structures are well-considered. Thus, the preservation of geodiversity will promote the conservation of biodiversity as well as nature. Mountains have outstanding nature conservation value, and they can incorporate a disproportionate amount of the world’s protected areas, hotspots, and global biodiversity (Gordon 2018).

-**Preservation:** Geodiversity has an intrinsic value (Gray 2013), and elements of geodiversity, such as those of biodiversity (Crofts et al. 2008, Vucetich et al. 2015), deserve to be treated with respect and preserved for future generations (Slaymaker et al. 2009, Gordon 2018).

-**Scientific research and education**: Mountains provide supporting evidence for tectonic processes and long-term landscape evolution since at least the Palaeozoic, and geodiversity is enabling understanding of Earth’s history (Gordon 2018). Geodiversity supports valuable paleoenvironmental and paleoclimatic archives spanning tens to thousands of years in the form of ice-core records, lake and peat bog sediments, and the geomorphological and sedimentary evidence of Quaternary glacier fluctuations (Lowe & Walker 2015, Gordon 2018). Mountain geodiversity has additional value in helping to raise awareness of climate change, natural hazards, and human impacts on fragile geomorphological environments (Reynard & Coratza 2016).

-**A complement to biodiversity:** The calculation of geodiversity can be complemented with biodiversity calculations in the same location (Pellitero et al. 2014). One single value of geodiversity represents the diversity of vegetation, fauna, climate, soils, relief, and geology, helping to obtain natural diversity assessments (Serrano and Ruiz-Flaño 2007).

-**Anthropogenic advancement**: Social advancements of the human demand connectivity and structural development of infrastructures. Mountains act as barriers for some regions, and people make roadways in the mountains to improve mobility. Building roads or highways lead to soil erosion, and debris flows directly in the mountains (Fig 5.1). Risk of landslides increases in the wet season. The adverse effects of building structures in the mountains could be the following (Watson 2005):

-Increased isolation of populations or species;

-Changes in habitat vegetative composition, often to weedy and invasive species;

-Changes in microclimates by altering temperature and moisture regimes;

-Changes in the flow of energy and nutrients;

-Changes in availability of cover and increases in edge effect;

-Increases in opportunities for exploitation by humans.

Picture 5.1: Construction of roads leading to degradation processes in the mountains (on the highway from Ladakh to Kashmir) (Source: Author 2018).

5.3 Concluding summary

The knowledge of the spatial distribution of geodiversity is a beneficial tool since it can be used as a surrogate for biodiversity to a great extent. Establishing meaningful indices for geodiversity offers novel chances for land management, more sustainable use of natural resources, and identifying priority areas for nature conservation while considering both biotic and abiotic structures (Pellitero et al. 2014). Geodiversity indices are especially crucial for geo-conservation, which is highly significant for geo-tourism as it focuses on high geodiversity areas, and tend to be the most spectacular (Pellitero et al. 2014). In addition, a geodiversity map is a primary requirement for the mitigation of risk-prone areas and disaster management systems.

The automated technique presented here is very suitable for worldwide GIS users because all the digital information used in this method is cost-free. While the GIS analysis to quantify geodiversity has used the lowest values from all predictors, the scientific accuracy has been ensured with this fuzzy logic. The statistical correlation between geodiversity and species richness proved a positive relationship: 50% in Sikkim and 56% in J&K, and geodiversity serves as a surrogate for at least half the amount of species richness for the Himalayas. The scale is another critical factor for this kind of mapping. The antithetical relative importance of explanatory variables between districts and study areas proved the sensitive nature of species richness' dependence on independent variables. Further studies are needed to verify the biodiversity-geodiversity relationship with different scales and environments.

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Appendix A

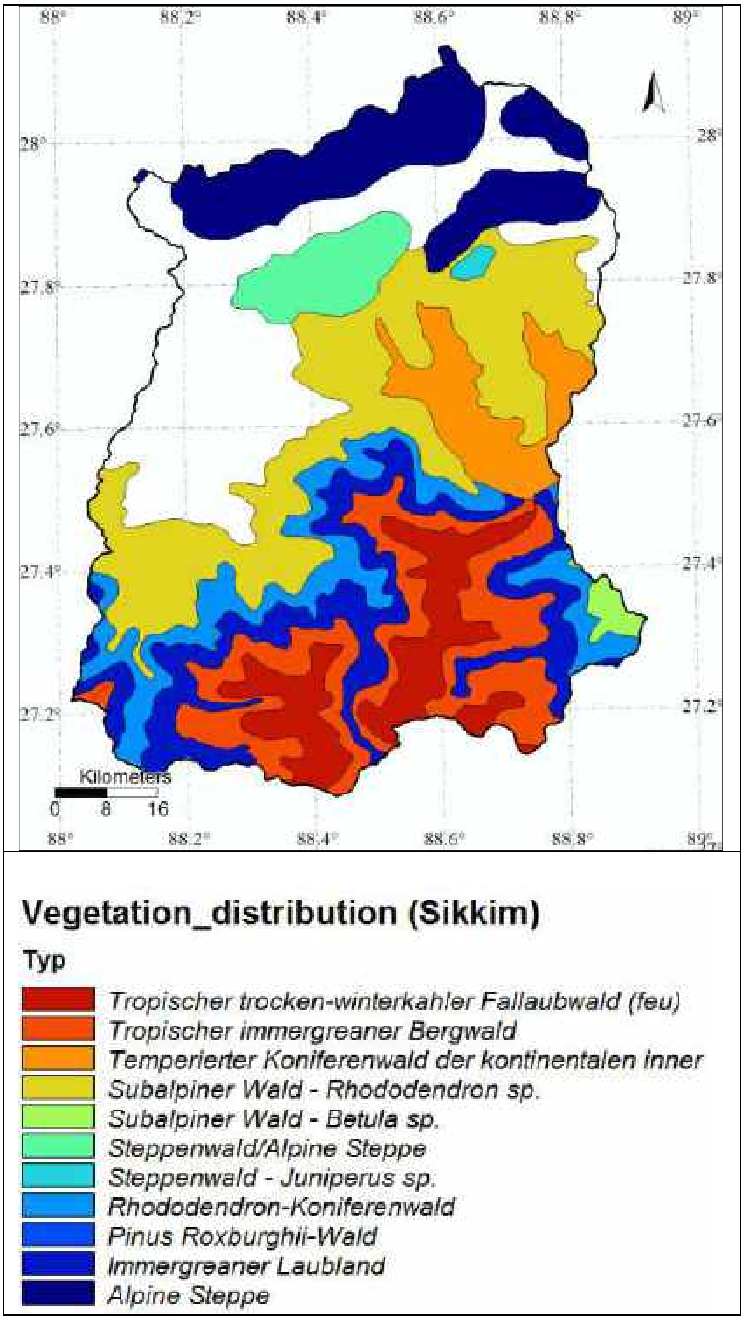

Figure A.1: Vegetation distribution in Sikkim (Schweinfurth 1957, regenerated by Kim Stolle).

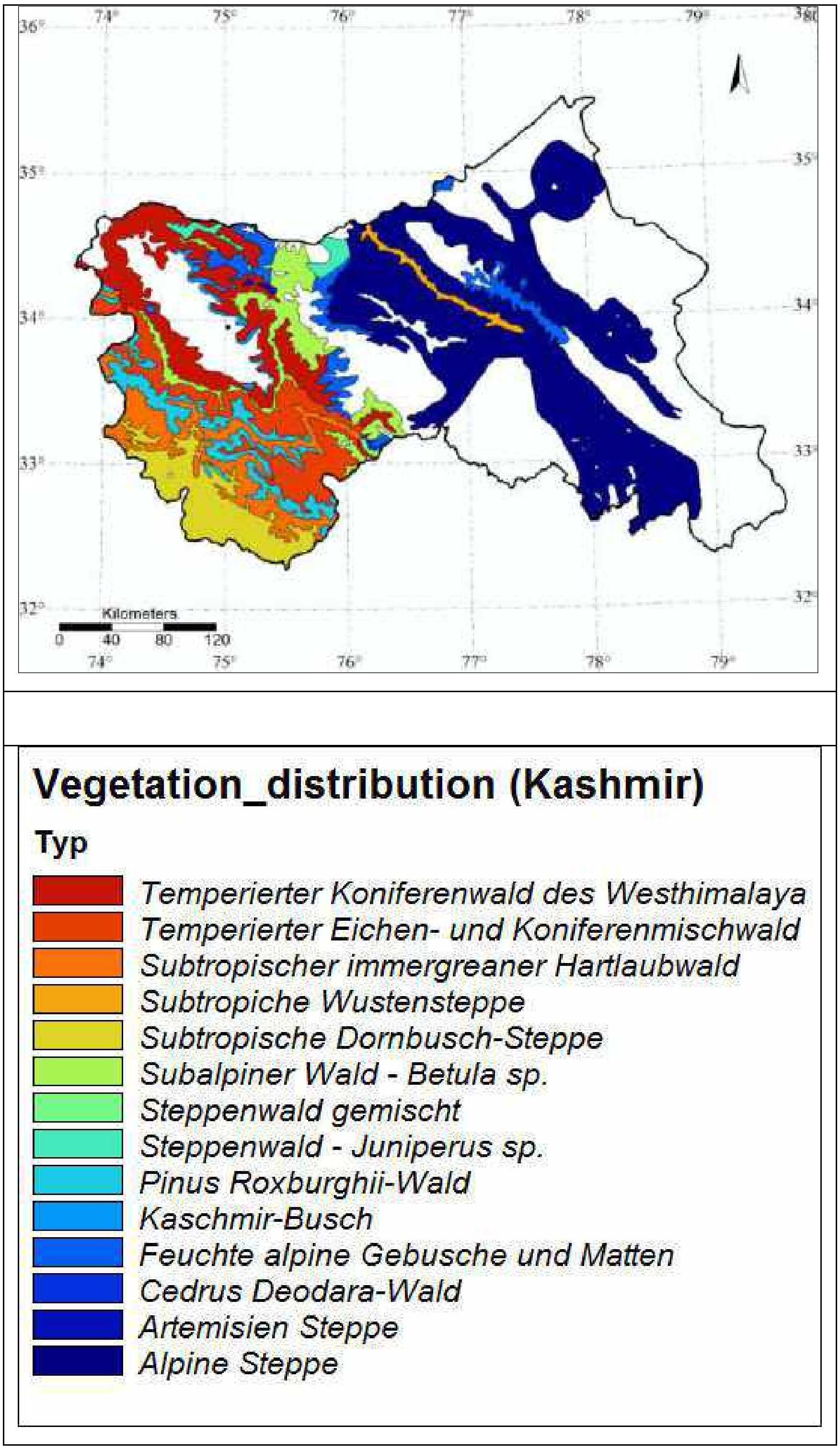

Figure A.2: Vegetation distribution in J&K (Schweinfurth 1957, regenerated by Kim Stolle).

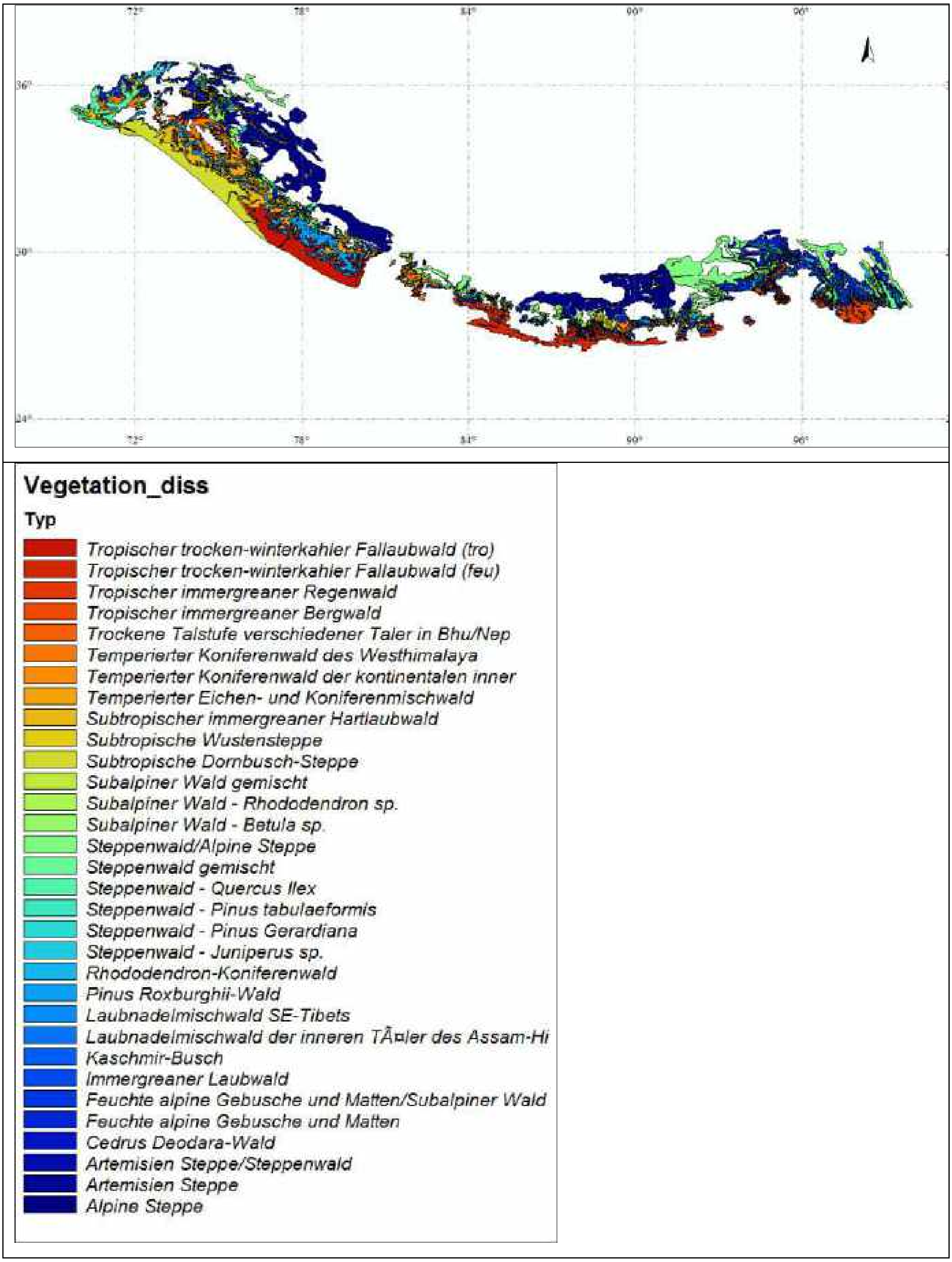

Figure A.3: Vegetation distribution in the Himalaya (Schweinfurth 1957, regenerated by Kim Stolle).

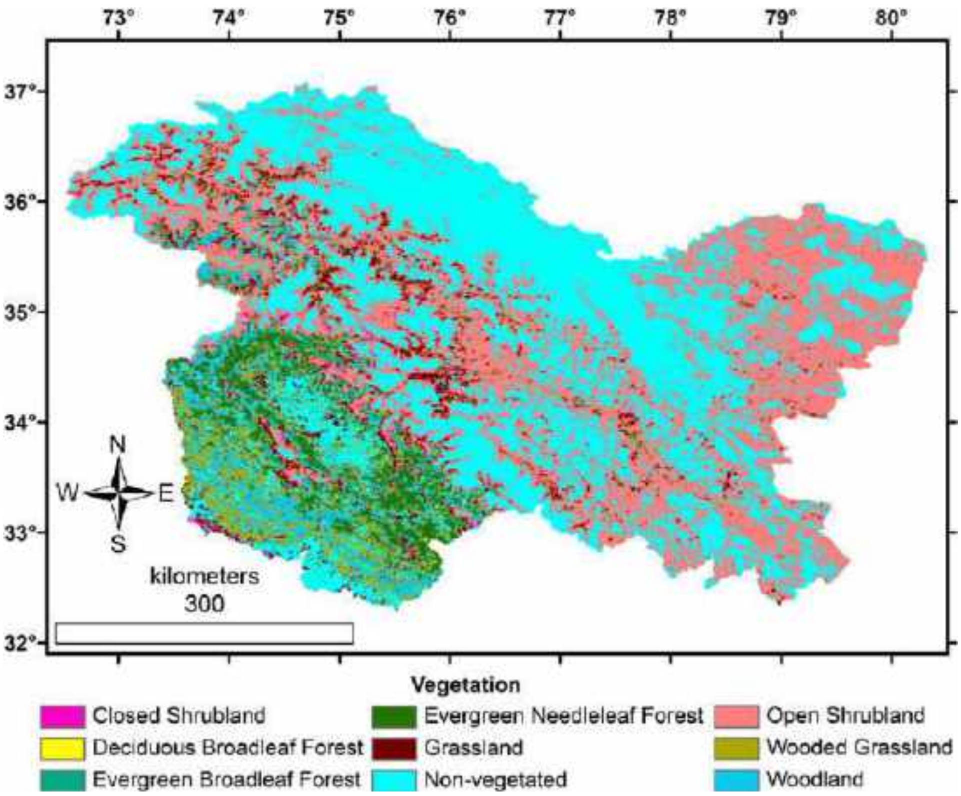

Figure A.4: Major land cover/vegetation types in J&K . (Source- Rashid et al. 2015)

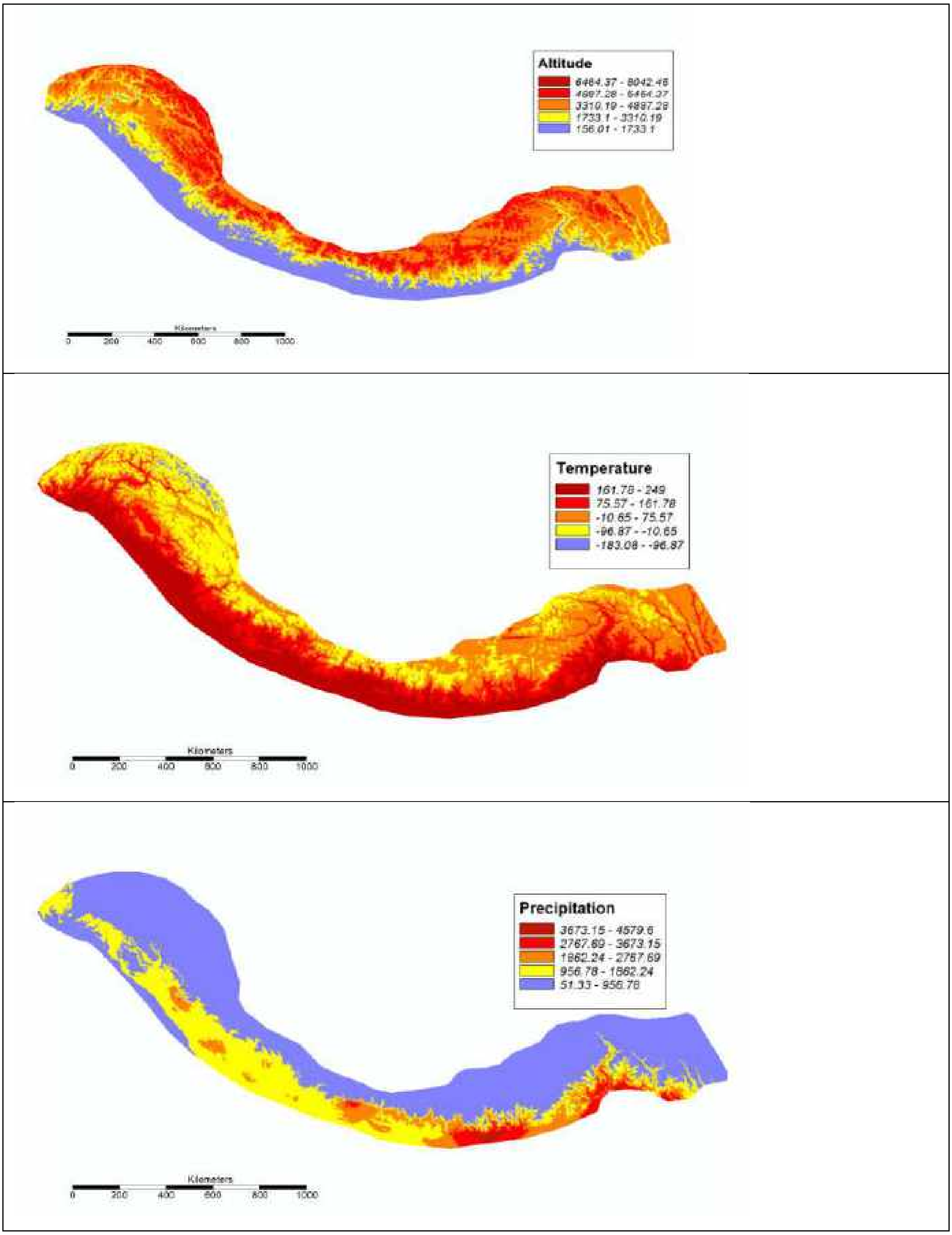

Figure A.5: Different abiotic variables of the Himalaya generated from SRTM data.

Table A. 1: Minimum, maximum and mean values of all variables in different geodiversity areas in Sikkim.

		Sikkim				
Variables	Values	Sikkim	Low geodiversity	Moderate geodiversity	High geodiversity	Very high geodiversity
Geodiversity	Min.	0	0	0.09	0.17	0.25
	Mean	0.17	0.12	0.13	0.2	0.29
	Max.	0.52	0.09	0.17	0.25	0.5
Species richness	Min.	0	0.01	0.01	0.01	0.01
	Mean	0.55	0.46	0.58	0.57	0.56
	Max.	0.94	0.94	0.94	0.94	0.944
Precipitation	Min.	539	576	868	1162	1454
	Mean	1820	1523	1708	1909	2102
	Max.	3594	3379	3594	3352	3330
Temperature	Min.	-15	-13	-14	-14	-11.34
	Mean	1.99	0.51	3.01	1.87	1.55
	Max.	17.23	17.22	16.9	16.26	15.36
Slope	Min.	0.1	0.3	2.52	4.14	6
	Mean	25.99	15.15	22	28.6	36.7
	Max.	62.99	62.9	62.6	61	59.8
SOC	Min.	21.69	23.69	39.6	55.6	71.7
	Mean	94.49	66.26	84.8	104.3	116.9
	Max.	215.45	211	213.3	209.6	207.7
Altitude	Min.	282	282	457.8	650	846
	Mean	3195	3454	2995	3223	3299
	Max.	5779	5532	5601	5610	5643
TRI	Min.	0.12	1.57	13.06	24.5	36
	Mean	33.63	18.93	27.8	36.9	49.6
	Max.	132.41	132	123.9	115	110
TWI	Min.	7.7	7.7	7.9	9.2	10.7
	Mean	14.7	15.28	14.7	14.4	14.5
	Max.	25.9	25.9	24.9	23.47	23.5

Table A. 2: Geodiversity values in 20 point locations and relation with other variables in Sikkim.

Sikkim								
ID_Geodiversity	Species richness	Precipitation (mm)	Temperature (°C)	Slope (Degree)	SOC (g/kg)	TRI	TWI	Altitude (m)
1_Very high (0.36)	0.76	1909	6.94	42.8	107.9	59.1	16.8	2089
2_Very high (0.34)	0.61	2207	-1.65	40.2	139	55.1	16.29	3801
3_Very high (0.33)	0.94	1769	12.8	44.1	89	62.5	17.69	1280
4_Very high (0.37)	0.61	2925	3.39	46.5	154.9	69.45	14	2670

5_Very high (0.36)	0.007	2360	8.66	42	100.7	57.6	16	1895
6_High (0.19)	0.071	2056	9.49	24.1	83.6	31.3	13.8	1959
7_High (0.21)	0.56	2491	1.75	25.6	165	33.8	17.6	2940
8_High (0.20)	0.74	2608	6.06	24.6	93.2	32	11.8	2416
9_High (0.22)	0.77	2468	7.8	33.1	132.3	42	10.9	2144
10_High (0.20)	0.61	2172	3.66	27.2	120.8	33	14.5	2771
11_Moderate (0.16)	0	1735	10.2	27.7	54.9	35	13	1728
12_Moderate (0.11)	0.944	1425	11.1	28.2	45.1	34	17	1298
13_Moderate (0.16)	0.91	1520	13.7	26.9	54.7	32.5	12.9	827
14_Moderate (0.14)	0.61	1705	1.7	19.6	153.1	23	13.3	3336
15_Moderate (0.16)	0.61	1149	3.5	46.2	110.9	67.7	14.6	2985
16_Low (0.03)	0.24	1253	-6.7	5.4	46.2	6.2	17	4911
17_Low (0.03)	0.61	653	3.6	32.5	125.8	42	16.6	2844
18_Low (0.06)	0.37	1687	11.8	9.3	41.7	10.9	16.5	1372
19_Low (0.06)	0.74	791	8.9	25.2	94.3	32.5	13.5	2174
20_Low (0.06)	0.37	2615	-2.1	10.83	110.2	14.54	17.5	3694

Table A. 3: Minimum, maximum and mean values of all variables in different geodiversity areas in J&K.

J&K						
Variables		J&K	Low geodiversity	Moderate geodiversity	High geodiversity	Very high geodiversity
Geodiversity	Min.	0	0	0.04	0.08	0.12
	Mean	0.06	0.016	0.05	0.09	0.14
	Max.	0.26	0.04	0.08	0.12	0.26
Species richness	Min.	0.01	0.01	0.01	0.01	0.01
	Mean	0.14	0.06	0.1	0.2	0.34
	Max.	0.91	0.8	0.88	0.91	0.91
Precipitation	Min.	134	134	234	365	501
	Mean	1001	673	887	1315	1646
	Max.	2808	2772	2777	2808	2808
Temperature	Min.	-12	-11.6	-11.9	-11.9	-12
	Mean	2.46	2.6	0.72	3.99	3.74
	Max.	19.93	19.9	19.28	19.13	18.4
Slope	Min.	0.1	0.1	0.18	0.3	6
	Mean	15.6	8.06	15.36	21.54	26.47
	Max.	40.5	33.18	40.5	40.4	40.34
SOC	Min.	5.6	5.6	13	23.37	33.6
	Mean	40.6	28.01	37	207.89	68.58

	Max.	222	189.9	203	49.8	222
Altitude	Min.	693	693	695	712	807
	Mean	3446	3485	3742	3139	3142
	Max.	5731	5650	5694	5728	5731
TRI	Min.	0.12	0.12	0.41	0.53	7.7
	Mean	20	10.12	19.24	27.9	35.17
	Max.	53.46	44.06	51.77	52	53.46
TWI	Min.	7.8	7.8	8	8	8.15
	Mean	11.2	10.9	11.4	11.2	11.36
	Max.	14.5	14.5	14.15	13.9	13.8

Table A. 4: Geodiversity values in 20 point locations and relation with other variables in J&K.

J&K								
ID_Geodiversity	Species richness	Precipitation (mm)	Temperature (°C)	Slope (Degree)	SOC (g/kg)	TRI	TWI	Altitude (m)
1_Very high (0.23)	0.57	1337	2.12	37.9	97.3	54.8	12	3517
2_Very high (0.23)	0.9	1673	1.75	42	84	64	11.2	3081
3_Very high (0.21)	0.69	2012	8	33	59	47	11	2362
4_Very high (0.19)	0.53	2623	-2.3	32	83	44.7	11.7	3894
5_Very high (0.28)	0.68	2131	0.86	29	85	41	12	3456
6_High (0.11)	0.08	1295	-6.8	23	131	31	11.9	4911
7_High (0.10)	0.79	1771	4.26	23	65	28	11	2966
8_High (0.10)	0.07	1009	-8.05	25	122	34	12	5192
9_High (0.11)	0.57	637	0.48	26.97	45.8	34.9	12.46	3668
10_High (0.10)	0.004	1668	9.99	24.11	28.9	31.8	11	2029
11_Moderate (0.06)	0.577	370.8	-2.42	31	19	42	19.9	3944
12_Moderate (0.06)	0.089	931	-6.8	20.7	68.7	26	11	4666
13_Moderate (0.07)	0.52	563	2.23	9.3	62.8	11.3	10.4	3648
14_Moderate (0.08)	0.488	2059	5.91	27	50	35	11	2815
15_Moderate (0.08)	0.49	2201	11	20	35.9	28.9	11.6	1822
16_Low (0.01)	0.06	1305	18.17	6.9	24.7	8.7	9.09	798
17_Low (0.03)	0.38	1901	1.67	9.1	101.7	11.1	9.8	3377

18_Low (0.03)	0.54	375	-0.5	14.9	12	19	12	3704
19_Low (0.01)	0.08	495	-4.2	7.7	20	9.6	12	4593
20_Low (0.019)	0.91	321	2.2	28	8	39	11	3048

Appendix B

Published Articles

Quantification of Geodiversity of Sikkim (India) and Its Implications for Conservation and Disaster Risk Reduction Research

Raunaq Jahan, Udo Schickhoff, Jürgen Böhner and Olaf Conrad

Abstract

Geodiversity is the term which describes the variability of earth's surface materials, forms and physical processes. Conservation of geodiversity has become increasingly significant in recent decades since it has become obvious that geodiversity provides the abiotic preconditions for habitat development and maintenance and has a crucial influence on biodiversity. The Himalaya is one of the mountain systems showing highest levels of geodiversity and biodiversity. However, no research has been done on the quantification of geodiversity or on the relationships between geodiversity and biodiversity. Sikkim, located in the humid eastern Himalaya, has been selected as a study area within this global hot spot of biodiversity. The main approach of this research was to explore the geodiversity of Sikkim, using topographical and climatological information, and analyse the importance of geodiversity in the context of climate change and future conservation of natural resources. We used several quantitative approaches to produce geodiversity information which could be able to explain biodiversity patterns in the study area, since species richness models can be derived from explicit measures of geodiversity. A detailed database on species (flora) richness has been drawn from several floras and published literature. In Sikkim, the altitudinal range between 500 and 2000 m shows the highest species diversity. At higher altitudes, species diversity decreases, in particular above 5000 m. We used System for Automated Geoscientific Analysis (SAGA) GIS software for automated

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quantification of geodiversity. We produced a geodiversity index map which almost matches the high richness areas of the biological richness map by the Indian Institute of Remote Sensing (IIRS). Quantifying geodiversity indices for biodiversity hotspots such as Sikkim may contribute to biodiversity as well as geodiversity conservation, and further the understanding of geodiversity–biodiversity relationships.

Keywords

Biodiversity · Climate change · Conservation · Disaster risk reduction Geodiversity · Sikkim · The Himalaya

Introduction

Geodiversity is now a very common aspect of physical geography and geology. In a simple way, it is defined as the heterogeneity of the geological, pedological, climatological and geomorphological properties of the earth's surface (Nieto 2001; Gray 2004, and references therein, Kozlowski 2004; Carcavilla et al. 2007; Bruschi 2007; Serrano and Flaño 2007; Panizza and Piacente 2008; Benito-Calvo et al. 2009). Importance of geodiversity has been increasing for the future monitoring of ecosystem services, particularly in a context of climate change and rising sea levels, conservation and sustainable management of environmental resources (Gordon and Barron 2012). Geodiversity has great significance for ecosystem services, economic development and vital relevance to historical and cultural heritage (Gordon and Barron 2012). Ecosystem services are typically grouped into four main categories as set out in the Millennium Ecosystem Assessment (MA) (2005) framework: provisioning, regulating and cultural services that directly affect people and supporting services needed to maintain the other services. Geodiversity has a significant role in contributing to ecosystem services, as it provides basic raw materials which effects on ecosystem processes in freshwater coastal and upland systems (Gordon and Barron 2011; Gray 2011, 2012). For example, Scotland's organic soils play a major role as a terrestrial sink of carbon which is considered in climate change mitigation and adaptation (Bardgett et al. 2011; Smith et al. 2011).

Geodiversity is an important parameter to be considered in the assessment and management of natural areas and an important natural factor underpinning biological, cultural and landscape diversity (IUCN 2008). UNESCO built the Global Geoparks Network and highlighted the cultural and economic importance of geodiversity as a means to promote geoconservation as part of a wider strategy for regional sustainable socio-economic and cultural development to save our environment (Eder and Patzak 2004). Geodiversity has been widely valued, for instance, by the Nordic Council of Ministers (Johansson 2000) and by the Australian Natural Heritage Charter (Australian Heritage Commission 2002). Quantification of geodiversity has been the focus of natural scientists in recent decades. Cendrero (1996) took first attempts to assess geological diversity and proposed that diversity of elements of geological interest and their intrinsic value, in particular, to be one of the criteria to be taken into account to classify geological heritage. He presented geological diversity on a scale from one to five according to the number of different elements present in a study area. Durán et al. (1998) contended that geodiversity assessment should consider space and time, and Gray (2004) raised awareness of the values of the geodiversity and outlined the need for a more holistic approach to nature conservation and land management.

Burnett et al. (1998) and Nichols et al. (1998) were the first authors to try to assess geodiversity employing a methodology based on the Shannon–Weaver diversity index, which was used by biologists in the assessment of biodiversity.

These early studies showed that variation in terrain and soil properties and areas of high geomorphological heterogeneity were also characterized by high values of the biodiversity index. Johansson et al. (1999), Nieto (2001) and Stanley (2001) described their idea of geodiversity including an integrative and scale-sensitive which were restricted to geological elements and processes. According to Kozlowski (2004), geodiversity includes surface waters and takes the consequences of anthropogenic processes into account as well. The main purpose of the geodiversity quantifications is the conservation of the earth resources as well as the conservation of biological richness. Benito-Calvo et al. (2009) tested landscape diversity indices to assess regional geodiversity in the Iberian Peninsula using GIS techniques. Their terrain classification generated from morphometric, geological and morphoclimatic regional classifications was applied to compute richness, diversity and evenness indices and to assess quantitatively the current regional geodiversity among the main geological regions of Iberia. Hjort et al. (2012) quantified geodiversity for a boreal landscape in Finland which was used to improve biodiversity models. Pereira et al. (2013) assessed geodiversity of Paraná State, and Silva et al. (2013) assessed geodiversity of Xingu drainage basin using geology, geomorphology, palaeontology, soils and mineral occurrence. Their main approach of geodiversity index production was to use this as a tool in land use planning, particularly in identifying priority areas for conservation, management, and use of natural resources at the state level. Pellitero et al. (2014) calculated mid- and large-scale geodiversity using lithology, structures, geomorphology, hydrology, fossils, soils and slope. Their approach was intended to promote geodiversity protection within an integrated environmental management system. But their geodiversity index should not be used as a surrogate indicator of biodiversity, as climate data were not included in calculation while it is a potential resource for biodiversity development (Parks and Mulligan 2010).

The concept of geodiversity has been put forward as a novel alternative and potentially useful means to assess and model spatial biodiversity patterns in recent years (see Parks and Mulligan 2010, and the references therein). Geodiversity includes geology, geomorphology, pedology, topography, hydrology and climate (Benito-Calvo et al. 2009; Parks and Mulligan 2010) which are meticulously linked with key abiotic drivers of biodiversity such as energy, water and nutrients (Richerson and Lum 1980; Hjort et al. 2012). Geodiversity also provides essential supporting services for biodiversity as well as the provision of minerals, nutrients, landform mosaics and geomorphological processes for habitat creation and maintenance. Fragoso-Servón et al. (2015) calculated geodiversity of the Yucatan Peninsula in south-eastern Mexico, considering geomorphology, geology, hydrology and soil properties as components of geodiversity. They used a simple additive model of thematic diversity and assured from their results that a study with detailed information could provide important insights into the spatial distribution of biological diversity. Manosso and Nóbrega (2015) identified and defined eight compartments or landscape units for a quantitative evaluation of geodiversity in a unit of Cadeado Range, Paraná State. They made an integrated analysis of the set of elements of the geoecological structure, i.e. geomorphological, geological, pedological, hydrological and socio-economic features, to understand the spatial distribution of geodiversity. Räsänen et al. (2016) explained vascular plant species richness patterns in a fragmented landscape, and according to their study, landscape and topography explained the majority of the variation, but the relative importance of topography and geodiversity was higher in explaining native species richness.

Geodiversity contributes to understand the drivers and effects of environmental change (e.g. climate change, sea-level rise and carbon dynamics in organic soils). Changes in geomorphological processes make changes in habitats, sometimes it becomes more dynamic and difficult to adapt for species. An extreme climatic event, for instance, may cause problems for freshwater and brackish water habitats when tsunami or cyclones in coastal areas destroy the surrounding ecosystem and ecosystem recovery is difficult.

Some environmental hazards, for example, coastal flooding and erosion, flash floods or landslides occur more frequently in some places, and it becomes mandatory to have strategic planning for those areas. If sufficient geodiversity information is available for those areas, it is possible to take proper action for sustainable development, risk management and geodiversity maintenance. A good example is Flood Risk Management (Scotland) Act 2009 (2009), which develops 'natural flood management and integrated catchment solutions and the restoration of the natural function of floodplains as flood buffers'. Palaeo-environmental archives and geomorphological records are able to provide long-term perspectives on trends, rates of change and future trajectories in ecosystems (Dearing et al. 2010). Geodiversity has significant values to inform about the past condition of habitats, species and ecosystems and speed of their changes. Geoconservation has been a part of statutory nature conservation in the UK for more than 60 years, and the main intention is to conserve and enhance geological, geomorphological or soil features, processes, sites and specimens, including associated promotional and awareness raising activities (Brown et al. 2012).

The quantification of geodiversity in high mountain regions is still missing, especially in the Himalayan range. The Greater Himalaya have much higher biodiversity values than the global average (Körner 2004); the eastern Himalaya have the highest plant diversity and richness within this mountain system (Xu and Wilkes 2004; Mutke and Barthlott 2005; Salick and Byg 2007). Biodiversity studies in the Himalaya include country-specific (e.g. Samant and Dhar 1997; Gairola et al. 2013) and species-specific studies (e.g. Grau et al. 2007; Srinivasan et al. 2014). However, there are still no biodiversity studies providing specific geodiversity information on the Himalayan region. Singh and Anand (2013) described the term geodiversity according to the diversity of geological features and assessed geodiversity of India and the Himalayan range qualitatively. Rawat and Sharma (2012) described geodiversity of Dabka watershed in the Lesser Himalaya for their geohydrological database modelling of a landslide susceptibility assessment. Their major geodiversity parameters were average slope, geology, geomorphology, soil types, land use, drainage density and drainage frequency, and they expressed geodiversity as least-stressed, moderately stressed, highly stressed and extremely stressed categories. They used these geodiversity categories to produce a landslide susceptibility index (LSI), but not for a geodiversity index. All these previous studies touched geodiversity issues of the Himalaya, but did not quantify geodiversity and did not specify its relationship to biodiversity. So there is a major deficit of quantification of geodiversity and biodiversity in the high mountain regions like the Himalaya. Spatial distribution of species richness has not been calculated yet for the species-rich areas in the Himalaya. The aim of this chapter is to present an automated way to quantify biodiversity from a geodiversity index, to assess species richness information for different altitudinal zones and to analyse the scope of geodiversity in the context of biodiversity conservation and climate change research.

Study Area

Sikkim is bounded by Nepal in the west and Bhutan in the south-east, Tibet in the north and the north-east, and West Bengal plains in the south. Sikkim is the least populous state in India, covering an area of 7096 km^2. Sikkim is nonetheless geographically diverse due to its location in the Himalaya; the climate ranges from subtropical to high alpine and Kangchenjunga, the world's third highest peak, is located on Sikkim's border with Nepal.

Sikkim is one of the richest treasure houses of plant diversity in the country because of its unique geographical position, high annual precipitation, a wide range of topography and the presence of perennial streams and rivers (Singh and Dash 2002). This region has a wide range of climatic conditions due to varied topography and a great deal of altitudinal variation from ca 200–8598 m (Fig. 1).

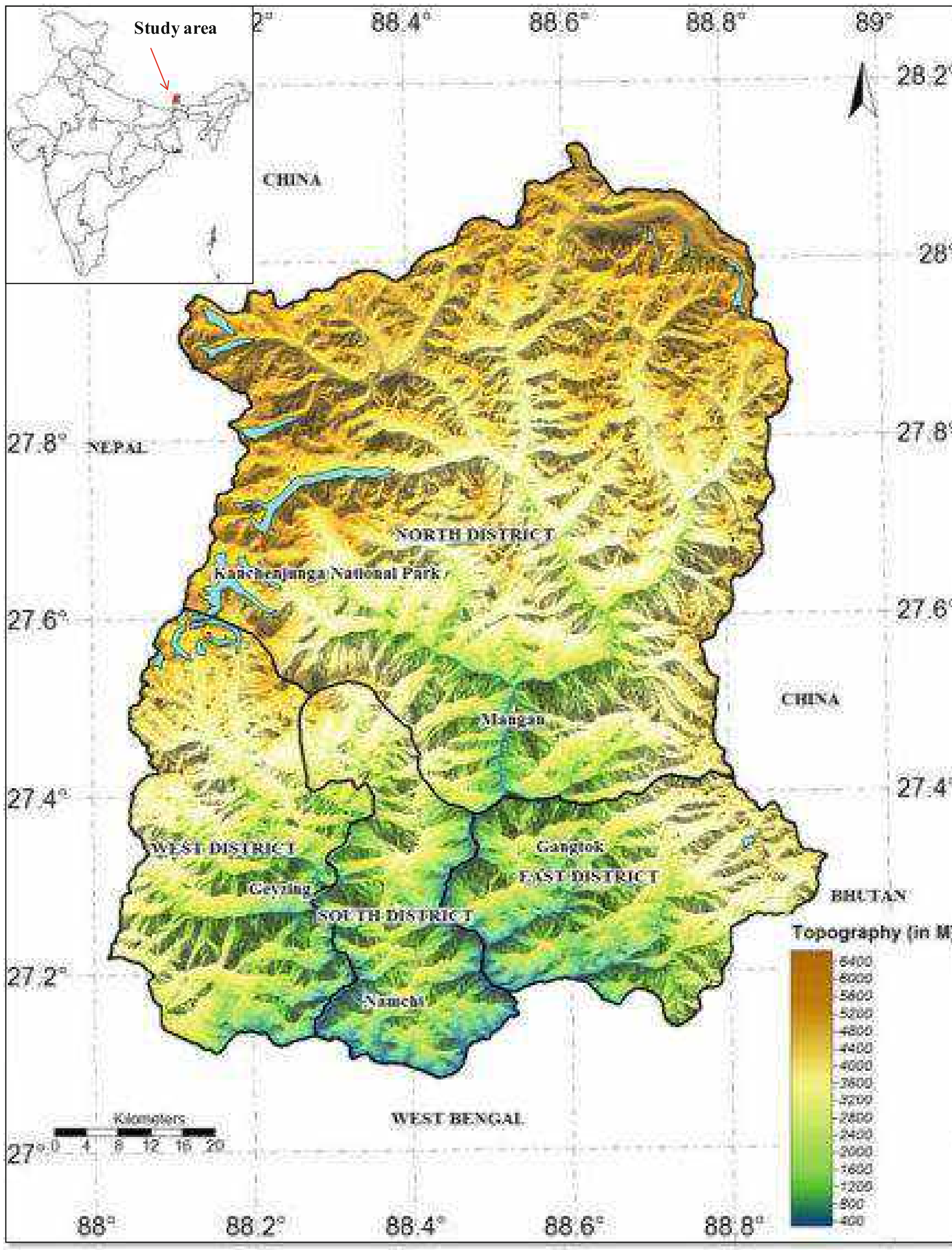


Fig. 1 The topographic map of Sikkim (map prepared by first author)

All the important forest types of eastern Himalaya like sub-Himalayan wet mixed forests, subtropical hill forests, Himalayan subtropical pine forest, wet temperate forests, mixed coniferous forests, eastern oak-hemlock forests, oak-fir forests, moist alpine scrubs and dry alpine scrubs are found in Sikkim (Champion 1936). Pure chir pine forests are the dominating feature in small pockets in dry valleys of south Sikkim, and sal forests are found up to around 900 m altitude along the valleys of Rangeet and Teesta. Singh and Dash (2002) and Forest, Environment and Wildlife Management Department of Government of Sikkim (2017) classified the vegetation cover of Sikkim according to altitudinal distribution (Fig. 2) which is summarized in Table 1.

Materials and Methods

Database of biodiversity has been produced from published floras of Bhutan and on Sikkim. A database of 5417 vascular plant species, including information on family, habitat, location according to altitude and district, and community affiliation has been prepared using published sources (Hajra and Verma 1996; Grierson and Long 1991; Singh and Dash 2002). In order to quantify geodiversity, we tried to identify the physical heterogeneity of the topography of Sikkim. This classification was elaborated using GIS techniques (SAGA 3.1.0) and has involved morphometric and morphoclimatic classification together. Classification of morphometric features was the basic task for geodiversity mapping, which was composed of morphometric variables obtained from the SRTM DEM (Shuttle Radar Topographic Mission; NASA). Temperature and rainfall data were collected from CHELSA database (Karger et al. 2016). We selected digital elevation model (DEM)-based topographical variables elevation, slope, analytical hillshading, topographic wetness index, topographic roughness index and climatological variables (temperature and precipitation) with a spatial resolution of 90 m. SRTM data had been pre-processed using fill-sinks (Wang Liu) of primary DEMs before our calibration started. Elevation data have a very high range of values (0–8000 m), and that is why this layer was normalised before calculation. Analytical hillshading calculated twice to have more emphasis on north and east facing slope values. Numbers of different physical elements were classified according to ISODATA (Interactive Self-Organizing Data Analysis Technique, SAGA GIS 3.1.0, Conrad et al. 2015) clustering methods, and each topographical variables was counted according to every coarser grid on the image. The tool 'diversity of categories' is able to count the number of categories in each cell or coarser grid. The new edition of this tool counts different classes cell by cell in a moving window using kernel method. So the changes of diversity were changed slightly from one cell to another. Another edition of this tool is search mode and search distance. Most of the previous studies counted the number of categories in each square, but here we used search mode 'circle' to show the features more natural. Search distance was another important option to count the range of diversity. Gaussian weighting function was taken 0.7 which means 70% of the distance from one cell to next 3 cells was counted for weight in diversity measurement.

Results and Discussion

We made a database on the flora of Sikkim from different published sources. Altogether there were 503 species, for which information on altitude was missing. So a total of 4914 species were used for showing their distribution. The results show that the highest species diversity can be found in the altitudinal range between 500 and 2000 m (Fig. 3). The altitude between 0 and 500 m the number of species found around 1408, from 500 to 2000 m the total number of species were 5581 and after that, the number of species started to decrease according to high altitude. At 5500–6000 m altitude, only 24 species were found in the Sikkim Himalayan range. Higher altitudes show a decreasing number of species diversity, in particular above 5000 m. Indian

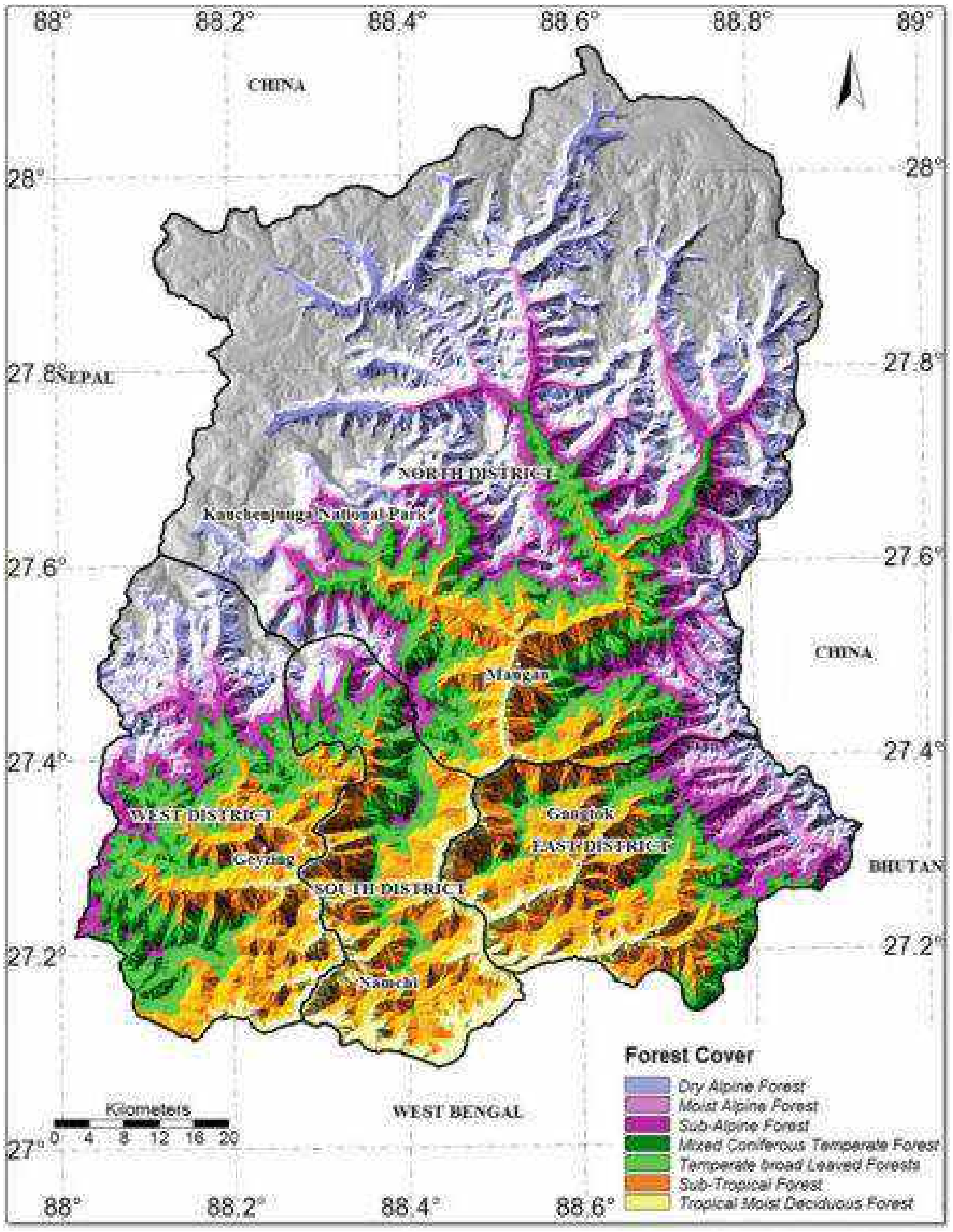


Fig. 2 Altitudinal zonation of vegetation map of Sikkim (map prepared by first author according to the information in Table 1)

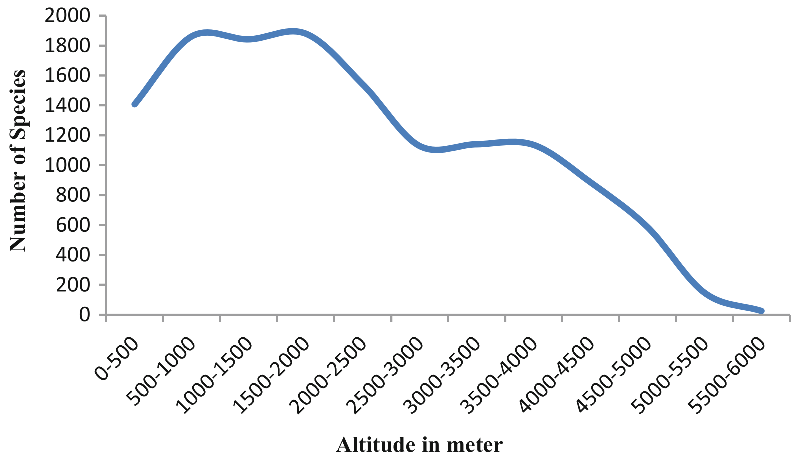
Table 1 Vegetation distribution in Sikkim. *Source* Singh and Dash (2002), Forests, Environment and Wildlife Management Department, Government of Sikkim (2017)

Vegetation	Altitudinal range	Characteristics	Places
Tropical moist deciduous forest	Up to 900 m	Consist of tropical moist deciduous to semi-evergreen. Shorea robusta as a dominant species. Common species are: Saccharum spec., Oroxylum indicum, Meizotropis buteiformis	Rangpo Chhu, Sherwani, Jorethang, Rangit
Subtropical forests	Between 900 and 1500/2000 m	Mixed forest. Common species are: Adina cordifolia, Alangium chinense, Bischofia javanica, etc. Ferns and fern allies along with species of orchids constitute rich epiphytic flora of this region	Tong, Gyalzing, Sangklang Selem, Chakung Chhu, Gangtok, Gyalzing, Rongli
Temperate broadleaved forests	Between 1700 and 2700 m	Common species are: Alnus nepalensis, Betula utilis, Engelhardtia spicata, etc. Shrubby vegetation is quite dense and diverse in temperate forests	Chunthang-Lachung, Yumthang
Mixed coniferous temperate forest	Between 2700 and 3000 m	Abies densa, Acer campbellii, Betula utilis, Rhododendron, Abies densa, Taxus baccata, Tsuga dumosa, Larix griffithiana	Lachen, Zemu, Yathang, Lachung
Sub-alpine forest	Above 3000 m	This zone supports Rhododendrons, Berberis, Cotoneasters, Diapensia, Euonymus, etc.	Above Yathang
Moist alpine forest	3600–4000 m		
Birch rhododendron scrub forest		Betula utilis, Sorbus foliolosa, Rhododendron campanulatum	Thangu, Maiminchu
Deciduous alpine scrub		Berberis spec. Lonicera spec., Rosa spec.	Changu, Thangu
Dwarf rhododendron scrub		Rhododendron lepidotum	Thangu
Alpine pastures		Allium, Anemone, Delphinium	Chopta Yumasong
Dry Alpine Scrub			
Dwarf juniperus scrub	Above 3600 m	Juniperus recurva, J. wallichiana	Chopta, Changu
Dry alpine scrub	Above 4000 m	Ephedra gerardiana, Meconopsis spec., Ribes spec.	Chopta

Institute of Remote Sensing (IIRS) and Biodiversity Information System (BIS) have produced a spatial distribution of biological richness information for whole India. According to Roy et al. (2015), this vegetation type map is the most comprehensive one, developed for India so far which was prepared using 23.5 m seasonal satellite remote sensing data, field samples and information relating to the biogeography, climate and soil. Figure 4 shows the biological richness map for Sikkim produced on BIS data.

Other assessments of geodiversity used geomorphological, geological and soil features (Serrano and Ruiz-Flaño 2007b), or used geology, geomorphology and hydrology but omitted soils and topography in their assessment (Hjort

Fig. 3 Species richness according to different altitude in Sikkim



and Luoto 2010), or compiled climate and topography-based variables with geological, geomorphological and hydrological features (Parks and Mulligan 2010; Hjort et al. 2012) but all of them followed the same formula (Serrano and Ruiz-Flaño 2007b) to obtain geodiversity of their study areas. We did not include geological and soils information in our study, as the digital form of that information is not available from the free data sources and cost-effective. Benito-Calvo et al. (2009) calculated several classification maps (e.g. morphometric map, 10 classes; morphoclimatic map, 5 classes; geological map, 15 classes) to finalize their geodiversity indices, but in our method, we used all data of SRTM and CHELSA together to produce one classification map using ISODATA clustering tool, which was used to calculate diversity of categories per 90 m area. Determination of subsurface properties of soils is also difficult (Hjort and Luoto 2010) and has rarely been used as a factor for geodiversity assessment (cf. Pellitero et al. 2014 for the information of methodologies and formulae used for geodiversity calculation to date). As most of the studies follow more complex classifications and require greater computation capacity, it is comparatively easier to produce a geodiversity index using our automated method.

Geodiversity of Sikkim has been quantified and turned to normalized values from 0 to 10 and later classified as five classes with same interval, like very high (8–10), high (6–8), moderate (4–6), low (2–4) and very low (0–2) categories (Figs. 5 and 6). In case of Sikkim, geodiversity is the lowest in Kanchenjunga National Park areas. Kanchenjunga National Park area is mainly covered by several glaciers, snow fields and rocky wastes. Zemu glacier, Nepal gap glacier, Tent Peak glacier, Hidden glacier are the nearest to Kanchenjunga peak and also a place for tourist interest. There are also some other glaciers scatterd in the Kanchenjunga National park, for instance, Chungsang glacier, Lhonak North and Lhonak South glaciers in the northern part and Talung glacier, Zumthul Phuk glacier in the southern part. Geodiversity of these glaciers was found to be very low to moderate, corresponding to the low biological richness index (Figs. 4, 5 and 6). The forest of western and northern part of Mangan city (in north district) shows higher biological richness as well as higher geodiversity index. Near the eastern border of Sikkim, the area from east district to the north district has very high biological diversity as well as high geodiversity index in the produced map (cf. Figs. 4, 5 and 6a, b).

If we compare these areas with the altitudinal gradient and Fig. 2, we can see that the elevational range from 1700 to 3000 m (temperate broadleaf forest to sub-alpine forest areas) has high geodiversity as well as high biological richness. This high biological richness area consists of forest cover, alpine scrub, grass and scrub, glacial moraines and screes. In the middle

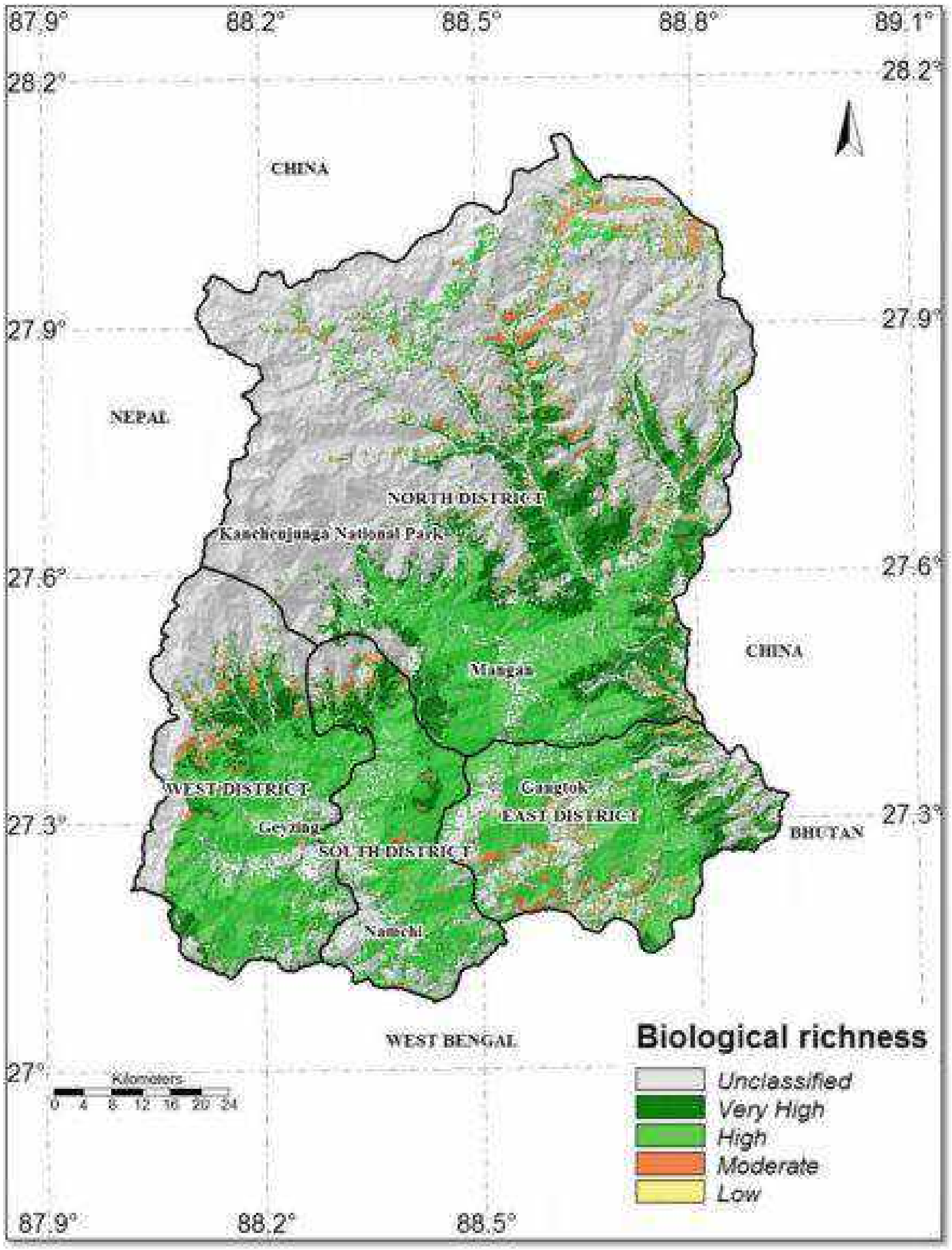


Fig. 4 Biological richness in Sikkim (map prepared by first author using data from BIS in India)

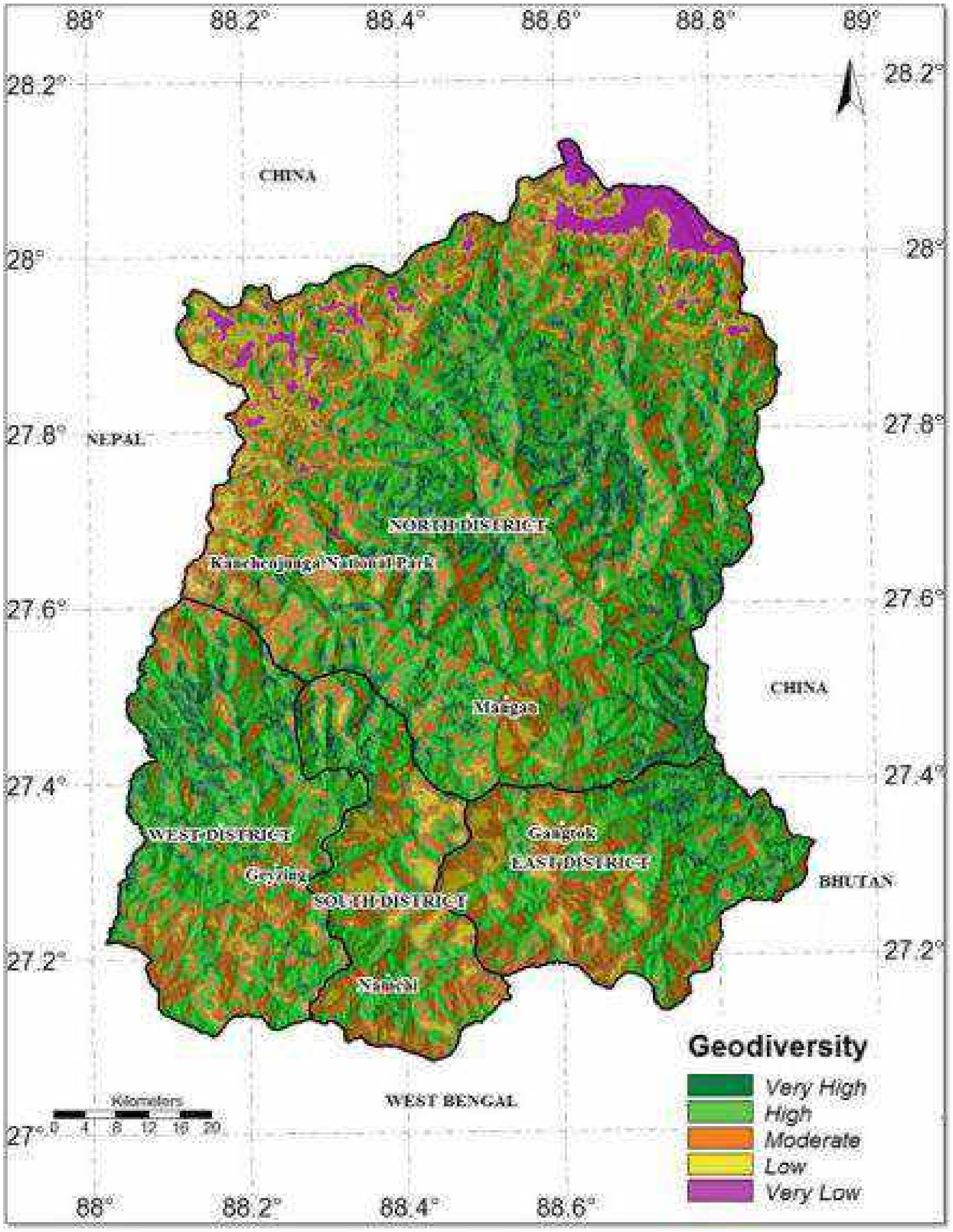


Fig. 5 Geodiversity of Sikkim (map prepared by first author)

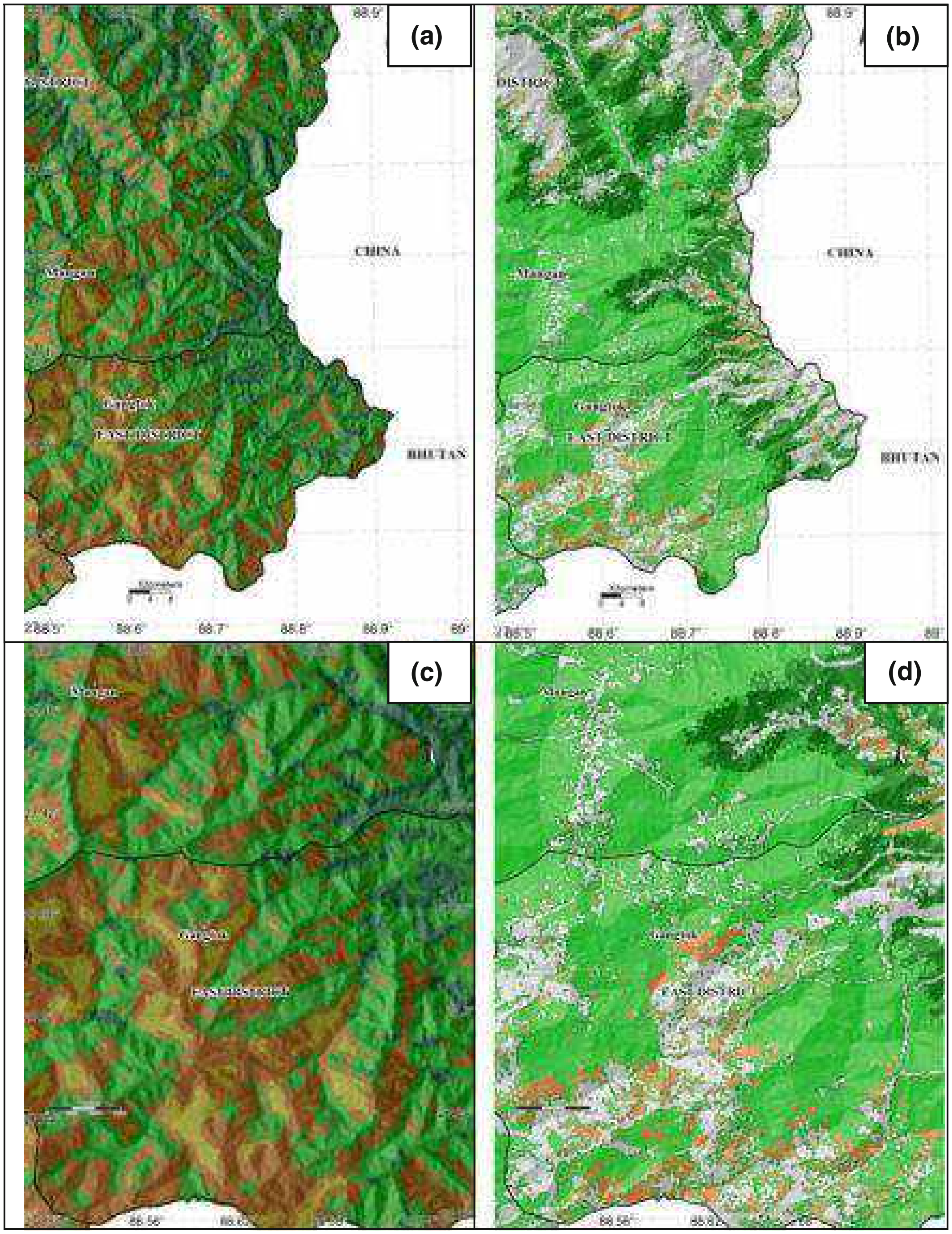


Fig. 6 Comparing of geodiversity in the eastern part of Sikkim (**a**) and biological richness, (**b**) and moderate to high geodiversity in Gangtok city, (**c**) and biological richness, (**d**) (maps prepared by first author)

of the east district, the city of Gangtok, which is the main urban settlement surrounded by agricultural fields, shows low to moderate geodiversity (Figs. 5 and 6c, d). In west district of Sikkim, the northern areas have high to very high biological diversity and geodiversity index is also shown high to very high in the map.

In the north district of Sikkim, the higher biological diversity has the shape of tree branches which almost matches with higher geodiversity areas in the same area. In the Kanchenjunga National Park, the geodiversity near the boundary of Sikkim is around 2–3, thus representing a low geodiversity index. At the same time, the biological diversity is low. The less diversified areas range from low to moderate in the southern part of the south district. Parts of the east district in Sikkim show similarly low values for both geodiversity index and biological richness. The main advantage of our method is the ability to surrogate the biodiversity information of remote unclassified areas which was difficult to produce by Biodiversity Information System (BIS) in India. As most of the studies followed more complex classification and required greater computation capacity, in comparison to them, our automated method is easier to produce geodiversity index.

The geodiversity calculation for Sikkim was satisfactory because its distribution almost matches the spatial distribution of biological richness by IIRS. The geographical organization of most geodiverse areas is strongly related to its more diverse geomorphological areas. Sikkim should be taken into account for the management of natural resources. As Sikkim is one of the great tourist spots in India, geotourism should also be focused on high geodiversity areas. Hjort et al. (2012) and references therein suggested conservation of high geodiversity areas as means to long-term biodiversity preservation, because a diverse geomorphological landscape consisting of various different abiotic habitats provides a setting for a wider number of niches available for species to occupy (Pellitero et al. 2014). Telwala et al. (2013) made a study about climate-induced elevational range shifts in the two alpine valleys of Sikkim where they found that the ongoing warming in the alpine Sikkim Himalaya has transformed the plant assemblages. According to their results, warming-driven geographical range shifts resulted in increased species richness in the upper alpine zone, compared to the ninetieth century, which can cause species extinctions, particularly at mountain tops. So conservation of species requires proper monitoring through species richness data in these mountain systems.

Implications of Geodiversity for Conservation and Disaster Risk Reduction

Sikkim is situated in a high-risk area with regard to earthquakes and landslides and is considered one of the most disaster-prone regions of India according to the multihazard map of UNDP (SSDMA 2016). In the case of Sikkim, geoconservation is threatened by natural hazards. The geodiversity index map can be used as a tool for disaster risk reduction actions and high geodiversity areas could be taken high priority areas in terms of reducing disaster risk. Deforestation can create a constant risk of landslides or other disasters in hilly regions and this should be banned for high biodiversity areas in Sikkim. Thus, strategies for sustainable conservation of geodiversity and biodiversity might significantly contribute to reducing disaster risk in Sikkim. The following steps could be undertaken to conserve biologically rich and geodiverse areas and reduce the risk of disaster in Sikkim:

- Combine the geodiversity map with the disaster-prone areas of Sikkim and take proper management action to reduce the risk of disaster for biologically rich areas.
- Increase knowledge on the areas of high-risk areas and high geodiversity areas.
- Identify scientifically driven explanations on the main causes of vulnerability caused by natural or manmade disasters in Sikkim.

- Raise awareness within local communities about conservation of geodiversity as well as biodiversity and preparedness in order to cope with potential disasters they are already exposed to.

Conclusion

In order to conserve geodiversity as well as biodiversity, the knowledge of the spatial distribution of geodiversity is a very helpful tool since it can be used as a surrogate for biodiversity to a great extent. Establishing meaningful indices for geodiversity offers novel chances for land management, more sustainable use of natural resources and identifying priority areas for nature conservation while considering both biotic and abiotic structures (Pellitero et al. 2014). Geodiversity indices are especially important for geoconservation which is highly significant for geotourism, as it focuses on high geodiversity areas, which tend to be the most spectacular (Pellitero et al. 2014). In addition, a geodiversity map is the primary requirement for mitigation of risk-prone areas and disaster management systems.

The automated technique presented here is very suitable for worldwide GIS users because all the digital information used in this method is cost-free. Scale is another important factor for this kind of mapping. Further, studies are needed to verify the biodiversity–geodiversity relationship at different scales and environments.

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Vegetation-environment relationships, species richness, and climate change impacts along the elevational gradient in the Sikkim Himalaya – General findings and preliminary results from a reconnaissance field trip

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Summary

With respect to biogeography, biodiversity and vegetation ecology, the Sikkim Himalaya has been much less intensively studied than Nepal or western Himalayan regions. Field-based studies providing empirical data on vegetation-environment relationships or spatial species richness patterns are very rare. The number of studies on climate change and its impacts on the cryosphere and biosphere in Sikkim is also limited. To address these research gaps, a reconnaissance field trip to Sikkim was conducted in 2015. This paper presents the preliminary results, embedded in comprehensive analyses on elevational species richness patterns and climate change impacts. We detected a hump-shaped pattern of species richness along the elevational gradient, and attributed this plateau-like mid-peak pattern to the optimal constellation of energy- and moisture-related variables in the submontane and lower montane zones. The plot-based analysis of vegetation and environmental variables along the elevational gradient from c. 1800 to c. 4600 m showed a steep turnover in species composition with a very low floristic overlap, even at the family level, suggesting steep elevational gradients in habitat conditions. Enhanced climate warming at higher elevations in Sikkim causes increasing rates of glacier recession and downwasting. Substantial species geographic range shifts and transformation of plant assemblages are to be expected over coming decades.

Zusammenfassung

Der östliche Sikkim-Himalaya ist im Hinblick auf Biogeographie, Biodiversität und Vegetationsökologie bislang weit weniger intensiv untersucht worden als Nepal oder die westlichen Himalaya-Regionen. Feldstudien, die empirische Daten über die Beziehungen zwischen Vegetation und Umwelt oder räumliche Muster des Artenreichtums liefern, sind sehr selten. Auch die Zahl der Studien über den Klimawandel und seine Auswirkungen auf die Kryosphäre und Biosphäre in Sikkim ist sehr begrenzt. Um diese Forschungslücken zu schließen, wurde im Jahr 2015 eine Erkundungsreise von Vegetationsökologen und Studierenden nach Sikkim durchgeführt. In diesem Beitrag werden vorläufige floristische und bodenchemische Ergebnisse vorgestellt, die in Analysen zu den Mustern des Artenreichtums in Höhenlagen und den Auswirkungen des Klimawandels eingebettet sind. Wir fanden eine glockenförmige Verteilung der pflanzlichen Diversität entlang des Höhengradienten mit einem Hotspot an Diversität in mittleren Höhenlagen. Diese Verteilung führen wir auf die optimale Konstellation von energie- und feuchtigkeitsbezogenen Umweltparametern in den submontanen und niedrigmontanen Zonen im mittleren Bereich des Höhengradienten zurück. Die Aufnahmeflächen-basierte Analyse von Vegetations- und Umweltvariablen entlang des Höhengradienten von ca. 1800 m bis ca. 4600 m über Meereshöhe zeigte einen rapiden Wechsel in der Artenzusammensetzung mit geringer floristischer Überlappung, selbst bezüglich der pflanzlichen Familienzugehörigkeit, was auf steile Höhengradienten in den Umweltvariablen hindeutet. Die Erwärmung des Klimas in höheren subalpinen und alpinen Lagen Sikkims führt zu einem verstärkten Gletscherschwund und zu zunehmenden Gletscherabbrüchen. In den kommenden Jahrzehnten sind erhebliche Verschiebungen des geographischen und höhenspezifischen Verbreitungsareals von Arten und eine Veränderung der Pflanzengemeinschaften zu erwarten.

Key words: Biodiversity, biogeography, climate change, dendrochronology, elevational zonation, glacier recession, Himalaya, Khangchendzonga National Park, Sikkim, submontane to alpine flora

Introduction

At a global scale, the distribution of biodiversity is highly uneven, reflecting gradients of increasing species diversity from the poles to the Equator, from arid to humid regions, and from regions with low, gentle terrain to mountain regions with distinct elevational zonation. Geographic gradients of diversity are overlain with centres of extraordinarily high species richness which are well-known for vascular plants (Barthlott et al. 1996, 2005; Mutke & Barthlott 2005, Mutke et al. 2011, Brummitt et al. 2021). Globally, 20 centres with at least 3000 species per 10,000 km^2 could be identified (Fig. 1). The top five centres harbouring more than 5000 species per 10,000 km^2 cover elevational gradients of at least 2800 meters (Barthlott et al. 2007), indicating that global centres and hotspots of biodiversity are predominantly located in mountain regions. Thus, the latitudinal gradient of increasing species richness towards the inner tropics is modified by secondary maxima in extratropical mountainous regions. While peaking around the equator, alpine plant species richness has secondary peaks even in temperate regions (Testolin et al. 2021). The global centres of highest species richness include the Himalaya (cf. Fig. 1), one of the most species-rich and endemic-rich ecoregions which are at the same time threatened by anthropogenic interferences. Thus, the Himalaya is included in the 36 global biodiversity hotspots currently listed by Conservation International, defined by a combination of a minimum number of 1500 endemic vascular plant species and a proportion of more than 70% of natural habitat lost (Myers 1988, Myers et al. 2000). Above-average species richness in mountain regions is related to the topographic complexity and associated high levels of geodiversity, i.e. the environmental heterogeneity and small-scale diversity of habitats resulting from steep climatic and ecological gradients in fragmented and topographically diverse terrain (Körner 2002, 2021; Körner et al. 2005, Schickhoff 2011a). A quarter of all terrestrial biodiversity is situated in mountains of the world (Körner et al. 2017), characterized by high proportions of endemic species and home to more than 85% of all species of amphibians, birds, and mammals (Rahbek et al. 2019). Over evolutionary time scales, mountains have generated high levels of diversity through in situ adaptations and diversification (Badgley et al. 2017, Hoorn et al. 2018, Muellner-Riehl et al. 2019, Perrigo et al. 2020).

In addition to latitudinal diversity patterns, the variation in species richness along elevational gradients has stimulated biogeographic studies since long. A frequent pattern found in studies of a variety of plants, vertebrates, and invertebrates, conducted from sea level to mountain summits, is that of a unimodal or hump-shaped pattern, with species richness initially increasing with elevation, peaking at mid-elevations and declining with approach to ice-covered summits (Whittaker & Niering 1975, Rahbek 1995, Vetaas & Grytnes 2002, Colwell et al. 2004, McCain & Grytnes 2010, Lomolino et al. 2017).

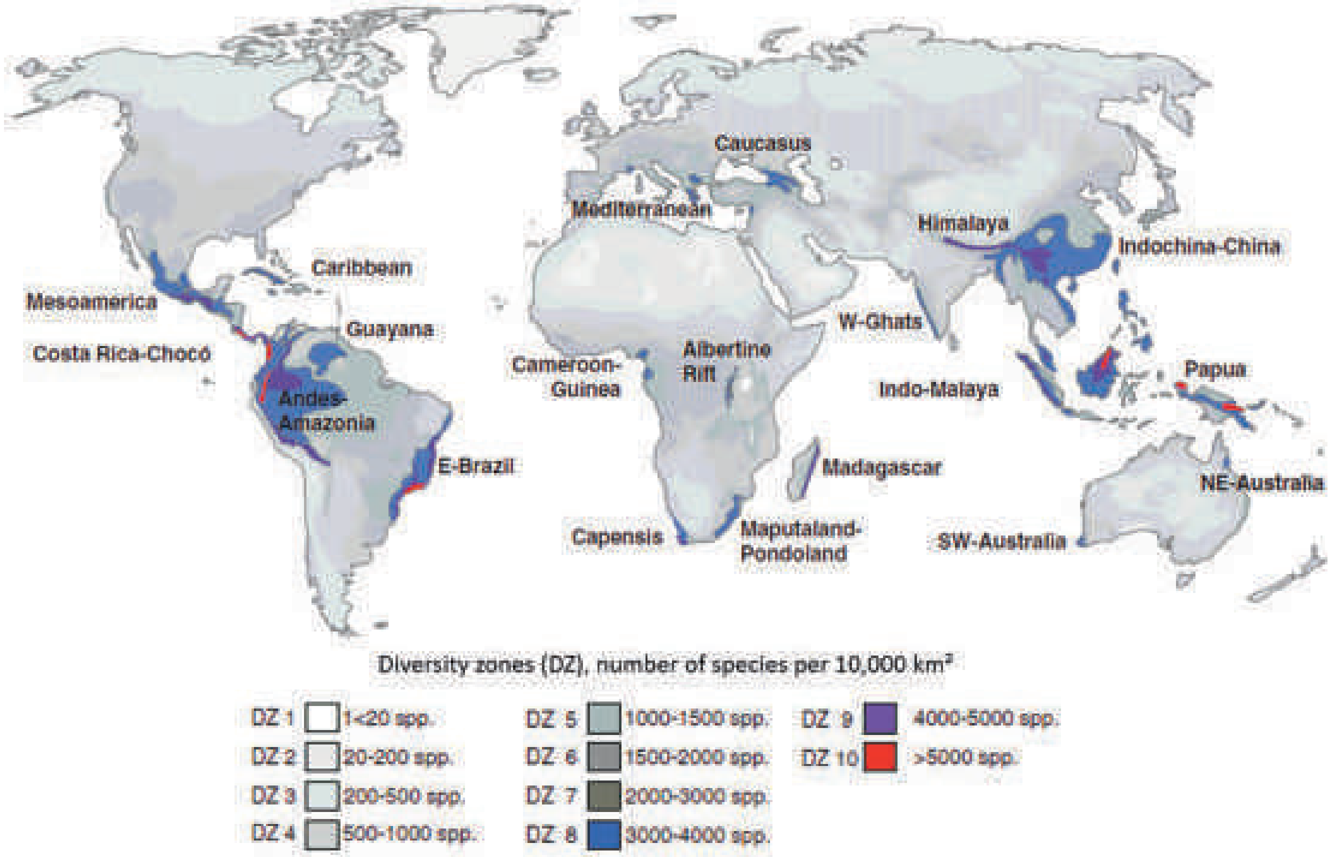

Fig. 1: Global distribution of vascular plant species richness, highlighting the 20 centres of highest species richness including the Sikkim-Himalaya (modified from MUTKE et al. 2011).

The mid-peak pattern is most widespread in non-flying small mammals and plants (Fig. 2). Several taxon- and life form-specific deviations from this general pattern were assessed (e.g., MUTKE 2011, KLUGE et al. 2017, LAIOLO et al. 2018), however, intermediate elevations show in general an optimal combination of many factors and processes involved in maintaining species populations of many taxonomic groups, in particular of plants. Regular elevational gradients in climatic conditions (energy- and humidity-driven variables, and related productivity), in geographic variables such as isolation and area of habitats, and in fundamental processes affecting diversity such as speciation, immigration, and extinction interfere at intermediate elevations to produce favourable conditions for higher species richness (LOMOLINO 2001, MCCAIN & GRYTNES 2010, LOMOLINO et al. 2017, RAHBEK et al. 2019, VETAAS et al. 2019).

In the past two decades, an increasing number of studies aimed at detecting elevational patterns of plant species richness in the Himalaya. Published results often correspond to the unimodal or hump-shaped pattern, the findings, however, show life form-specific differentiations, and are sometimes contradictory even within the same life form or plant functional type. Contrasting results may also become apparent when comparing plot-based field studies with studies based on metadata from published floras or plant lists. VETAAS & GRYTNES (2002) analysed plant lists of Nepal and found total richness showing a plateau-like mid-peak pattern along the elevation gradient from 1000 to 5000 m a.s.l., with a gentle decrease above 2500 m and a steep decrease above 4000 m. Endemic species had a clear, unimodal response along the gradient with a peak at higher elevations (between 3500 and 4500 m). Tree species in Nepal showed peak richness in the lower half of the elevational gradient, with richness increasing up to 1000 m and decreasing afterwards (BHATTARAI & VETAAS 2006), while the midpeak elevation of gymnosperms is at 3300 m (PANDEY et al. 2020). Tree species in Sikkim showed a comparable pattern, however, peak richness differed between 500 and 1500 m in two studies (ACHARYA et al. 2011a, RANA et al. 2019a). BHATTARAI et al. (2004) observed a unimodal relationship between species richness of ferns and elevation in Nepal, with a pronounced mid-elevation peak at 2000 m corresponding to an optimum interaction of energy- and moisture-related variables. Similar patterns were found for orchid species richness in the central and eastern Himalaya with a mid-elevation peak at 1600 m (ACHARYA et al. 2011b), and for liverworts, mosses, and lichens in Nepal with peaks at 2800 m, 2500 m, and 3100-3400 m, respectively (GRAU et al. 2007; BANIYA et al. 2010). OOMMEN & SHANKER (2005) reported a low-elevation plateau midpeak pattern for woody plant species in the western Himalaya. Along the elevational gradient in Nepal, water-related variables are more significant predictors of patterns of tropical genus diversity, while energy-related variables play a larger role for patterns of temperate genus diversity (LI & FENG 2015).
Based on a data set of c. 3900 plant species, KLUGE et al. (2017) analysed the entire flora of Bhutan along an elevational gradient up to 5800 m and found highest species richness at mid-elevations (1500-2000 m), with life form-specific peaks of richness increasing in elevation from trees over shrubs and herbs to graminoids. Endemic species richness peaks substantially higher (4500 m) than total species richness. MANISH et al. (2017) corroborated in a plot-based study along an elevational gradient from 300 to 5300 m in Sikkim more or less

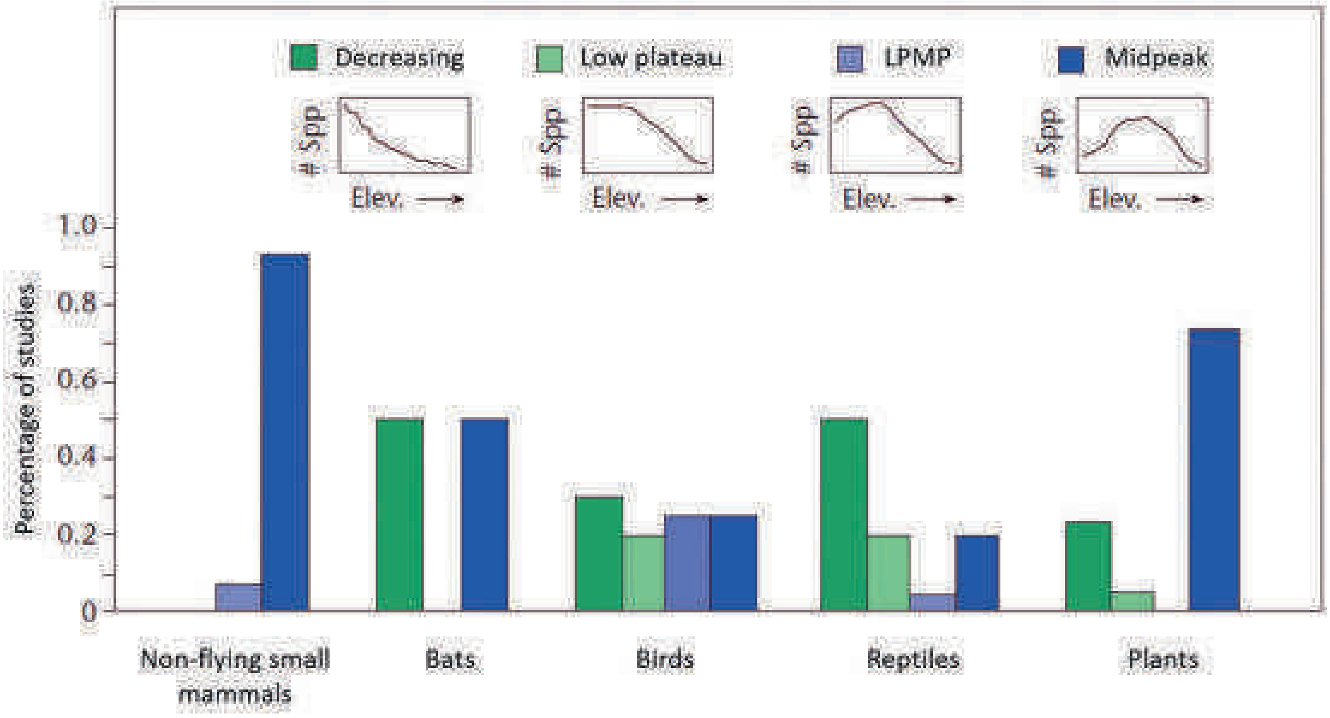

Fig. 2: The percentage of the four main richness patterns along elevational gradients in mountains across the globe, including decreasing (dark green), low-elevation plateau (light green), low-elevation plateau with a midpeak (LPMP, light blue), and midpeak (blue) for several taxonomic groups (modified from McCain & Grytnes 2010).

the findings of metadata analyses, showing a hump-shaped distribution and confirming that endemics peak at higher elevations than non-endemics across all growth forms. However, the mid-elevation peak of total species richness was found to be lower (1800 m) than in Nepal where it increases to 2500 m in West Nepal (Subedi et al. 2020). Rana et al. (2019b) compared elevational patterns of species richness along the Himalayan Arc and highlighted the east-west gradient of increasing midpeak elevation from c. 1000 up to 2500-3000 m, while the pronounced peak in species richness in the east is modified to a more plateau-like shape towards the northwest. Midpeak elevation increases again towards the Tibetan Plateau and in the Hengduan Mountains further east, where clear hump-shaped patterns were found (Liang et al. 2020, Sun et al. 2020, Yu et al. 2020). In a plot-based study in Sikkim, Sharma et al. (2019) detected a hump-shaped pattern with a mid-elevation peak around 1500 m. By contrast, a plot-based study by Nowak et al. (2021) showed a linear decrease of species density along an elevation gradient between 400 and 4100 m in northern Myanmar. Along this tree-dominated vegetation gradient, grasses show an increase with elevation, while epiphytes correspond to the hump-shaped pattern. A general problem of plot-based studies, in particular at elevations below 2000 m, is that elevational distribution patterns of plant species are substantially altered by pervasive human impacts, impeding meaningful discussions on relationships between species richness and elevation (Bhattarai & Vetaas 2003, Carpenter 2005, Miehe et al. 2015a, Long et al. 2018). More solidly grounded knowledge exists with regard to the elevational zonation of vegetation in the Himalaya, even though many small scale patterns and local characteristics are currently still unknown or have not yet been sufficiently documented (e.g., Yang et al. 2020). Pioneering works include the comprehensive accounts of Schweinfurth (1957) for the entire Himalayan Arc and of Champion et al. (1965), Champion & Seth (1968), Stainton (1972), Dobremez (1976), and Puri et al. (1983-89) for various subregions. Condensed overviews were provided by Miehe (1991, 2004). Expanding on these overviews, Miehe et al. (2015b) published the most detailed vegetation classification to date focusing on Nepal, but representing a vast part of the Himalayan mountain system. In Sikkim, systematic research on flora and vegetation started in the 19th century (e.g., Hooker 1849, 1852, 1854; Clarke 1877, Gammie 1894, King & Pantling 1898), followed by pioneering contributions by Smith & Cave (1911), Smith (1913), Lacaita (1916), Osmaston (1935), Wien (1937), Choudhury (1951), Rao (1963), Mehra & Bir (1964), and Troll (1967). Results of the botanical explorations have been incorporated in major floras of Sikkim and Bhutan (Hara 1966-1974, Biswas 1967, Grierson & Long 1983-2001, Hajra & Verma 1996, Srivastava 1998, Gogoi et al. 2021). In recent decades, numerous publications have been added, broadening the knowledge of plants, vegetation, biogeography and ecology of Sikkim (e.g., Singh & Sundriyal 2005, Chettri 2010, Tambe & Rawat 2010, Arrawatia & Tambe 2011, Telwala et al. 2013, Manish & Pandit 2018, 2019; Pandey et al. 2018a, Banerjee et al. 2019, Bhutia et al. 2019, Kandel et al. 2019). The state of research has improved in recent years, however, the variety of newer publications should not obscure the fact that the knowledge of biodiversity, vegetation ecology and biogeography is still very limited and that the Sikkim Himalaya has been much less intensively studied compared to Nepal or western Himalayan regions. At the same time, mountains of the world, the Himalayas in particular, are subjected to substantial and accelerating changes associated with effects of climate change and globalization (Schickhoff et al. 2021). In Sikkim, present-day plant assemblages and community structures are already substantially different from those of the past century (Telwala et al. 2013). Thus, this paper presents general findings and summarizes preliminary results of a reconnaissance field trip to Sikkim in 2015, conducted by a biogeography study group of the University of Hamburg, in order to contribute to the knowledge of vegetation-environment relationships along elevational gradients in Sikkim. Field data are complemented by evaluations of the spatial distribution and the elevational pattern of species richness, and of climate change impacts as particularly indicated by glacier recession. Embedded in this treatise on Sikkim is a case study in Khangchendzonga National Park.

Materials and methods

Study area

Sikkim, located in the eastern Himalaya between 27°05' – 28°09'N and 87°59' – 88°56'E, is the second smallest state of India with a size of 7,096 km² (Fig. 3). Sikkim has international borders with Nepal in the West, with the Tibet Autonomous Region in the North and Northeast, and with Bhutan in the East. Its only neighboring Indian state is West Bengal, adjoining to the South. The high-mountain topography and its biophysical conditions in Sikkim are outstanding, characterized by extreme elevational variation ranging from 244 m in the southern foothills to the towering heights of the Khangchendzonga massif at 8,586 m within a horizontal distance of less than 200 km (Hajra & Verma 1996). In total, 449 glaciers with an area of 705.54 km² cover the high elevation regions of Sikkim (Raina & Srivastava 2009). The Zemu is the largest glacier with an area of 80.75 ± 1.57 km² and 25.5 km length (Rashid & Majeed 2020). In 2017, a total of 466 glacial and high altitude lakes with an area of 31.24 km² were observed (Shukla et al. 2018). The ongoing climate change-induced glacier recession (Bolch et al. 2012; 2019; Hock et al. 2019) has led to an increase in number (~9%) and area (~24%) of glacial lakes in the region (Shukla et al. 2018).

The climate of Sikkim is largely dominated by the Indian summer monsoon, and characterized by the alteration between wet and dry seasons, typical for Asia's monsoonal climates. Sikkim is located in a transitional zone between the monsoon-dominated lowlands of India and the cold and dry highlands of Tibet, however, influenced by the close proximity to the Bay of Bengal, Sikkim is one of the most humid regions in the Himalayas with mean annual precipitation of 2,000 to 3,000 mm on the Himalayan south slope (cf. Böhner et al. 2015). More than 80% of the annual precipitation is received during the monsoon season (June to September). Recent studies highlighted the vulnerability of the eastern Himalayan region in the course of climate change (Bawa & Ingty 2012; Kumar et al. 2020; Kumre et al. 2020; Arora et al. 2021; Basu et al. 2021). The warming trend in Sikkim has accelerated, average warming rates are 0.2°C per decade over the period 1951-2014 (Krishnan et al. 2019; Chettri et al. 2020).
Being a small state, Sikkim is endowed with extremely rich geodiversity and supports an extraordinarily high biological diversity. Over short horizontal distances, the vegetation changes from tropical forests in the Himalayan foothills to patches of uppermost flowering plants in alpine deserts (Rawat & Tambe 2011; Kandel et al. 2019). At present, an area of c. 5,800 km² in Sikkim is covered with forests, which is 82% of the geographical area of the state (Forest Survey of India 2019). About 30% of the state's area is included in the protected area network (strict categories). The Khangchendzonga Biosphere Reserve (KBR), located in the two districts of North and West Sikkim, was formed in the year 2000. It has a total area of 1,784 km², and an additional buffer zone area of 826 km², thus representing 37% of the total area of Sikkim. The Khangchendzonga National Park (KNP), where the vegetation sampling along the Yoksum-Dzongri-Goecha La-Trail took place, is included in the KBR. In recent years, effects of land use, tourism development and climate change have increased remarkably, posing threats to the rich biological diversity of

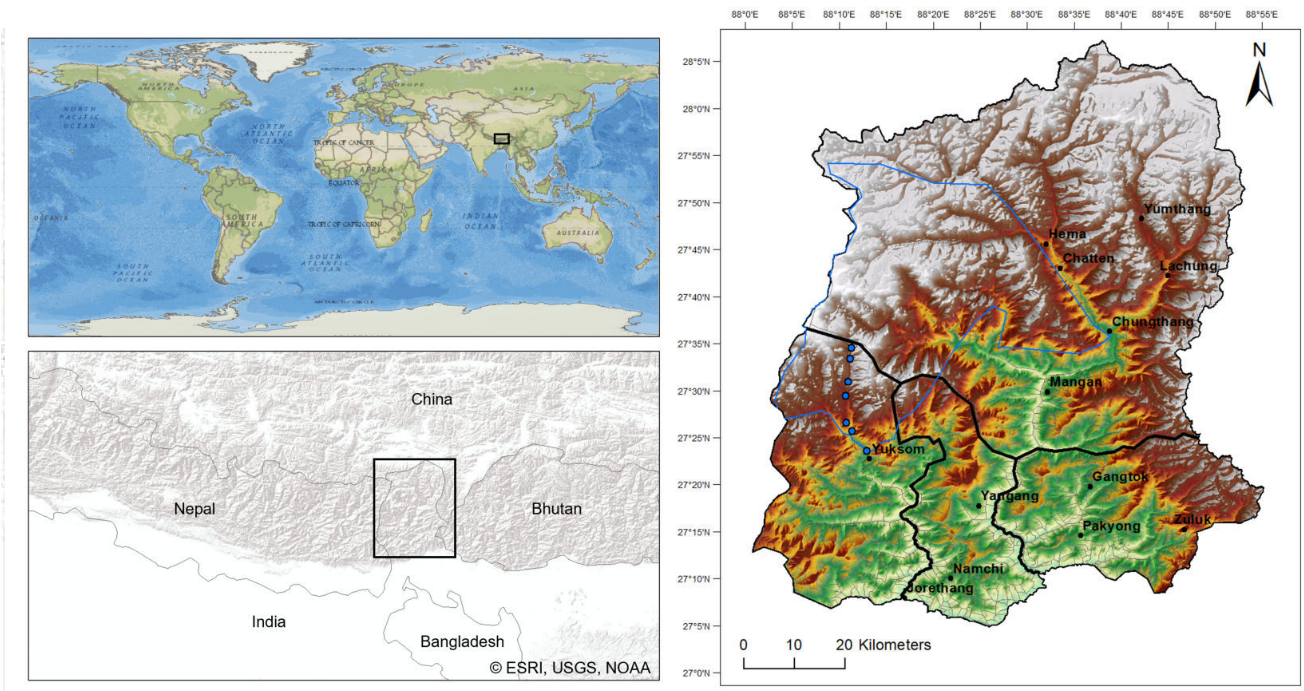

Fig. 3: Map of the study area Sikkim (left) including the sampling locations in the Khangchendzonga National Park (right). Blue dots represent quadrats of 10 m x 10 m size for floristic inventory and soil data collection (n = 7) across the altitudinal gradient from 1800 m asl to 4600 m asl.

the KBR (Maity & Maiti 2009; Dinda 2013). In general, fragmentation and loss of natural habitats and related forest degradation and biodiversity decline is increasingly observed in Sikkim, primarily linked to rapid population growth, construction of roads and hydropower projects, and intensified land uses (Singh & Chauhan 1999; Forest Survey of India 2019). The conservation corridors between the protected areas and their transition zones, also transboundary, are vital for the protection of forests and biodiversity in the region. The cooperation of governmental and non-governmental institutions, global conserving institutions and local communities is considered to be of prime importance for the success of conservation projects (Chettri et al. 2008, Sharma 2008, Chettri 2011)

Field sampling and data analysis

Field sampling took place during a reconnaissance field trip to Sikkim in March 2015 (Fig. 4). Along the Yoksum-Dzongri-Goecha La-Trail in the KNP we placed seven plots at irregular distances in order to cover the major vegetation types and elevational zones along the elevational gradient from c. 1800 m to c. 4600 m. The selection of plot sites was based on subjective sampling. We surveyed potential plot sites and selected sites providing the best representation of the vegetation of the respective elevational zone, bearing in mind the accessibility which is often constrained due to excessively steep slopes. We excluded sites disturbed by human impact and placed sampling plots at a sufficient distance from the trail (at least 10 m) to avoid edge effects. At each site we delimited a square-shaped 100-m² plot. We collected the following structural and environmental variables: snow cover, rock cover, moss cover, and total vegetation cover plus slope inclination and slope aspect. Coordinates and elevation were determined for each 100 m² plot with a hand-held GPS (global positioning device). At each plot, we took a soil sample from the top 10 cm, which was then air dried for further analysis conducted in the laboratory of the Bayreuth Center of Ecology and Environmental Research (BayCEER) of the University of Bayreuth. Analysed soil chemical parameters included pH, C, C_{org}, N, Al, Fe, P, K, Mg, Mn, Cu, B, and Mo as well as H+ (cation exchange capacity), Al3+, Ca2+, Fe3+, K+, Mg2+, Mn2+, and Na+. We collected phytosociological data including a detailed inventarisation of all vascular plants following the Braun-Blanquet approach (Braun-Blanquet 1964; Kent 2012). However, we did not use the Braun-Blanquet cover-abundance scale, but estimated cover values in percentages (+, 3, 5, 10, 20, 30, 40, …). A voucher specimen of each species was collected for final identification. We identified some of the samples in the field, however, the final identification of the majority of the collected specimen was conducted in the herbarium collection of the Royal Botanic Garden Edinburgh using the ‘Flora of Bhutan’ (Grierson & Long 1983-2001) as support.

The elevational occurrence of each species was analysed using the information in the ‘Flora of Bhutan’ (Grierson & Long 1983-2001). For the phytogeographic analysis and the assignment of plant species to floristic regions we used the classifications of Takhtajan (1986) and Miehe et al. (2015a). For the visualization of results we used R (R Core Team 2020). To capture the current climate we used CHELSA climate data (Karger et al. 2017), which has been shown to be superior to other global climate data sets for the Himalayan region (Bobrowski et al. 2021). For each plot we extracted the following values to characterize the prevailing climate conditions: mean annual temperature, mean temperature of the growing season, annual precipitation sums, and average winter precipitation.

The database of species richness in Sikkim has been produced evaluating published floras of Bhutan and Sikkim (Grierson & Long 1983-2001, Hajra & Verma 1996) and secondary sources (Singh & Dash 2002). The database contains 5,087 vascular plant species of Sikkim, and includes information on family, habitat, elevational distribution, and phytogeography. Information on elevational distribution in different floras was not always congruent. To solve this problem, data of the same species were combined. We produced a species richness map based on our database using SAGA GIS 6.3.0. For 440 species information on elevational distribution was missing, thus 4,647 species were used for respective evaluations.

Results and discussion

Elevational zonation of vegetation and patterns of species richness

Located in the Himalayan Biodiversity Hotspot at the juncture of the Malesian, Palearctic and Sino-Japanese realms, Sikkim is one of the biologically richest subregions of the Himalaya, including high levels of both species richness and endemism (cf. Takhtajan 1986, Olson et al. 2001, Wambulwa et al. 2021). The rich diversity of flora and fauna is related to the complex topography in Sikkim and the associated high levels of geodiversity (Jahan et al. 2017). In mountain environments in general, steep climatic gradients over a very short vertical distance primarily cause a distinct elevational zonation of vegetation. The vertical thermal gradient represents a change in temperature conditions otherwise only observed over a vast latitudinal distance. At a global scale, the zonation into elevational vegetation zones is primarily a response to the elevational lapse rate of temperature. The approximately parallel course of the snow line, the alpine treeline, other elevational vegetation limits and their correspondence to temperature conditions suggest that heat deficiency generally determines this elevational configuration (Schickhoff 2011b). When ascending mountains of temperate midlatitudes, the colline (submontane), montane, subalpine, alpine, subnival, and nival vegetation zones can usually be differentiated according to structural and floristic patterns of plant formations. The treeline separates the subalpine from the alpine zone. However, this elevational zonation pattern is not easily transferable to mountains in other ecozones. Specific regional terms of elevational vegetation zones (see examples in Richter 2001) are more suitable for global comparisons.

Along the elevational gradient in Sikkim, the vegetation can be broadly differentiated into tropical forests (hill zone), subtropical forests (submontane zone), warm/cool temperate forests (lower montane zone), cold temperate forests (upper montane or subalpine zone), and alpine dwarf thickets and grasslands (alpine and subnival zones) (Table 1; see also Bhutia et al. 2019, Kandel et al. 2019). Tropical moist and dry forests are confined to elevations below 1000 m a.s.l., i.e below the lower limit of frost. Where the natural plant cover in this hill zone has not been replaced by terraced fields or degraded commons,

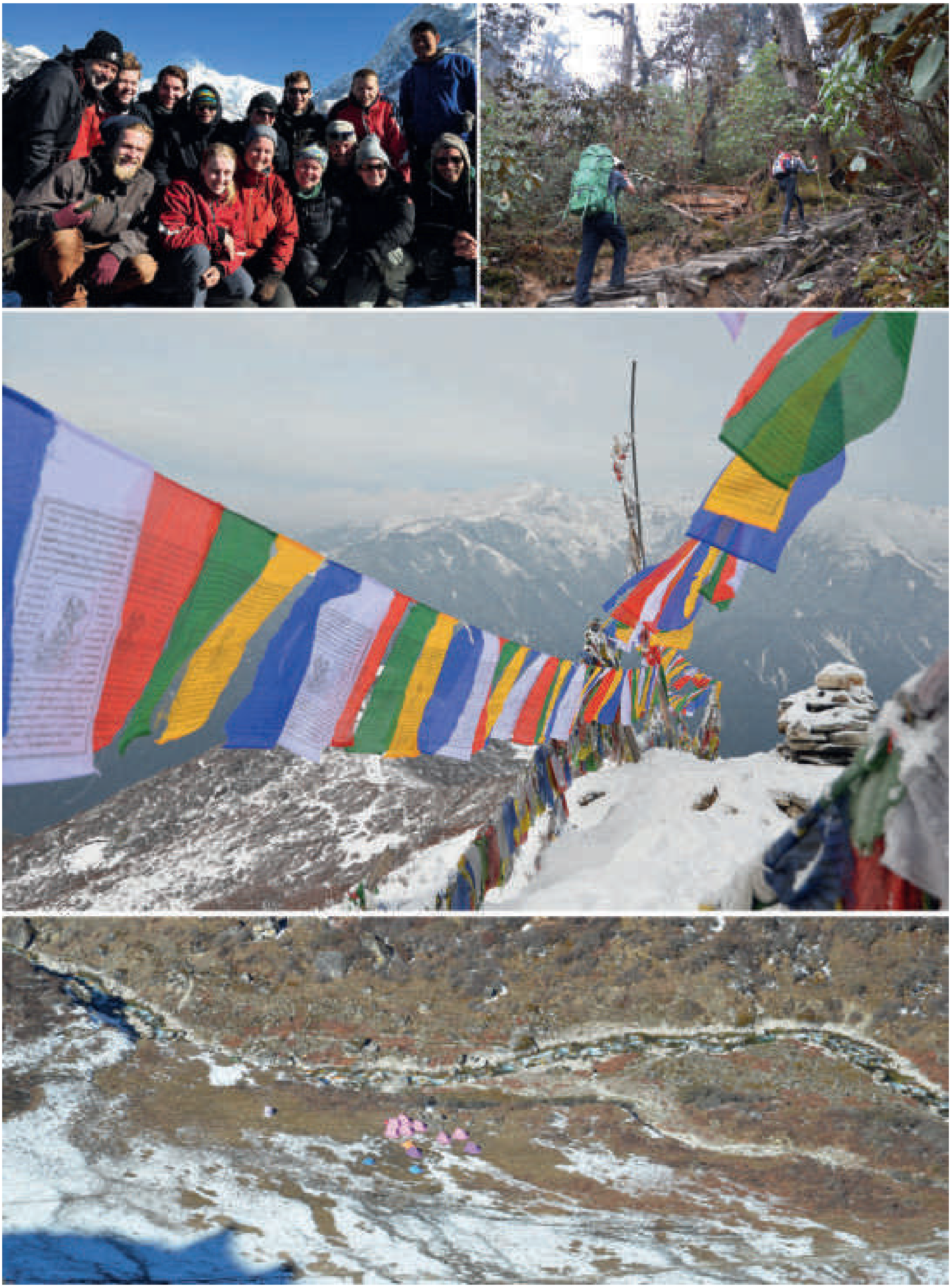

Fig. 4: Reconnaissance field trip to the Khangchendzonga National Park in Sikkim (India) in the eastern Himalaya in 2015 - initiated by the University of Hamburg with students and scientists around Prof. U. Schickhoff (Photographs: A. Jentsch).

large tracts are covered by dense broadleaved evergreen and semi-evergreen forests, receiving up to 5000 mm of summer rainfall, thus representing the world's northernmost tropical rainforests (cf. Miehe et al. 2015b). *Shorea robusta* (Dipterocarpaceae) forests are widespread, in particular along the Teesta and Rangit rivers. Other common tree species include *Lagerstroemia parviflora*, *Bombax ceiba*, and *Terminalia* spp. The undergrowth is often luxuriant, epiphytic orchids are common, and occasionally tree ferns (*Cyathea* spp.) and screw pines (*Pandanus nepalensis*) occur. In the submontane zone between 1000 and 2000 m, these forests grade into subtropical forests which are mainly characterized by laurophyllous tree species such as *Schima wallichii* (Theaceae), *Castanopsis* spp. (Fagaceae), *Engelhardia spicata* (Juglandaceae), *Machilus odoratissima* (Lauraceae), *Eurya acuminata* (Pentaphylacaceae), *Macaranga pustulata* (Euphorbiaceae), a prolific growth of shrubs, herbs and ferns on the forest floor, and a larger number of epiphytes (orchids, ferns) with increasing elevation. However, the subtropical broadleaved evergreen forests have been largely converted to terraced fields or settlement areas and occur as relict forests on steep, shady slopes or in protected areas only. In the upper submontane and lower montane zones, *Alnus nepalensis* groves are common on landslide areas and in deeply incised ravines. In drier valleys, patches of chir pine forests (*Pinus roxburghii*) occasionally occur.

Warm temperate forests (lower cloud forests) and cool temperate forests (middle cloud forests) constitute the natural vegetation of the lower montane zone between 2000 and 3000 m. The lower cloud forests (2000-2500 m) indicate the average elevation of the lower condensation level of the cloud belt, and are still dominated by broadleaved trees, in particular by Fagaceae spp. (*Quercus lamellosa*, *Lithocarpus pachyphylla*, *Castanopsis tribuloides*), Lauraceae spp. (*Litsea sericea*, *Machilus odoratissima*) and other laurophyllous species (*Symplocos ramosissima*, *Magnolia doltsopa*, *Ilex dipyrena*) (cf. Dash & Singh 2011). Trees are covered with epiphytic ferns, orchids, foliose lichens and mosses. Humidity and cloudiness further increase in the middle cloud forest zone (2500-3000 m), indicated by the trees being clad with epiphytes, in particular with pending mosses. Fagaceae spp. (*Quercus lamellosa*, *Lithocarpus pachyphylla*, *Quercus semecarpifolia*) dominate the upper tree layer, coniferous species (in particular *Tsuga dumosa*) and *Rhododendron* spp. become more prominent, while Lauraceae spp. in the understorey decrease in density and abundance. In the upper cloud forests in the upper montane or subalpine zone between 3000 and 4000 m, the oaks are gradually replaced by conifers (*Abies densa*) in the upper tree layer and *Rhododendron* spp. in the understorey. With increasing elevation, in particular above the zone of the summer rain maximum (roughly between 2500 and 3500 m), epiphytic diversity decreases, with trunks and branches of trees now being predominantly covered by liverworts. The treeline ecotone is characterized by the prevalence of *Rhododendron* (*R. grande*, *R. wightii*, *R. campanulatum*) (Rawat & Tambe 2011) and uppermost *Abies densa* stands which become fragmented into patches towards the treeline at c. 4000 m. Along the Himalayan NW-SE gradient of decreasing winter cold and increasing humidity levels, north-facing slopes show a floristic change from deciduous *Betula utilis*- to evergreen *Rhododendron*-dominated alpine treelines, associated with the increasingly less continental climatic conditions (Schickhoff 2005). In Sikkim, *Betula utilis* is no longer the principal treeline species (cf. Pandey et al. 2018b). *Juniperus* groves occur on sunny slopes in the treeline ecotone. Above the upper limit of trees and taller shrubs, i.e. in the alpine and subnival zones (above 4000 m), the vegetation is dominated by alpine dwarf thickets and grasslands. *Rhododendron* dwarf shrub heaths (*R. setosum*, *R. anthopogon*, *R. lepidotum*) are more widespread in the lower alpine zone and on shady slopes, while in the upper alpine zone and on sunny slopes Cyperaceae mats (in particular *Kobresia nepalensis*) with many species of the genera *Carex*, *Bistorta*, *Potentilla*, *Primula*, *Ranunculus* and others become dominant. The closed vegetation cover becomes fragmented into patches of turf and isolated cushions in the subnival zone. Only a few plant individuals occur in sheltered habitats of rock outcrops at even higher elevations. The spatial differentiation of the elevational vegetation zonation in Sikkim (Fig. 5) illustrates the contrast between the prevalence of tropical, subtropical, and warm/cool temperate forests in the South and the dominance of vegetation of the alpine, subnival and nival zones in the North.

From a systematic evaluation of data on the flora of Sikkim (Grierson & Long 1983-2001, Hajra & Verma 1996, Singh & Dash 2002) we obtained the high total number of 5087 vascular plant species, distributed over 1514 genera of 236 families. Thus, the total number of plant species in Sikkim is not much lower than in Bhutan (5500 species, Grierson & Long 1983-2001) or in Nepal (6200 species, Press et al. 2000). A recent study in the Khangchendzonga Landscape which includes Sikkim and adjoining parts of eastern Nepal, northern Bengal, and western Bhutan found a total number of appromixately 5200 seed plant species (Kandel et al. 2019). The most species-rich families in Sikkim are Orchidaceae, Poaceae, Asteraceae, Cyperaceae, Fabaceae, Rubiaceae, Rosaceae, Scrophulariaceae, Primulaceae, Gentianaceae, Euphorbiaceae, Ranunculaceae, and Lauraceae (Fig. 6), while *Carex* (Cyperaceae) and *Primula* (Primulaceae) are the most species-rich genera, followed by *Saxifraga* (Saxifragaceae), *Juncus* (Juncaceae), and *Pedicularis* (Orobanchaceae) (Fig. 7). Orchidaceae species (in particular epiphytic orchids) are very widespread in the tropical and subtropical forests up to the lower cloud forest zone (Table 2). A similar pattern was found for the species of Rubiaceae, Euphorbiaceae, and Asclepiadaceae which are families having core distribution areas in subtropical and tropical habitats. Species of Poaceae, Cyperaceae, Fabaceae, and Asteraceae are common throughout all elevational zones, while families representing a typical Holarctic distribution such as Ranunculaceae, Primulaceae, Gentianaceae, and Rosaceae are more strongly represented at higher elevations (cf. Table 2).

The elevational species richness pattern we found in Sikkim corroborates the results of the majority of previous studies in the central and eastern Himalaya and other low latitude mountains. Species richness increases to mid-elevations which show the highest species richness (1000-1500 m: 1695 species; 1500-2000 m: 1751 species), before gently decreasing again, with a steeper decrease above 4000 m. At higher elevations, the number of vascular plant species further declines, with only 167 species occurring above 5000 m. Thus, along the elevational gradient a hump-shaped pattern of species richness can be identified, more specifically a plateau-like mid-peak pattern (Fig. 8). The elevational species richness of most of the

Table 1: Elevational zonation of vegetation in Sikkim (based on field notes of authors and Hajra & Verma 1996, Miehe et al. 2015b).

Vegetation	Elevational zone	Characteristic species
Tropical deciduous / evergreen forests	Hill; up to 900-1000 m	*Shorea robusta, Dillenia pentagyna, Lagerstroemia parviflora, Bombax ceiba, Terminalia tomentosa, Bauhinia variegata, Cedrela toona, Stereospermum tetragonum, Adina cordifolia*
Subtropical deciduous / evergreen forests	Submontane; 1000-2000 m	*Schima wallichii, Castanopsis tribuloides, Castanopsis indica, Engelhardia spicata, Phoebe hainesiana, Macaranga pustulata, Machilus odoratissima, Quercus glauca, Toona ciliata, Alnus nepalensis*
Warm/cool temperate deciduous / evergreen forests (lower/ middle cloud forests)	Lower montane; 2000-3000 m	*Quercus lamellosa, Lithocarpus pachyphylla, Ilex dipyrena, Rhododendron arboreum, Magnolia doltsopa, Castanopsis tribuloides, Betula alnoides, Acer campbellii, Quercus semecarpifolia, Tsuga dumosa*
Cold temperate deciduous / evergreen forests (upper cloud forests)	Upper montane (subalpine); 3000-4000 m	*Abies densa, Rhododendron hodgsonii, Betula utilis, Acer caudatum, Rhododendron campanulatum, Rhododendron wightii, Prunus rufa, Juniperus indica, Larix griffithiana*
Alpine dwarf thickets and grasslands	Alpine/subnival; above 4000 m	*Rhododendron setosum, Rhododendron anthopogon, Cassiope fastigiata, Kobresia nepalensis, Bistorta vivipara, Bistorta macrophylla, Rhodiola* spp., *Potentilla* spp., *Carex* spp., *Primula* spp.

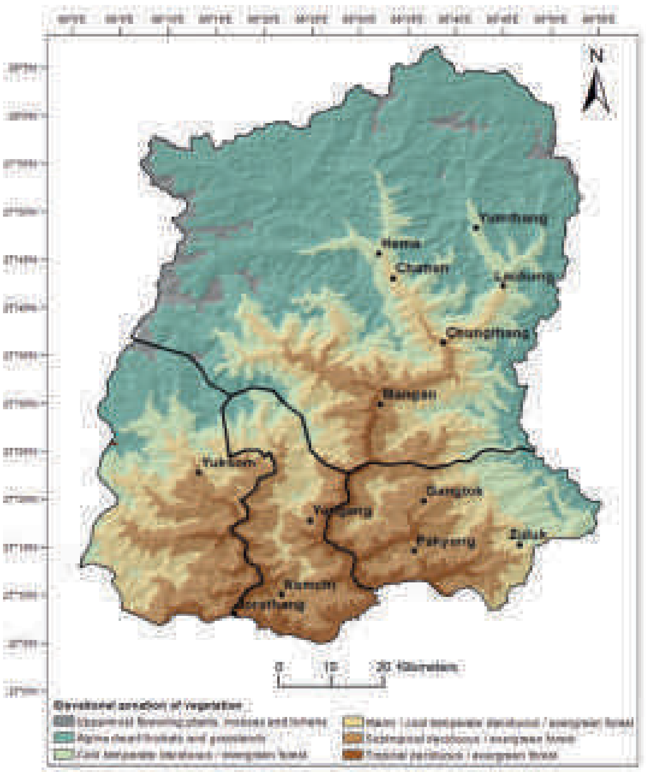

Fig. 5: Elevational zonation of vegetation in Sikkim (extension of elevational zones according to Table 1) (modified from Jahan et al. 2017).

different life forms resembles this pattern, with trees, shrubs, and lianas having their peak richness shifted towards lower elevations (Fig. 9). Herbs exhibit a different pattern along the elevational gradient. As already highlighted by Kluge et al. (2017), the richness of herbs shows a wide peak plateau between c. 2000 and 4000 m with a maximum richness around 4000 m (cf. Fig. 9). Thus, herbs are the dominant life form above the treeline, followed by graminoids whose richness gains dominance over those of shrubs and trees above 3500 m. The species richness of epiphytes (vascular plants) decreases significantly in the middle cloud forest zone above 2500 m. The spatial distribution of species richness (Fig. 10) illustrates the contrast between the species-rich southern valleys and the species-poor high-elevation areas in western and northern Sikkim.

The mid-elevation species richness peak and decreasing richness values towards both ends of the elevational gradient correspond to findings of previous studies in the central and eastern Himalaya (Vetaas & Grytnes 2002, Li & Feng 2015, Kluge et al. 2017, Manish et al. 2017, Sun et al. 2020). As obvious from the elevational vegetation zonation, the mid-elevation peak in species richness shows an elevational coincidence with subtropical and lower cloud forest zones which are particularly species-rich (Miehe et al. 2015a). We have not yet conducted statistical correlations between the species richness pattern and explanatory factors, however, taking into account the elevational trends of climatic variables (Fig. 11) it may well be assumed that the optimal constellation of energy- and moisture-related variables in the submontane and lower montane zones explains the outstanding species richness in these elevational bands. Here, the temperature is in an optimal range (neither extremes of high energy input nor stressful frost events), the mean growing season temperature varies between 20 and 25 °C, and there is still a maximum number of growing degree days (cf. Fig. 11). Simultaneously, the annual precipitation which is dominated by the monsoon regime active during the growing season is more than sufficient (between 2000 and 2500 mm), resulting in a favourable water balance at mid-elevations. As recently highlighted by Miehe et al. (2015a), Kluge et al. (2017), and Sun et al. (2020), the constellation of high rainfall, moderately high temperature and the absence of severe frosts, i.e. the maximum productive water-energy ratio available in the ecosystem (cf. Vetaas et al. 2019), is the principal driver of the peak richness at mid-elevations where biological processes are least limited and where more species are allowed to coexist. However, the elevational richness gradient is not only influenced by ecological site factors. Maximum species richness also shows an elevational coincidence with the floristic overlap of tropical and temperate species, suggesting that evolutionary history plays a role in shaping the species richness gradient (Li & Feng 2015; Kluge et al. 2017; Sun et al. 2020). For instance, the maximum old (more ancestral) taxa (endemic species) of the majority of growth forms are

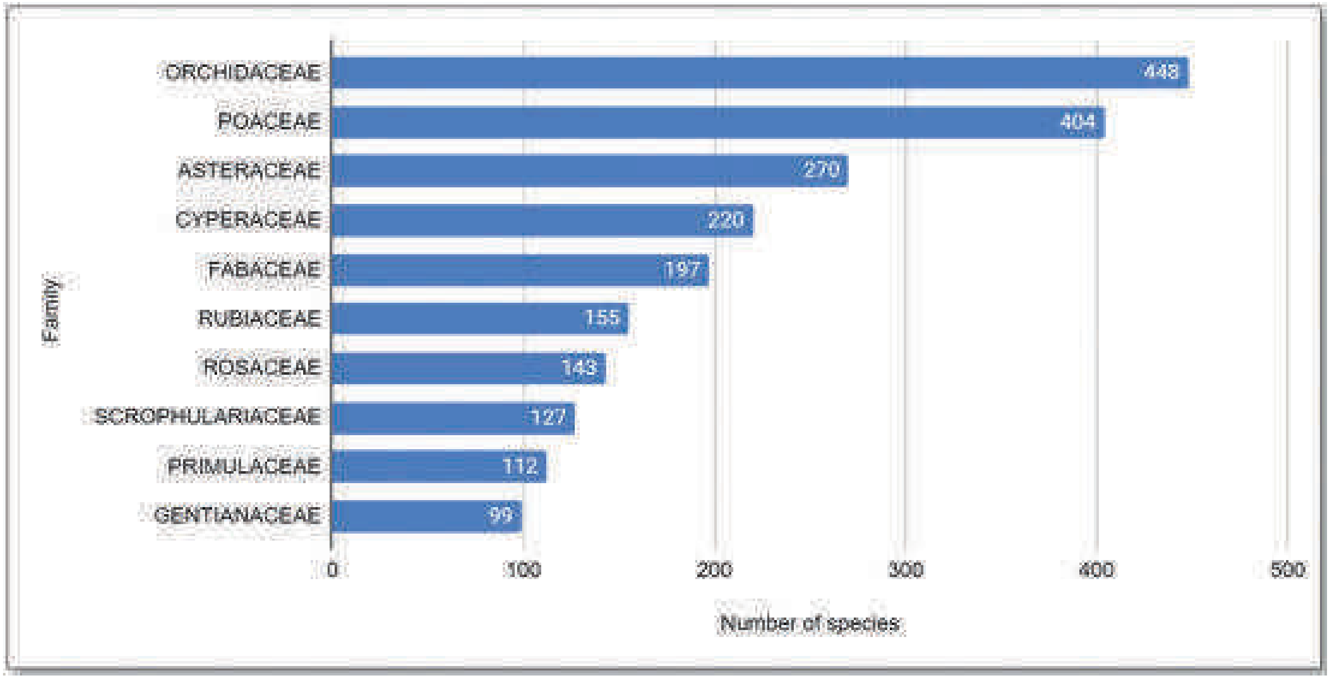

Fig. 6: The ten most species-rich families of the Sikkim flora (vascular plant species).

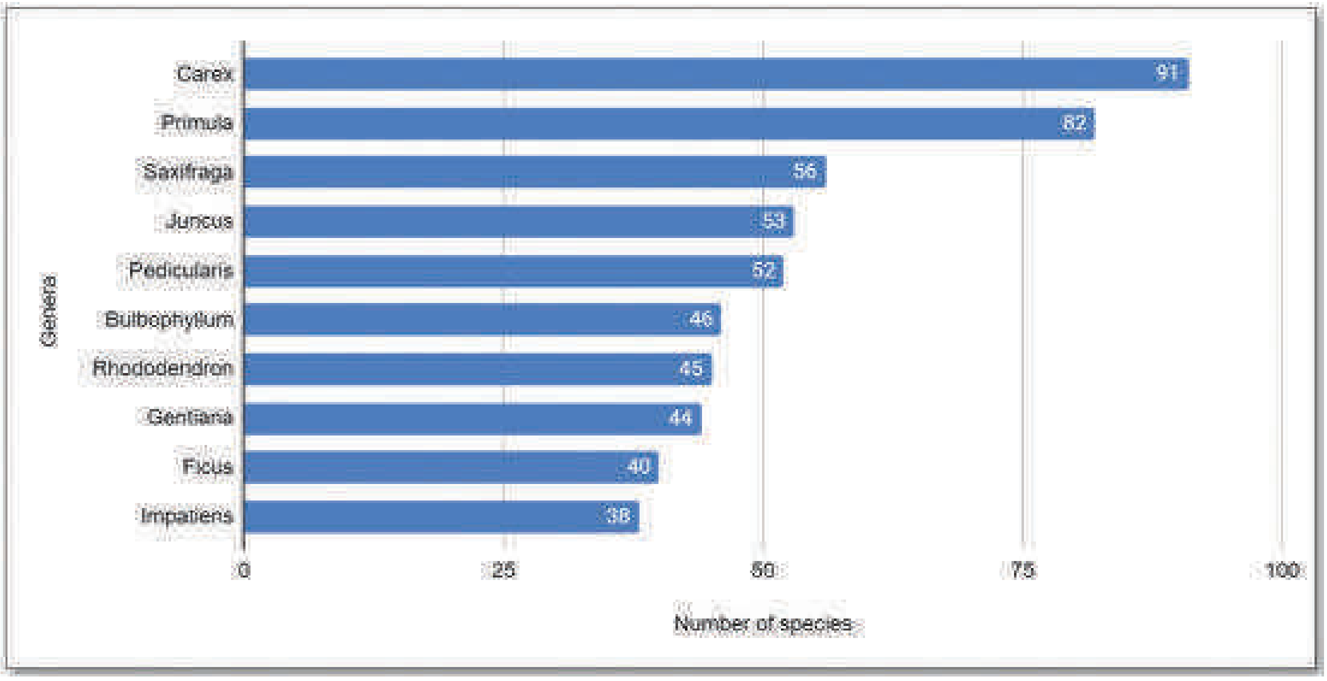

Fig. 7: The ten most species-rich genera of the Sikkim flora (vascular plant species).

present at mid-elevations in Sikkim (Manish & Pandit 2018), while endemic species richness peaks at higher elevations than non-endemic species richness (Kluge et al. 2017; Manish et al. 2017). In addition, spatially related variables such as the decrease of available habitat area with increasing elevation and the mid-domain effect need to be taken into account to provide a comprehensive explanation of the elevational richness gradient.

Case study: Khangchendzonga National Park

The plot-based analysis of vegetation and environmental variables along the elevational gradient from 1800 to 4600 m reflected substantial changes in habitat conditions as well as a steep turnover in species composition. The mean annual temperature and the mean growing season temperature decrease from 13°C (Plot 1; 1883 m) to below 1°C (Plot 7; 4578 m) and from c. 19°C to c. 8°C, respectively (Table 3). By contrast, annual precipitation and average winter precipitation sums show insignificant changes only. Annual precipitation is in the range of 2600-3200 mm. Edaphic conditions were found to fluctuate along the elevational gradient from tropical forests to the alpine treeline. However, it is obvious that nutrient availability in soils significantly decreases above 4000 m (above

Table 2: Distribution of species numbers of the most species-rich families along the elevational gradient in Sikkim (*Scrophulariaceae* not split up).

No.	Family	Elevation above sea level (in meter)					
		<=1000	1001-2000	2001-3000	3001-4000	4001-5000	5001-6000
1	ORCHIDACEAE	158	205	85	42	5	0
2	POACEAE	107	142	107	72	55	15
3	FABACEAE	91	74	36	19	12	0
4	RUBIACEAE	91	89	40	16	3	0
5	CYPERACEAE	76	83	85	96	55	14
6	ASTERACEAE	72	104	96	120	100	28
7	EUPHORBIACEAE	72	45	9	3	1	0
8	ASCLEPIADACEAE	41	36	18	2	0	0
9	SCROPHULARIACEAE	39	36	44	59	57	8
10	ROSACEAE	11	35	87	69	39	2
11	PRIMULACEAE	5	17	32	75	66	1
12	LAMIACEAE	11	17	15	13	10	2
13	GENTIANACEAE	5	15	24	60	58	14
14	BORAGINACEAE	12	17	17	23	22	9
15	RANUNCULACEAE	4	13	29	48	37	1

treeline), in particular nitrogen and phosphorus availability, along with a steep decline in carbon and organic matter contents while base saturation and cation exchange capacity are sufficient (cf. Table 3). Soil C:N ratios increase towards the *Rhododendron* krummholz and the alpine dwarf thickets and grasslands. Low nitrogen and phosphorus availability in soils above the treeline is likely caused by a lower litter input from dwarf shrub and grassland vegetation, and a decline in litter mineralization in this elevational zone resulting in small accumulations of soil organic matter. Nutrient availability above the treeline appears to be not limited by low soil pH (cf. Table 3). The species inventory of the seven plots (Table 4) indicates that the floristic overlap between the plots is very low, only a limited number of species has occurrences in more than one plot. Even on the family level, floristic similarities between the seven plots are rather low.

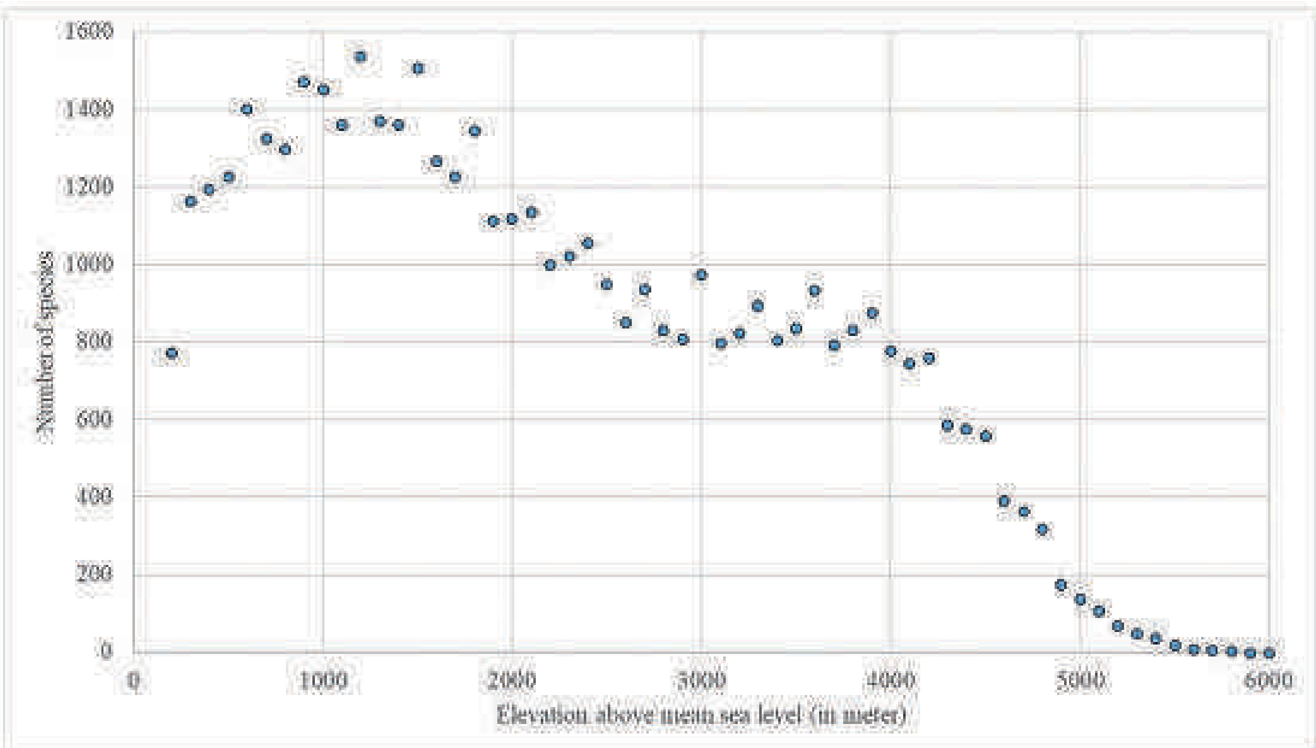

Fig. 8: Elevational species richness based on all vascular plant species in Sikkim (modified from Jahan et al. 2017).

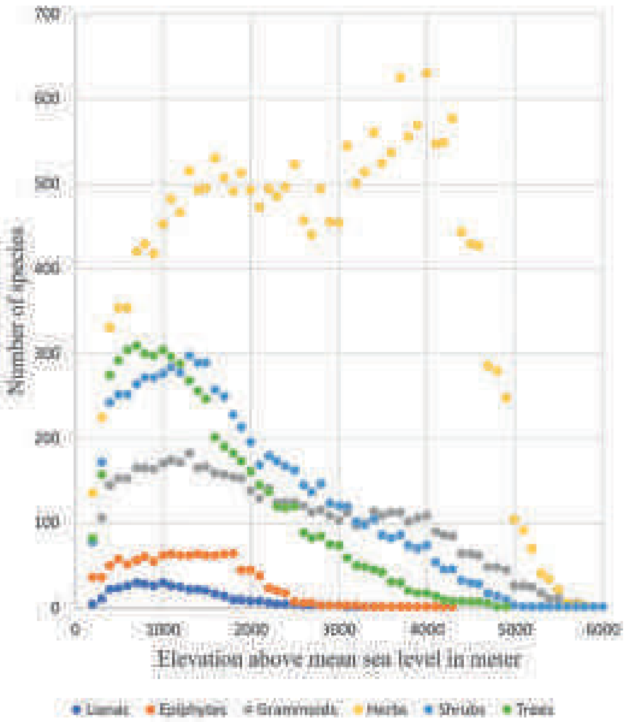

Fig. 9: Elevational species richness of different life forms in Sikkim.

Plot 1 – Subtropical forest (submontane zone)

The lowermost plot (1883 m) represents the upper subtropical forests in the transition zone to the lower cloud forests (Fig. 12). *Castanopsis hystrix* (Fagaceae) is the dominant tree species, forming 70% of the upper canopy, associated with Lauraceae spp. (*Cinnamomum tamala*, *Litsea albescens*) and *Macaranga pustulata* (Euphorbiaceae) in the understorey as well as abundant lianas (*Rhaphidophora grandis*, *Tetrastigma serrulatum*) and epiphytic ferns (*Vittaria elongata*, *Microsorum punctatum*, *Hymenophyllum simosianum*). The trees reach an average height of 20 to 30 m, occasionally up to 50 m. The elevational distribution of the species of Plot 1 (Fig. 13) underlines the transitional character of this forest between the upper subtropical and the lower cloud forest zone: The distribution of the majority of species extends well into the lower cloud forest. A transitional character is also obvious in terms of the phytogeography of the recorded species (Fig. 14). Sikkim is located at the transition area between the Holarctic Kingdom and the Palaeotropic Kingdom and at the crossroads between the Sino-Japanese, the Central Asian, the Irano-Turanian, the Indian, and the Indo-Chinese Floristic Region (Takhtajan 1986, Miehe et al. 2015a). While Holarctic species dominate throughout the elevational gradient, the species of Plot 1 are

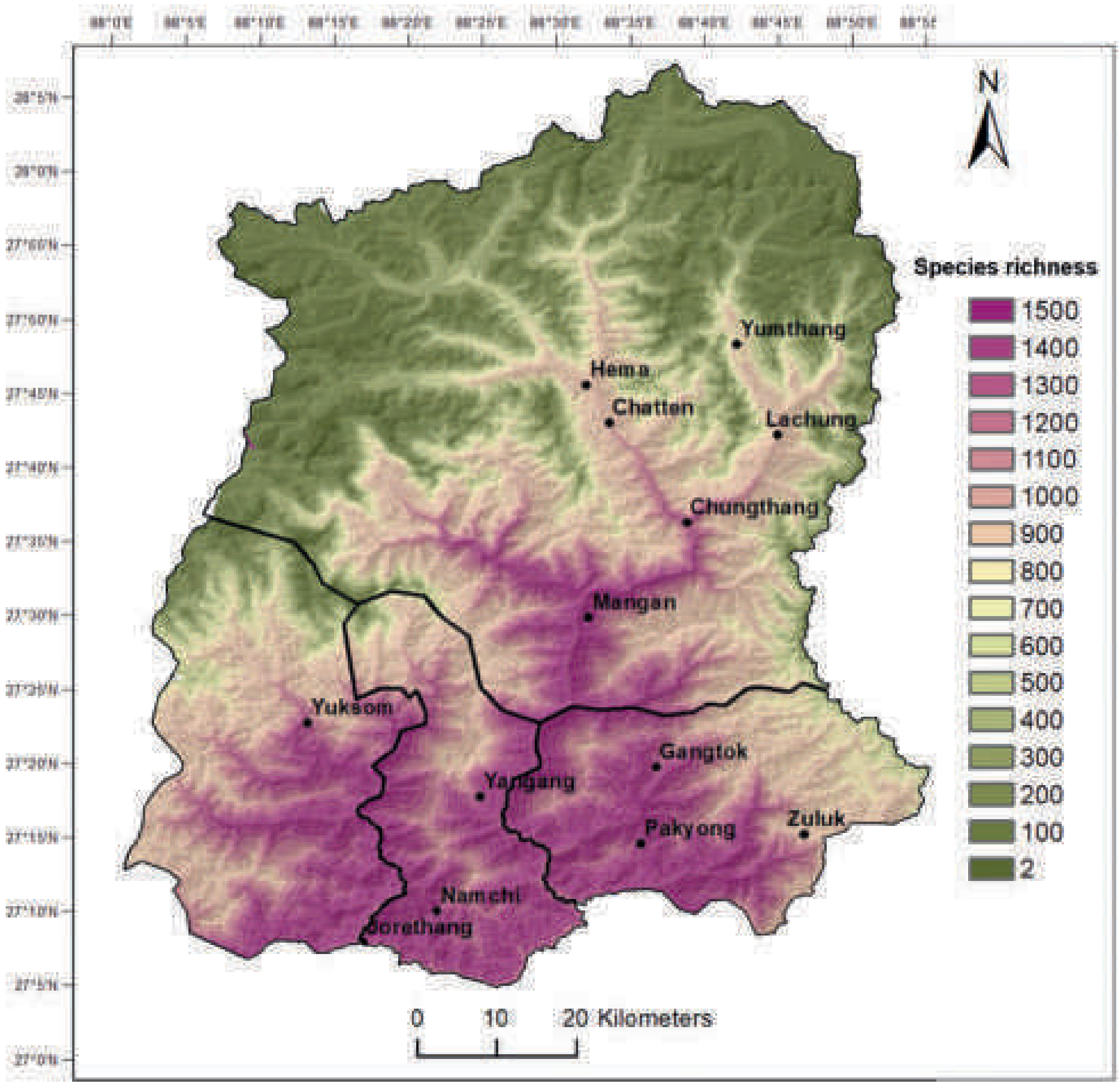

Fig. 10: Spatial distribution of species richness in Sikkim (elevational bands of 100 m).

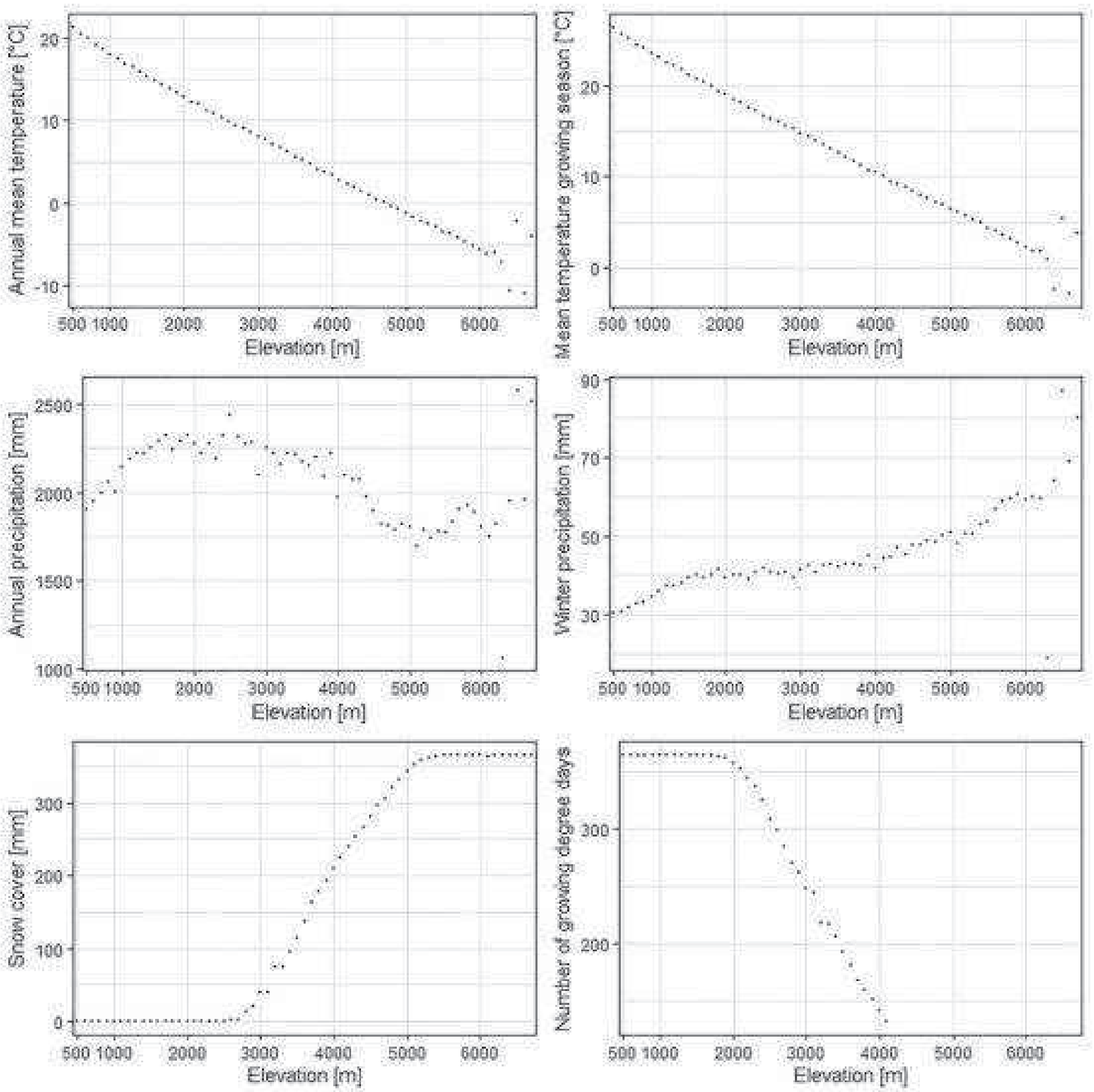

Fig. 11: Elevational trend of climatic variables in Sikkim, with dots representing average values within elevational bands of 100 m, based on grid cell data of 1 km² (CHELSA climate data; Karger et al. 2017).

characterized by a considerable percentage of Palaeotropic floristic elements, in particular elements of the Indo-Chinese Floristic Region. This floristic overlap of tropical and temperate species contributes to a not inconsiderable extent to the maximum species richness of the upper subtropical and lower cloud forests (cf. Elevational zonation of vegetation and patterns of species richness).

Plot 2 – Lower/middle cloud forest (lower montane zone)

This plot (2532 m) is located at the transition from the lower to the middle cloud forest (cf. Fig. 12), representing a typically dense evergreen oak forest stand with a closed canopy, dominated by *Fagaceae* species (*Quercus lamellosa*, *Lithocarpus pachyphylla*). *Quercus lamellosa*, constituting 70% of the upper canopy, can attain a height of 60 m (Miehe et al. 2015b). The understorey consists of smaller trees/large shrubs (*Lindera heterophylla*, *Mahonia acanthifolia*, *Rhododendron arboreum*, *Acer* spec., *Zanthoxylum oxyphyllum*, *Sarcococca saligna*) and bamboos (*Yushania maling*), the latter reaching a cover of 20%. Epiphytic orchids (inter alia *Eria alba*) and epiphytic ferns (*Oleandra wallichii*, *Selliguea griffithiana*) are well represented. The elevational distribution of the majority of the recorded species is largely confined to the lower cloud forest zone (Fig. 13) and shows an overlap with the species of Plot 1 (cf. Fig. 14), suggesting that most of the species are still rather thermophilic. This is reflected in the chorological spectrum (cf. Fig. 15), showing a still considerable percentage of Palaeotropic elements from the Indo-Chinese and Indian floristic regions.

Table 3: Environmental data of study plots across the elevational gradient in Kangchendzonga National Park, Sikkim, including vegetation cover, plant species richness, climatic parameters and soil chemistry.

Kangchendzonga NP, Sikkim	**Plot 1**	**Plot 2**	**Plot 3**	**Plot 4**	**Plot 5**	**Plot 6**	**Plot 7**
Elevation [m asl]	**1883**	**2532**	**3295**	**3669**	**3934**	**4301**	**4578**
Latidude [N]	27,39	27,43	27,44	27,49	27,52	27,56	27,57
Longitude [E]	88,22	88,19	88,18	88,18	88,18	88,19	88,19
Inclination [°]	40	45	20	15	5	20	5
Covervegetation	100	100	100	100	100	60	30
Cover rock	0	0	0	0	0	40	80
Cover snow	0	0	0	20	0	20	20
Cover moss	5	0	30 epi	40	90	30	0
Species number	21	26	9	4	13	18	6
Mean annual temperature [°C]	13,07	10,21	7,53	4,29	2,8	1,77	0,84
Mean temperature growing season [°C]	19,46	16,81	14,26	11,26	9,87	8,95	8,08
Annual precipitation sums [mm]	2649	2680	2667	3091	3226	2796	2759
Average winter precipitation [mm]	39	39	39	44	54	44	42
C [%]	12,3	10,7	8,61	21,4	15,3	7,74	2,84
C org [%]	12,2	10,6	8,33	21,4	14,8	7,42	2,68
N [%]	0,82	0,71	0,48	1,08	0,64	0,46	0,12
pH (KCl)	3,8	3,8	3,8	3,4	3,3	4,9	6,5
Al [g/kg]	35,3	43,9	34,4	14,9	9,98	22,8	17,6
Fe [g/kg]	28,7	40,6	39,8	6,21	7,62	23	16,9
P [mg/kg]	769	937	508	765	730	453	441
K [g/kg]	4,11	5,47	13,5	4,88	2,59	7,39	4,74
Mg [g/kg]	3,25	6,09	10,1	1,22	0,97	7,09	4,63
Mn [mg/kg]	456	358	534	79,2	93,9	355	295
Cu [mg/kg]	25	22,5	21	8,75	6,13	12,6	12,9
B [mg/kg]	2,98	5,07	2,21	6,64	3,96	2,98	5,44
Mo [mg/kg] 1,25	2,5	2,77	1,82	1,33	1,52	1,28	<
C/N	14,97	14,91	17,32	19,81	23,09	16,13	21,97
H+[mmolc/kg]	3,04	2,56	3,04	11,83	11,12	-0,29	-0,69
Al3+ [mmolc/kg]	45,74	98,68	51,29	12,74	62,42	0,97	< 0.4
Ca2+ [mmolc/kg]	76,21	15,13	60,39	78,80	23,76	178,74	169,85
Fe3+ [mmolc/kg]	1,66	3,21	7,82	5,22	12,19	0,20	< 0.2
K+ [mmolc/kg]	4,23	2,37	2,64	8,25	5,27	3,87	1,06
Mg2+ [mmolc/kg]	15,78	4,95	11,27	16,89	10,73	9,28	1,57
Mn2+ [mmolc/kg]	8,08	1,61	3,85	1,08	0,14	1,56	0,44
Na+ [mmolc/kg]	1,15	0,96	0,92	2,15	1,60	1,11	0,62
Cation exchange capacity [mmolc/kg]	155,88	129,46	141,21	136,95	127,24	195,45	172,85
Base saturation [%]	62,44	18,09	53,26	77,47	32,47	98,75	100,14

Table 4: Plant species inventory and species cover (in %) of plots across the elevational gradient in Kangchendzonga National Park, Sikkim.

Species	Family	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7
Abies densa	Pinaceae	0	0	40	20	0	0	0
Acer cf. *campbelli*	Aceraceae	3	0	0	0	0	0	0
Acer spec.	Aceraceae	0	+	0	0	0	0	0
Acronema tenerum	Apiaceae	0	0	0	0	+	0	0
Ainsliaea aptera	Asteraceae	3	0	0	0	0	0	0
Ainsliaea latifolia	Asteraceae	0	+	0	0	0	0	0
Allardia glabra	Asteraceae	0	0	0	0	0	+	+
Anaphalis contorta	Asteraceae	+	0	0	0	0	0	0
Anaphalis royleana	Asteraceae	0	0	0	0	0	+	0
Athyrium puncticaule	Athyriaceae	10	0	0	0	0	0	0
Betula utilis	Betulaceae	0	0	+	20	0	0	0
Bistorta vaccinifolia	Polygonaceae	0	0	0	0	10	0	0
Calamagrostis filiformis	Poaceae	0	0	0	0	0	20	0
Calamagrostis scabrescens	Poaceae	0	0	0	0	+	0	0
Carex cf. *cruciata* var. *argocarpa*	Cyperaceae	0	3	0	0	0	0	0
Carex cf. *gracilenta*	Cyperaceae	0	0	0	0	0	+	0
Carex cf. *longipes*	Cyperaceae	5	0	0	0	0	0	0
Carex haematostoma	Cyperaceae	0	0	0	0	0	10	+
Cassiope fastigiata	Ericaceae	0	0	0	0	10	0	0
Castanopsis hystrix	Fagaceae	70	0	0	0	0	0	0
Cimicifuga foetida	Ranunculaceae	0	3	0	0	0	0	0
Cinnamomum tamala	Lauraceae	+	0	0	0	0	0	0
Deschampsia cespitosa	Poaceae	0	0	0	0	+	0	0
Dryopteris fibrillosa	Dryopteridaceae	0	10	10	0	0	0	0
Elatostema monandrum	Urticaceae	0	+	0	0	0	0	0
Elsholtzia strobilifera	Lamiaceae	0	0	0	0	0	+	0
Eria alba	Orchidaceae	0	+	0	0	0	0	0
Eurya cavinervis	Pentaphylacaceae	0	0	50	0	0	0	0
Exbucklandia populnea	Hamamelidaceae	+	0	0	0	0	0	0
Gymnocarpium spec.	Cystopteridaceae	0	5	0	0	0	0	0
Hedychium gardnerianum	Zingiberaceae	3	0	0	0	0	0	0
Hymenophyllum exsertum	Hymenophyllaceae	0	+	0	0	0	0	0
Hymenophyllum simosianum	Hymenophyllaceae	+	0	0	0	0	0	0
Ilex dipyrena	Aquifoliaceae	0	0	0	0	0	0	0
Juncus thomsonii	Juncaceae	0	3	0	0	0	+	0
Juniperus indica	Cupressaceae	0	0	0	0	+	5	0
Kobresia nepalensis	Cyperacea	0	0	0	0	0	30	20
Lauraceae spec.	Lauraceae	10	0	0	0	0	0	0
Lindera heterophylla	Lauraceae	0	+	0	0	0	0	0
Lithocarpus pachyphylla	Fagaceae	0	3	0	0	0	0	0
cf. *Litsea albescens*	Lauraceae	+	0	0	0	0	0	0
Macaranga pustulata	Euphorbiaceae	3	0	0	0	0	0	0
Mahonia acanthifolia	Berberidaceae	0	10	0	0	0	0	0
Meconopsis horridula	Papaveraceae	0	0	0	0	0	0	+
Melia azedarach	Meliaceae	+	0	0	0	0	0	0
Microsorum punctatum	Polypodiaceae	5	0	0	0	0	0	0

Species	**Family**	**Plot 1**	**Plot 2**	**Plot 3**	**Plot 4**	**Plot 5**	**Plot 6**	**Plot 7**
Oleandra wallichii	Oleandraceae	0	+	0	0	0	0	0
Orchidaceae 1 spec.	Orchidaceae	0	+	0	0	0	0	0
Orchidaceae 2 spec.	Orchidaceae	0	+	0	0	0	0	0
Pleurospermopsis sikkimensis	Apiaceae	0	0	0	0	0	+	0
Poa pagophila	Poaceae	0	0	0	0	0	0	+
Potentilla arbuscula	Rosaceae	0	0	0	0	10	50	3
Potentilla cf. *microphylla*	Rosaceae	0	0	0	0	0	+	0
Primula glomerata	Primulaceae	0	0	0	0	0	+	0
Prunus rufa	Rosaceae	0	0	0	20	0	0	0
Psychotria erratica	Rubiaceae	+	0	0	0	0	0	0
Quercus lamellosa	Fagaceae	0	70	0	0	0	0	0
Rhaphidophora grandis	Araceae	20	0	0	0	0	0	0
Rhodiola bupleuroides	Crassulaceae	0	0	0	0	0	30	0
Rhododendron anthopogon	Ericaceae	0	0	0	0	10	0	0
Rhododendron arboreum	Ericaceae	+	5	0	0	0	0	0
Rhododendron barbatum	Ericaceae	0	0	30	0	0	0	0
Rhododendron campanulatum	Ericaceae	0	0	0	0	5	0	0
Rhododendron lanatum	Ericaceae	0	0	0	0	+	0	0
Rhododendron lepidotum	Ericaceae	0	0	0	0	30	10	0
Rhododendron setosum	Ericaceae	0	0	0	0	40	0	0
Rhododendron wightii	Ericaceae	0	0	40	60	0	0	0
Rosa sericea	Rosaceae	0	0	5	0	0	0	0
Rubus acuminatus	Rosaceae	0	+	0	0	0	0	0
Rubus ellipticus	Rosaceae	0	5	0	0	0	0	0
Rubus hypargyrus var. *hypargyrus*	Rosaceae	0	0	5	0	0	0	0
Rubus spec.	Rosaceae	0	+	0	0	0	0	0
Sarcococca saligna	Buxaceae	0	5	0	0	0	0	0
Saxifraga brachypoda	Saxifragaceae	0	0	0	0	0	+	0
Selliguea griffithiana	Polypodiaceae	0	+	0	0	0	0	0
Silene gonosperma	Caryophyllaceae	0	0	0	0	0	+	0
Smilax myrtillus var. *rigida*	Liliaceae	0	3	0	0	0	0	0
Spiraea arcuata	Rosaceae	0	0	0	0	+	0	0
Tetrastigma serrulatum	Vitaceae	+	0	0	0	0	0	0
Vaccinium nummularia	Ericaceae	0	0	+	0	0	0	0
Viola hookeri	Violaceae	+	0	0	0	0	0	0
Vittaria elongata	Pteridaceae	3	0	0	0	0	0	0
Yushania maling	Poaceae	0	20	0	0	0	0	0
Zanthoxylum oxyphyllum	Rutaceae	0	+	0	0	0	0	0
Total: 84	45	21	26	9	4	13	17	6

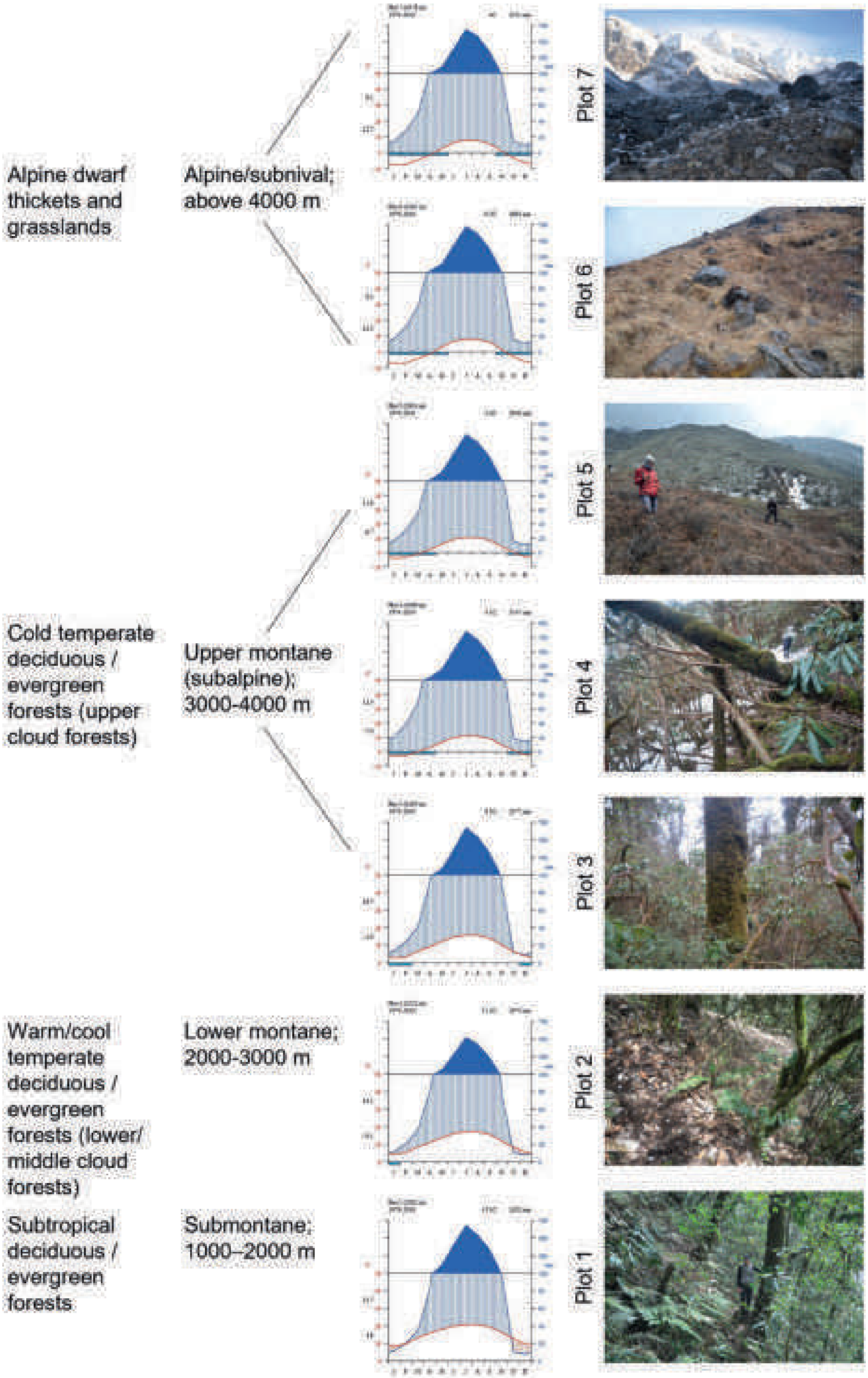

Fig. 12: Illustration of the study plots along the elevational gradient (Climate data: Gerlitz et al. 2014, Karger et al. 2017. Photographs: A. Jentsch, March 2015).

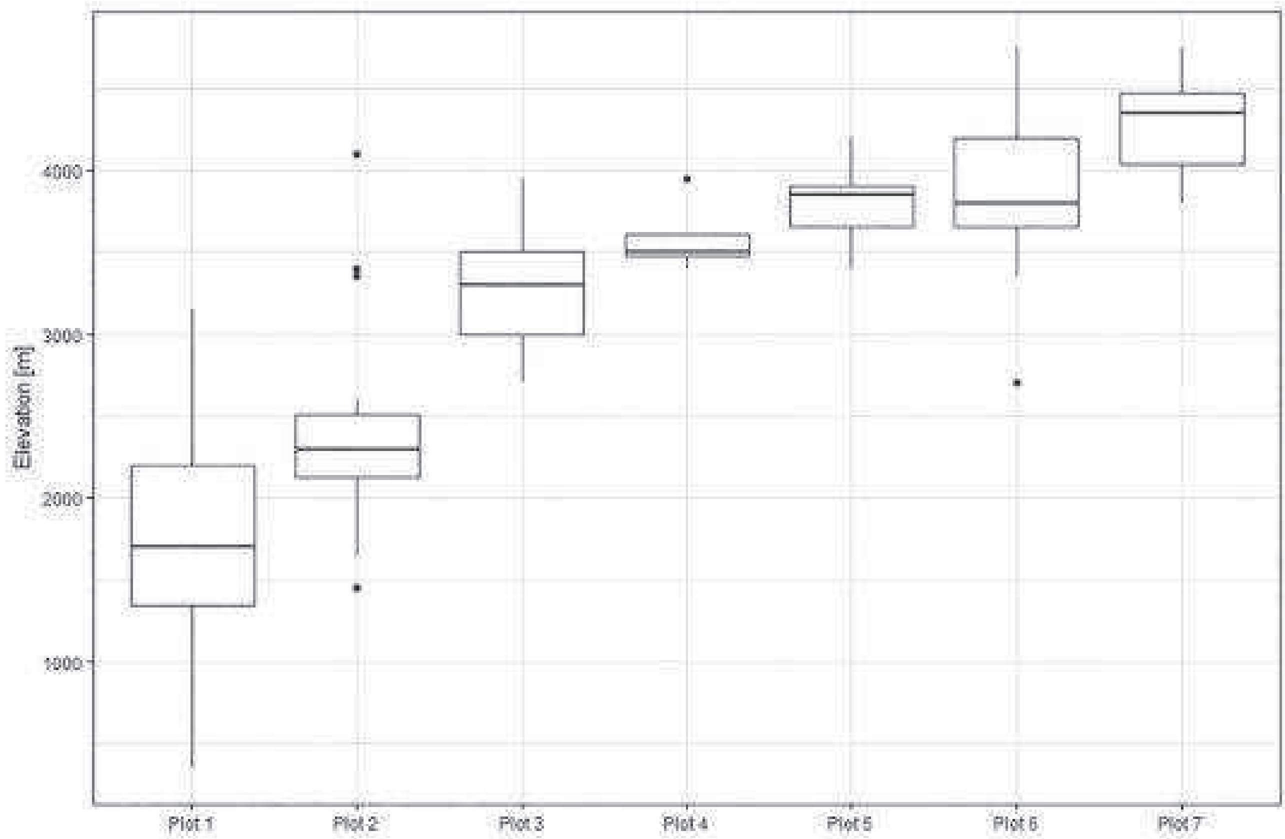

Fig. 13: Median elevational distribution of the sampled perennial plant species for each study plot.

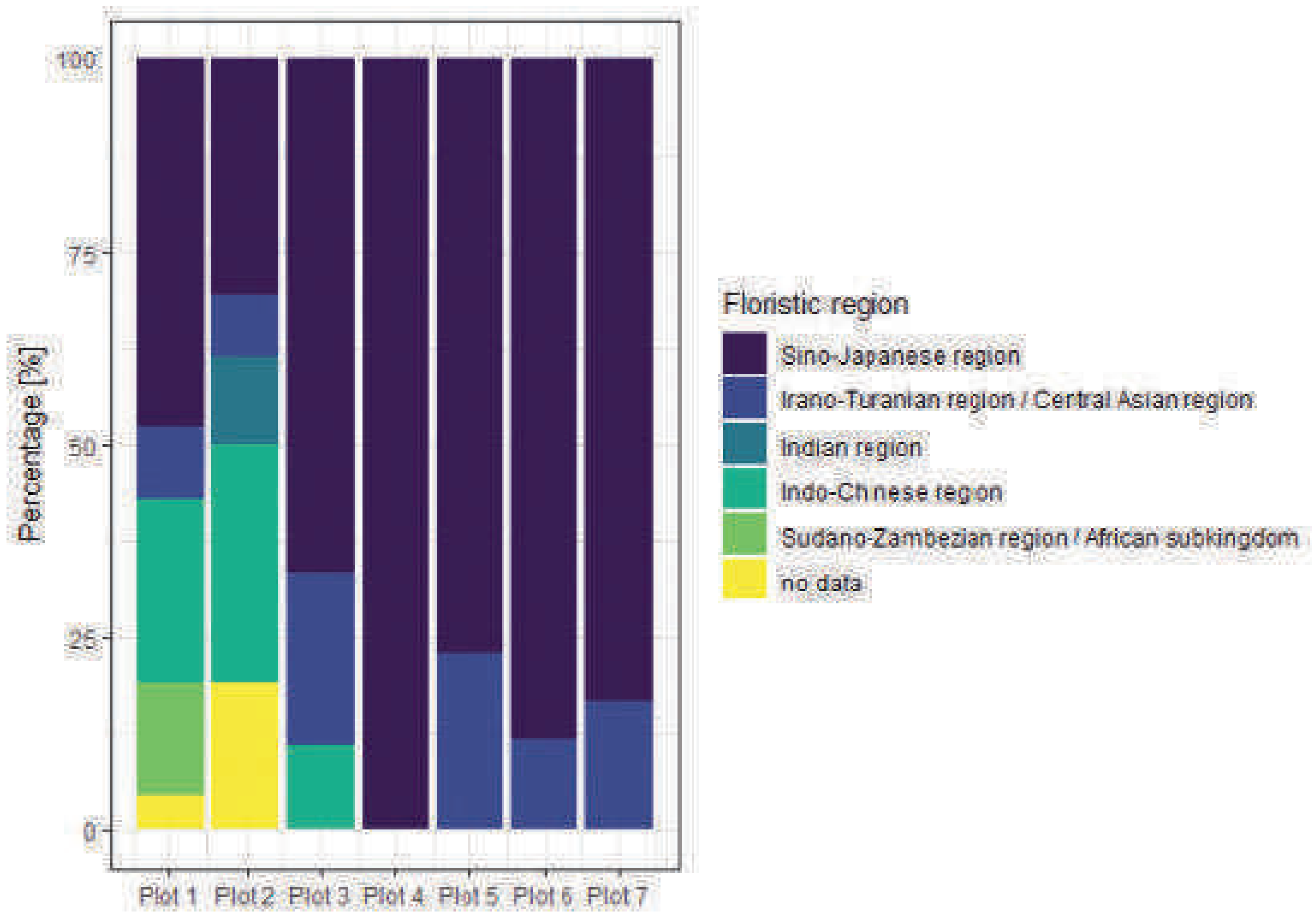

Fig. 14: Phytogeographic distribution of the sampled perennial plant species for each study plot.

Fig. 15: Cardamom fields near Yuksum village. Kangchendzonga National Park harbours submontane forests at low elevation, which are rich in tree species including *Schima wallichii, Castanopsis tribuloides, C. indica, Quercus glauca* and *Alnus nepalensis*. Evergreen epiphytes, ferns and orchids are growing on deciduous trees, which just start leaf unfolding in March/April. In lower montane forests, *Rhododendron wightii, R. arboreum* and *Magnolia doltsopa* beautifully contribute to the tree layer (Photographs: A. Jentsch)

Plot 3 – Upper cloud forest (Upper montane (subalpine) zone)

This plot (3295 m) was placed in a typical East Himalayan upper cloud forest (cf. Fig. 12), represented by an open *Abies densa* forest (40% upper canopy cover) with large-leaved *Rhododendron* species (*R. wightii*, *R. barbatum*) as common understorey trees and shrubs (Fig. 16). *Abies densa* (Pinaceae) and *Rhododendron wightii* (Ericaceae) are East Himalayan endemics. In one of the gaps in the canopy, *Betula utilis* (*Betulaceae*) complemented the understorey (Fig. 17). The trunks and branches of trees were clad with dense cushions of mosses and liverworts. *Eurya cavinervis* (Pentaphylacaceae) was a conspicuous tall shrub in the undergrowth (50% cover) which is, however, more representative of the lower and middle cloud forest, and here at its upper distribution limit. The herb layer was poorly developed. The elevational distribution of the recorded species is markedly different from those of Plot 2 and has no overlap (cf. Fig. 14), pointing to a steep climatic gradient between the lower/middle forest with more thermophilic species and the upper cloud forests with more cold-adapted species. Accordingly, the percentage of Palaeotropic floristic elements (from the Indo-Chinese floristic region) in the chorological spectrum of Plot 3 is very low (cf. Fig. 15).

Plot 4 – Transition zone upper cloud forest – Rhododendron thicket (Upper montane (subalpine) zone)

This plot (3669 m) represents the transition zone between the uppermost cloud forest stands and the zone of evergreen *Rhododendron* thickets (cf. Fig. 12). In the Khangchendzonga Biosphere Reserve, these thickets extend over several hundreds of meter upslope from the uppermost *Abies densa* stands and dominate the treeline ecotone (Fig. 18). They decrease gradually in height, from 3 to 4 m at their lower limit to dwarf shrub size at the transition from the treeline ecotone to the lower alpine zone. Depending on the snow load in winter, krummholz-like growth forms may be developed. *Rhododendron* thickets are typically very species-poor, also reflected in this plot. Apart from some individuals of tall-growing *Abies densa* and smaller *Betula utilis* and *Prunus rufa*, it is a monospecific stand of *Rhododendron wightii*, attaining a cover of 60%. Almost half of the forest floor is covered with mosses. The elevational distribution of the species of Plot 4 shows some overlap with those of the upper cloud forest species of Plot 3, but does not coincide with those of the species of alpine dwarf thickets and grasslands. Plot 4 species are exclusively Holarctic species of the Sino-Japanese floristic region (cf. Fig. 15).

Plot 5 – Alpine dwarf thicket (Lower alpine zone)

This plot (3934 m) is located just above the upper limit of trees and taller shrubs (cf. Fig. 12) at the lower limit of the alpine zone which approximately covers the elevational zone between 4000 and 5000 m. Under slightly cooler topoclimatic conditions, alpine dwarf thickets may have their lower limit somewhat below 4000 m, as in this case in the upper Prek Valley which is influenced by cold catabatic winds descending from the glaciers of the Khangchendzonga massif. The plot represents a typical *Rhododendron* dwarf thicket of 40-50 cm height, composed of *R. setosum* (40% cover), *R. lepidotum* (30%), *R. anthopogon* (10%), *R. campanulatum* (5%), and *R. lanatum* (<5%). The shrub cover is complemented by *Cassiope fastigiata* (Ericaceae), *Potentilla arbuscula* (Rosaceae), *Bistorta vaccinifolia* (Polygonaceae), *Spiraea arcuata* (Rosaceae), and *Juniperus*

Fig. 16: *Abies densa* in the upper cloud forest - a mysterious experience (Photograph: A. Jentsch).

Fig. 17: The upper montane forest is characterized by *Abies densa* with *Rhododendron hodgsonii, R. campanulatum, R. wightii, Acer caudatum* and *Prunus rufa* in the understorey. *Betula utilis* is present but rare (next to Udo Schickhoff). *Juniperus indica* and *Larix griffithiana* increase in abundance in the treeline ecotone and above (Photographs: A. Jentsch and U. Schickhoff).

indica (Cupressaceae). Some herbs and graminoids occupy openings of the shrub canopy. During the winter season, the shrubs are protected from harsh climatic conditions (wind and frost effects) by a thick snow cover (Fig. 18). The average elevational distribution of the species of Plot 5 overlaps to some extent with those of thickets and grasslands further upslope. Plot 5 consists exclusively of Holarctic species, with the majority being Sino-Japanese elements (c. 75%) (cf. Fig. 15).

Plot 6 – Morainic scrub (Middle alpine zone)

This plot (4301 m) represents the vegetation of morainic scrub, a vegetation type widespread in glaciated valleys of the Khangchendzonga Landscape along lateral and terminal moraines between 3900 and 4500 m (cf. Tambe & Rawat 2010). The diagnostic species is *Potentilla arbuscula* (Rosaceae) which dominated this plot with a cover of 50%, while *Rhododendron* dwarf shrubs were less significant. In the herb layer, graminoids (*Kobresia nepalensis*, *Calamagrostis filiformis*, *Carex haematostoma*, *Juncus thomsonii*) prevailed, together with *Rhodiola bupleuroides* (Crassulaceae) which attained a cover of 30%. The species of Plot 6 are distributed over a wide range in the alpine zone; they are exclusively of Holarctic origin, with the share of Sino-Japanese elements rising to c. 85% (cf. Fig. 15).

Plot 7 – *Kobresia nepalensis* mat (Upper alpine zone)

The uppermost plot (4578 m) along the elevational gradient represents a *Kobresia nepalensis* mat (cf. Fig. 12), the most widespread alpine Cyperaceae mat on southern exposures of the monsoon-influenced Himalayas (Miehe et al. 2015b). It is also the most widespread and dominant vegetation in the Khangchendzonga Landscape between 4000 and 5100 m (Tambe & Rawat 2010). *Kobresia nepalensis* is the diagnostic species, usually forming a mat cover with a height of 10-20 cm. In Plot 7, located on a smooth slope (5°) on a ridge top in the upper Prek Valley, the *Kobresia* cover (20%) was fragmented, open soil patches resulted from an extensive rock cover as well as from frost heaves. Companion species included *Potentilla arbuscula* (*Rosaceae*), *Carex haematostoma* (Cyperaceae), *Poa pagophila* (Poaceae), *Meconopsis horridula* (Papaveraceae), and *Allardia glabra* (Asteraceae). All of these species are cold-adapted and of subalpine-alpine distribution. The great majority can be categorized as Sino-Japanese elements, some species (e.g., *Carex haematostoma*) are of Central Asian origin (cf. Fig. 15).

Climate change and glacier recession in Sikkim

Evidences of accelerated and above average climate change over the last century based on direct (station-based meteorological observations) and indirect sources (glacier recession, river hydrology and vegetation phenology) are clearly visible in High Mountain Asia (HMA), in particular in the Hindu-Kush-Himalayan region (Schickhoff et al. 2016, Hock et al. 2019, Schickhoff & Mal 2020). In general, the Hindu-Kush-Himalayan region has experienced warming from 1901 to 1940, cooling from 1940 to 1970, and a strong amplification of warming rates to 0.2°C per decade over the period 1951-2014, with climate change and related impacts on the mountain cryosphere, hydrology and vegetation dynamics being more pronounced in the eastern Himalayas including Sikkim (Ren et al. 2017, Sun et al. 2017, Krishnan et al. 2019). Instrumental record-based climate change studies are rather rare in the Sikkim Himalaya, as there are very few weather stations, which are largely confined to the lower elevations and valley floors. Consequently, station-based climate change studies in the upper Sikkim (Fig 20) and elsewhere in the Himalayas are almost unavailable (Singh & Mal 2014), expect in a few localities in central and eastern Nepal (Shrestha et al. 2000, 2017; Salerno et al. 2015) and in the north-western Himalayas (Dimri & Dash 2010; 2012, Chevuturi et al. 2018).

According to a recent study (Kumar et al. 2020), mean annual temperature over the two stations (Gangtok and Tadong), located in southern Sikkim, have experienced warming trends (0.005 to 0.035 °C a^{-1}, respectively) since the 1960s. However, an earlier study (Sharma & Shrestha 2016) revealed enhanced trends for annual temperature for Gangtok for 1978-2009 period, while for Tadong the trends are comparable.
Warming trends of annual minimum temperature for Tadong are more pronounced (0.065 °C a^{-1} for 1981-2010) than for Gangtok (0.036 °C a^{-1} for 1961-2017) (Kumar et al. 2020). While this trend for annual minimum temperature trend for Tadong is comparable, the magnitude of the Gangtok station trends is shallower than those revealed by Sharma & Shrestha (2016). The trends for seasonal temperature are poorly understood in the Sikkim Himalayas. According to Sharma & Shrestha (2016), the minimum temperature trends in the winters are rather steep as compared to annual mean minimum and annual temperatures between 1978 and 2009. Shallow warming trends of maximum temperature are observed for Tadong as compared to the cooling (-0.027 °C a^{-1}) for Gangtok (Kumar et al. 2020).
Another study (Yadav et al. 2016) suggests enhanced positive trends of mean monthly minimum temperature in East Sikkim across the period 1985-2009, while for mean monthly maximum temperature relatively shallower warming trends are observed, with November and December showing strongly negative and August slightly negative trends. Overall, annual mean and minimum temperatures show an increase, while the mean maximum temperature is trendless (Patle et al. 2019). Station-based temperature trends for the upper/higher Sikkim are not available, however a model based study suggests warming trends in Khangchendzonga Biosphere Reserve for annual and all seasons expect for the monsoon (Shrestha & Devkota 2010, Chettri et al. 2012). In addition, warming trends at higher elevations are significantly stronger as compared to lower elevations.
The magnitude of annual precipitation trends for Sikkim and sub-Himalayan West Bengal region doubled from 1.30 mm a^{-1} (1871-1950) to 2.96 mm a^{-1} (1951-2008), and is significantly higher as compared to entire eastern Himalayan precipitation trends (Jain et al. 2013). Overall, the annual precipitation has increased over the last century (Praveen et al. 2020). Precipitation trends in the monsoon, post-monsoon and winter seasons increased manifolds from 1871-1950 to 1951-2008, while during the pre-monsoon season the increasing precipitation trends are rather shallow (Jain et al. 2013). While pre-monsoon and monsoonal precipitation trends over the last century correspond well to those reported by Praveen et al. (2020), post-monsoon and winter precipitation trends are rather conflicting between both studies.

Fig. 18: The lower alpine zone is dominated by dense, relatively tall growing *Rhododendron wightii* thicket, whereas the upper alpine zone is characterized by relatively small-growing dwarf shrubs including *R. setosum, R. lepidotum, R. anthopogon, R. campanulatum* and *R. lanatum* and *Juniperus indica*. (Photographs: A. Jentsch).

Fig. 19. Above the treeline in Kangchendzonga National Park: *Juniperus indica*, *Rhododendron setosum* and *R. anthopogon* dominate the alpine dwarf shrub thickets, whith *Koebresia nepalensis* characterizing high elevation grasslands up to the subnival zone. Glacial ice of Mount Kangchendzonga (8,586 m asl.) reaches down to 4200 m asl. Scientists from left to right: Anke Jentsch (University of Bayreuth), Suraj Mal (University of Delhi), Maria Bobrowski and Udo Schickhoff (both University of Hamburg). (Photographs: A. Jentsch).

Fig. 20: Mount Khangchendzonga accumulating unconsolidated debris or glacial till to glacial moraines, Sikkim, Eastern Himalaya 2015 (Photograph: A. Jentsch).

Station-based trends for annual precipitation are not homogeneous in the region, as Tadong station reveals positive trends (7.1 to 4.4 mm a^{-1}), while Gangtok reveals negative trend (-1.354 mm a^{-1}) since the 1960s (Kumar et al. 2020), contradicting with those revealed by Sharma & Shrestha (2016). In the eastern Sikkim, monthly precipitation trends are rather variable, with the months of January, February, May and September showing negative trends while other months show positive trends for 1985-2009 (Yadav et al. 2016). On average, the annual precipitation shows an increase between 1985 and 2013 (Patle et al. 2019).

As previously mentioned, high-altitude climate stations are unavailable in the Sikkim Himalayas, hence station-based results are more representative of southern and lower elevations. For the higher elevations, model and remote sensing data-based studies, therefore, are urgently needed. However, studies from the adjacent Tibetan Plateau and HMA in general suggest an enhanced warming at higher elevations in the region (Qin et al. 2009, Pepin et al. 2015, Salerno et al. 2015, Li et al. 2020, Mal et al. 2021a). In the Khangchendzonga Biosphere Reserve, similar elevation dependent warming has been observed (Shrestha & Devkota 2010, Chettri et al. 2012). Here, precipitation trends in general are trendless.

In high elevation zones, where meteorological observations are unavailable or rare, glaciers provide important information for climate change research because of their sensitivity and their comparatively fast response to changing climatic conditions (Bhattacharya et al. 2016, 2021; Bolch et al. 2019, Krause et al. 2019, Mal et al. 2019). Changes in mass-balance, length, area and flow dynamics clearly reflect changing climatic conditions in the wider region (Bhambri et al. 2017). Also non-climatic factors such as debris cover and local physiography significantly influence/modify glacier responses in HMA (Venkatesh et al. 2012, Pratap et al. 2015, Shukla & Qadir 2016). It has been found that relatively smaller glaciers react much faster than larger valley glaciers (Bhambri et al. 2011, Schmidt & Nüsser 2012, 2017; Mal & Singh 2013, Schickhoff & Mal 2020). At the same time, central and eastern Himalayan glaciers have retreated much faster than western Himalayan glaciers, and have shown an elevation-dependent response behaviour (Kääb et al. 2012, Bajracharya & Shrestha 2014, Bajracharya et al. 2015). In the Sikkim Himalaya (Fig. 21), a total of 449 glaciers covering an area of 705.54 km^2 has been reported (Raina & Srivastava 2009). Recession estimations for all the glaciers are not available. A study based on the samples of 38 glaciers (excluding Zemu glacier) suggested an overall loss of 6.9±1.5 km^2, which is ~3% between 1989/90 and 2010 (Basnett et al. 2013). Another study (Garg et al. 2019), based on 23 sampled glaciers, revealed an area loss of 5.44 ± 0.87% between 1991 and 2015, which was significantly higher in the latter half of the study period. This result is well in line with that of a recent study on the glaciers of Choombu Chhu watershed in northern Sikkim (Chowdhury et al. 2021). Relatively smaller and clean-ice (debris-free) glaciers with pro-glacial lakes show an enhanced recession in recent decades (Basnett et al. 2013), indicating the importance of non-climatic factors and a chain reaction of climatic factors (Bolch et al. 2011, Dobhal et al. 2013, Shukla & Qadir 2016, King et al. 2018, Krause et al. 2019). The glacier recessions show relatively weaker relationships with increasing elevation, however, decreasing debris cover and lake presence are factors that enhance recession rates at higher elevations (Basnett et al. 2013). On average, the recession rate of 23 sampled glaciers in the Sikkim Himalayas is observed to be 17.78 ± 2.06 m a^{-1} from 1991 to 2015, which slightly increased in the latter half of the study (Garg et al. 2019). The flow of glaciers in the Sikkim Himalayas has slowed down by ~25% with a significant downwasting of −0.77 ± 0.08 m a^{-1} since 2000 (Garg et al. 2019).

Zemu glacier, the largest glacier in the region (Fig. 22), does not show significant recession in recent decades. The retarded response might be attributed to relatively steeper bed-rock slope that leads to higher downslope movement offsetting the recession caused by climate change (Venkatesh et al. 2012, Basnett et al. 2013). However, the surface area of Zemu glacier has reduced by about 30.4% between 1931 and 2018, with enhanced recession between 2014 and 2018 (Rashid & Majeed 2020). As a result of ongoing climate change in the region, Zemu glacier has fragmented into seven parts between 2003 and 2014, while the snout/front recession rate is far lower (less than 10 m^{-1}) since 1931 (Venkatesh et al. 2012, Garg et al. 2019, Rashid & Majeed 2020) as compared to other valley glaciers in the Himalayas (Bhambri et al. 2012, Bolch et al. 2019, Krause et al. 2019, Mal et al. 2019). The mass-loss rate of Zemu glacier (6.782 ± 2.05 Gt) remained unchanged since 1931 (Rashid & Majeed 2020).

Climate change in Sikkim investigated by dendroecology

Sites of dendroecological studies hitherto conducted in the Sikkim region cover the elevational gradient from the subtropical wet hill forests of Kalimpong in northern West Bengal close to the Sikkim border at 2051 m a.s.l. (Shah & Mehrotra 2017) to the subalpine conifer-broadleaved forest of Yumthang at 3880 m a.s.l. (Bhattacharyya & Chaudhary 2003). Investigated species comprise *Abies densa* (Chaudhary et al. 1999, Bhattacharyya & Chaudhary 2003, Shekhar & Bhattacharyya 2015), *Larix griffithiana* (Chaudhary et al. 1999, Shah et al. 2014a, Yadava et al. 2015), *Toona ciliata* (Shah & Mehrotra 2017), and *Tsuga dumosa* (Borgaonkar et al. 2018, Ram et al. 2019). The majority of studies focuses on dendroclimatological

Fig. 21: Historical map of the larger Kangchendzonga area and Zemu glacier in Sikkim (Edmund J Garwood 1899).

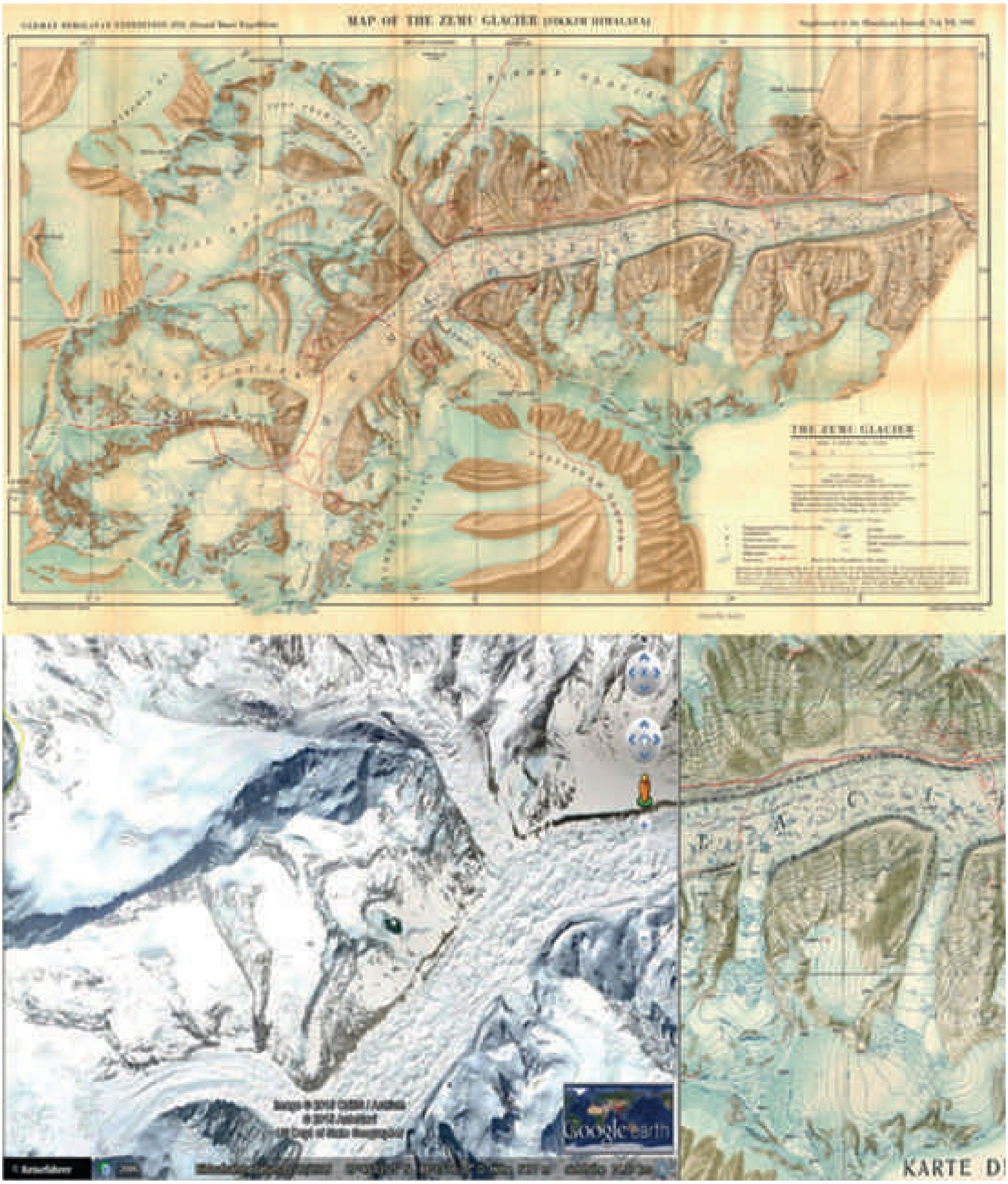

Fig. 22: Historical map of map of Zemu glacier from 1931 (Paul Bauer 1933) merged with Google Earth screenshot by Leander Beierkuhnlein of 2015, who concluded in accordance with R. Finsterwalder that the rate of downslope ice flow of the Zemu glacier is currently between 28 m/year - 80 m/year (L. Beierkuhnlein 2016).

aspects, i.e. tree growth–climate correlation (Chaudhary et al. 1999, Shah & Mehrotra 2017, Ram et al. 2019) and climate reconstruction (Bhattacharyya & Chaudhary 2003, Shekhar & Bhattacharyya 2015, Yadava et al. 2015, Borgaonkar et al. 2018). Two studies reconstruct stream flow of important tributaries of Teesta River (Shah et al. 2014a, Shekhar & Bhattacharyya 2015). Several of these papers combine results from Sikkim with other East Himalayan tree-ring chronologies, building networks to improve the quality of climate reconstructions of the region. Available studies use solely tree-ring width and no other dendrochronological parameters.

Tree growth–climate relationships of *Tsuga dumosa* point to adverse effects on annual tree increment by both moisture deficits in spring and high temperatures in late summer, with the latter indicating high evapotranspiration and reduced available moisture (Borgaonkar et al. 2018, Ram et al. 2019). Similar results were obtained for *Larix griffithiana* (Yadava et al. 2015). Temperature reconstructions of Yadava et al. (2015),

Bhattacharyya & Chaudhary (2003) and Borgaonkar et al. (2018), reaching back as far as to the beginning of the 18th century, show fluctuations of warm and cool epochs. Pacific Decadal Oscillation, El Niño Southern Oscillation and volcanic eruptions play an important role as drivers of these variations (Borgaonkar et al. 2018). Moreover, these reconstructions show warming trends since the mid-19th and the beginning of the 20th century, and indicate that the warmest periods were experienced towards the end of 20th century.
Mountains as "water towers" of the Earth play a key role for supplying water to people in lowlands. This applies in particular for the Himalayas, considered to be one of the world's most important and vulnerable water towers (Immerzeel et al. 2020). Climate change-induced reductions in river flow will affect availability and sustainable management of water and sanitation for millions of people in the Indo-Gangetic plains. Such reductions have been increasingly detected by dendroclimatological studies. Shah et al. (2014a) reconstructed stream flow of river Lachen Chhu using total annual tree-ring, early- and latewood widths of *Larix griffithiana*. Low streamflows correlate well with region-wide drought events and streamflow high spectral power frequency matches ENSO range. Discharge of Lachen Chhu's tributary Zemu Chuu during spring was reconstructed by an *Abies densa* chronology (Shekhar & Bhattacharyya 2015). Extremely low discharge corresponds to past monsoon failure and droughts. Reconstructions indicate a decreasing trend since the 1990s which corresponds to trends in other Indian regions and may cause serious socio-economic consequences (Shekhar & Bhattacharyya 2015).
In summary, the reviewed dendroecological studies conducted in Sikkim provide important contributions to improve the knowledge of past, current and future climate and other environmental conditions of the region and beyond. Given the still small number of studies, there is still an untapped potential to further explore and utilize the environmental information contained in Sikkim's tree-rings especially for the improvement and extension of climate reconstructions and for other ecology-related purposes such as forest management, treeline and glacier research (e.g., Chowdhury et al. 2021, Singh et al. 2021). However, this potential is limited by the availability of old trees from undisturbed forests which are increasingly threatened by various anthropogenic disturbances (Shah et al. 2014b).

Conclusion

While principal patterns of elevational zonation of vegetation in the Sikkim Himalaya are reasonably well known, the knowledge of small-scale vegetation patterns and local characteristics derived from plot-based vegetation descriptions and analyses is still very meagre. We documented a plot-based vegetation case study including climatic and soil chemistry data along the elevational gradient in the Khangchendzonga National Park, in order to contribute to the knowledge of specific vegetation patterns and to increase the database on vegetation-environment relationships. The results more or less corroborate those of previous studies. Compared to the elevational zonation of vegetation, gradients of elevational species richness are much less well known. In this respect, Sikkim is a highly under-researched area. The results of our analyses of richness patterns along the elevational gradient largely correspond to results of previous studies in Nepal and Bhutan. With regard to diversity patterns it needs to be highlighted that more plot-based field studies on elevational richness gradients are urgently needed since the results provide the ground-truthing for studies based on metadata from published floras or plant lists. Detailed field studies in mountain biogeography and biodiversity conservation are even more the order of the day, since in the current Anthropocene mountain environments are changing on all continents at an unprecedented rate. Accelerating processes of economic globalization require adaptation strategies of mountain people, expressed in changing land use systems which are often not sustainable. Rates of climate warming in mountains, in particular in the Himalayas, substantially exceed the global mean, yielding dramatic effects on cryosphere, hydrosphere, and biosphere. Biotic responses to climate change such as phenological shifts, changing species distribution patterns, invasion of non-native species, and changes in primary production are currently altering species composition of communities and structure and functioning of ecosystems, before detailed inventories and field-based studies can be conducted to reveal basic knowledge on vegetation and species richness patterns in remote mountain regions.

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Altitudinal distribution and spatial pattern of species richness of the high mountain flora: A case study on Ladakh (Himalaya)

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Abstract: Species diversity is a well-documented resource in biodiversity, but its spatial pattern for remote areas like Ladakh is lacking. I estimated species profiles for all growth forms applying published data on the floristic and elevational distribution of vascular plants in Ladakh and converted them to the spatial distribution of species richness. The spatial distribution of species richness has been quantified according to 100 m a.s.l. and visualised by the SAGA software. I found the highest species diversity and the peak of all growth forms at around 3000 m a.s.l. The heights of species richness curves shift upward along the elevational gradient in the order of epiphytes/lianas – trees – graminoids – shrubs – herbs. The humped patterns of species richness found in Ladakh are consistent with findings from previous Himalayan mountain studies. Further research and fine-scale local data can facilitate the evolutionary issues and conservation purposes of flora in Ladakh.

Introduction

A primary current focus in species richness is how to ensure the sustainability of biodiversity. It is generally accepted that high mountains are the most suitable habitat for species richness. Ladakh is a land of unearthly beauty in the Transhimalaya of Northwest India, containing around 1250 species of vascular plants, including cultivated ones (Dvorský et al., 2018). The plants and wildlife of this high altitude cold desert are adapted to the harsh circumstances, with a small population, and get very little precipitation (< 100 $mm.yr^{-1}$) (Kala & Mathur, 2002; Singh and Gupta, 1990). Over half of the plants in the region have been identified as having therapeutic use (Kala and Mathur, 2002; Kumar et al., 2011; Singh and Chaurasia, 2000), which is very important for the economic growth of the inhabitants of Ladakh in the emerging world market.

There is extensive literature on the identification and exploration of species in Ladakh (Blatter, 1984; Dickoré and Nüsser, 2000; Khuroo et al., 2011, 2010; Klimeš and Dickoré, 2005; Sharma and Jamwal, 1988; Shukla and Srivastava, 2020; Singh and Kachroo, 1987; FRLHT, 2010) and since the early nineteenth century, the association between vegetation and altitude has been established (Bunzhuo et al., 1997; Kala and Mathur, 2002; Mani, 1978). However, although the species distribution individually was demonstrated by Dvorský et al. (2018), the regional distribution of total species richness in Ladakh has received little consideration.

There is a growing demand for biodiversity conservation in high mountains in the national and international context. The present paper presents the altitudinal and spatial distribution of species richness, including information about dominant families and genera of flora in

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Ladakh. This research will help to develop a strategy for the conservation of biodiversity in this area.

Methods

Study area

Ladakh has been a part of the Jammu and Kashmir state since 1947 and has been explored by scientists from several disciplines, including botany, ecology, geography, etc. Ladakh covers about 87,000 km^2 or, including disputed territories, 117,000 km^2, of high mountain terrain bordering Pakistan lies to the western part, and China is to the northern and eastern part (Fig. 1). This region ranges from approximately 2550 m in the Indus Valley along the Pakistani border to 7672 m on the Saser Kangri Peak in the Eastern Karakorum (Dvorský et al., 2018).

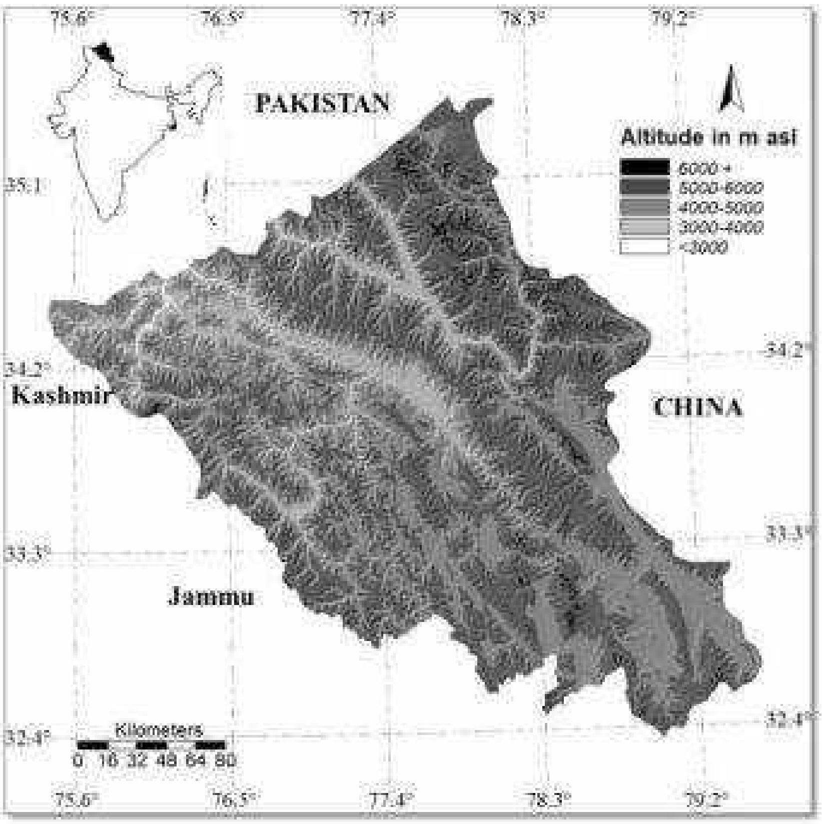

Figure 1: Physical map of Ladakh.

Methods

The current investigation involved gathering and analyzing data on the flora of Ladakh. The information on flora was collected from numerous published sources on Ladakh and Jammu & Kashmir (Blatter, 1984; Dickoré and Nüsser, 2000; Khuroo et al., 2011, 2010; Klimeš and Dickoré, 2005; Sharma and Jamwal, 1988; Shukla and Srivastava, 2020; Singh and Kachroo, 1987; FRLHT, 2010). A total of 1379 species was recorded with elevation information and then analyzed for the elevational distribution. The abundance of species for dominant families and genera were calculated, and the total number of species for 100 m interval was quantified. The species data subsequently converted as the richness of species or spatial distribution of species by the tool 'Change grid value' in SAGA 7.9.0 (System for Automated Geoscientific Analyses) GIS software (Conrad et al., 2015).

Results

It was apparent beforehand that species richness pattern would be a desirable outcome of elevational zonation of vegetation. The vegetation of Ladakh displays striking vertical zoning, which is diversified by aspect, exposer, and substrate (Dvorský et al., 2018). As can be seen in figure 2 (upper), the elevational zones of different vegetation belts are subsequently distributed. The submontane belt (up to 2900 m a.s.l.) is the lowest altitudinal vegetation zone, comprising only a small part (less than 1%) of the arid gorge section in the lower Indus valley (Dvorský et al., 2018). The montane belt extends between about 2900 and 3700 m a.s.l. and hosts a semi-desert vegetation (7% of total area), characterized by scattered coarse subshrubs, sturdy herbs, including several halophytes (Dvorský et al., 2018). This belt supports the most considerable oasis cultivation because of high summer temperatures and large tracts of relatively level ground. The subalpine vegetation belt stretches from around 3700 m up to 4200 m in the west and more than 4400 m in the east of Ladakh (Dvorský et al., 2018). The alpine belt is composed of herbs and dwarf shrubs and altitudinally extends from 4,200 to 4,900 m
a.s.l. (occasionally 5,500 m a.s.l. on the Tibetan border) (Dvorský et al., 2018). The subnival vegetation belt is located above 5200 m a.s.l. to 5600 m a.s.l. and a very sparse vegetation can be seen there (Dvorský et al., 2018).

Figure 2 (lower) shows the elevational zones of vegetation in which half of the total area is the alpine belt and the subnival vegetation belt covers 33% of the entire region. That represents the dominance of the higher portion (more than 80%) of the study area falls in the high altitude of the cold desert.

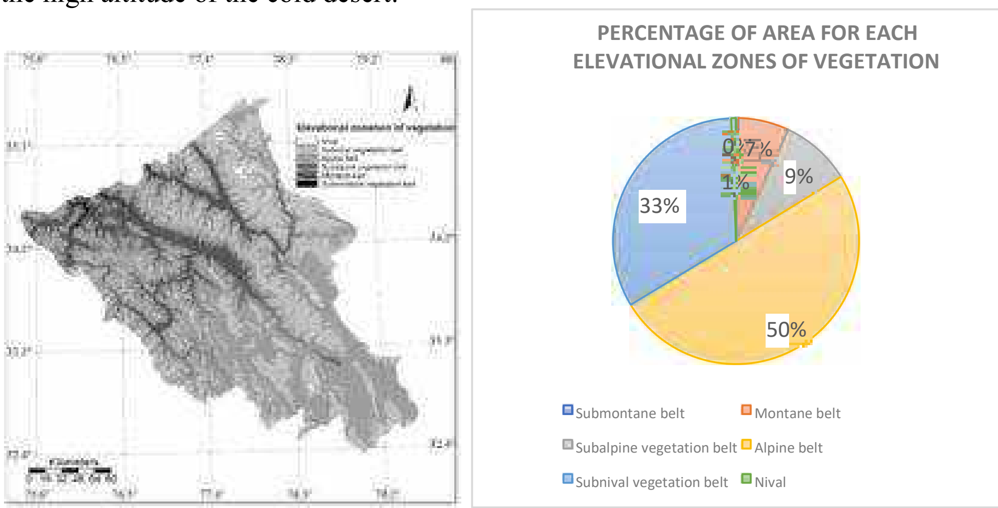

Figure 2: Elevational zonation of vegetation in Ladakh (upper figure) and the percentage of land covered by each vegetation zone at different elevations (lower figure) (according to Dvorský et al., 2018)

The current analysis found a total of 1379 species spread throughout 461 genera in 95 families. The leading families are Poaceae (with 194 species), followed by Asteraceae

(162), Fabaceae (91), Cruciferae (88), Cyperaceae (58), Scrophulariaceae (51), Ranunculaceae (48), etc. and the dominant genera are Astragalus (39), followed by Carex (32), Corydalis (26), Nepeta (24), Artemisia (24), Polygonum (21), Potentilla (19), Stipa (17), etc. (Fig. 3 and 4). These analyses of family and genera show a considerably higher number of species than the recent study by Shukla and Srivastava (2020).

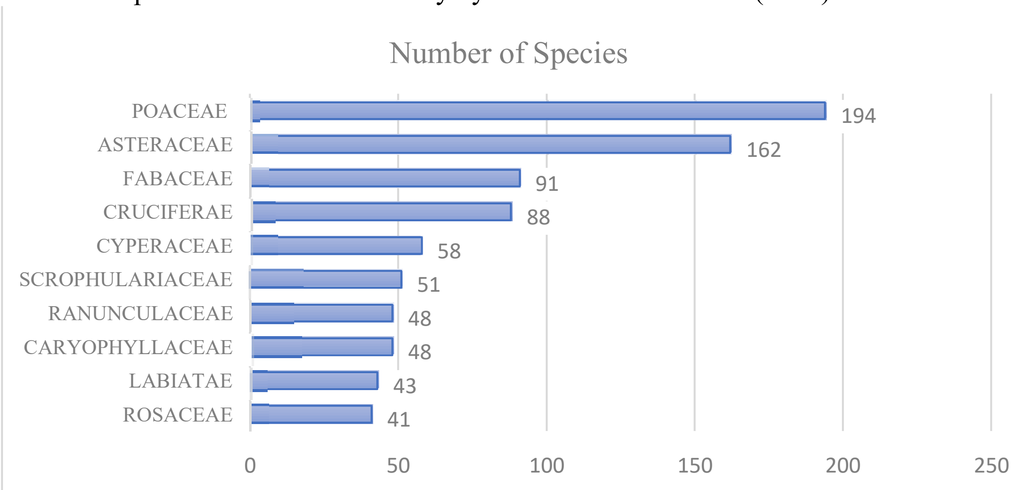

Figure 3: The ten most species-rich families of the Ladakh flora (vascular plant species).

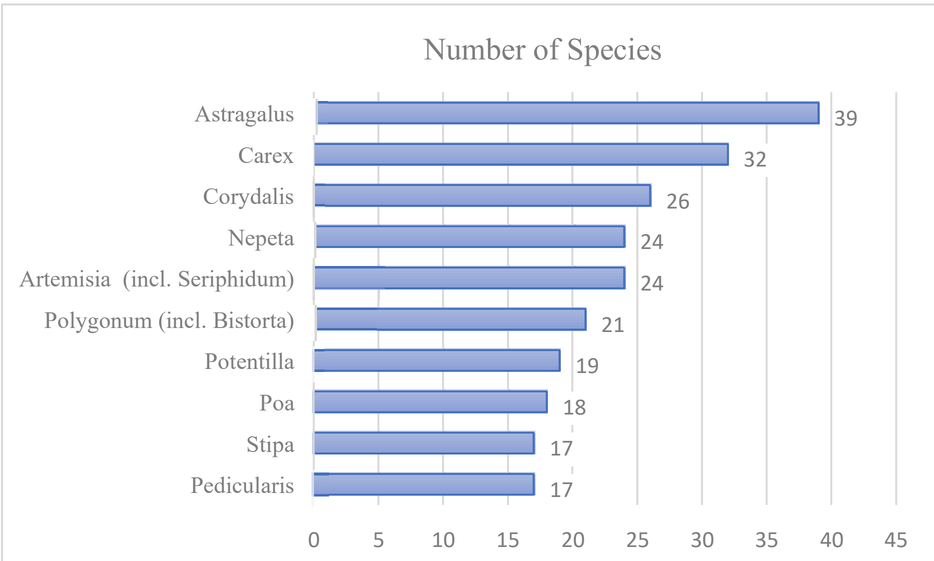

Figure 4: The ten most species-rich genera of the Ladakh flora (vascular plant species).

There were 1140 species with information about altitude in Ladakh and used to generate the species richness distribution pattern along gradients. Between 3000 and 3500 m a.s.l., most plant species (667) were discovered, with the number of species decreasing as elevation ascended. Figure 5 depicts the elevational distribution of plant species in Ladakh graphically. This distribution pattern has been converted to a spatial extent (Fig 6), and the highest species richness (more than 600 species) was observed in the montane and submontane vegetation zone. Alpine vegetation belt has moderate species richness (around 300 to 400 species), and the higher altitude region has very poor species richness.

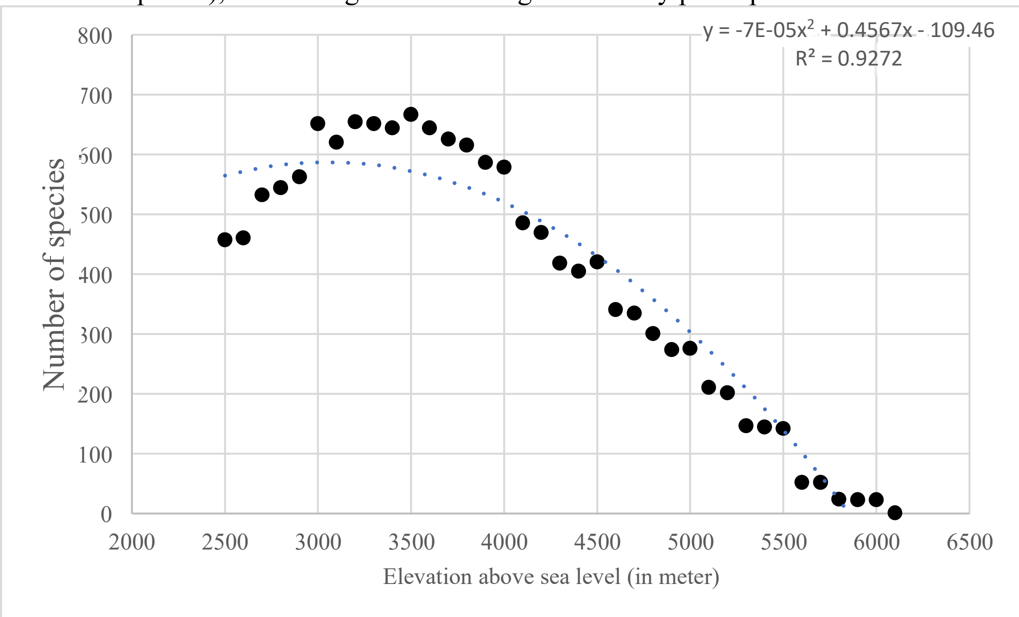

Figure 5: Species richness according to different altitudes in Ladakh.

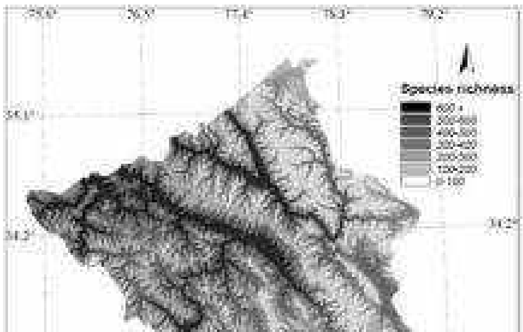

Figure 6: Spatial distribution of species richness in Ladakh.

As shown in figure 7, the richness distribution of each growth form of the species also differs, and the herbaceous species show the highest richness along the whole study area (Fig 7, right). The peak of this unimodal distribution consists of around 550 species and is distributed from 3,000 to 4,000 m a.s.l. which is notably higher than other growth forms of that region. To compare, the second dominating growth form of plant in Ladakh is a shrub, and the highest number of shrubs is also found in the elevation range between 2,800 to

3,500 m a.s.l. followed by graminoids and tree species (Fig. 7, left). Only two epiphytes and lianas can be seen in these montane areas.

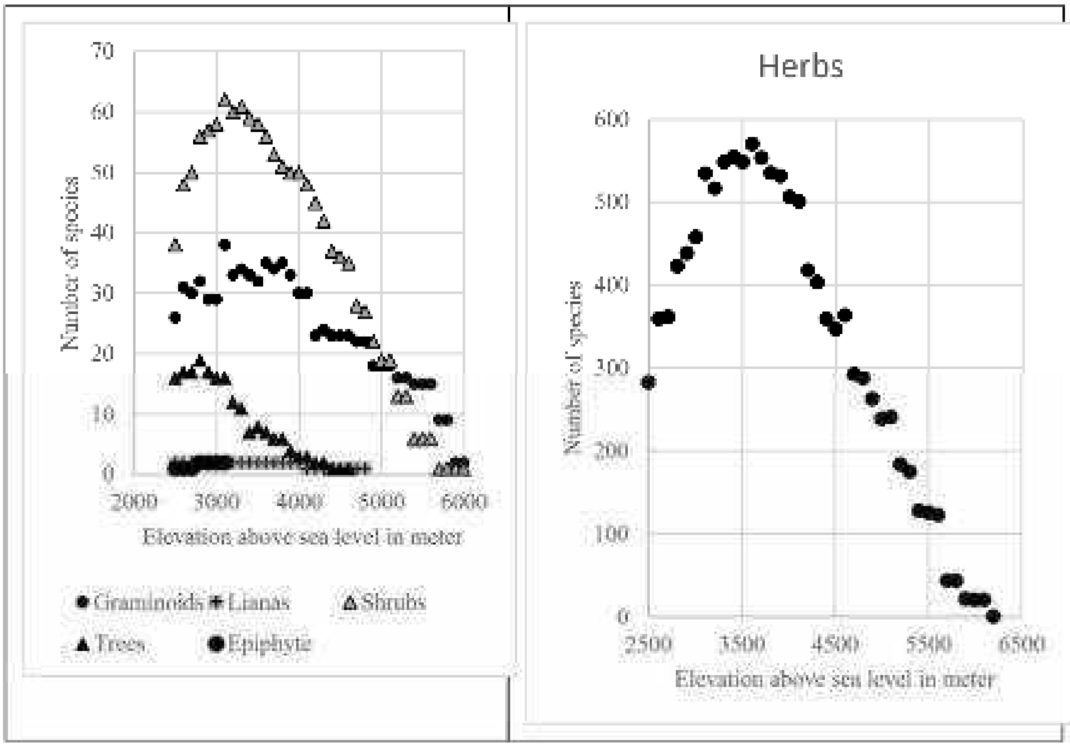

Figure 7: Elevational species richness of different life forms in Ladakh.

Discussion

Prior work has documented the occurrences of species in different parts of the Himalaya, and the spatial distribution, including elevation records, has been documented precisely (Dvorský et al., 2018). However, these studies have either explored floral records or have not focused on the spatial distribution of those flora and species richness. In this study, I analyzed species data for 100 m elevation and plotted the distribution of species richness over space in Ladakh. I found that the elevational distribution of vegetation revealed a humped shape and a unimodal pattern in virtually all cases.

The results suggest that I have unique peaks in species richness, distributed along the gradient of elevation from the montane belt to subalpine vegetation. These findings extended to draw spatial information for the species-rich areas in the study area. In addition, the added spatial information of the species richness in our study was related to elevational zonation of vegetation or vertical differences of species distribution. Therefore, this study indicates that the updated vegetation distribution can be used for analyzing further spatial factors or variables that have relative importance for species richness. There is a decline in richness at high elevations due to less precipitation in the mountainous area (Bhattarai et al., 2004; McCain, 2007; McCain and Grytnes, 2010; Vetaas et al., 2019). In temperate to cold climates, thermal energy could be a critical variable (Hawkins et al., 2003; Vetaas et al., 2019; Whittaker et al., 2006).

Conclusion

Plant growth forms influence elevational richness gradients in our study area. Like other studies (Manish et al., 2017; Kluge et al., 2017), varied growth forms have different elevational richness patterns, but the dominant growth form with the highest number determines the overall shape. Montane belt has the highest species richness, consisting of only 7% area of the entire region. For the conservation approach, analyzing the richness patterns of each growth form is essential, especially for medicinal plants. It is crucial to have assessments for small plots and conservation of remote areas like Ladakh for nature conservation and study of mountain biogeography. Spatial distribution of species richness is also applicable to a correlation between geodiversity and species richness, while mountains represent varied diversity of all variables. This research will also bring light to the botanical studies of Bangladesh's conservation areas and hill tracts to manage biodiversity.

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Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare upon oath that I have written the present dissertation independently and have not used further resources and aids than those stated.

Raunaq Jahan

Hamburg, 27.09.2022
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