Spatial Patterns of Species Richness and Distribution in Breeding Land Birds of the Central Indian Highlands, India

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THE AWARD OF THE DEGREE OF
DOCTOR OF PHILOSOPHY IN FORESTRY
(Forest Ecology and Environment)

By

R. JAYAPAL
Wildlife Institute of India
Dehra Dun
2006

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

CERTIFICATE

This is to certify that the thesis entitled "**Spatial patterns of species richness and distribution in breeding land birds of the Central Indian Highlands, India**" submitted for the award of Doctor of Philosophy in Forestry (Forest Ecology & Environment) to Forest Research Institute (Deemed University), Dehra Dun is a record of original research work done by Mr. **R. JAYAPAL** at Wildlife Institute of India, Dehra Dun under our guidance and supervision. We further certify that this research work has not previously formed the basis for the award of any other degree or diploma and it fulfils all the requirements laid down in the Ordinance governing award of Ph.D. degree of Forest Research Institute (Deemed University).

Mr. QAMAR QURESHI
(Supervisor)
Senior Reader
Wildlife Institute of India
Dehra Dun

Dr. RAVI CHELLAM
(Co-supervisor)
Reader
Wildlife Institute of India
Dehra Dun

Date: 15 November, 2006
Place: Dehra Dun

Post Box No. 18, Chandrabani, Dehradun - 248001. India
EPABX : +91-135-2640111 to 2640115 2640990 ; FAX : 2640117 GRAM : WILDLIFE;
E-Mail : wii@wii.gov.in

DECLARATION

I hereby declare that the thesis entitled **"Spatial patterns of species richness and distribution in breeding land birds of the Central Indian Highlands, India"** submitted for the award of Doctor of Philosophy in Forestry (Forest Ecology & Environment) to Forest Research Institute (Deemed University), Dehra Dun is a record of original research work done by me under the supervision of Mr. Qamar Qureshi, Senior Reader, Wildlife Institute of India, Dehra Dun and under the co-supervision of Dr. Ravi Chellam, Senior Reader, Wildlife Institute of India, Dehra Dun, and it has not formed the basis for the award of any other degree or diploma. I also declare that the thesis embodies the result of my own work and observations and in that respect the investigation appears to advance knowledge in the subject.

Date: 15 November, 2006
Place: Dehra Dun

(R. JAYAPAL)
Candidate

Countersigned:

(Mr. Qamar Qureshi)
Supervisor

(Dr. Ravi Chellam)
Co-supervisor

FOREST RESEARCH INSTITUTE
(Deemed University)
DEHRA DUN

This is to certify that Mr. **R. JAYAPAL** enrolment no. 0303/WII/E1346/R-749/7-903 carried out research work under Shri. Qamar Qureshi and Dr. Ravi Chellam, Wildlife Institute of India, Dehra Dun. The topic of the research registered with FRI Deemed University was **"Spatial patterns of species richness and distribution in breeding land birds of the Central Indian Highlands, India"**. The scholar presented his work in the pre-thesis submission seminar held on 10 November, 2006 and the RAC found the work to be satisfactory and approves the work to be presented in the form of thesis for evaluation by examiners for "Award of Ph.D. Degree" by FRI Deemed University.

Supervisor

Co-Supervisor

Head of Division

Expert Member

Expert Member

P.K. Mathur

Expert Member

Chairman RAC

No. 1287- 903/2003-DUC
Forest Research Institute (Deemed University)
P.O.: I.P.E., Kaulagarh Road
Dehra Dun – 248 195

Dated 20/5/ 2003

☎: 0135 – 2751826
EPBX: 2757021-28 – 4439, 4495 (Ext.)
E-Mail: arorasd@icfre.up.nic.in

To,
Sh. R. Jayapal
Wildlife Institute of India,
P.B. No: 18,
Dehra Dun – 248 001.

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Chandrabani

2. Dr. Ravi Chellam, Reader, Wildlife Institute of India, 4~~, Kalidas Road~~, Dehra Dun.

Chandrabani

3. The Nodal Officer, Wildlife Institute of India, 4~~, Kalidas Road,~~ Dehra Dun.
4. The Guard File.

Registrar
F.R.I., Deemed University

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Executive Summary

1. Variations in number and distribution of species in space constitute one of the fundamental themes in ecological research. It is being increasingly recognized that studies on species diversity at regional scale are essential to understand the mechanisms of maintenance of biological diversity. Emergence of macroecology, where large-scale ecological phenomena are examined to test biogeographical hypotheses, has considerably widened the scope of these approaches to include application of empirical patterns in finding solutions to conservation issues. This study, adopting this macroecological framework, investigates the spatial patterns in species richness and distribution of breeding land birds in central India.

2. The study was conducted across the Satpura and Vindhya Ranges, collectively known as Central Indian Highlands, in Madhya Pradesh, India between March, 2002 and September, 2005. The study area was divided into 11 '*biogeographic regions*' on the basis of topography, natural vegetation, and eco-climatology. All the regions were then gridded into quarter-degree cells or '*quadrats*' (c. 27 X 26.5 km). Primary data on distribution of breeding land birds were collected for each quadrat using a spatially hierarchical sampling scheme. In total, distribution of 190 species of birds was mapped for 284 quadrats. Alongside, vegetation composition and structure were measured for some key habitat types in intensive sampling sites. Data on environmental variables including topography, climate, productivity, landscape heterogeneity, forest cover, and human population were extracted for each quadrat from remote-sensing data and other sources.

3. Bird species composition is found to be primarily determined by vegetation structure at regional level and by floristic composition at local scale. This finding is consistent with earlier observations that birds respond, in their species composition, to vegetation structure across habitats and to vegetation composition within habitats. Among the foraging guilds of birds, composition of insectivorous birds is influenced by vegetation structure as predicted, but phytophagous guild (comprising birds that largely feed on plant products like nectar, fruits, and seeds) does not show any selection for vegetation composition in contrast to patterns observed elsewhere. I attribute this anomaly to availability of a wider choice of food plants for phytophagous birds in central Indian forests and partly to weak species-environment relationships on account of their nomadism.

4. When the relationship between local and regional species richness in birds of Central Indian Highlands is examined in constrained regression, quadratic curve is found to be better fit than linear model. A similar trend is obtained with unconstrained regression as well, which yielded a slope value less than one and an intercept greater than zero implying a non-linearity in the relationship. The fact that the local species richness does not increase, ad infinitum, with the size of the regional species pool suggests that bird communities in Central Indian Highlands are composed of truly saturated assemblages. This species saturation, notwithstanding a poor species pool, is paradoxical, warranting further investigations. It is hypothesized that sparse niche differentiation of the structurally impoverished tropical deciduous forests of central India, rather than any historical constraints, contributes to the observed species saturation of local bird communities in the landscape despite a depauperate avifauna.

5. The species-area relationship in central Indian birds is best described by power function curve with a slope of 0.12. The acutely low slope points to the extremely sparse nature of spatial gradient in bird species diversity of Central Indian Highlands. When the species-area curves are examined separately for habitat-specialists and generalists, the slope is observed to be much higher in habitat-specialists (0.23) than in generalists (0.05). This finding strongly supports the habitat diversity hypothesis of species-area relationships. The values of intercepts of the curves show that the minimum number of generalist bird species that breed in a quadrat in the study area is around 54 but only 8 species of habitat-specialists are to be expected from a quadrat. This disparity highlights the generally high catholicity of habitat choice among the birds of Central Indian Highlands. Nonetheless, a region-wise analysis of species accumulation curves and species density rankings identify Satpura Plateau and Betul Plateau as '*diversity hotspots*' for central Indian avifauna.

6. Bird species turnover and taxonomic distinctness are observed to be unrelated to regional species richness ('*gamma diversity*'). The absence of correlations among these three attributes implies a greater role for ecological factors, vis-à-vis historical forces, in maintaining species trajectories in central Indian birds. However, when species richness, turnover, and taxonomic distinctness are examined at the level of quadrats, a striking bimodality is observed among the quadrats with two distinct clusters as species-rich ($S > 90$) and species-poor ($S < 90$). Overlaying of land-cover data reveals that these two groups correspond to forested and non-forested quadrats. This dichotomy suggests that species diversity of forest and non-forest birds are governed by independently evolved regulatory mechanisms. A subsequent re-analysis of the relationships among the three attributes of species distribution yields contrasting patterns between species-rich and

species-poor quadrats, displaying evidences of Simpson's Paradox. In particular, its manifestation in the relationship between species richness and turnover is interesting and can be linked to statistical properties of the species turnover measure. In other words, it means that there is less than expected rate of species-gain in non-forested quadrats and greater than expected rate of species-loss in forested quadrats among the breeding birds of Central Indian Highlands.

7. Species richness of birds is found to be significantly related to all the major environmental factors, even after the spatial effects are partitioned out using partial regressions. While bird species richness is positively associated with primary productivity (NDVI), landscape diversity, and forest cover, it decreases with rise in cropping area, human population density, and urbanization. Among climate, species richness increases with variables that describe water availability (i.e., rainfall, wet day frequency, and moisture availability), but shows inverse relationship with energy-related parameters (i.e. temperature, diurnal temperature range, and potential evapotranspiration). This finding supports the 'water-energy balance' hypothesis of species richness gradients, which states that temperature limits number of species at higher latitudes and rainfall determines species richness at warm lower latitudes.

8. Among all the environmental variables, elevation range, landscape diversity, and forest cover emerge as the predictors of bird species richness in both spatial (generalized least squares regression) and non-spatial (ordinary least squares regression) models, though rainfall is also selected as an additional predictor in the latter. While the GLS explains 72 % of variation in bird species richness, the accuracy of the OLS regression is observed to be 62 %. The fact that both spatial and non-spatial models converge on nearly the same set of environmental variables as predictors of bird species richness underplays the importance of spatial autocorrelation in ecological data. When land-use patterns are subsequently modeled independently with bird species richness, it is shown that every 10 sq. km. increase in cropping area in a quadrat would result in loss of one species of forest birds.

9. Application of Indicator Species Analysis extracts seven distinct biomes among the breeding birds of Central Indian Highlands along the gradients of vegetation physiognomy, elevation, and rainfall: open tracts (moist & semiarid), scrub jungle, dry deciduous forests (high & low-rainfall), and moist deciduous forests (high & low-elevation). Among the four forest-biomes, both low-elevation moist deciduous forests and high-rainfall dry deciduous forests are the most dominant in geographical extent. On the other hand, high-elevation moist deciduous forests, despite occupying a smaller area, are

characterized by bird species with very high indicator values, signifying a notable presence of biome-specialists.

10. Examined against IUCN's 10 % biome-area target for adequacy of Protected Area (PA) network, the low-rainfall dry deciduous forests emerge as the only under-protected biome in Central Indian Highlands with just 6 % area under PA network and the remaining three forest-biomes have more than 10 % area currently enjoying legal protection. In particular, the high-elevation moist deciduous forest biome features a fairly high proportion of area (c. 20 %) under PA network.

11. Conservation assessment of sites in low-rainfall dry deciduous forest biome, using irreplaceability values, reveals that the first four top-ranking quadrats, all lying within Malwa Plateau, are marked by a complete absence of PAs. Correspondingly, the reserve selection algorithm selects Choral RF from the highest ranking quadrat as the topmost prioity site to complement the existing PA network. Interestingly, Rodgers & Panwar (1988), in their biogeographical review of PA network in India, had earlier proposed a PA status for Choral RF.

12. The findings of the study clearly illustrate the bias in PA network that a single-species approach can potentially bring about. The recent rediscovery of the critically endangered Forest Owlet (*Heteroglaux blewitti*), after a gap of 113 years, from these low-rainfall dry deciduous forests highlights the importance of extending adequate protection to all major biomes and the need for multi-species approach in design and maintenance of an efficient PA network.

Chapter 1. Introduction

> *It must be made clear, however, that our knowledge of the ornithology of the Satpura and Vindhya mountains, as well as that of the Aravallis, is as yet very incomplete and defective.*
>
> \- **Sálim Ali** (1949)

This observation, made by one of the founders of modern field ornithology in the Indian Subcontinent, sadly continues to remain true even after 50 years. At times, it makes one wonder if scientific exploration of the natural wealth of the country had ended with the exit of the British. On the other hand, as E.O. Wilson (2000) warns, the acceleration in human onslaught on tropical forests has reached so high a proportion that the need for accurate documentation of biodiversity has never been more exigent than now. Overwhelmed by a mix of these facts and thoughts, a survey was originally conceived to collect primary data on distribution of breeding birds of the Satpura and Vindhya Ranges, collectively known as Central Indian Highlands. It was also realized that these data over a huge landscape could offer infinite scope for testing several biogeographical hypotheses. Subsequently, this study was designed to address some of the key questions in macroecology, a relatively new field where biogeographical patterns are explained with contemporary ecological data.

1.1. Macroecology: an emerging field

Studies on structure and organization of local avian assemblages have been a major area of research in community ecology since the pioneering works of David Lack and Robert MacArthur in mid twentieth century (Wiens, 1989). A vast number of these studies seek to explore the relationships between bird species diversity and habitat attributes such as vegetation structure, composition, and heterogeneity (e.g., MacArthur & MacArthur, 1961; Willson, 1974; James & Wamer, 1982; Mills *et al.*, 1991; Germaine *et al.*, 1998; Haney & Lydic, 1999; and more recently Sekercioglu, 2002; Shirley, 2004). A central goal of these investigations is to identify patterns and processes that describe and govern bird communities in a neighbourhood and accordingly a majority of them concern local scale phenomena, though there were a few notable regional approaches (e.g., Williams, 1964; MacArthur, 1972).

A growing number of studies on species diversity issues at mesoscale in early 1990s (see Ricklefs & Schluter, 1993), and concurrent emergence of a new paradigm in ecological biogeography that came to be known as macroecology (Brown & Maurer, 1989) considerably widened the scope of community research from local to regional and continental scales. Incidentally, early 1990s also saw a resurgence of interest in geographical ecology, searching for patterns in relationships between species abundance, body size, and range size (e.g., Gaston & Lawton, 1990; Nee *et al.*, 1991; Gaston & Blackburn, 1996). Both these schools of thought together gave rise to a new research agenda that marked the unification of community ecology and biogeography, an approach originally founded by Robert MacArthur (1972). This assorted body of research undertakings, with a common theme of investigating large-scale interactions between environment, species numbers, and life-history parameters of species, is now collectively known as macroecology, significantly expanding the scope and aims of the original programme of macroecology as set out by Brown and Maurer (1989). The popularity of this emerging field is also borne out by the fact that two major international journals were launched in 1990s to cater to the rising number of studies in macroecology – *Global Ecology and Biogeography*, and *Diversity and Distributions*.

This new discipline progresses by asking several fundamental questions, both old and new, that are important in advancing our understanding of biological diversity. Prominent among them are:

- Why are some areas rich in species diversity? (e.g., Bini *et al.*, 2004)
- What determines the number of species found in an area? What are the environmental and ecological determinants of species richness? (e.g., Currie 1991; Bohning-Gaese 1997; O'Brien, 1998; Lennon *et al.*, 2000; Hawkins *et al.*, 2003)
- Are species combinations in a community driven by competition? How do we test that they are not by chance alone? (e.g., Diamond, 1975a; Connor & Simberloff, 1979; Gotelli, 2000)
- How does species diversity change in space and time, and why? (e.g., Ricklefs & Schluter, 1993)
- What is the biological significance of species-area relationships? How do we define the landscape boundaries of species turnover in space, and why are they important in conservation biology? (e.g., Connor & McCoy, 1979; Rosenzweig, 1995; Lomolino, 2001; Storch *et al.*, 2003)

- How does local species richness increase with regional species pool? Is a curvilinear relationship an evidence of community saturation? (e.g., Ricklefs, 1987; Cornell and Lawton, 1992; Srivastava 1999; Hillebrand & Blenckner, 2002)
- Is population density of a species related to its geographical range size? (e.g., Brown, 1984; Gaston & Lawton 1990; Holt *et al.*, 1997)
- How do we measure species diversity for biological monitoring and conservation evaluation? Why is it important to incorporate phylogenetic information into diversity measures? (e.g., Faith, 1992; Humphries *et al.*, 1995; Debinsky & Humphrey, 1997)
- How good are surrogate taxa like umbrella or flagship species as a conservation tool? Does multiple species approach produce more optimal solutions for spatial conservation issues? (Roberge & Angelstam, 2004; McCarthy *et al.*, 2006)

Thus, enquiries in macroecology often require datasets that combine both ecological traits (e.g., life-history parameters, species interactions, and habitat requirements) and biogeographical attributes like range size, geographical distribution, and endemism (Whittaker *et al.*, 2005). In fact, the very appeal of macroecological framework lies in its heuristic value by which contemporary patterns in species diversity and distribution can be explained by weighing ecological factors against historical forces (e.g., Ricklefs & Schluter, 1993).

1.2. Some conceptual issues & applications

Macroecology, like any other young area of research, is also marked by a few handicaps and shortcomings, largely mediated through some of the emergent properties of data typically used in geographical ecology. Foremost among them is the inconsistency of species richness, measured simply as number of species found in a sampling unit (Gaston, 1996). Species richness tends to change frequently with the vagaries of taxonomic revisions in species limits. In particular, phylogenetic species concept is known to inflate the number of species in comparison to the traditional biological species concept (e.g., Peterson & Navarro-Sigüenza, 1999). However, increasing evidences show that macroecological patterns are more likely to remain the same with the application of different species concepts (e.g., Isaac & Purvis, 2004; Dillon & Fjeldså, 2005).

Other conceptual issues in macroecology essentially concern the spatial nature of data employed in large-scale studies. In general, macroecological investigations are carried out over spatially contiguous gridded areas. This gives rise to several methodological challenges customarily associated with spatial data (Haining, 1990). A particularly ubiquitous problem is the spatial scale, which may influence the nature of ecological relationships being modeled (e.g., Foody, 2004). Conducting an investigation simultaneously at multiple scales is a promising approach to overcome such scale-effects (e.g., Rahbek & Graves, 2001). On the other hand, arguments over optimal scale of study in macroecology have also been described as superfluous, making scale a non-issue (e.g., Blackburn & Gaston, 2002).

Spatial autocorrelation among data collected over conterminous sampling units ('*grid-cells* or *quadrats*') is another property of ecological data that may unduly exaggerate the strength of relationship between predictor and response variables in the model (Legendre, 1993; Lennon, 2000). This often warrants use of non-conventional statistical techniques like generalized regression or other variance-partitioning methods that explicitly address the underlying spatial structure in the data (e.g., Borcard *et al.*, 1992; Selmi & Boulinier, 2001; Diniz-Filho *et al.*, 2003).

Despite these limitations, studies in macroecology have produced several useful models and constructs, which have been increasingly recognized as invaluable tools in conservation biology. Some of the more popular applications include:

- Species-accumulation curves in identification of diversity hotspots (e.g., Pomeroy, 1993; Hobohm, 2003)
- Impact assessment of changes in land use patterns on species diversity using species-area relationships (e.g., Flather, 1996)
- Species-area curves in calculation of extinction debt and rate of faunal relaxation following habitat fragmentation (e.g., Brooks *et al.*, 1999)
- Island biogeography theory in optimum design of nature reserves (e.g., Worthen, 1996)
- Species richness-environment models in predicting effects of long-term changes in climate and environment on species diversity and distributions (e.g., Thomas & Lennon, 1999; Oindo *et al.*, 2001)
- Mapping of species diversity of a landscape to aid in developing regional conservation plans (e.g., Harrison & Martinez, 1995)

- Developing a representative and complementary PA network using patterns of geographical distribution in species diversity and endemism (e.g., Rodrigues *et al.*, 2004)

1.3. Macroecological studies on Indian avifauna

The marked paucity of empirical studies from tropical forests has been recognized as one of the major constraints in discovering general laws in ecology (Lawton, 1999). This is borne out by the fact that Pearson and Carroll (1998) remains the only study on Indian birds in true macroecological framework, though some regional works have evinced interest in broad-scale patterns of bird species richness (e.g., Daniels *et al.*, 1991; Pramod *et al.*, 1997; Sankaran, 1997; Thiollay, 1998; Davidar *et al.*, 2001).

Way back in 1986, Dorst and Vuilleumier studied the high-altitude bird communities of Tibetan facies in Kashmir and compared them with the avian assemblages of the Andes and Africa. They observed a marked character-wise convergence in tropical communities across the continents.

Daniels *et al.* (1991) studied the birds of the Western Ghats in Uttar Kannada district and assessed the impacts of the changes in land use pattern of the region on distribution of local bird communities. Their regional approach was probably the first of its kind in India. In an extended study, Pramod *et al.* (1997) examined the birds of the entire Western Ghats to identify phylogenetically and ecologically unique assemblages of birds using indices of ubiquity and habitat hospitality. Though they gathered a fairly large set of data representing avifauna of ten major biomes in the region, surprisingly no further analysis was carried out to discern any macroecological patterns.

Sankaran (1997) analyzed the distribution of endemic avifauna of the Nicobar Islands to develop a more representative PA network for the region. On the contrary, Thiollay (1998) examined the distribution and abundance patterns of diurnal raptors in South Asia (including Andaman and Nicobar islands) from a more theoretical perspective. His study found little evidence for 'area effect' in explaining the current distribution of raptor communities, and detected 'island syndrome' among insular assemblages. He also inferred that habitat fragmentation and biogeographical history together might explain the composition of contemporary raptor communities in the region.

Pearson and Carroll (1998), in a veritable macroecological tradition, gridded the Subcontinent into 275 X 275 km quadrats, and analyzed the spatial patterns in species richness of birds, butterflies, and tiger beetles using geostatistical techniques; they found significant degree of congruence between birds and tiger beetles but no relationship was observed between annual rainfall and species richness of any of these three taxa.

Davidar *et al.* (2001) studied the forest birds of the Andaman Islands to assess the relative roles of area, habitat, and geographical location in predicting the species richness gradients in Andaman avifauna. Their results pointed to the importance of wet tropical forests in maintaining high diversity assemblages of birds in the islands. They also found evidences for the role of historical biogeography in structuring the bird communities at regional level.

1.4. Why a study on birds of Central Indian Highlands?

The current study was conducted to examine the spatial patterns of species richness and distribution in breeding land birds of Central Indian Highlands in Madhya Pradesh. This landscape, comprising the Satpura and the Vindhyan Ranges divided by the Narmada valley, is characterized by nearly contiguous stretches of tropical deciduous forests. Though the mean elevation of the hill ranges varies between 300 and 600 m, some of the peaks in the Satpura Range exceed 1000 m. Biogeographically, these peninsular hills, with moist montane forests along their crests, are thought to have served as the dispersal highway in the historical past for the Indo-Malayan birds from the Himalayas in the north-east to the Western Ghats in the south-west (Ali, 1949; also see Hora, 1949 for the '*Satpura Hypothesis*'). But the fact that they currently feature a relatively depauperate avifauna with just two species of birds endemic to the region, despite having a remarkable forest cover and a rich and momentous historical past, throws up several interesting paradoxes. To resolve these puzzles, it is necessary to study the interplay of biogeography and ecology of the region's avifauna and to investigate patterns of bird species diversity and factors that shape them. As it has been demonstrated elsewhere (and in the present thesis as well), this knowledge is also very critical to evolve holistic conservation plans for a landscape. This is well illustrated by the critically endangered Forest Owlet (*Hetroglaux blewitti*) - a species endemic to Central India and rediscovered in 1997 after a gap of 113 years (King & Rasmussen, 1998); eight out of ten sites which are currently holding the fragmented populations of Forest Owlet lie outside PA network highlighting the severe bias in reserve planning in central India.

Besides these biogeographical concerns, there are also other features that make Central Indian Highlands an ideal landscape to test macroecological hypotheses. They include:

- Homogeneity of the landscape with few confounding socio-ecological factors
- Shared geological history with marked gradients in climate, soil, and vegetation
- Strategic geographic location, beset by three biogeographic zones and six provinces (Rodgers & Panwar, 1988)
- Presence of various transition zones of ecological significance (e.g., sal and teak biomes, dry and moist deciduous forests, and semiarid and moist grasslands)
- Hybridization interface for several sister taxa of birds as the landscape forms the southern and northern limits of distribution for many species (Ali & Ripley, 1983)
- Well-documented records of forestry operations available for over a century (e.g., Rangarajan, 1996)
- Forest-based economy of the region, along with increased conflicts between socio-economic pressures and ecological concerns, gives opportunities to test multiple-choice models of reserve selection algorithms
- A rich floral and faunal diversity of the landscape with tiger as the flagship species of conservation efforts
- Not least of all, fine logistics and accessibility of the region that would make large-scale surveys to collect primary data feasible within the constraints of time and money.

Inadequacies in taxonomic and distributional data, respectively termed as *Linnaean* and *Wallacean* shortfalls, are identified as one of the stumbling blocks for the progress and maturation of conservation biogeography (Whittaker *et al.*, 2005). Though lower-level taxonomy is relatively well-resolved among birds (but see Rasmussen & Anderton, 2005), our current knowledge of distribution range of many species of birds is far from complete. One of the prime objectives of this study was, therefore, to build a reliable and authentic distribution database for the breeding birds of Central Indian Highlands.

1.5. Organization of the thesis

The present thesis is organized into seven chapters that include the first two introductory sections followed by five main chapters:

Chapter 1, as being read, introduces the general concepts and framework of macroecology and presents a brief account of the past studies on birds of the Indian subcontinent with macroecological outlook. Chapter 2 contains a concise description of the Central Indian Highlands -the study area of the present investigation, with notes on geography, climate, natural vegetation, socio-economics, and flora & fauna of the landscape. In Chapter 3, I investigate the relative roles of forest composition *versus* structure in determining bird species composition at the landscape level, and how these associations change with spatial scale and different foraging guilds of birds. Chapter 4 examines the relationship between local and regional species richness of birds to test if the avifauna of Central Indian Highlands is species-saturated and to assess the relative contribution of ecological *versus* historical factors to bird species diversity of the region. Chapter 5 investigates the spatial patterns in species diversity of birds in Central Indian Highlands. I study, in this chapter, species-area relationships to describe spatial organization of the number and distribution of birds; I also explore the nature of associations among species richness, species turnover, and taxonomic diversity among the birds of Central Indian Highlands. In Chapter 6, I investigate the relationship between bird species richness and environment. Specifically, I attempt to develop an environmental model of bird species richness using geostatistical techniques to predict the number of bird species that breed in an area on the basis of biotic and abiotic factors including topography, climate, primary productivity, landscape diversity, forest cover, human population, and urbanization. Chapter 7 seeks to identify distinct biomes among the breeding birds of Central Indian Highlands and to extract indicator species for each biome; I also examine, in this chapter, the adequacy of Protected Area (PA) network under each biome, and develop reserve selection algorithms on the basis of rarity and range size of bird populations to identify and prioritize sites for addition to the existing PA network.

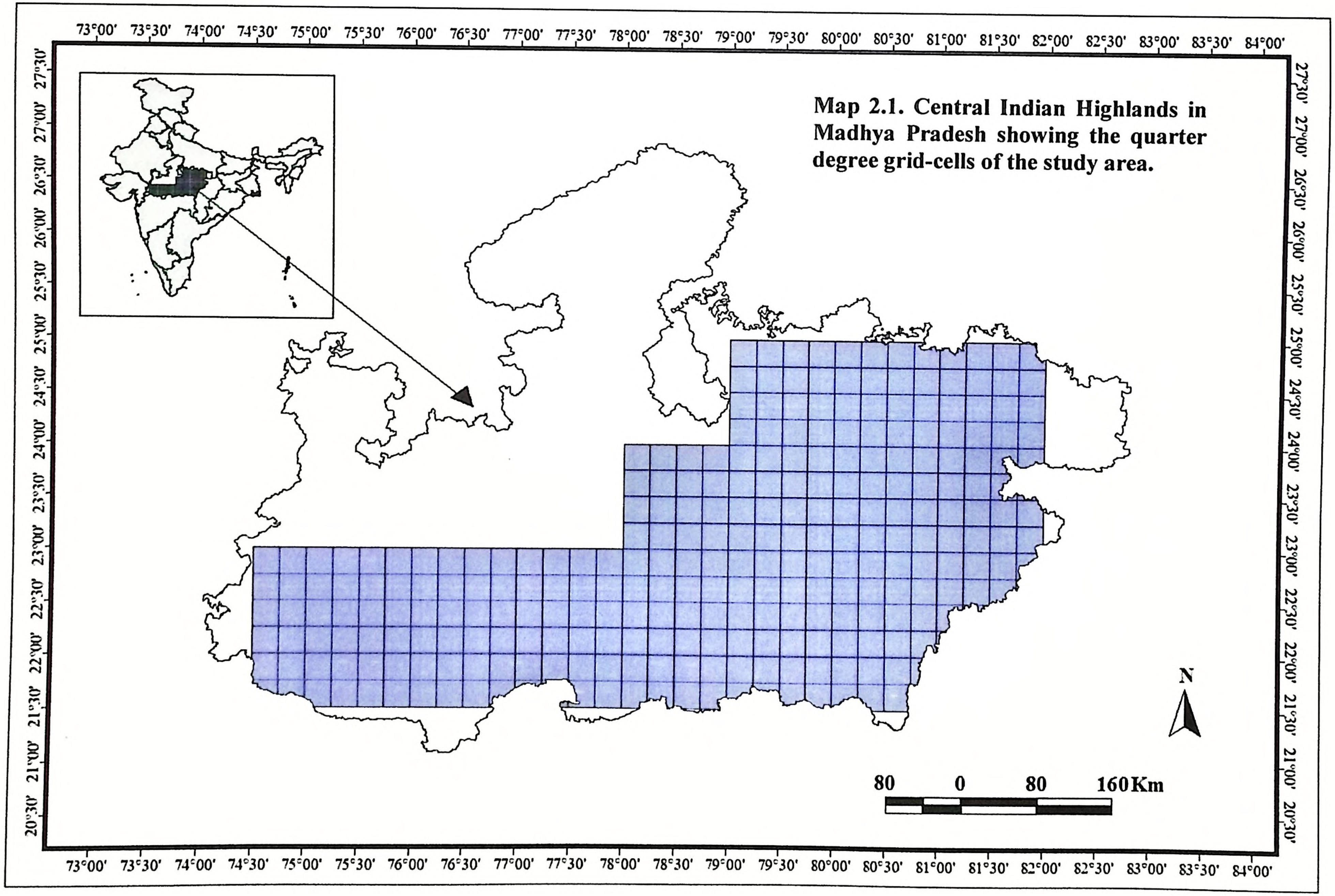
Chapter 2. Study Area

The study was conducted over the Satpura and Vindhya Ranges, collectively known as Central Indian Highlands in the state of Madhya Pradesh (M.P.), India between March, 2002 and September, 2005. In the biogeographic classification of India (Rodgers & Panwar, 1988), this region largely corresponds to the Province '*Central Highlands*' falling under the Deccan Zone (see Map 2.1). Covering an area of about 200,000 sq. km., this vast landscape boasts fairly extensive tracts of tropical dry and moist deciduous forests.

2.1. Physical features

Central Highlands of India comprise two parallel chains of hills, viz., the Satpuras and the Vindhyas, which run almost continuously from east-northeast to west-southwest orientation separated by the Narmada River. The entire ranges stretch across four states, viz., Gujarat, Maharashtra, Madhya Pradesh, and Chhattisgarh. However, the study was carried out only within Madhya Pradesh, which encompasses almost 80 % of the hill ranges. The Vindhyas lie to the north of Narmada, extending from Jobat in Gujarat (22°27' N; 74°35' E) to Sasaram in Bihar (24°57'N; 84°02'E) through Malwa Plateau and Baghelkhand (Kaimur Hills). The Satpuras, in parallel to the Vindhyas, lie south of Narmada and are composed of several, disjointed ranges that include Rajpipla Hills (sometimes considered as part of Western Ghats), Nimar Hills, Gawilgarh Hills, Pachmarhi Hills, Mahadeo Hills, and Maikal Ranges. The mean elevation of the Vindhyas varies between 450 to 600 m, though a few points rise above 900 m. In contrast, the Satpuras are marked with several high peaks, the highest being Dhupgarh near Pachmarhi (1348 m).

Geologically, the tectonic structure is characterized by the '*Satpura Strike*' and radiometric aging indicates that the Satpura orogeny is of 950 – 1050 million years old (Krishnan, 1982). The western part of Vindhyas is chiefly typified by the Deccan Trap, while the Gondwanas and archaean gneisses characterize the eastern part of Satpuras (Krishnan, 1982). The Central Highlands serve as a key catchment area and major watershed for several perennial rivers including Narmada, Chambal, Betwa, Tons, Ken, Sone, Wainganga, Wardha, and Tapti.



Map 2.1. Central Indian Highlands in Madhya Pradesh showing the quarter degree grid-cells of the study area.

Table 2.1. Physical and administrative attributes of the regions of Central Indian Highlands.

Sl.No.	Region	Approx. Area (km^2)	Maximum elevation (m)	Major rivers	Major forest types [a]	Districts, covered
1	Malwa Plateau	18,590	797	Chambal, Sipra	Tropical dry-deciduous forest (teak-mixed) and Tropical dry-deciduous forest (mixed)	Jhabua, Dhar, Indore, and Dewas
2	Nimar Hills	14,300	1048	Beda, Chota Tawa	Tropical dry-deciduous forest (teak-mixed) and Tropical dry-deciduous forest (mixed)	Barwani, West and East Nimar
3	Lower Narmada Valley	18,590	709	Narmada	Tropical dry-deciduous forest (mixed)	West Nimar, Dewas, Harda, Sehore, and Hoshangabad
4	Betul Plateau	11,440	1101	Tapti	Tropical dry-deciduous forest (teak dominant), Tropical dry-deciduous forest (teak-mixed), and Tropical dry-deciduous forest (mixed)	Betul
5	Sagar-Damoh Plateau	22,880	667	Dhasan, Bearma, Narmada	Tropical dry-deciduous forest (mixed)	Sagar and Damoh
6	Satpura Plateau	9,295	1348	Tawa, Dudhi	Tropical dry-deciduous forest (teak dominant), Tropical dry-deciduous forest (teak-mixed), Tropical moist-deciduous forest (sal dominant), Tropical moist-deciduous forest (sal-mixed), and Subtropical broad-leaved hill forest	Hoshangabad, Betul, and Chhindwara
7	Seoni-Chhindwara Plateau	22,880	869	Kanhan, Pench, Wainganga	Tropical dry-deciduous forest (teak dominant), Tropical dry-deciduous forest (teak-mixed), and Tropical dry-deciduous forest (mixed)	Chhindwara, Narsimhapur, and Seoni
8	Vindhya Scarplands	17,875	561	Ken	Tropical dry-deciduous forest (teak dominant), and Tropical dry-deciduous forest (teak-mixed)	Chhatarpur, Panna, and Satna
9	Kaimur Hills	15,730	691	Hiran, Katni, Mahanadi	Tropical dry-deciduous forest (teak-mixed)	Jabalpur, Katni, Satna, and Rewa
10	East Maikal Range	32,175	1130	Son, Banas	Tropical moist-deciduous forest (sal dominant) and Tropical moist-deciduous forest (sal-mixed)	Shahdol, Umaria, Katni, and Sidhi
11	South Maikal Range	19,305	1112	Narmada, Banjar, Wainganga	Tropical moist-deciduous forest (sal dominant) and Tropical moist-deciduous forest (sal-mixed)	Mandla, Balaghat, and Dindori

[a] Adopted from Joshi *et al.* (2004)

For the present study, the entire study area was gridded into contiguous quarter-degree cells (15′X 15′) or '*quadrats*' (corresponding to Survey of India's 1:50,000 scale toposheets), with each quadrat measuring about 27 X 26.5 km in size (c. 715 sq. km.). These quadrats were then grouped, a priori, into 11 conterminous landscape units ('*biogeographical regions*') on the basis of natural vegetation, drainage, topography, and eco-climatic attributes, as follows: Malwa Plateau, Nimar Hills, Lower Narmada Valley, Betul Plateau, Sagar-Damoh Plateau, Satpura Plateau, Seoni-Chhindwara Plateau, Vindhya Scarplands, Kaimur Hills, East Maikal Range, and South Maikal Range. [See Map 2.2 & Table 2.1 for a brief account of the physical and administrative attributes of each of these regions].

2.2. Climate

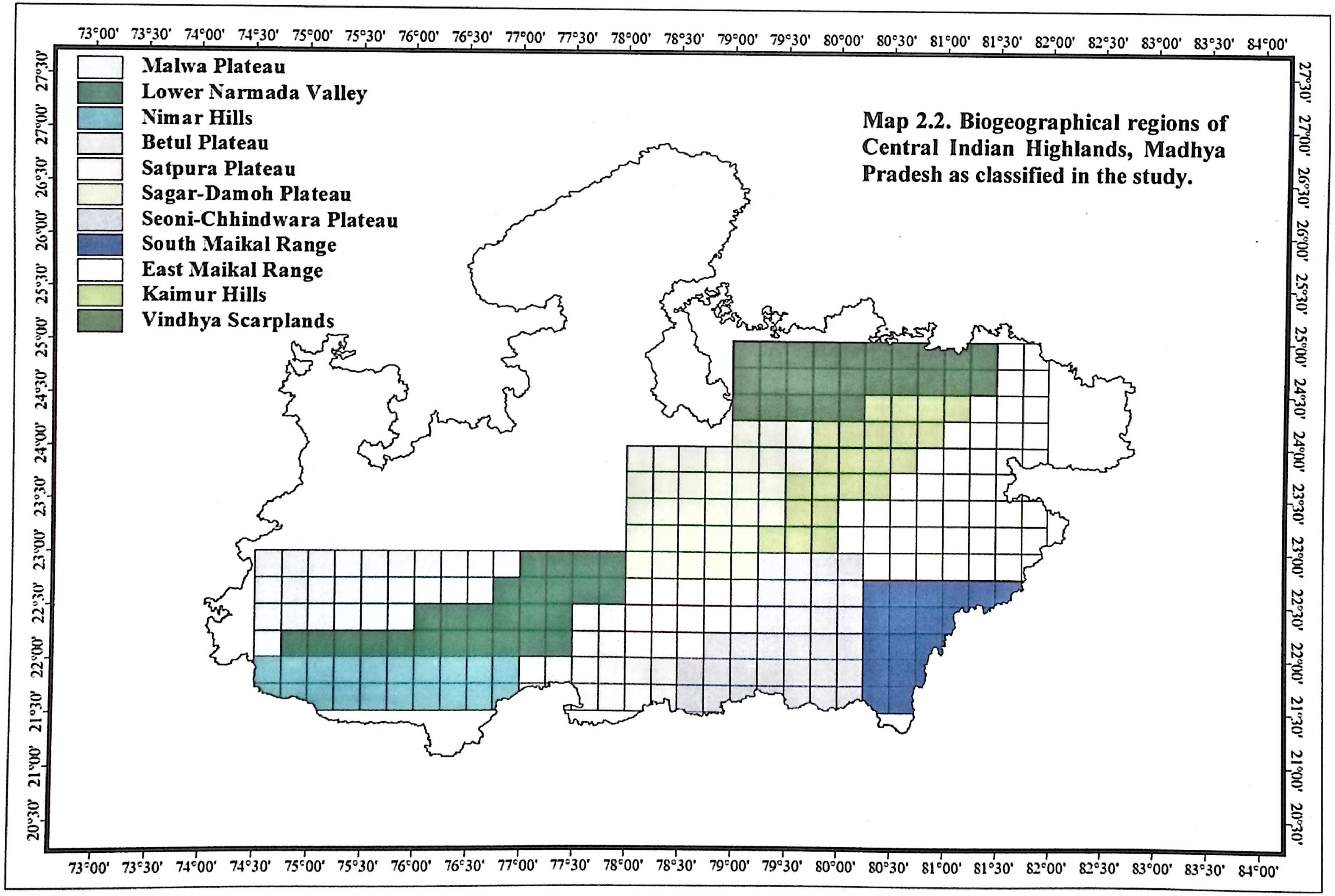
The general climate of the landscape is quintessentially tropical and it receives a large part of its annual rainfall from the south-west monsoon from July to September. Refer to Table 2.2 for 1961-1990 mean climatic normals, computed for each of the biogeographical regions of Central Indian Highlands using the ten-minute climatology of New *et al.* (2002).

Table 2.2. Climate data for each of the biogeographical regions in Central Indian Highlands, as extracted from New *et al.* (2002).

Region	**Mean temperature (°C)**		**Total annual rainfall (mm)**	**No. of wet days/yr**	**Relative Humidity (%)**
	Min	**Max**			
Malwa Plateau	18.7	32.5	934	42	50
Nimar Hills	19.3	33.7	842	41	50
Lower narmada Valley	19.6	33.4	1056	43	50
Betul Plateau	18.9	31.6	1191	54	50
Sagar-Damoh Plateau	19.3	32.1	1234	47	52
Satpura Plateau	18.6	30.8	1388	54	51
Seoni-Chhindwara Plateau	19.2	31.9	1255	58	53
Vindhya Scarplands	18.6	32.2	1099	49	55
Kaimur Hills	18.8	32.0	1199	54	55
East Maikal Range	18.6	31.2	1212	61	57
South Maikal Range	19.1	31.2	1351	65	56
Entire study area	**19.0**	**32.0**	**1163**	**52**	**53**

2.3. Natural vegetation & PA network

The natural vegetation in Central Indian Highlands is, for the most part, represented by tropical dry- and moist-deciduous forests, dominated by associations of teak (*Tectona grandis*) in western and central ranges, and sal (*Shorea robusta*) in



Map 2.2. Biogeographical regions of Central Indian Highlands, Madhya Pradesh as classified in the study.

the east. In addition, there are fairly extensive tracts of semiarid grasslands in Malwa Plateau in the west, and a few localized pockets of moist grasslands in the east.

According to Champion and Seth (1968), the forests of Central Indian Highlands are classified into five major groups and seven subgroups, as following:

I. Tropical Semi-evergreen Forests
  - Northern tropical semi-evergreen forests

II. Tropical Moist Deciduous Forests
  - South Indian moist deciduous forests
  - North Indian moist deciduous forests

III. Tropical Dry Deciduous Forests
  - Southern tropical dry deciduous forests
  - Northern tropical dry deciduous forests

IV. Tropical Thorn Forests
  - Southern tropical thorn forests

V. Subtropical Broadleaved Hill Forests
  - Southern subtropical broadleaved hill forests

Also refer to Appendix 2.1 for a detailed account of all the forest types that are found in the study area along with their distribution and floristics. According to the Forest Survey of India (2001), 29 % of the total land area of Central Indian Highlands is covered under both open and dense forests [See Table 2.3 for region-wise data on extent of different forest cover types in the study area.]. There are also 20 Protected Areas (6 National Parks + 14 Wildlife Sanctuaries) in the landscape and they occupy about 13 % of the total forest area [see Appendix 2.2 for a list of PAs in Central Indian Highlands].

Table 2.3. Region-wise distribution and extent of forest cover in Central Indian Highlands, Madhya Pradesh. [Source: IRS 1D-LISS III & Forest Survey of India, 2001].

	Area under forest cover (sq. km)			**Total forest cover (sq. km)**	**% Area under forests**
Region	**Scrub jungle**	**Open forests**	**Dense forests**		
Malwa Plateau	47	1176	1113	2289	12.3
Nimar Hills	88	1012	1328	2340	16.3
Lower narmada Valley	64	1435	3045	4480	24.2
Betul Plateau	122	829	3317	4146	36.7
Sagar-Damoh Plateau	122	2742	2607	5349	23.6
Satpura Plateau	34	1662	3235	4897	52.8
Seoni-Chhindwara Pl.	207	2299	5467	7766	33.9
Vindhya Scarplands	292	2171	1823	3994	22.7
Kaimur Hills	293	2691	1729	4420	28.4
East Maikal Range	367	4008	5098	9106	28.6
South Maikal Range	73	1874	7876	9750	50.5
Entire study area	**1709**	**21899**	**36638**	**58537**	**29.0**

2.4. People, forests & economy

Politically, Central Indian Highlands in Madhya Pradesh cover 28 districts (see Table 2.1), and the total human population in the entire study area is 3,31,40,675 as per 1991 census. The mean population density of the landscape is 164 persons / sq. km., which is far lower than the country average of 267. [See Table 2.4 for region-wise demographic data]. Among the regions, Malwa Plateau and Kaimur Hills are conspicuous for their relatively high density of population, attributable to the presence of two urban agglomerates of the study area, viz., Indore and Jabalpur.

Table 2.4. Region-wise distribution of human population, area under crop-fields, and road length in Central Indian Highlands, Madhya Pradesh.

Region	Total Population (1991)	Population density (per sq. km)	Area under crop-fields (sq. km) [a]	Total length of roads (km) [b]
Malwa Plateau	4654240	251	15660	284
Nimar Hills	2399742	167	11489	74
Lower narmada Valley	2510560	136	13176	161
Betul Plateau	1396349	124	6914	105
Sagar-Damoh Plateau	3467817	153	17042	993
Satpura Plateau	1148497	124	4299	210
Seoni-Chhindwara Pl.	3886934	170	14788	828
Vindhya Scarplands	2907677	166	13015	463
Kaimur Hills	3008338	193	10724	615
East Maikal Range	5309232	167	21321	916
South Maikal Range	2451289	127	8120	429
Entire study area	**33140675**	**164**	**136548**	**5076**

[a] Source: UMD-GLCF data (Hansen *et al.*, 2000)
[b] Source: Digital Chart of the World, 1993 (ESRI, 1993)

A majority of the people of central India belong to scheduled tribes, a large fraction of which continue to live in forest villages. At least in three districts (viz., Jabhua, Dhar, and Mandla), they constitute more than 50 % of the total population (Table 2.5). Some of the major tribal communities living in Central Indian Highlands (with number of districts where they are predominant) are: Gonds (15), Kols (6), Bhils (5), Korkus (4), Baigas (3), and Saurs (2) (Bhatt, 1997).

Agriculture and collection of Non-Timber Forest Products (NTFPs) are the two major occupations of the population. Agriculture is mainly of subsistence farming in nature, as most of the people are marginal farmers with per capita land holding less than 2 acres. There are two distinct cropping patterns with respect to season: kharif (rice, maize, and jowar) and rabi (wheat and gram).

Table 2.5. Proportion of tribal populations and their distribution in the entire Central Indian Highlands.

Percentage category (% of tribals to total population)	**No. of districts in the entire Central Indian Highands**
Dominant (80 – 100 %)	1
High (50 – 80 %)	2
Important (20 – 50 %)	7
Significant (10 – 20 %)	5
Low (5 – 10 %)	5
Marginal (1 – 5 %)	2
Negligible (< 1 %)	10

Collection of NTFPs, with an estimated annual net revenue of 400 crore rupees, is the mainstay of the local economy (Dobhal, 1996). The major nationalized NTFPs are tendu leaves (*Diospyros melanoxylon*), sal seeds (*Shorea robusta*), and harra dye (*Terminalia chebula*), while the non-nationalized products include chironjee (*Buchanania lanzan*), amla (*Phyllanthus emblica*), and mahua (*Madhuca indica*).

2.5. Mammals & birds

The Central Indian Highlands, as its impressive network of protected areas would testify, are home to a remarkable array of mammals and birds typical of the tropical deciduous forests of the Subcontinent.

Tiger (*Panthera tigris*) is undoubtedly the flagship species of wildlife conservation in the landscape, as Central Indian forests hold one of the best protected populations in South Asia through the establishment of seven Tiger Reserves in the region (five in Madhya Pradesh alone). Other major mammals include leopard (*Panthera pardus*), dhole (*Cuon alpinus*), sloth bear (*Ursus ursinus*), gaur (*Bos gaurus*), sambar (*Cervus unicolor*), swamp deer (*Cervus duvaucelli*), chital (*Axis axis*), barking deer (*Muntiacus muntjak*), nilgai (*Boselaphus tragocamelus*), chowsingha (*Tetracerus quadricornis*), and Indian giant squirrel (*Ratufa indica*).

Historically, the wild fauna of Central Indian Highlands included Asian elephant (*Elephas maximus*), cheetah (*Acinonyx jubatus*), and Asiatic lion (*Panthera leo*), which all became locally extinct within the last couple of centuries. The once abundant and contiguous populations of species like swamp deer (*Cervus duvaucelli*), wild buffalo (*Bubalus arnee*), wolf (*Canis lupus*), and tiger have suffered severe declines in the recent past and they are to be found only in isolated fragments today.

Though central India may not match either the Himalayas or the Western Ghats in terms of bird diversity or endemism, the fact that the deciduous forests of the highlands hold a remarkable proportion of bird species endemic to the peninsular India (12 out of 30 species) makes them particularly noteworthy. The much-protected landscape also harbours significant populations of some of the globally threatened species which have become rare and critical elsewhere in their range; these include White-rumped Vulture (*Gyps bengalensis*), Long-billed Vulture (*Gyps indicus*), Red-headed Vulture (*Sarcogyps calvus*), Lesser Florican (*Sypheotides indicus*), and Malabar Pied Hornbill (*Anthracoceros coronatus*). Although Forest Owlet (*Heteroglaux blewitti*) and Green Munia (*Amandava formosa*) are, strictly speaking, the only species endemic to central India, the forests of Central Indian Highlands also shelter some of the rarer elements of peninsular Indian avifauna like Indian Spotted Eagle (*Aquila hastata*), Marshall's Iora (*Aegithina nigrolutea*), White-bellied Minivet (*Pericrocotus erythropygius*), and Spotted Creeper (*Spilornis spilonotus*). See Table 2.6 for a list of important breeding birds of biogeographical regions in Central India.

Table 2.6. Some characteristic breeding birds of the biogeographical regions of Central Indian Highlands. See Appendix 5.2 for a complete list of birds (with their scientific names) recorded in each of the regions during the study.

Region	**Important breeding birds**
Malwa Plateau	Lesser Florican, Asian Brown Flycatcher, and Southern Grey Shrike
Nimar Hills	Grey Junglefowl, Banded Bay Cuckoo, Forest Owlet, and Southern Grey Shrike
Lower Narmada Valley	Asian Brown Flycatcher, Southern Grey Shrike, and Striated Grassbird
Betul Plateau	Grey Junglefowl, Bar-winged Flycatcher-shrike, Malabar Whistling Thrush, Red-whiskered Bulbul, and Purple-rumped Sunbird
Sagar-Damoh Plateau	Spotted Creeper and Marshall's Iora
Satpura Plateau	Grey-headed Canary Flycatcher, Black-crested Bulbul, Blue-bearded Bee-eater, Malabar Whistling Thrush, Bar-winged Flycatcher-shrike, Malabar Pied Hornbill, Brown-cheeked Fulvetta, and Ashy Drongo
Seoni-Chhindwara Plateau	White-browed Bulbul, Spot-bellied Eagle Owl, Red Junglefowl, White-rumped Needletail, Malabar Pied Hornbill, and Ashy Drongo,
Vindhya Scarplands	Marshall's Iora, White-bellied Minivet, Pallas's Fish Eagle, Long-billed Vulture, and Striated Grassbird
Kaimur Hills	Pallas's Fish Eagle, Striated Grassbird, Painted Spurfowl, and Indian Spotted Eagle
East Maikal Range	Bengal Bushlark, Painted Bushquail, Blue-bearded Bee-eater, Large-tailed Nightjar, Red Junglefowl, Malabar Whistling Thrush, Spangled Drongo, Puff-throated Babbler, and Malabar Pied Hornbill
South Maikal Range	White-rumped Shama, Red Junglefowl, Malabar Pied Hornbill, Bar-winged Flycatcher-shrike, Jungle Myna, Painted Bushquail, Crested Goshawk, Puff-throated Babbler, Brown-cheeked Fulvetta, Indian Scimitar Babbler, and Scarlet Minivet

The paucity of literature on historical bird records from central India seriously undermines our attempts to document the changes in distribution and population status of birds over the last century. For example, Forsyth's (1889) incidental remarks indicated that several species like Black-crested Bulbul (*Pycnonotus melanicterus*), Painted Spurfowl (*Galloperdix lunulata*), Lesser Adjutant (*Leptoptilos javanicus*), and Common Flameback (*Dinopium javanense*) [or Greater Flameback *Chrysocolaptes lucidus*?], which are now seen only in a few select localities, were quite common in central India around late 19th century.

The recent rediscovery of the Forest Owlet (*Heteroglaux blewitti*) in 1997 after a gap of 113 years (King & Rasmussen, 1998) reiterates the significance of avifaunal studies in the region for conservation planning. Surprisingly, there are only a handful of systematic studies in the past on birdlife of the Satpuras and Vindhyas, with most of them undertaken during the first half of the 20th century (e.g., King, 1911 in Damoh and Sagar; D'Abreu, 1912 in Balaghat; Osmaston, 1922 in Pachmarhi; Briggs, 1931 in Mhow; Ali & Whistler, 1939 & 1940 in Malwa Plateau; Hewetson, 1939 in Betul; Newton, 1987 in Kanha; Sawarkar, 1988 in Melghat; Mehta, 1998 in Bori and Melghat). The last comprehensive checklist for the entire Central Indian Highlands with some annotations on distribution range, movements, and breeding status was made by Hewetson in 1956. The only published scientific collections from the region were by D'Abreau (1912 & 1935), who was the curator of the Nagpur Museum. The other collection by Walter Koelz (1929-1950), currently housed at University of Michigan Museum of Zoology, remained largely unknown till Rasmussen and Anderton (2005) have recently catalogued it.

Chapter 3. Influence of Vegetation Composition and Structure on Bird Species Composition

3.1 INTRODUCTION

The structure and composition of avian assemblages and how they are influenced by habitat features have been one of the most pervasive themes of investigation in community ecology (Lee & Rotenberry, 2005). In particular, habitat selection in forest bird communities has evoked much attention from both theoretical and empirical perspectives. This interest is also, in part, due to the increasing recognition of impacts on forests, of human activities like extraction of timber and other products, livestock grazing, shifting cultivation, and infrastructure development (Canterbury *et al.*, 2000). These activities often alter vegetation structure ('*physiognomy*') and forest species composition ('*floristics*'), the two key components of habitats for forest birds in general (Rotenberry, 1985).

Since MacArthur and MacArthur (1961) found a positive relationship between breeding bird diversity and foliage height diversity, an increasing number of studies on bird-habitat associations have followed suit. A majority of them, however, examined the influence of either vegetation structure or composition on bird communities (Table 3.1), and only a handful of studies have explicitly addressed the question of importance of floristics *versus* physiognomy in structuring bird communities.

Table 3.1. Various quantitative approaches adopted in studies on bird-habitat relationships.

Contrasted variables		
Bird community attributes	**Habitat attributes**	**References**
Species diversity/richness	Vegetation structure	Willson, 1974; Rotenberry & Wiens, 1980; James & Wamer, 1982; Erdelen, 1984; Daniels *et al.*, 1992; Haney & Lydic, 1999; Sekercioglu, 2002
Species diversity/richness	Vegetation composition	Anderson *et al.*, 1983; Lynch & Whigham, 1984; Rice *et al*, 1984; Poulsen, 2002
Guild diversity/composition	Vegetation structure	Beedy, 1981; Rice *et al.*, 1983; Hino, 1985; Raman *et al.*, 1998, Shirley, 2004
Guild diversity/composition	Vegetation composition	Germaine *et al.*, 1998; Cueto & de Casenave, 2000;

The findings of several of these studies, which investigated the roles of both forest composition and structure were, however, limited in their scope, as their community parameter was again either total bird density (e.g., Lynch & Whigham, 1984; Robinson & Holmes, 1984; Arnold, 1988; Estades, 1997; Rodewald & Abrams, 2002) or diversity / richness measures (e.g., MacDonald & Kirkpatrick, 2003). But the usefulness of conventional diversity and abundance indices in describing communities has long been questioned on account of their inadequacy in reflecting taxonomic distinctness (Erdelen, 1984; Ganeshaiah *et al.*, 1997; Poulsen, 2002), and statistical weaknesses (Austin, 1999). On the contrary, species composition of avian assemblages probably offers the most accessible and direct measure of community structure in studies that seek to record changes in birds in response to habitat modifications (Fleishman *et al.*, 2003).

The question as to how much vegetation composition and structure independently contribute to bird species composition was first addressed by Rotenberry (1985), who demonstrated that 55% variation in species composition in grassland birds was due to floristics and 35% could be explained by vegetation structure. In a majority of subsequent studies most of which were on forest bird communities, vegetation composition emerged as the most significant factor (e.g., Lopez & Moro, 1997; Fleishman *et al.*, 2003; Lee & Rotenberry, 2005). While others found both floristics and physiognomy as equally important (e.g., Mac Nally, 1990; Bersier & Meyer, 1994), a few studies could not find any evidence for either of the components (e.g., Koen & Crowe, 1987). Such variations in avian responses have been attributed to several factors, among which the scale of investigation and the food habits of birds have empirical support.

Rotenberry (1985) hypothesized that vegetation structure was probably important at coarse regional scale (across habitats), and floristics might determine bird species composition at a more local scale (within habitats). A few studies have subsequently corroborated this proposition (e.g., Wiens *et al.*, 1987; Bersier & Meyer, 1994). The observation that vegetation structure outranks floristics in bird-habitat relationships at large scale, and vice versa is also in conformity with the hierarchical model of habitat selection in animal communities (Lee & Rotenberry, 2005).

It has also been observed that avian foraging guilds, classified on the basis of food types, respond differentially to changes in vegetation structure and floristics; for example, Cueto and de Casenave (2000) noted significant associations between vegetation structure and insectivore guild and between forest composition and frugivore-insectivore guild. This is probably based on the premise that distribution of primary consumers (like frugivores and granivores) is dependent on the composition of food-plant species in the habitat (Rice *et al.*, 1983), and distribution of secondary consumers (like insectivores) is influenced by vegetation structure as insect diversity is known to increase with the structural complexity of habitats (Holmes *et al.*, 1979).

Here, I first investigate the relative roles of vegetation structure and floristics in determining species composition of breeding land birds of the Central Indian Highlands at the regional level, and then I test the proposition that response of birds would change with scale by examining within-habitat associations between birds and vegetation. I also explore if species composition of foraging guilds differs in response to variations in vegetation structure and composition. Finally, I discuss the conservation implications of these relationships in the light of recent evidences for the impacts of human activities on structural and compositional integrity of forested habitats. The relevance of the study is indicated by the fact that the region is noted for its forest-based economy and extraction of non-timber forest products (in particular, the leaves of 'tendu', *Diospyros melanoxylon*) remains a mainstay of livelihood for the local people.

3.2 METHODS

3.2.1. Study area

The study was conducted in Central Highlands in Madhya Pradesh between April and July during 2002-05. These highlands, comprising the Satpura and the Vindhya Ranges, extend over an area of about 200,000 sq. km. and are predominantly covered with tropical dry- and moist-deciduous forests. I collected data on birds and vegetation from 36 sampling sites laid in five regions viz., Seoni-Chhindwara Plateau, South Maikal Range, East Maikal Range, Betul Plateau, and Satpura Plateau. While both the Maikal Ranges are characterized by sal (*Shorea robusta*)-dominant forests, other localities represent teak (*Tectona grandis*)-dominant forest biome. The sampling sites were chosen in order that a wide array of habitat gradients (including floristics, topography, moisture, canopy cover, successional age, and protection status) was adequately represented. [See Appendix 3.1 for a list of the sampling sites and their attributes].

3.2.2. Birds

Breeding birds of each site were sampled, for species richness and composition, by 'standardized area search method' (adopted from Slater, 1994; Dieni & Jones, 2002; Watson, 2004), in which a rectangular block of 850m X 60m (c. 5 ha in area) was laid and walked at a steady pace for one hour along a transect that traversed lengthways through the centre of the block. Each block was walked for two to three consecutive mornings between 0600 and 0700 hrs until there were no significant additions to bird species inventory. Sampling was not carried out during days of inclement weather. I also took care that each transect block was placed well within a homogeneous patch of vegetation (typical of the site) to avoid any edge effects. All the land bird species encountered during sampling were recorded barring birds in overhead flight.

Bird survey was designed and executed with two key assumptions: i) birds are non-randomly distributed across habitats, and ii) all the species that occur in a given habitat/block are detected. The choice of breeding land birds was particularly made in consideration of the first assumption, since breeding birds are known to be more habitat-specific (Mills *et al.*, 1991; Lopez & Moro, 1997). The second assumption was achieved through the choice of the sampling method. A notable merit of the area search method is that it allows the observer to wander from the transect to confirm the identity of doubtful species or unknown vocalizations, and observer can also use natural history knowledge to detect secretive and unobtrusive birds (Bibby *et al.*, 2000).

3.2.3. Vegetation

In each bird-sampling block, six square plots of 10 X 10 m (0.01 ha) were laid randomly with a minimum of 100 m interval between plots for measuring vegetation structure and composition. In total, 214 vegetation plots were laid (two sites had 5 plots each) in which eight structural variables, viz., tree abundance, tree species richness, tree girth at breast height (GBH), tree height, percent canopy cover, shrub abundance, number of standing dead trees (snags), and bamboo abundance were measured. I classified all woody plants with a height of >2 m as trees, and all plants between 0.5 and 2 m were considered as shrubs. Each tree was assigned to one of the following height classes: 2-5 m, 5-10 m. 10-15 m, and >15 m; tree height diversity was, then, derived by using Shannon's index as: $\sum [Pi^* \ln(Pi)]$, where Pi = proportion of trees in the i^{th} height class. Percent canopy cover was measured directly by means of a spherical densiometer as the average of densiometer readings taken from the centre of the plot in four directions.

The measurements for all the structural variables were then averaged across the plots to compute mean values for each sampling block. In addition, an abundance matrix of tree species composition was also developed for each site. Unidentified trees, which constituted about 3 % of tree population in each region (barring Betul Plateau where the sampling site at 'old coffee plantation' had quite a few unidentified exotic shade trees), were not included in the analysis.

3.2.4. Analysis

I derived dissimilarity matrices between all pairs of 36 sites with respect to bird species composition (using Bray-Curtis distance), vegetation structure, and tree species composition (both using city block measure). The matrices were then analysed using Mantel's tests to detect any significant associations with 10,000 randomized runs (McCune & Grace, 2002). Since spatial proximity is known to significantly contribute to the observed similarities in faunal and floral communities, I used partial Mantel tests to control for the effects of geographic distance between sites (after Legendre & Troussellier, 1988). The distances were computed from GPS readings of location data collected at the centre of each sampling block. I fixed the significance level of α as $P \leq 0.05$ in all the tests. The dissimilarity matrices were derived using SPSS Release 8.0.0, while the partial Mantel's tests were performed with the software **zt** version 1.0 (Bonnet & Van de Peer, 2002).

To investigate the within-habitat patterns of associations between bird species composition and vegetation attributes, the sampling sites were classified on the basis of forest structure and composition into subsets of similar habitats. To avoid subjectivity and bias, I used hierarchical clustering technique using UPGMA linkage and city block distance in SPSS to identify and extract sites that were comparable structurally and floristically. The clusters were, then, assessed for statistical significance with Multi-Response Permutation Procedure (Mielke *et al.*, 1976) using the software PC-ORD (McCune & Mefford, 1999). MRPP is a non-parametric technique in which 'a priori' groups are examined, using all possible permutations of cluster membership, to test if between-groups separation and within-group homogeneity of clusters are more than expected by chance (McCune & Grace, 2002). I used the same distance measure (city block) as adopted in the cluster analysis to derive matrices for MRPP. Then, I again ran the partial Mantel tests with select sites to examine the relative response of bird species composition to floristics and vegetation structure within a given habitat, keeping geographical distance between sites as the covariate.

To ascertain if response of birds to habitat features was mediated by food type, breeding birds were categorized into two foraging guilds on the basis of predominance of animal or plant matter in their food: insectivorous birds and phytophagous birds. The phytophagous guild comprised frugivores, nectarivores, and granivores (after Beskaravayny, 1996). To avoid ambiguity, birds with mixed food habits and raptors were removed from the analysis. Information on food habits of birds was largely drawn from Ali and Ripley (1983) and additionally from personal observations in the field. I computed dissimilarity matrices between all pairs of 36 sampling sites with respect to species composition of these two feeding guilds. These were, then, contrasted with matrices of floristics and vegetation structure using partial Mantel tests.

3.3. RESULTS

3.3.1. Birds

A total of 101 species of birds were recorded from 36 sampling sites, and this was about 53 % of total land bird species that are known to breed in Central Indian Highlands (Ali & Ripley, 1983). The site occupancy patterns revealed that a majority of birds were marked by localized distribution (with 56 species found in less than 10 sites); in particular, species like Malabar Pied Hornbill (*Anthracoceros coronatus*), Streak-throated Woodpecker (*Picus xanthopygaeus*), White-rumped Needletail (*Zoonavena sylvatica*), Crested Treeswift (*Hemiprocne coronata*), and Malabar Whistling Thrush (*Myophonus horsfieldii*) were encountered at just one site each. On the other hand, generalist birds like Jungle Babbler (*Turdoides striatus*), Red-vented

Bulbul (*Pycnonotus cafer*), Black-rumped Flameback (*Dinopium benghalense*), and Rufous Treepie (*Dendrocitta vagabunda*) were found to occupy more than 30 sites sampled. A complete list of birds recorded during sampling along with their site-occupancy is given in Appendix 3.2.

3.3.2. Vegetation

In total, 59 species of woody plants were recorded from all the vegetation plots. In general, either teak or sal was the predominant species forming climax vegetation with the varying proportions of tree species like *Terminalia alata*, *Lagerstroemia parviflora*, and *Anogeissus latifolia*, and bamboo (*Dendrocalamus strictus*) characterizing further sub-associations. In Seoni-Chhindwara Plateau, allelopathic *Cleistanthus collinus* often formed near-monospecific stands, especially in low-lying tracts. A summary account of all the woody plant species recorded in five regions along with their proportional abundance is given in Appendix 3.3.

3.3.3. Bird composition, floristics & vegetation structure: regional patterns

Geographic distance between sites was found to have a weak, yet statistically significant influence over similarities in bird species composition. Partial Mantel tests, after controlling for this distance effect, showed that bird species composition had significant association with vegetation structure, but not with woody plant species composition across habitats at the regional level (Table 3.2). Intriguingly, floristics and vegetation structure remained uncorrelated.

Table 3.2. Associations among bird species composition, floristics, vegetation structure, and distance between sites, as shown by Mantel's tests across habitats in Central Indian Highlands (Matrix size: 36).

Contrasted matrices		Covariate	Mantel's *r*	*P*
Bird composition	Distance		0.294	< 0.001
Floristics	Vegetation structure	Distance	0.068	0.221
Bird composition	Floristics	Distance	-0.096	0.123
	Vegetation structure	Distance	0.438	< 0.001

3.3.4. Bird composition, floristics & vegetation structure: within-habitat patterns

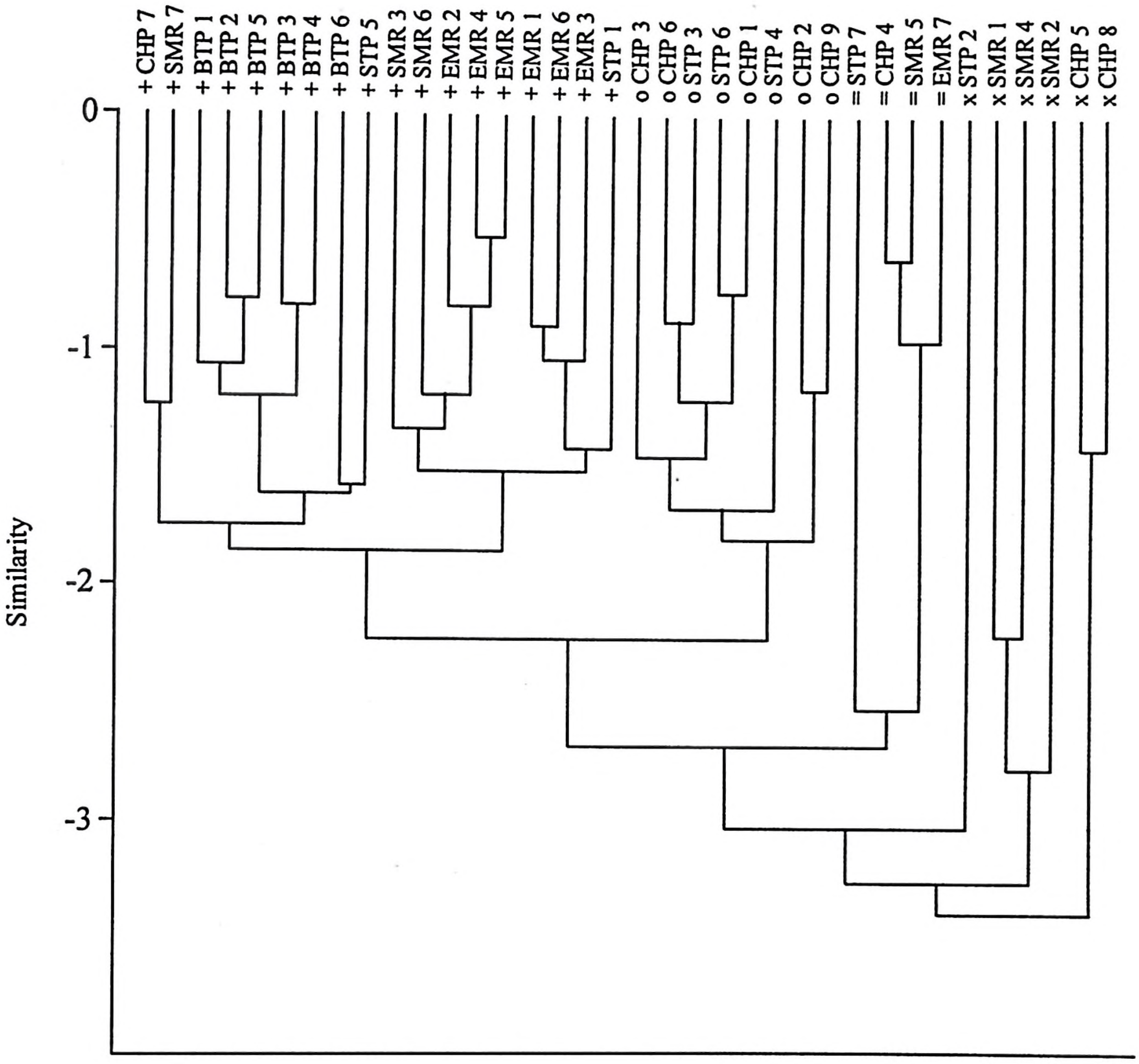
The hierarchical cluster analysis classified all the sampling sites into four distinct groups with respect to floristic composition [59 species of woody plants] and forest structure [8 structural variables] (Figure 3.1). These clusters were found to represent four habitats on a gradient of moisture and canopy openness, as follows: moist-deciduous forest (18 sites), dry-deciduous open forest (6 sites), dry-deciduous closed forest (8 sites), and open scrub jungle (4 sites). Results of MRPP showed that these clusters were statistically significant with respect to both between-clusters difference ($T = -14.781$, $P < 0.0001$) and chance-corrected within-group agreement ($A = 0.222$, $P < 0.0001$). Among these four habitats, moist-deciduous forest was chosen to test for within-habitat patterns of associations among bird composition, floristics, and physiognomy. This habitat was preferred because others were found to be less suitable on account of either sampling inadequacy or being equivocally demarcated; for example, the open scrub jungle was represented by a very small number of sites and there was a lack of clarity in branching of the dry-deciduous habitats into open and closed forests with longer internodes characterizing the former.

The effect of distance between sites on similarities in avian assemblages was observed to be more pronounced when only sites of moist-deciduous forest were compared. Partial Mantel tests, restricted to moist forest habitat, showed that bird species composition was significantly related to floristic composition (Table 3.3). This was in sharp contrast to the regional pattern where vegetation structure was observed to be the significant predictor. The independence of floristics and physiognomy, however, remained scale-invariant, as they were found to be unrelated in within-habitat analysis as well.

Table 3.3. Within-habitat associations among bird species composition, floristics, vegetation structure, and distance between sites, as shown by Mantel's tests between sites of moist-deciduous forest habitat in Central Indian Highlands (Matrix size: 18).

Contrasted matrices		Covariate	Mantel's *r*	P
Bird composition	Distance		0.487	< 0.001
Floristics	Vegetation structure	Distance	-0.052	0.313
Bird composition	Floristics	Distance	0.202	0.042
	Vegetation structure	Distance	0.135	0.089

Figure 3.1. Dendrogram showing classification of sampling sites into four habitat types in Central Indian Highlands. The legends are as follows: + moist-deciduous forest, o dry-deciduous closed forest, , x dry-deciduous open forest, and = open scrub jungle. See Appendix 3.1 for description of sites.



3.3.5. Guild composition, floristics & vegetation structure

An analysis of food habits of birds yielded 50 species of insectivores and 17 species of phytophagous birds. The insectivorous guild included woodpeckers, cuckoos, swifts, shrikes, drongos, minivets, flycatchers, chats, robins, nuthatches, babblers, and prinias. The phytophagous guild was formed by parakeets, barbets, hornbills, pigeons, doves, koel, sparrows, munias, sunbirds, and flowerpeckers (See Appendix 3.2 for species composition of the two guilds).

Mantel's tests, after the distance-related covariances between sites were partialled out, showed that vegetation structure regulated the species composition of insectivore guild to a significant extent, while floristics did not seem to have any influence. On the contrary, there was no evidence for the role of either vegetation structure or forest species composition on the composition of phytophagous guild (Table 3.4).

Table 3.4. Associations among species composition of feeding guilds, floristics, and vegetation structure, as shown by partial Mantel's tests across habitats in Central Indian Highlands (Matrix size: 36).

Contrasted matrices		Covariate	Mantel's *r*	*P*
Insectivorous birds	Floristics	Distance	-0.015	0.425
	Vegetation structure	Distance	0.338	< 0.001
Phytophagous birds	Floristics	Distance	-0.082	0.207
	Vegetation structure	Distance	0.145	0.071

3.4. DISCUSSION

Species composition of breeding birds in Central Indian Highlands was significantly correlated with vegetation structure. This is seemingly at variance with the findings of some previous studies (e.g., Lopez & Moro, 1997; Fleishman *et al.*, 2003; Lee & Rotenberry, 2005) in which vegetation composition was identified as the key habitat feature in fashioning composition of avian assemblages. The disagreement is probably due to differences in the ecological scale of investigations, as evident from the regional scope of the present study, which included a wide selection of habitats in its sampling regime. For example, when the analysis was restricted to sites representing moist-forest habitat, vegetation structure gave way to floristics as the significant correlate of bird species composition. This concurs with Rotenberry's (1985) observation that physiognomy is crucial at larger scale and floristics at local level in ecological distribution of birds. Direct empirical support for Rotenberry's hypothesis is, however, few and far between (e.g., Wiens *et al.*, 1987; Bersier & Meyer, 1994), though several studies, including some earlier ones, have found circumstantial evidences to that effect (e.g., Robinson & Holmes, 1984; Mac Nally, 1990; Estades, 1997; Drapeau *et al.*, 2000).

To understand why vegetation structure should function as a habitat cue for forest birds at the landscape level and floristics at a more local scale (as evidences for the contrary seem to be non-existent), it is useful to consider the following: first, it would be far easier for forest birds to associate search image of a suitable habitat with its structural features (e.g., Robinson & Holmes, 1984); vegetation composition could then complement the selection of optimal habitats from a suite of structurally similar forest types. Secondly, we might critically examine the rate at which both the features of forested habitats change in space with respect to species turnover in avifaunal assemblages along an environmental gradient (e.g., Mac Nally, 1990). In tropical deciduous forests of central India where there exist not more than two major forest associations (teak & sal), vegetation heterogeneity is mediated largely through structural diversity of forests rather than floristics. In other words, structural changes in forests tend to have overriding imminence much before any major floristic changes take effect in space. Therefore, it is not surprising that birds respond more to forest structure than composition in Central Indian Highlands as species diversity is known to vary as a function of environmental heterogeneity (e.g., Rahbek & Graves, 2001). It has also been shown in Neotropical deciduous forests that vegetation structure is influenced by precipitation while forest species diversity remains unaffected (Lerdau *et al.*, 1991). This contradiction between floristics and physiognomy of tropical forests probably explain the hierarchical nature of their relationships with bird composition. The idea that forest birds select habitats first on the basis of vegetation structure and then on the basis of forest species composition also brings to the fore the importance of scale in ecological processes (Wiens *et al.*, 1987; Hill & Hamer, 2004). In this respect, it mirrors the interaction of multi-scale factors in organization of bird communities (Hutto, 1985; Vander Haegen *et al.*, 2000; Hagan & Meehan, 2001; MacFaden & Capen, 2002; Grand & Cushman, 2003).

It is a well-established fact that vegetation structure and composition affect foraging behaviour of birds (Wiens, 1989). For example, structurally complex habitats, by virtue of their niche abundance, may accommodate a high insect diversity, as greater the number of available niches lesser the competition for space (Holmes *et al.*, 1979; Gunnarsson, 1990; O'Connor, 1991). As a corollary, insectivorous birds could be expected to respond positively to structural aspects of a habitat. Though it is also probably true that several insects are host-specific at least for part of their life-cycle (e.g., Hemipterans and Lepidopterans), the catholicity of bird-insect associations far outweigh insect-plant interactions (see Robinson & Holmes, 1984) and it is also possible for a single tree to harbour more than one species of herbivorous insects (Novotny *et al.*, 2002; Strauss & Irwin, 2004; Lee & Rotenberry, 2005); so, it is less likely that insectivorous birds discriminate floristics more than structure. On the contrary, distribution of birds feeding largely on plant produces like nectar, fruits, or seeds (*phytophagy*) is known to be governed by the distribution of food plants (Rice *et al.*, 1983).

These interactions between food habits and habitat selection in birds have been empirically supported in a recent study by Cueto and de Casenave (2000), who observed that insectivorous birds recognized structural differences and frugivore-insectivore guild showed a marked propensity for plant species composition. But evidences from central Indian avifauna showed mixed patterns, conforming only in part to these generalities. For example, insectivores did respond significantly to the structural aspects of vegetation, as predicted; but phytophagous guild seemed to have been influenced by neither vegetation structure nor forest composition. The apparent indifference of phytophagous birds to floristic composition is probably due again to the availability of a wide choice of food-plant species in tropical deciduous forests of central India (see Appendix 3.3) obviating conditions for development of any narrow bird-plant associations. Further, birds dependent on plant resources often move over considerable distances in search of food, and therefore their relationships with habitat features in the immediate vicinity tend to be weaker and less predictable. Alternatively, these relationships may become more explicit when floristics (a taxonomical attribute) is replaced with 'functional composition' of woody plant species such as those yielding nectar, fruit, and seeds as food for birds (corresponding to functional diversity as defined in Martinez, 1996 and Marcot & Vander Heyden, 2001).

An interesting observation of the study is the apparent absence of correlation between floristics and physiognomy in central Indian forests; this is presumably due to the fact that the forest composition in central India is numerically dominated by either teak or sal making floristics *statistically* less varying than structure. There are several studies that acknowledge both vegetation composition and structure as equally important factors in habitat selection of bird communities (e.g., Arnold, 1988; Poulsen, 2002; Rodewald & Abrams, 2002; Mac Nally, 1990). This is particularly expected in the absence of statistical independence of floristics and vegetation structure. Establishing this orthogonality is a prerequisite for assessing the relative contributions of both features to the variation in bird species composition. It can be achieved either by directly contrasting the two habitat matrices first for presence of any correlation (as done here) or by examining the influence of one habitat feature on bird species composition after controlling for any concomitant effects from the other feature (e.g., Fleishman *et al.*, 2003; Lee & Rotenberry, 2005). Geographic distance between sampling sites is another potential confounding factor in quantifying the relative influences of floristics and physiognomy. It is widely recognized that spatial proximity often tends to overestimate the strength of species-environment relationships (Legendre & Troussellier, 1988; Borcard *et al.*, 1992). Hence, a statistical technique like partialling out the covariates is strongly recommended to compute the true proportion of variation in bird species composition due solely to either floristics or physiognomy.

In general, the degree to which each of these components independently contributes to variations in avian assemblages is found to be almost always less than 50 % (Rotenberry, 1985; Fleishman *et al.*, 2003). In the present study, vegetation structure across habitats explained about 19 % of bird species composition and floristics only about 4 % within moist-forest habitat (though both the findings were statistically significant). This goes to show that there may be other independent factors, apart from vegetation structure and composition, which govern composition of bird communities. For example, Koen and Crowe (1987) found no evidence for either floristics or physiognomy and suggested historical and edaphic factors as possible mechanisms for organization of bird and invertebrate communities. Though relative contributions of habitat features to bird species composition may appear smaller in degree, their importance remains pivotal for birds on two accounts. First, habitat modifications (either in structure or in composition) still evoke distress response from local avifauna (see Hill & Hamer, 2004 for a review). Secondly, the remaining unexplained part of bird species composition is likely to be a cumulative function of several small independent factors many of which are probably neither contemporary (e.g., historical events) nor amenable to precise quantification (e.g., competition).

I conclude from these findings that both vegetation composition and structure are important, albeit at different spatial scales, in preserving the integrity of species composition of avian assemblages in Central Indian Highlands. Tropical forests have long been under severe pressure from mankind for a variety of forestry and land resources, and the stress factors often accrue large enough to break the limits of resilience of these fragile ecosystems (Folke, 2004). For example, there are growing evidences for irreversible changes, brought by anthropogenic activities, on both forest structure and composition. Some of these disruptive agencies include extraction of timber (Sekercioglu, 2002) and non-timber forest products (Ticktin, 2004), livestock grazing (Hobbs, 2001), shifting cultivation (Raman *et al.*, 1998), and infrastructural development (Germaine *et al.*, 1998). In fact, assessing the impacts of changes in structure and composition of forests on faunal communities is central to evolving site-specific conservation action plans (Hill & Hamer, 2004). To develop solutions that seek to meet socio-economic needs from forestry sector at minimum ecological cost, we require reliable data on species-environment relationships at multiple scales.

3.5. SUMMARY

1. I investigated the relative contributions of vegetation composition (floristics) and vegetation structure (physiognomy) to species composition of breeding land birds of the Central Indian Highlands. I also examined if these relationships were influenced by ecological scale and food habits of birds.
2. Data on birds were collected by using standardized area search method from 850 X 60 m transect blocks at 36 sites covering a wide range of vegetation types. Vegetation composition and structure were measured at each bird-sampling block by laying six square plots of 10 X 10 m. The structural variables included tree species richness, tree abundance, tree girth, tree height, canopy cover, shrub abundance, snag abundance, and bamboo cover.
3. I derived dissimilarity matrices between all pairs of 36 sites with respect to floristics, vegetation structure, and bird species composition. Mantel's randomization tests were conducted to detect significant associations among the matrices, after partialling out the effect of geographic distance between sites. These associations were then examined again, for within-habitat patterns, in sites corresponding to moist-deciduous forest habitat, identified through hierarchical clustering. In addition, relationships between guild composition of insectivorous and phytophagous birds and habitat components were also analyzed by means of partial Mantel tests.
4. Bird species composition was found to be significantly related to vegetation structure at the regional level, and floristics emerged as the key factor at local scale within moist-forest habitat. This finding is consistent with earlier observations that birds respond, in their species composition, to vegetation structure across habitats and to vegetation composition within habitats.
5. Composition of insectivorous birds was influenced by vegetation structure, as predicted, but phytophagous guild did not show any selection for vegetation composition in contrast to patterns observed elsewhere. I explain this anomaly as a result of availability of a wide choice of food plants for phytophagous birds in central Indian forests and weak species-environment relationships on account of their nomadism.

Chapter 4. Local *versus* Regional Bird Species Richness: Evidences for Community Saturation

4.1. INTRODUCTION

What determines the upper limit to number of species that co-exist in a given habitat or locality ('local species richness') has always been intriguing ecologists. In general, two explanatory mechanisms are hypothesized: ecological and historical factors. The former includes ecological interactions at the local level such as competition, predation, parasitism, stochastic fluctuations in abiotic components, and habitat disturbance. The historical factors include colonization, extinction, dispersal, vicariance events, and fluctuating range boundaries (Cornell & Lawton, 1992; Hillebrand & Blenckner, 2002). Alternatively, ecological factors are sometimes referred to as 'local factors / processes' and historical factors as 'regional factors / processes', in accordance with the scale at which these mechanisms operate (Cornell & Lawton, 1992). If we assume that the size of regional species pool is a function of biogeographical history of the region, then it is possible to assess the relative roles of ecological and historical processes in limiting the local species richness by regressing local richness against regional richness. If local richness increases monotonically with regional richness ('*linear model*'), weaker ecological interactions are indicated along with a greater role for historical forces. On the contrary, an asymptotic relationship ('*curvilinear model*') points to the predominant role of strong species interactions in limiting the number of species that can be accommodated in a locality (Ricklefs, 1987; Hugueny *et al.*, 1997). Accordingly, the linear and curvilinear models are often believed to signify 'interactive' and 'non-interactive' communities respectively (Cornell, 1993).

More frequently, these two relationships are interpreted as evidences of community saturation (Terborgh & Faaborg, 1980; Cornell, 1985a; Ricklefs, 1987; He *et al.*, 2005). For example, the regression curve of local *versus* regional species richness is typified by a slope value that lies between 0 and 1. A strongly linear relationship with a slope close to one is interpreted as an evidence of non-saturation of the local assemblages. In other words, the fact that the local species richness increases with an increase in regional species pool suggests that the local communities can accommodate more species. On the other hand, communities showing an asymptotic curve / curvilinear relationship with regional species pool (with slope of the regression line nearing zero) may be transcribed as 'saturated', as these assemblages do not seem to take in additional species beyond a limit even though the regional pool does harbour these species. See Table 4.1 for different approaches in describing community attributes on the basis of regression curves of local *versus* regional richness.

Table 4.1. Relationships between local and regional species richness & various mechanistic explanations of the nature of regression curves.

Nature of relationship between local & regional richness	**Alternative terms for regression curves / models**	**Slope value of the regression curve**	**Inferences**			
			History vs. ecology	**Spatial processes**	**Saturation of local assemblages**	**Community interactions**
Linear	Type I curve or pool-enrichment model or proportional sampling curve	Close to 1	Historical factors	Regional processes	Unsaturated assemblages	Non-interactive
Curvilinear	Type II curve or compromise model or ceiling curve	Close to 0	Ecological factors	Local processes	Saturated assemblages	Interactive
	(Cornell, 1985a; Hugueny *et al.*, 1997)		(Ricklefs, 1987; Hugueny *et al.*, 1997; Zobel, 1997; Shurin & Allen, 2001; He *et al.*, 2005)	(Cornell & Lawton, 1992; Cornell & Karlson, 1997; Huston 1999; Shurin *et al.*, 2000; Gering & Crist, 2002)	(Terborgh & Faaborg, 1980; Cornell, 1985a & 1985b; Ricklefs, 1987; Griffiths, 1997; Mouquet *et al.*, 2003; He *et al.*, 2005)	(Cornell, 1985a & 1985b; Cornell & Lawton, 1992; Cornell, 1993)

Though the regression approach is seemingly simple and straightforward, this is not without problems - both conceptual (see Caley & Schluter, 1997) and methodological (see Griffiths, 1999; Srivastava, 1999; Hillebrand & Blenckner, 2002). For example, Caley and Schluter (1997) demonstrated that curvilinearity was not necessarily indicative of community saturation when regional species pool showed log-normal distribution in their abundances, and small sample sizes might also give rise to non-linear relationships between local and regional richness (but see Westoby, 1998 for comments).

On the methodological front, at least five major issues have been raised as potentially influencing the nature of relationships between local richness and regional species pool. First, what to compare while plotting local *versus* regional richness? Similar habitats between different regions or different habitats in a single region? (Srivastava, 1999). The consensus is that only communities found in structurally similar habitats should be compared between different regions (or provinces ideally with low proportion of shared species) to elicit any meaningful inferences about community saturation (Srivastava, 1999; Ricklefs, 2000; Hillebrand & Blenckner, 2002). The second issue relates to how large should be an area over which local richness is to be measured (Westoby 1998; Huston, 1999; Srivastava, 1999; Hillebrand & Blenckner, 2002; Karlson & Cornell, 2002). This is important because any inference about community saturation would require that the local sampling sites are small enough for all the constituent species to interact among themselves. Consequently, it is observed that local richness sampled over large areas show linear relationships with regional species pool, while local richness computed over small areas tend to have non-linear associations (e.g., Karlson & Cornell, 2002; He *et al.*, 2005). The third issue involves the definition of regional species pool, the limits of which remain contentious; some ecologists favour the view that all the species, which are known to occur in the region and can potentially colonize any of the habitats used for sampling local richness, should form the regional species pool (Cresswell *et al.*, 1995; Srivastava, 1999; Hillebrand & Blenckner, 2002). On the contrary, others consider that regional richness should be computed as a cumulative sum of species richness observed across all the local sampling sites within the region (Angermeier & Winston, 1998; Ricklefs, 2000; Shurin *et al.*, 2000). While the former approach tends to minimize the effects of autocorrelation between local and regional richnesses, the latter avoids a potential pitfall of regional species pool being inflated to a ridiculously large extent. The remaining two issues in local-regional richness studies are essentially statistical in nature: use of constrained *versus* unconstrained regression and evaluation of regression models. Since it is true that local species richness has to be zero when regional species pool contains no species (but not necessarily so when regional pool is a hypothetical list), most studies constrain the regression curve to pass through the origin (e.g., Caley & Schluter, 1997; Cornell & Karlson, 1997; Hugueny *et al.*, 1997; Shurin *et al.*, 2000; He *et al.*, 2005). But a few ecologists strongly disapprove of constrained regressions on statistical grounds (e.g., Griffiths, 1999; Srivastava, 1999), as the strength of regression coefficient is inordinately overestimated in regression through origin. It, then, follows that local-regional richness curve using unconstrained regression is better assessed through regression parameters (esp. slope) rather than by the conventional variance-based tests, like ANOVA (Srivastava, 1999; Hillebrand & Blenckner, 2002).

In this chapter, I investigate the nature of relationship between local and regional species richness of breeding birds in tropical deciduous forests of Central Indian Highlands. Specifically, I address if avian assemblages of central Indian forests are saturated and I also examine the relative roles of ecological *versus* historical factors in limiting the number of bird species occupying a habitat. The Satpura Ranges of the Central Indian Highlands are widely thought to be the dispersal highway for Indo-Malayan birds, in the historical past, from the Himalayas in the north-east to the Western Ghats in the south-west (Ali, 1949). These ranges are, however, currently characterized by generally depauperate avifauna with very low endemism and species diversity compared to either Himalayas or the Western Ghats. By studying local-regional richness plots, I attempt here to infer whether this impoverishment is an outcome of strong ecological interactions (precluding any new species to colonize) or owing to historical constraints.

4.2. METHODS

4.2.1. Study area

The study was conducted in Central Highlands (comprising the Satpura and the Vindhya Ranges) in Madhya Pradesh between April and July during 2002-05. The forest birds were sampled from 35 sites in six regions viz., Seoni-Chhindwara Plateau, South Maikal Range, East Maikal Range, Betul Plateau, Satpura Plateau, and Sagar-Damoh Plateau. All the sites were forested habitats with each one representing floristically distinct forest type. The number of sites sampled in each region varied from eight (in Chhindwara Plateau) to three (in Sagar-Damoh Plateau), depending on the number of distinct forest types that occur in the region. The woody vegetation in Central Indian Highlands is generally characterized by predominance of either sal (*Shorea robusta*) or teak (*Tectona grandis*); while South and East Maikal Ranges are covered by sal-dominant forests, other regions are located in teak-dominant forest biome [See Appendix 4.1 for a descriptive list of sampling sites in each region].

4.2.2. Birds

I used 'standardized area search method' (adopted from Slater, 1994; Dieni & Jones, 2002; Watson, 2004) to estimate the number of bird species that breed in a given habitat. In each site, a rectangular block of 850m X 60m (c. 5 ha in area) was laid and walked at a steady pace for one hour along a transect that traversed lengthways through the centre of the block. Each block was walked for two to three consecutive mornings between 0600 and 0700 hrs until there were no significant additions to bird species inventory. The transect blocks were placed well within patches of homogeneous forests to minimize edge effects. Sampling was not carried out during days of inclement weather. All the land bird species encountered during sampling were recorded barring birds in overhead flight.

Failure to detect rare species has been identified as one of the potential causes of pseudosaturation observed in local assemblages (Caley & Schluter, 1997; Hillebrand & Blenckner, 2002), and therefore area search method was adopted to increase the detection probability of rare species. A notable merit of this technique is that it allows the observer to wander from the transect to confirm the identity of doubtful species or unknown vocalizations, and observer can also use natural history knowledge to detect rare and unobtrusive birds (Bibby *et al.*, 2000).

4.2.3. Analysis

I defined local richness as the mean number of bird species observed across all the sites within a region (after Angermeier & Winston, 1998; Shurin *et al.*, 2000; Ricklefs, 2000). This was based on the premise that all the species encountered in the region had an equal probability of occupying any of the sites. This proviso was adequately justified by the fact that all the sampling sites, both within and across regions, represented structurally similar macrohabitats. In addition, breeding birds are generally known to be habitat-specific (e.g., Lopez & Moro, 1997) enabling us to compute the local richness as mean alpha diversity. This would also overcome the issue of pseudosaturation of communities arising from comparison of assemblages with non-overlapping species composition, as mediated through sampling of structurally different macrohabitats, within a region (Cornell & Lawton, 1992; Hugueny *et al.*, 1997; Srivastava, 1999). Subsequently, the regional species pool was derived as the cumulative sum of bird species observed across all the sampling sites within the region (after Schluter & Ricklefs, 1993; Angermeier & Winston, 1998; Shurin *et al.*, 2000; Ricklefs, 2000). The alternative method of estimating regional richness as total species pool extracted from published faunal lists (e.g., Griffiths, 1997; Srivastava, 1999) was not favoured as it tended to unduly overestimate the regional species richness (see Ricklefs, 2000); it was also possible that some bird species, not encountered during sampling of local sites, would never be able to colonize any of the sites and hence contrasting local richness against an inflated regional pool would again lead to pseudosaturation of communities (i.e., saturation as non-interactive equilibrium: Cornell & Lawton, 1992).

The local richness was, then, regressed against regional richness after estimation of both the parameters for all the regions. Since regional pool was defined as the cumulative number of species summed over all the constituent local assemblages, local and regional richness would be expected to converge at the origin. So constrained regression (with no constant term in the model) was performed (after Cornell & Karlson, 1997; Shurin *et al.*, 2000; He *et al.*, 2005) and the relationship was tested for both linear and non-linear fits. Among the nonlinear models, quadratic curve was chosen as test criterion for evidence of community saturation, since quadratic term in a second-order polynomial could be tested for statistical significance (after Caley & Schluter, 1997; Cornell & Karlson, 1997; Shurin *et al.*, 2000). The linearity was assessed in terms of both model parameters (regression coefficient and ANOVA test of the model) and regression term (i.e., slope of the curve along with associated t-tests for statistical significance for H_0: $\beta = \beta_0$ and H_0: $\beta = \beta_1$).

In view of serious reservations expressed over the statistical validity of regressions through the origin (e.g., Griffiths, 1999; Srivastava, 1999), unconstrained regression was also carried out to test for curvilinearity in the data. The decision-tree, developed by Griffiths (1999), was followed. In this approach, local richness was regressed against regional richness in log-log space; however, I used ordinary least squares (OLS) model instead of reduced-major-axes (RMA) regression as adopted in Griffiths (1997), since error rate in regional richness was not expected to exceed that of local richness in the study. The regression parameters were statistically tested for inferring saturation of communities as follows:

- For the regression model, $\log y = a + b.\log x$,
    - ➔ If y-intercept was greater than zero ($a > 0$), relationship was curvilinear (i.e., saturated communities).
    - ➔ If y-intercept was either negative or equal to zero, then slope parameter (b) was to be assessed as follows:
        - ▪ If $b < 1$, saturation was indicated.
        - ▪ If $b = 1$, relationship was linear (i.e., unsaturated communities).

Community saturation was also investigated in terms of diversity components on the basis of how alpha and beta diversities responded to gamma diversity as follows (after Cornell, 1985a; Griffiths, 1997; Loreau, 2000):

- In saturated communities, beta diversity increases monotonically with gamma, but alpha remains unaffected.
- In unsaturated communities, alpha increases with gamma, but there is no correlation between beta and gamma diversities.

Table 4.2. Characteristics of diversity components in saturated and unsaturated communities.

Contrasted diversity components		**Unsaturated community**	**Saturated community**
Alpha	Gamma	↑	↔
Beta	Gamma	↔	↑

Following Koleff & Gaston (2002), local species richness was appropriated as alpha diversity (of Whittaker, 1972) and regional richness was equated with gamma diversity; the beta diversity ('*spatial turnover*') was defined as the ratio of gamma to alpha diversity. Pearson's correlation coefficients were computed between gamma and alpha and between gamma and beta diversity components of all the six regions. All the statistical analyses were done in SPSS Release 8.0.0, except the slope parametrization which was calculated and tested manually in linear constrained regressions following Zar (1999).

4.3. RESULTS

4.3.1. Birds

In total, 97 species of forest birds were recorded from 35 sites sampled across six regions in the study area. (See Appendix 4.2 for the region-wise list of birds observed during sampling). Mean number of species ('*local richness*') and cumulative sum of species ('*regional richness*') computed across all the sites in each region are given in Table 4.3.

Ideally, the number of sampling sites should be same across all regions to rule out the possibility of any area-effect on local species richness; but this could not be achieved in the study owing to phytogeographic and logistic constraints. Nonetheless, these regional differences in number of sites sampled was found to have no influence on local species richness of birds (Pearson's correlation coefficient, $R = 0.25$, $P > 0.05$, $N = 6$).

Table 4.3. Local and regional species richness of birds, sampled in six regions across Central Indian Highlands.

Sl. No.	Region	No. of sites, sampled	Local species richness	Regional species richness
1	Chhindwara Plateau	8	34.5	65
2	South Maikal Range	6	29.7	66
3	East Maikal Range	6	31.5	64
4	Betul Plateau	6	30.0	59
5	Satpura Plateau	6	34.2	64
6	Sagar-Damoh Plateau	3	32.3	47

4.3.2. Local vs. regional richness: constrained regression

When local species richness was regressed through origin against regional richness, the regression was found to be statistically significant for both linear and quadratic models; however, quadratic curve (Figure 4.1) emerged as a marginally better fit in terms of ANOVA (F-value) and regression parameters (R^2) [See Table 4.4]. Moreover, the slope of the curve obtained in the linear regression was found to be less than categorical (i.e., $\beta \neq \beta_0$ & $\beta \neq \beta_1$) as to saturation of communities, prompting for the linear model to be discarded in favour of the quadratic curve. This curvilinear relationship observed between local and regional richness signified species saturation of avian assemblages in central Indian forests.

Figure 4.1. Constrained regression of local *versus* regional richness among breeding birds of six regions of Central Indian Highlands. The dashed line is the upper limit to local richness showing the proportional sampling curve of unsaturated communities. The thin solid line shows the fitted quadratic curve and the thick solid line is the linear fit (see the text for parameter values).

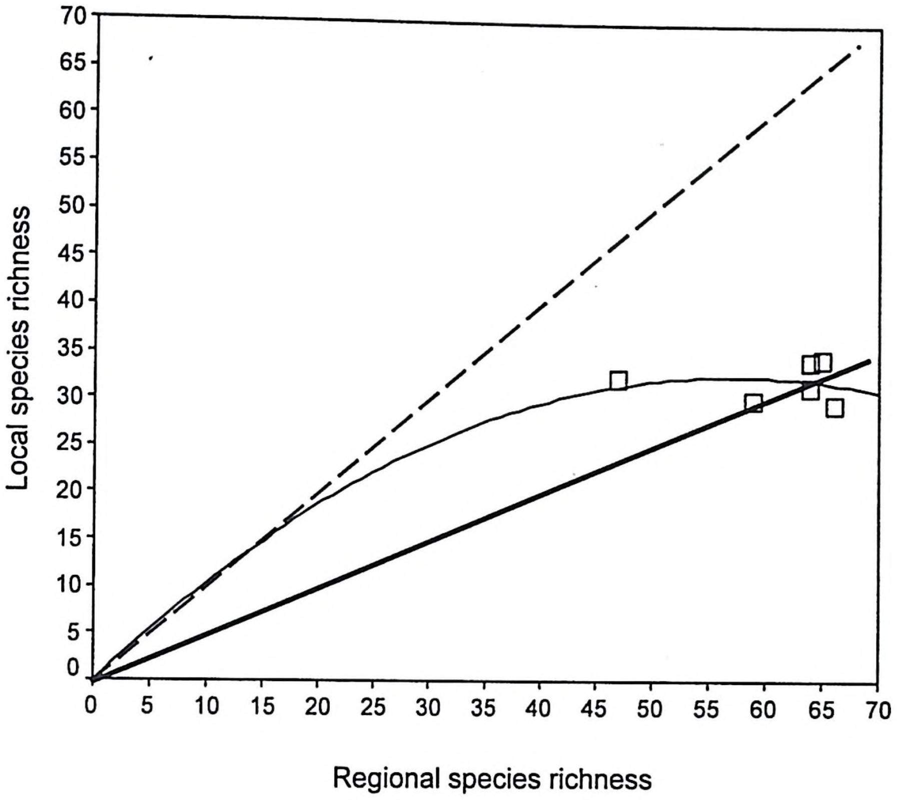


Table 4.4. Constrained regressions of local *versus* regional species richness of birds of Central Indian Highlands: linear and curvilinear models along with tests of model fitness and regression parameters.

Linear Model	**I. Analysis of Variance**					
($y = b.x$)	Source	SS	df	F	P	$R^2 \pm 1$ SE
	Regression	6086.85	1	342.80	<0.0001	0.986 ± 4.214
	Residual	88.78	5			
	Total	6175.63	6			
	II. Parameter Estimates					
	Parameter ± 1 SE		t	P	Tested for	
	$b = 0.52 \pm 0.03$		18.51	<0.0001	$H_0: \beta = \beta_0$	
			-17.05	<0.0001	$H_0: \beta = \beta_1$	
Quadratic Model	**I. Analysis of Variance**					
($y = b_1.x + b_2.x^2$)	Source	SS	df	F	P	$R^2 \pm 1$ SE
	Regression	6152.98	2	543.28	<0.0001	0.996 ± 2.379
	Residual	22.65	4			
	Total	6175.63	6			
	II. Parameter Estimates					
	Parameter ± 1 SE		t	P		
	$b_1 = 1.138 \pm 0.181$		6.27	0.003		
	$b_2 = -0.009 \pm 0.003$		-3.42	0.026		

4.3.3. Local vs. regional richness: unconstrained regression

Unconstrained linear regression between local richness and regional richness in a log-log space yielded a y-intercept which was significantly greater than zero *and* a slope parameter that was closer to zero (Figure 4.2 & Table 4.5). This fulfilled both the conditions of curvilinearity of relationship as outlined in Griffith's (1999) decision-tree. The results were, again, strongly suggestive of saturation of breeding bird communities.

Figure 4.2. Unconstrained regression of local *versus* regional species richness of six regions in Central Indian Highlands. Dashed line is the linear fit while the solid line is quadratic fit.

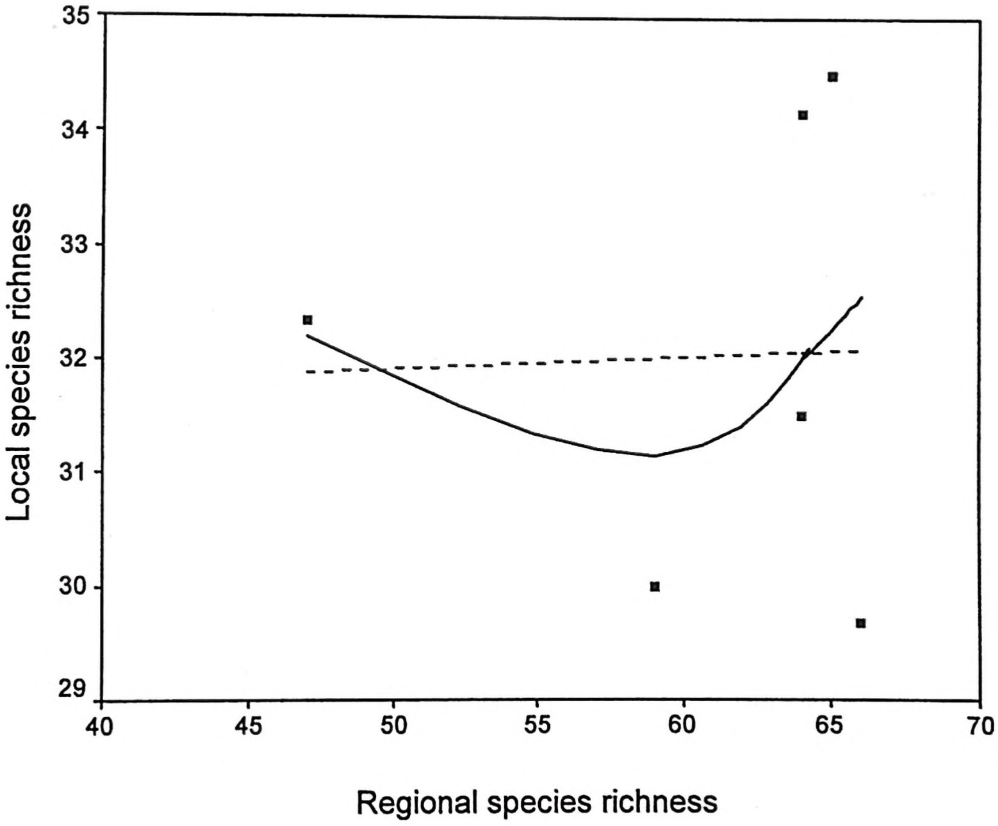


Table 4.5. Results of unconstrained linear regression between local and regional richness among breeding birds of Central Indian Highlands, along with statistical significance of model parameters (N = 6). Note that the statistical evaluation of the overall model fitness was not considered as the theoretical decision-tree assumes linear fit (see Griffith, 1999).

Regression Model	Stat. significance of model parameters
OLS Linear ($\log y = a + b.\log x$)	$a = 1.490$, $\lvert t\rvert = 3.400$, $P = 0.027$ $b = 0.008$, $\lvert t\rvert = 0.032$, $P = 0.976$

4.3.4. Local vs. regional richness: diversity components

While beta diversity showed a significant positive relationship with gamma diversity (Figure 4.3), alpha remained independent of gamma diversity (Table 4.6). The absence of covariation between alpha and gamma components of diversity further corroborated the observed saturation of avian assemblages.

Figure 4.3. Relationship between gamma and beta diversity of forest bird communities in Central Indian Highlands (N = 6).

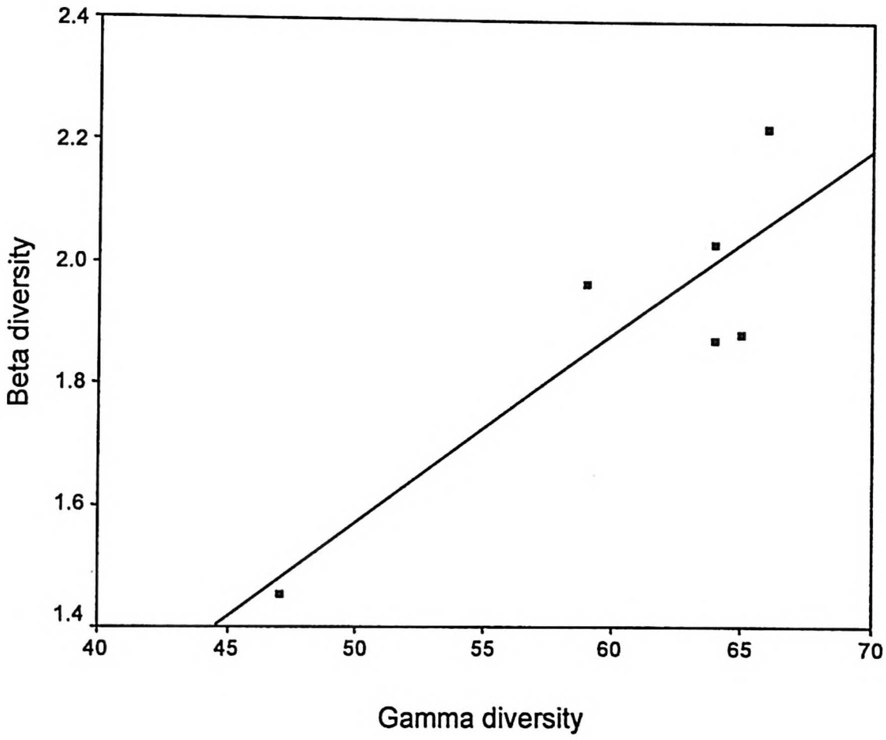


Table 4.6. Results of correlation analyses of diversity components among avian assemblages in central Indian forests (N = 6).

Contrasted diversity components		*R*	*P*
Alpha	Gamma	0.038	0.943
Beta	Gamma	0.869	0.025

4.4. DISCUSSION

The results of the study unequivocally support the hypothesis that the breeding bird communities in tropical deciduous forests of Central Indian Highlands are composed of saturated local assemblages. Given the generally depauperate avifauna of peninsular India, it is indeed surprising to find that the central Indian birds are species-saturated. For, saturation is usually known to be an attribute of species-rich climactic fauna showing community equilibrium (Cornell & Lawton, 1992). If we assume community saturation as a direct outcome of occupation of nearly all the available niche positions (e.g., Cornell, 1985b), it follows that saturated communities with modest species richness could have been an evolutionary consequence of poor niche differentiation of local habitats. This is well borne out by the natural history observation that the deciduous forests of central India are structurally simple (offering limited niche space), compared to the lofty and structurally complex woody vegetation of either the Western Ghats (Daniels *et al.*, 1992) or the Eastern Himalayas (Datta, 1998), the two key Endemic Bird Areas in the neighbourhood. And bird species richness has been shown to increase significantly with structural diversity of vegetation among central Indian avifauna (Pai, 1993; Jayapal, 1997).

It is widely held that saturated communities are the ones with strong interspecific interactions and notable presence of habitat-specialists, while weak ecological interactions and a predominance of generalist species characterize unsaturated communities (Cornell, 1985a; Cornell & Lawton, 1992). Evaluating the strength of species interactions in central Indian avifauna is evidently beyond the scope of this study, though numerical dominance of insectivores (in relation to phytophagous birds; see Appendix 4.2) does point to fairly interactive nature of the bird communities [see Cornell (1985b) for relationships between food habits of organisms and nature of species interactions]. Nonetheless, there are also evidences for highly interactive yet unsaturated communities (e.g., reef-building corals in Cornell & Karlson, 1996; also see Fox *et al.*, 2000), and some studies have even found the saturation curves uninformative regarding species interactions (e.g., Hillebrand & Blenckner, 2002; Valone & Hoffman, 2002).

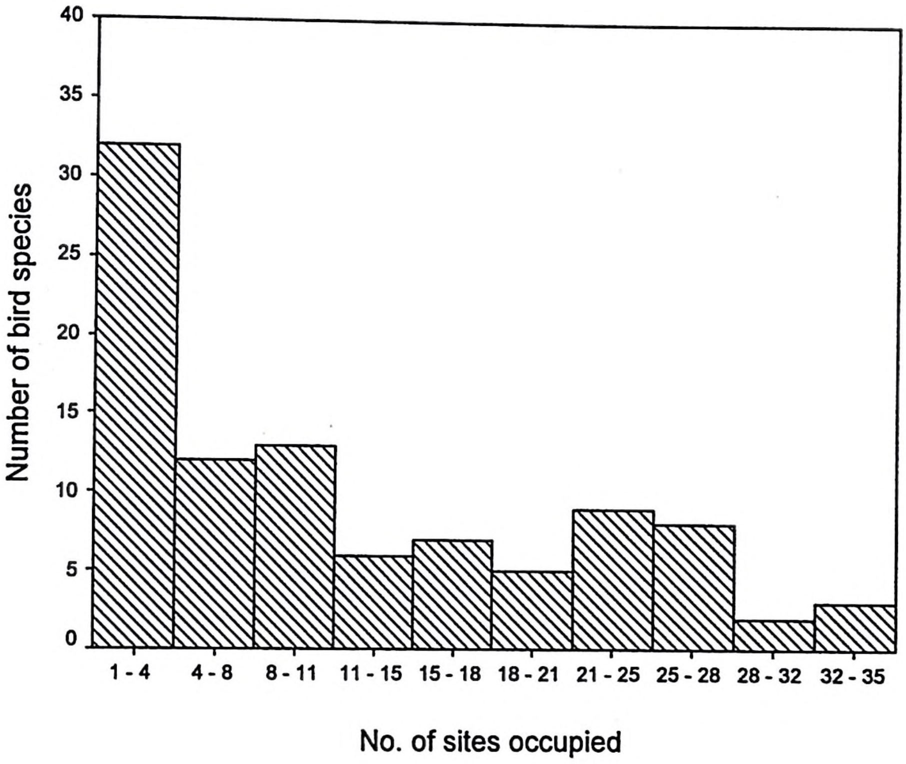
The putative relationship between community saturation and the degree of habitat specialization of constituent species has evoked much interest among evolutionary ecologists. The strong association of habitat-specialists with saturated communities could be traced to the apparent constancy of number of species in each habitat of the region regardless of the total species pool (Terborgh & Faaborg, 1980). It remains to be tested if this is a function of ecological release in which a species can potentially broaden its ecological amplitude or niche-width in the absence of interspecific competition (as speculated first in West Indian avifauna by Terborgh and Faaborg, 1980). Interestingly, a pertinent question arises here: if avian assemblages in central Indian forests are indeed saturated, wouldn't they be dominated by habitat specialists? On the contrary, a random walk through the forests in central India would probably return a preponderance of generalist birds ('tramps') that include parakeets, bulbuls, mynas, jungle babblers, tailorbirds, ioras, and sunbirds (see Table 4.7).

Table 4.7. A list of major bird species recorded on both extremes of the habitat-specialization gradient in central Indian forests. Note that 35 sites were sampled in total.

Habitat category	Bird species	No. of sites/habitats occupied
Habitat Generalists	Jungle Babbler *Turdoides striatus*	35
	Black-rumped Flameback *Dinopium benghalense*	34
	Rufous Treepie *Dendrocitta vagabunda*	34
	Red-vented Bulbul *Pycnonotus cafer*	33
	Oriental White-eye *Zosterops palpebrosus*	31
	Oriental Magpie Robin *Copsychus saularis*	28
	Purple Sunbird *Nectarinia asiatica*	28
	Plum-headed parakeet *Psittacula cyanocephala*	26
	Spotted Dove *Streptopelia chinensis*	26
	Chestnut-shouldered Petronia *Petronia xanthocollis*	25
Habitat Specialists	Brown-cheeked Fulvetta *Alcippe poioicephala*	5
	Bar-winged Flycatcher-shrike *Hemipus picatus*	4
	Scarlet Minivet *Pericrocotus flammeus*	3
	White-rumped Shama *Copsychus malabaricus*	2
	Spangled Drongo *Dicrurus hottentottus*	2
	Oriental Turtle Dove *Streptopelia orientalis*	2
	Yellow-legged Buttonquail *Turnix tanki*	2
	Malabar Pied Hornbill *Anthracoceros coronatus*	1
	Malabar Whistling Thrush *Myophonus horsfieldii*	1
	Spotted Creeper *Salpornis spilonotus*	1

But this paradoxical observation becomes clear when we examine dominance in terms of number of species, as originally suggested by Cornell (1985a), rather than number of individuals. For example, in the present study, 57 species of birds (c. 60%) were found to occupy less than 11 sites (c. 30 %) revealing a stronger presence of habitat-specialists than is generally assumed (see Figure 4.4). Since habitat-specialist birds often occur in too low a number to be detected by conventional distance-based methods, it is also important to employ appropriate sampling techniques (e.g., area search method) to make certain that all the species in a site/habitat are detected. It can also be argued that this spatial aggregation and numerical predominance of eurytopic species could have given rise to the observed impoverishment in species pool of local avian assemblages (see He & Legendre, 2002 for various simulation-scenarios of density compensation). But the lack of clarity over cause and effect warrants discretion before the direction of the relationship can be generalized [for example, see Terborgh and Faaborg (1980) for their reverse argument for the same phenomenon].

Figure 4.4. Site occupancy rate of birds in Central Indian Highlands, shown as the number of bird species in each class interval of number of sites occupied.



The fact that the forest bird communities in Central Indian Highlands are species-saturated despite being depauperate is an indication of dominant role of ecological interactions in limiting the number of species that co-exist. It has also been postulated that local diversity tends to vary as a function of the size of regional species pool in the absence of competition (Caswell & Cohen, 1993). Incidentally, the role of ecological factors has largely been underestimated in several local-regional richness studies leading to description of more communities as unsaturated than there would actually be (Griffiths, 1997; Hillebrand & Blenckner, 2002).

Historically, the Satpura Ranges in central India served as a major dispersal highway for terrestrial birds (esp. Indo-Malayan elements) from north-east to south-west (Ali, 1949). But it is not clear why they apparently failed to colonize central Indian forests; is it because of a hypothetical prevalence of unfavourable eco-climatic conditions in the past or presumed competition from 'peninsular elements' for scant niches? The results of the local-regional richness plots, however, suggest strong interspecific interactions which were also likely to have persisted in the past. There are some evidences, to this effect, from observations on current distribution patterns of birds in Central Indian Highlands (Jayapal *et al.*, 2005); for example, birds characteristic of hill-forests like Brown-cheeked Fulvetta (*Alcippe poioicephala*), Puff-throated Babbler (*Pellorneum ruficeps*), and Indian Scimitar Babbler (*Pomatorhinus horsfieldii*) are found only in select areas within their range and they are curiously absent from several localities where seemingly suitable habitats exist (e.g., East Nimar Hills, Mahadeo Hills, and Kurai Hills). This could not be explained by disturbance as these localities are relatively less-disturbed and some parts of the range, where the birds continue to thrive, are in fact severely affected by human disturbance (e.g., South Betul). It then leaves strong antagonistic interactions as the only plausible reason for their checkerboard distribution.

Habitat disturbance, *per se*, does influence the nature of correlation between local and regional richness. When community assembly time is held constant, local richness is expected to behave independently of the size of the regional species pool under both low and high levels of disturbance (Mouquet *et al.*, 2003); the former signifies true saturation of communities, while the latter gives rise to pseudosaturation. As the intermediate level of disturbance is known to augment species diversity (Connell, 1978; Johst & Huth, 2005), it can make local communities appear unsaturated despite high level of species interactions. Since a majority of sampling sites of the study were located in relatively less-disturbed forests, pseudosaturation is not suspected among the avian assemblages of the region.

Pseudosaturation is, however, known to arise as an artefact of several methodological shortcomings and limits imposed by community attributes, some of which are not mutually exclusive. These include overestimation of regional species pool (Cornell & Lawton, 1992), undersampling of local species richness (Caley & Schluter, 1997), inadequate sample size (Caley & Schluter, 1997), an inordinately large area of local sampling sites, relative to the size of the region (Hillebrand & Blenckner, 2002; He *et al.*, 2005), sampling of early successional communities (Mouquet *et al.*, 2003) and inclusion of introduced species in the regional pool (Griffiths, 1997; Irz *et al.*, 2004). A thoughtful appraisal of the methods adopted in the study and the selection of avian assemblages for analysis rules out the possibility of any of these factors contributing to the observed saturation of the region's avifauna.

For example, the regional species richness was computed here as cumulative sum of bird species recorded across all the local sampling sites in the region, and it was not extracted from hypothetical faunal lists, a known cause for overestimation of regional species pool. Similarly, the choice of area search method for bird surveys ensured detection of nearly all the species, including rare and cryptic ones, present in a site, and hence no local richness suffered from undersampling. There is also concern over the influence of varying number of replicates on local species richness (Srivastava, 1999); in other words, a low sample size is sometimes thought to result in detection of spurious saturation in communities owing to area effect. Though the number of regions used in the study (i.e., six independent data points each with 3-8 replicates) was less than optimal for regression analysis, the fact that there was no significant correlation between replicate size and local species richness ruled out the possibility of observed saturation in avian assemblages of Central Indian Highlands being artefactual. The remaining factors of pseudosaturation involve two attributes of community composition: presence of non-native species and dominance of early seral assemblages. There are no introduced species in central Indian avifauna and the bird communities studied are generally characteristic of mature near-climactic tropical forests (barring one assemblage of intermediate successional vegetation, sampled in a 'young regeneration forest' in South Maikal). In the absence of evidence for any of these factors, I conclude that breeding bird communities of Central Indian Highlands are truly saturated and this saturation along with a depauperate avifauna is probably mediated through sparse niche differentiation of the structurally impoverished tropical deciduous forests of central India.

A complementary explanation is provided by the 'compromise model' (Cornell, 1985a), where the slope of the constrained linear regression between local and regional richness lies midway between 0 and 1. It may be recalled here that the linear regression obtained for central Indian avifaunal assemblages also came up with results consistent with the compromise model. The model infers that isolated patches of niche vacancy are still available, though communities, on the whole, are saturated. These empty niches are likely to be of recent origin, as they largely arise as a fallout of local extinctions (see Huston, 1999). In fact, recent surveys (e.g., Jayapal *et al.*, 2005) have documented widespread instances of localized extinction in central Indian avifauna; in particular, habitat-specialists like Painted Bush Quail (*Perdicula* *erythrorhyncha*), Malabar Pied Hornbill (*Anthracoceros coronatus*), Spot-bellied Eagle Owl (*Bubo nipalensis*), Crested Goshawk (*Accipiter trivirgatus*), Black-crested Bulbul (*Pycnonotus melanicterus*), Striated Grassbird (*Megalurus palustris*), and Spotted Creeper (*Salpornis spilonotus*) seem to have suffered a major contraction in their distribution ranges in the second half of twentieth century. Ironically, saturated communities are also marked by a high ratio of extinction to immigration rates (He *et al.*, 2005).

In spite of several red herrings (e.g., pseudosaturation) and a few questionable interpretations (e.g., species interactions) that characterize local-regional richness plots, their usefulness as an exploratory tool in evolutionary ecology has been widely acknowledged (e.g., Ricklefs, 1987; Cornell & Lawton, 1992; Zobel, 1997; Lawton, 1999; Srivastava, 1999). It is, however, advisable to interpret these plots in conjunction with simultaneous examination of local ecological processes like density compensation, community resilience, and character convergence for stronger predictions about community saturation (MacArthur *et al.*, 1972; Wiens, 1989; Srivastava, 1999). The present study, being an exercise in macroecology, is limited by lack of data on population density of birds to test these supplementary hypotheses. It is hoped that future investigations will adequately address these issues to gain more insights into saturation of central Indian avifauna and evolutionary significance of their impoverishment.

4.5. SUMMARY

1. In this chapter, I examined the nature of relationships between local and regional species richness of birds in central Indian forests to test if the avian assemblages of the region were saturated and to hypothesize about the relative contributions of ecological *versus* historical forces in limiting the number of species coexisting in a habitat. It was presumed that a linear relationship would indicate unsaturated assemblages with more role for historical factors and curvilinearity would be an evidence for community saturation and dominance of ecological interactions.
2. I sampled breeding land birds in 35 sites over forested habitats covering six regions, each with 3-8 replicates. The birds were surveyed by standardized area search method in which 850 X 60 m transect blocks were sampled till all the species were detected. In total, 97 species of birds were recorded on transects.
3. Local species richness was computed as the mean number of bird species recorded in all the sites within the region. Regional richness was taken simply as the cumulative number of species summed over all the sampling sites in the region. I performed both constrained and unconstrained regressions between local and regional richness of six regions; linear model was contrasted with non-linear, quadratic curve by means of regression coefficients and goodness-of-fit tests in constrained regression. Alternatively, slope and *y*-intercept values were assessed for curvilinearity in unconstrained regression. Community saturation was also examined in terms of relationships among Whittaker's diversity components, viz., α, β, & γ.
4. Curvilinear model was found to be better fit than linear model in constrained regression, signifying saturation of communities. On a similar note, unconstrained regression also gave a slope value less than one and an intercept greater than zero implying saturation. Alpha diversity remained independent, while beta increased significantly with gamma diversity; thus, the diversity patterns were again consistent with that of saturated communities.
5. I conclude that forest bird communities of Central Indian Highlands are composed of truly saturated assemblages, notwithstanding a poor species pool. It is hypothesized that sparse niche differentiation of the structurally impoverished tropical deciduous forests of central India, rather than any historical constraint, contributes to the observed species saturation marked by a depauperate avifauna.

Chapter 5. Species-area relationships and spatial patterns in species diversity, species turnover, and taxonomic distinctness of breeding birds

5.1. INTRODUCTION

Increase in species numbers with area is probably one of the oldest observations in ecology, dating back to late 18th century (attributed to J.R. Forster in Lomolino, 2001). Often dismissed as a mere sampling artefact or even a truism (e.g., May, 1975; Connor & McCoy, 1979; Gilbert, 1980; Hill *et al.*, 1994; He & Legendre, 1996), species accumulation rate over area, however, continues to receive considerable attention in community ecology; this is, perhaps, because of a surprisingly narrow range of slope values within which most of the relationships have been observed to fall. In general, the relationship between number of species and area, [variously termed as species-area curve, species-accumulation function, species-diversity curve, or cumulative species richness curve (see Flather, 1996 for case-specific examples)] is traditionally expressed in two different regression models: the exponential (Gleason, 1922) and the power function (Arrhenius, 1921). The exponential model is described by the equation [$S = \log c + z \log A$] and the power function curve is rendered as [$S = cA^{z}$] or simply [$\log S = \log c + z \log A$], where S is the number of species, A the area, and *c* and *z* are constants. Less frequently, logistic model (Archibald, 1949) expressed as [$S = b/(c+A^{-z})$] where *b* is another constant term, is also fitted to species-area curves.

Studies on species-area relationships are plagued by several contentious issues ranging from the choice of regression model to the biological significance of slope and intercept parameters; they are also marked by disputes over methods of generating species-area curves and mechanisms that give rise to them.

Since early studies on species-area relationships were mostly carried out by plant ecologists, it is no surprise that the exponential model, first proposed in 1922 by H.A. Gleason - a pioneer phytogeographer, was the prevalent approach in the past (Connor & McCoy, 1979). It, however, gradually gave way to power function curve which latter became the most dominant model in species-area studies (Wiens, 1989; Lomolino, 2001). It could also be owing to the fact that a majority of early studies were conducted over small areas and exponential model would perform marginally better than power function in describing species-area curves drawn at a more local scale (He & Legendre, 1996). Notwithstanding a few critical reviews (e.g., Connor & McCoy, 1979; Martin, 1981), the power function curve remains the most widely used tool in species-area analysis in contemporary biogeographical literature (e.g., Sugihara, 1981; Rafe *et al.*, 1985; Pomeroy, 1993; Gisiger, 2001; Storch *et al.*, 2003). Sometimes, asymptotic models like logistic or sigmoidal curves are chosen over non-asymptotic expressions like power function or exponential curves on the premise that the regional species pool ought to be finite (e.g., Flather, 1996; He & Legendre, 1996; Lomolino, 2000). But this notion is hotly contested by Williamson *et al.* (2001), who maintain that species-area curve, in theory, does not plateau as both species and area are finite and non-negative.

The ecological interpretations of slope and less often intercept form probably the most controversial issue surrounding species-area studies. The slope (*z*) of species-area curves in power function model is empirically known to range, in a majority of cases, between 0.15 and 0.40, and has evoked much interest and debate among ecologists (e.g., May, 1975; Connor & McCoy 1979; Sugihara, 1981; Williamson, 1988; Rosenzweig, 1995; He & Legendre, 1996; Lomolino, 2001). It was Preston (1960), who first canonized the slope of 0.262 (with an estimated range of 0.17-0.33) as characteristic of equilibrium communities with lognormal distribution of species abundances, though this was not found to be universal (Connor & McCoy, 1979; Williamson, 1988). It was also observed previously that species-area curves of mainland communities were usually marked by a lower slope value (i.e., 0.12-0.19) in comparison to island assemblages in which the slope was known to vary between 0.20 and 0.40 (Preston, 1960; MacArthur & Wilson, 1963; Rosenzweig, 2003). This disparity was believed to be caused by significant differences in immigration-colonization rates between mainland and island ecosystems. In other words, a higher slope indicated greater isolation and therefore greater depauperation of communities (MacArthur & Wilson, 1963). But subsequent studies found the reverse to be true (e.g., Hamilton & Armstrong, 1965; Schoener, 1976; Connor & McCoy, 1979; Williamson, 1988; Lomolino, 1989). However, MacArthur's (1965) attempt to liken slope to beta diversity or species turnover and intercept to alpha diversity has gained widespread support (e.g, Connor & McCoy, 1979; Rosenzweig, 1995; Ricotta *et al.*, 2002; Koellner *et al.*, 2004; Scheiner, 2004), despite some reservations (e.g., Lomolino, 1989; Gray *et al.*, 2004). Earlier, Gould (1979) made some innovative interpretations of species-area curves on the basis of intercept when slopes of the curves were comparably similar. Intercept, though much less amenable to generalization compared to slope on account of it being unduly dependent on sampling effort, scale and taxa, is sometimes used to derive minimum expected number of species per sampling unit in back-transformed power models (see Connor & McCoy, 1979; Rosenzweig, 1995; Lomolino, 2001). [Note that constant term in power function curve is, strictly speaking, not a true intercept as pointed out by Lomolino (1989), but it is just a matter of statistical correctness and does not alter this interpretation]. Both the slope and the intercept are required to compute species density, a potential scale-invariant measure in ranking regions for their biodiversity value (Hobohm, 2003). Meanwhile, the idea that slope echoes evolutionary stages in taxon cycles, as originally proposed by Ricklefs and Cox (1972), has gained some currency in the absence of empirical evidence to the contrary (e.g., Williamson, 1988; Ricklefs & Bermingham, 2004). In a related development, slope has also been linked to degree of community saturation with lower values signifying species saturation of local assemblages (e.g., Martin, 1981; Storch *et al.*, 2003). The metapopulation model of species-area curves posits that the slope is a strong predictor of the ratio of population growth rate to variability in population growth of individual species, thus describing extinction trajectory of local assemblages (Matter *et al.*, 2002).

Though investigations into species-area relationships originally focused on large, unbounded mainland areas (Tjørve, 2003), they were later extended to island systems more so with the advent of island biogeography theory in 1963. But the fact that islands are composed of discrete units while continental quadrats are spatially contiguous gives rise to consistent differences in species-area relationships between mainland and island systems; in particular, the effect of geographical distance as a covariate emerges stronger in insular patterns (MacArthur & Wilson, 1963; Gilpin & Diamond, 1976; Connor & McCoy, 1979; Rosenzweig, 1995; He & Legendre, 2002). In fact, ecologists often choose to make the distinction clear by use of different terminologies; for example, Tjørve (2003) calls island types as 'isolate curves' and mainland relationships as 'sample curves'. Similarly, Gray *et al.* (2004) suggest that the term 'species-area curve' be restricted to islands while mainland patterns should be called 'species-accumulation curves' to reflect these differences. In mainland, samples are often sequentially nested to generate species-area curves, and the order of accumulation of samples is known to inordinately affect the shape of the curve (Palmer, 1990; Rosenzweig, 1995; Flather, 1996; Scheiner *et al.*, 2000; He & Legendre, 2002). This issue is usually addressed by adoption of either bootstrapped resampling (e.g., Flather, 1996) or randomization of quadrats (e.g., He & Legendre, 1996). Scale is another factor that is being increasingly shown to influence slope and therefore the shape of species-area curves (Shmida & Wilson, 1985; Palmer & White, 1994; Scheiner *et al.*, 2000; Gisiger, 2001; Turner & Tjørve, 2005). Recognizing these variations, Scheiner (2003) classified species-area curves into six types based on a combination of sampling attributes: quadrat type [mainland (nested, contiguous, or noncontiguous) or island], spatial explicitness, and species richness parameter (whether single estimate or mean). Since each type is credited with distinct statistical properties, their functional explanation is also expected to vary with the shape of the curve (see Tjørve, 2003).

The question as to why large areas harbour more species has received a slew of possible explanations. Many of these hypotheses are, however, not mutually exclusive and they can be grouped together to broadly represent three independent mechanisms (see Wiens, 1989; Hill *et al.*, 1994; Lomolino, 2001; Tjørve, 2003; Turner & Tjørve, 2005 for extensive reviews):

1. Sampling hypotheses

- Large areas receive greater cumulative sampling effort (Arrhenius, 1921; Gleason, 1922; Connor & McCoy, 1979; Coleman *et al.*, 1982)
- Large areas contain more individuals (Rosenzweig, 1995; Scheiner *et al.*, 2000)
- Large areas harbour more species due to passive sampling or random placement of individuals [i.e., distributions independent of both conspecific and heterospecific populations with only area exerting influence on distribution and hence number of individuals] (Coleman *et al.*, 1982; Williams, 1995; Veech, 2000; He & Legendre, 2002)

2. Habitat hypotheses

- Large areas are associated with high habitat diversity/environmental heterogeneity (Williams, 1964; Connor & McCoy, 1979; Rafe *et al.*, 1985; Shmida & Wilson, 1985; Williamson 1988; Rosenzweig, 1995; Scheiner *et al.*, 2000; Storch *et al.*, 2003)

- Large areas sustain greater primary productivity and are high in available energy (Wright, 1983; Wylie & Currie, 1993; Scheiner *et al.*, 2000)
- Large areas are less affected by varying scale and intensity of habitat disturbance (McGuinness, 1984)
- Large areas contain more species due to mass effect [i.e., establishment of species in unfavourable habitats as a spillover, spuriously increasing alpha diversity] (Shmida & Wilson, 1985)
- Large areas accommodate area-sensitive species in addition to others (Lomolino, 2001)

3. Biogeographical hypotheses

- Large areas are characterized by a low extinction-immigration ratio (Preston, 1960; MacArthur & Wilson, 1963; Gilpin & Diamond, 1976; Wissel & Maier, 1992; Heany, 2000)
- Large areas are more likely to intercept and trap immigrants (Schoener & Schoener, 1981; Lomolino, 1990)
- Large areas have more refugia and buffering agents against climatic and environmental fluctuations (McGuinness, 1984)
- Large areas, by virtue of their expansiveness, are more likely to have experienced vicariance events in the past (MacArthur & Wilson, 1963; Rosenzweig, 1995)
- Large areas include more biogeographical boundaries, giving rise to high species turnover (Rosenzweig, 1995)

Despite some uncertainties over its interpretations, species-area curve continues to be a major tool in both basic and applied ecology (Lomolino, 2001). It has been successfully used in community studies and biogeography to compute minimal area for sampling (Barkman, 1989), to standardize sampling effort (Moreno & Halffter, 2001; but see Willott, 2001), to estimate species richness (Palmer, 1990; Soberon & Llorente, 1993; He & Legendre, 1996; Koellner *et al.*, 2004; Krishnamani *et al.*, 2004), to measure species turnover (Rosenzweig, 1995; Koellner *et al.*, 2004; Ricotta *et al.*, 2002), and to characterize community structure (Martin, 1981; Rafe *et al.*, 1985; Storch *et al.*, 2003). Some of the potential applications of species-area curves in conservation biology include impact assessment of disturbance on ecological communities (McGuinness, 1984; Lawrey, 1991; Flather, 1996), design of nature reserves (Wilson & Willis, 1975; Humphreys & Kitchener, 1982), evaluation of vulnerability of communities to extinction (Matter *et al.*, 2002), calculation of extinction debt/deficit and rate of faunal relaxation after habitat fragmentation (Brooks *et al.*, 1999), and identification of diversity hotspots (Pomeroy, 1993; Veech, 2000; Hobohm, 2003).

Besides species-area relationships, spatial patterns in species diversity and turnover are another key area of research in studies on distribution of ecological communities in space. Several components of species diversity have been proposed and defined in relation to spatial scale of interest (Whittaker, 1972; Cody, 1975 & 1993; Schluter & Ricklefs, 1993; Whittaker *et al.*, 2001). Chief among them are alpha, beta, and gamma diversities; however, there is lack of uniformity and consistency in the way these diversity components, particularly beta and gamma, are defined. While alpha diversity is simply a measure of local species richness sometimes weighted by abundance, and thus describes the point diversity of any given area, there exist two major approaches for quantifying beta and gamma diversities. For example, Whittaker (1972) derived gamma diversity from the regional species pool and computed beta diversity as the ratio of alpha to gamma components. On the other hand, Cody (1975) defined beta diversity as the rate of species turnover between different habitats within a landscape, and gamma diversity as the rate of species turnover between similar habitats across different landscapes. Cody's gamma diversity is a potential tool in biogeographical studies as it is a product of historical and ecological constraints on speciation and dispersal (Schluter and Ricklefs 1993). Nevertheless, Whittaker's diversity components are more widely used in contemporary literature perhaps for their simplicity of calculation and applicability to meso-scale investigations. While alpha and gamma may become unpredictable under some circumstances, their ratio (beta) is, however, found to be theoretically stable and believed to offer more insights into community structure (Haydon *et al.*, 1993). In fact, Whittaker's beta diversity has been used for long a measure of species turnover in space.

Although there are scores of species turnover indices and measures available for presence-absence data, they seldom yield comparable or consistent results owing to vast differences in their statistical properties (Vellend, 2001). In a comprehensive review of all the published turnover measures, Koleff *et al.* (2003) find that indices which underscore species gain and loss (like symmetric similarity measures) perform better in most circumstances. In general, the relationship between species turnover and species diversity or richness has been anything but monotonic (Rosenzweig, 1995). To understand why species turnover gives inconsistent predictions, Lennon *et al.* (2001) partition turnover into three components: species continuity, species gain, and species loss; they demonstrate that species gain is inversely related to species richness, while species continuity and loss are positively associated. Therefore, any change in species turnover in response to species richness is largely a function of which of the turnover components is numerically superior and also to a certain extent the spatial scale (e.g., Whittaker *et al.*, 2001; Legendre *et al.*, 2005). Species turnover in space and its relationships with alpha and gamma diversities provide us a conceptual basis for understanding species diversity limits and mechanisms (Lennon *et al.*, 2001; La Sorte & Boecklen, 2005). They have also been used to develop measures for countrywide biodiversity monitoring programmes at different spatial scales (e.g., Switzerland: Weber *et al.*, 2004).

Species diversity as one that reflects richness along with evenness of abundances (e.g., Shannon Index) is the most dominant approach in measuring biodiversity in spite of it being denounced as theoretically equivocal (e.g., Hurlbert, 1971; Purvis & Hector, 2000) and statistically weak (e.g., Tóthmérész, 1995; Austin 1999). But the conventional diversity measures have also been found to be woefully inadequate in describing changes in species composition and taxonomic constitution of ecological communities (Erdelen, 1984; Humphries *et al.*, 1995; Ganeshaiah *et al.*, 1997; Poulsen, 2002). This led to the development, in early 1990s, of phylogenetic diversity measures which aimed to express community composition in terms of sum taxonomic relatedness (Vane-Wright *et al.*, 1991; Faith, 1992). But these measures also suffered, as conventional diversity indices, from their lack of statistical independence with respect to sampling effort and species richness. Subsequently, Clarke & Warwick (1998) developed a 'taxonomic distinctness' index with explicit statistical properties. Taxonomic distinctness of a community can be mathematically defined as the mean taxonomic path length between any two species chosen randomly from the community, and it is less affected by sampling intensity or species richness unlike its predecessors. It is sometimes expanded, with the inclusion of relative abundance, as a measure of 'taxonomic diversity' of assemblages. A frequently-held criticism over incorporating phylogenetic information into diversity measurement relates to the general lack of consensus among taxonomists regarding generic and species limits (e.g., Crozier, 1992; Krajewski, 1994). But this has now been found to be largely unfounded (see Isaac & Purvis, 2004; Dillon & Fjeldså, 2005), although the question of optimum number of taxonomic categories for computing phylogenetic diversity remains debated (see Polasky, 2001; Rodrigues & Gaston, 2002a; Ellingsen *et al.*, 2005). The taxonomic distinctness algorithms have been increasingly used in assessing structure and composition of faunal assemblages (e.g., von Euler & Svensson, 2001; Ellingsen *et al.*, 2005; La Sorte & Boecklen, 2005), to evaluate functional integrity of communities (e.g., von Euler, 1999), to measure biodiversity (e.g., Ricotta, 2004), and to prioritize reserves for conservation network (e.g., Polasky *et al.*, 2001; Rodrigues & Gaston, 2002a).

With this background, this chapter seeks to examine the spatial patterns of species diversity in breeding land birds of the Central Indian Highlands. To begin with, I investigate species-area relationships to describe spatial organization of the number and distribution of birds in central India. I subsequently test the habitat heterogeneity hypothesis (arguably the most passable explanation for species-area curves) by comparing the slopes of species-area curves after partitioning the birds into habitat specialists and generalists. This is then followed up with a broad-scale analysis of the relationships between three spatial components of species diversity (α, β, & γ) and species distribution attributes at the level of regions. Thereafter, the associations between bird species richness, species turnover, and taxonomic diversity are explored at the level of quadrats to deduce inferences about species diversity mechanisms and taxon cycles in central Indian avifauna. In the end, all the regions are ranked for their conservation significance using species density measure derived from species accumulation curves to identify 'diversity hotspots' of Central Indian Highlands.

5.2. METHODS

5.2.1. Study area

The study was conducted in Central Indian Highlands in Madhya Pradesh between April and July during 2002-04. These highlands, comprising the Satpura and the Vindhya Ranges, extend over an area of about 200,000 sq. km. and are predominantly covered with tropical dry- and moist-deciduous forests, dominated by associations of teak (*Tectona grandis*) in western and central parts, and sal (*Shorea* *robusta*) in the east. The average elevation of the hill ranges varies between 200-800 m, while some of the peaks in western and central ranges exceed 1000 m.

The entire study area was divided, a priori, into 11 conterminous landscape units ('biogeographical regions') on the basis of natural vegetation, drainage, topography, and eco-climatic attributes, as follows: Malwa Plateau, Nimar Hills, Lower Narmada Valley, Betul Plateau, Sagar-Damoh Plateau, Satpura Plateau, Seoni-Chhindwara Plateau, Vindhya Scarplands, Kaimur Hills, East Maikal Range, and South Maikal Range [See Appendix 5.1 for a brief description of these regions]. All the regions were, then, gridded into quarter-degree cells (15′ X 15′) or 'quadrats' (corresponding to Survey of India's 1:50,000 scale toposheets), with each quadrat measuring about 27 X 26.5 km in size (c. 715 sq. km. area). This returned 284 contiguous quadrats, in total, from the entire study area. Along the transitional boundaries of regions, quadrats were assigned to regions on the basis of the dominance of regional affinities with respect to both physical and phytogeographical characteristics.

5.2.2. Birds

I assembled data on distribution of land bird species that breed in Central Indian Highlands with the 284 quadrats as the primary sampling units of the study. As the study area was too expansive to cover within a short period, a spatially hierarchical multi-pronged sampling approach was adopted: i) conducting inventory-survey of breeding birds in key vegetation types across regions through stratified sampling, ii) drawing up bird-vegetation associations from the survey data for each region, iii) mapping the occurrence and extent of key vegetation types for all quadrats in each region, and finally iv) interpolating, within a region, species distributions for all quadrats from both these information layers [See Appendix 5.2 for a schematic diagram of the sampling protocol].

Accordingly, I collected data on bird-habitat associations from 36 major vegetation types extending over six regions [see Appendix 3.1 for a descriptive list of forest types sampled for bird-vegetation associations], using 'standardized area search method' (Slater, 1994; Dieni & Jones, 2002; Watson, 2004). This technique involved laying of 5 ha transect-blocks in homogeneous forest types and inventorying all the bird species that were presumably breeding in the site by careful and meticulous search-walks till all the species were detected [see Section 3.2.2 for detailed account of the 'area search method']. In addition, numerous on-foot surveys were also undertaken to supplement the transect data, particularly in regions that were not covered by stratified sampling and in a few undersampled forest types. Matrices on bird-vegetation associations were, then, constructed for each region from these field-surveys. In the mean time, land cover information describing vegetation type and land use patterns were extracted from ground-truthed data collected from GPS-aided surveys in nearly all the quadrats. I also used the Survey of India's 1:250,000 and 1:50,000 toposheets to classify and estimate the extent of habitat/vegetation types in all the quadrats. Using both bird-vegetation matrices and vegetation maps generated for a region, data on distribution of breeding birds were spatially interpolated for each quadrat within the region. The legitimacy of such an interpolation hinges on two key assumptions: i) birds are non-randomly distributed in their breeding season and ii) bird species known to occur in a given habitat in the focal quadrat is more likely to occur in the neighbouring quadrats as well, provided the neighbouring quadrats share same biogeographical history with the focal quadrat and the particular habitat is available in the neighbouring quadrats in good measure. There are increasing empirical evidences pointing to the veracity of these premises. For example, several studies have observed strong habitat affinities in breeding birds in contrast to non-breeding birds (e.g., Mills *et al.*, 1991; Lopez & Moro, 1997; Haney & Lydic, 1999; Grand & Cushman, 2003). The second assumption that species colonize quadrats according to the area of the suitable habitat within a quadrat has also been recently tested and validated with British birds (Storch *et al.*, 2003). The final product comprising presence/absence data of bird species for each of the 284 quadrats was, later, contrasted with the published literature on distribution of bird species in the Subcontinent (e.g. Ali & Ripley, 1983; Grimmett *et al.*, 1998; Kazmierczak & van Perlo, 2000; Rasmussen & Anderton, 2005) and in central India (see Chapter 2. Study Area for regional checklists published on central Indian avifauna). The comparison was necessary to check for gaps in species distribution maps as generated by our field surveys and to ascertain if the gaps were due either to sampling inadequacy or to recently fragmented distributions. If it was indeed the former (as would typically be expected of widespread and habitat-generalist species), I corrected for the gaps in the data. The detection of all the euryecious species found in a region has been suggested as a minimum requirement for the completeness of species-list of the region (Gómes de Silva and Medellín, 2001).

Though the field-surveys targeted all the land bird species that were known to breed regularly in the study area, several species were excluded from the final analysis owing to insufficient data. These included all the three species of buttonquail (*Turnix* spp.), Asian Palm Swift (*Cypsiurus balasiensis*), Brahminy Kite (*Haliastur indus*), Forest Owlet (*Heteroglaux blewitti*), Ashy Woodswallow (*Artamus fuscus*), White-bellied Minivet (*Pericrocotus erythropygius*), Spotted Creeper (*Salpornis spilonotus*), and Green Avadavat (*Amandava formosa*). In total, 190 species of land birds for which I had adequate data were included in the analysis. [See Appendix 5.3 for a region-wise list of the breeding land birds of Central Indian Highlands].

5.2.3. Analysis

5.2.3a. Species-area relationships

I adopted the '*sequential addition of randomized quadrats*' design (He & Legendre, 1996) to generate species-area curves for the central Indian avifauna. Unlike islands, generating species-area curves for mainland assemblages is not straightforward as the order in which samples are added is known to significantly influence the intercept and to a less extent the slope of the curve (Palmer, 1990; Rosenzweig, 1995; Flather, 1996; Scheiner *et al.*, 2000). Traditionally, species-area data for mainlands are derived by means of either classical 'nested quadrats' design (used mostly by plant ecologists at small spatial scales) or 'sequential addition of quadrats' technique (preferred by ecologists for eliciting patterns over very large areas). But the latter suffers heavily from the problem of non-independence of spatial units that are used in generating cumulative species richness values. He and Legendre (1996) addressed this problem by randomizing the order of quadrats prior to their sequential addition, which was also followed here.

In this method, the study area with 284 quarter-degree grids was divided into two equal parts allotting 142 quadrats randomly to each part. Out of these two halves, one was retained as the 'highest-order sampling block' for which cumulative bird species richness was derived. The remaining half of 142 grids was further divided into two halves, again apportioning grids at random to each part. Of these two parts, one half was retained as the next higher-order block and the other part was again cleaved into two with random allotment of quadrats. Thus, each hierarchical halving resulted in a progressively lower-order sampling block, the spatial units of species-area curves, and at each step, cumulative number of bird species was also computed across all the quadrats of the block. This was carried on successively to the last remaining quadrat which eventually formed the lowest-order sampling block. In the end, nine blocks ranging from the first block with 142 quadrats to the last block with just one quadrat along with their cumulative number of bird species were obtained. I, then, plotted the species numbers against the area for all the nine blocks, and three prevailing models, viz., exponential, power function, and logistic were fitted to the relationship using non-linear regression. The models were evaluated for statistical significance and goodness-of-fit on the basis of a combination of parameters including regression coefficients, F-ratio, and residuals. Randomization of quadrats into blocks and curve fitting was done in SPSS Release 8.0.0.

I also sought to test the '*habitat diversity*' hypothesis, arguably the most widely contested mechanism for species-area relationships. I, first, partitioned the birds into habitat- specialists and generalists, and then I derived species-area curves separately for the two classes. We would expect the species-area curve to have a steeper slope in the case of habitat-specialists, if habitat diversity was indeed a major factor fashioning the species-area relationships. Birds were classified as habitat-specialists and generalists on the basis of their occupancy of habitat types at the landscape level. Seven broad habitat types were considered: i) dry-deciduous forests, ii) moist-deciduous forests, iii) bamboo-dominant forests, iv) open grasslands, cultivation, and glades in forested tracts, v) scrub jungle, vi) agricultural fields, villages, and open countryside, and vii) urban environments. Bird species which were observed to breed regularly in four or more habitats out of the seven types were classified as habitat-generalists and birds restricted to three habitat types or less were categorized as habitat-specialists. In the end, 96 species were classified as generalists, while 94 species were grouped as habitat-specialists [See Appendix 5.4]. Though the classification criteria might appear oversimplified, it was adopted as a measure in correspondence with the spatial scale of the investigation. In any case, such a coarse set of definitions was only a conservative expression of the range of habitat occupancy in birds, and any further scaling-down would only serve to accentuate the observed patterns. Species-area curves were then drawn as before separately for habitat-specialists and generalists, keeping the same sets of randomized quadrats as sampling blocks. The regression model that was earlier found to be the best fit with the combined data was applied and the slopes of the resultant curves were compared.

5.2.3b. Species-accumulation curve & species density

Species-area curves extended to mainland assemblages with geographically defined regions as sampling units are often known as species-accumulation curves and they are widely applied in evaluating regions for their biological diversity. In an attempt to identify regions of high conservation significance in Central Indian Highlands, I plotted a species-accumulation curve by regressing bird species richness against area for all the 11 regions of the study area and by fitting a power-function model to the data in log-log space (following Pomeroy, 1993). The relative positions of regions in the species-area biplot were examined to assess their conservation value. In particular, regions that lay above the regression curve were deemed to harbour high diversity. I also considered the distance between each region and the line of mean bird species richness of all the regions as an unconstrained measure of the size of the regional species pool.

Further, I computed bird species density for each region on the basis of the species accumulation curve (as vertical distance between the region and the power-function curve). This was later used to rank all regions in terms of their avifaunal diversity, corrected for both geographical area of the region <u>and</u> the minimum expected number of bird species per unit area. Species density is mathematically expressed as follows (Hobohm, 2003):

$$\alpha = \log S - [z * \log A + \log c]$$

where, α = species density, S = number of bird species, A = area of the region, and z and c = species-area coefficients referring to slope and intercept respectively.

In the end, species density values and the visual interpretations of species-accumulation curve were used in conjunction with each other in identifying and ranking regions for their conservation significance in Central Indian Highlands from ornithological perspective.

5.2.3c. Species diversity, species turnover, & taxonomic distinctness

I estimated alpha, beta, and gamma components of bird species diversity for all the 11 regions from quadrat-wise data of bird species composition following the definitions of Whittaker (1972). Accordingly, alpha diversity was simply defined as the mean bird species richness of all the quadrats within a region, while their cumulative species richness was used as a measure of gamma diversity; thus, alpha and gamma signified the size of the local and the regional species pool respectively. Beta diversity was, then, expressed as the ratio of alpha to gamma components. Since beta diversity, as defined here, was not statistically independent of alpha or gamma, I did not use beta as a measure of species turnover [See Vellend, 2001 for critical comments over the use of Whittaker's beta]. Instead, I followed Lennon *et al.* (2001) to compute species turnover between a pair of quadrats, as follows:

$$\boldsymbol{\beta_{sim} = 1/n \sum\{[\min(b,c) / [\min(b,c)+a]\}}$$

where, a = number of species shared by two quadrats, b = number of species present in the neighbouring quadrat but absent in the focal quadrat, c = number of species present in the focal quadrat but absent from the neighbouring quadrat, and n = total number of neighbouring quadrats, which takes a maximum value of eight for a focal quadrat lying away from the edge. This measure is, in fact, a symmetrical form of the Simpson's similarity index, and the values of β_{sim} range from zero (no turnover with identical sets of assemblages) to one (complete change-over of species composition). It has also been credited, in a recent review, with several statistically desirable properties including the explicit partitioning of turnover variation into species gain and loss and its non-monotonous response to species richness gradients (Koleff *et al.*, 2003). Species turnover for each region was, then, calculated by averaging the turnover values across all the quadrats of the region.

I quantified taxonomic distinctness of breeding birds for each quadrat using the algorithm developed by Clarke & Warwick (1998). Taxonomic distinctness (TD) is a non-metric derivative of taxonomic diversity, and refers to the average phylogenetic path-length between any two species randomly chosen from the assemblage. The index is given for a quadrat as,

$$\mathbf{TD = [\Sigma\Sigma_{i<j}\omega_{ij}]/[s(s-1)/2]}$$

where, ω_{ij} = taxonomic distance between species *i* and species *j* measured in a phylogenetic space using a hierarchy of taxonomic categories, and s = total number of species present in the quadrat. I considered nine taxonomic categories above species (viz., genus, tribe, subfamily, family, superfamily, parvorder, infraorder, suborder, and order) within the framework of Sibley & Monroe's (1990) classification of birds to derive distances between all pairs of species in a quadrat (following von Euler & Svensson 2001; La Sorte & Boecklen, 2005). I used the statistical software PAST v.1.32 (Hammer *et al.*, 2004) to compute taxonomic distinctness for all the quadrats, which were then averaged to obtain the mean taxonomic distinctness of each region.

Analyses of bird species diversity and turnover were carried out at two spatial scales, viz., regions and quadrats. Relationships between alpha, gamma, and species turnover were examined for all the regions using Spearman's rank correlation, while associations between bird species richness, species turnover, and taxonomic distinctness were investigated at the level of quadrats by means of Pearson's correlation coefficient. All the statistical tests were done in SPSS Release 8.0.0.

5.3. RESULTS

5.3.1. Species-area relationships

Among the three models fitted to species-area relationship in breeding birds of Central Indian Highlands, both the power function and logistic curves were found to be statistically significant. However, the power function model yielded the best fit in terms of regression coefficients and residuals (Table 5.1), and was used in subsequent analyses.

Table 5.1. Regression models evaluated for species-area relationship in central Indian birds.

Model	Regression SS	Residual SS	*F*	*P*	$R^2 \pm 1$ SE
Power function [$S = cA^{z}$]	0.415	0.102	28.57	0.001	0.803 ± 0.120
Exponential [$S = \log c + z \log A$]	0.171	0.346	3.45	0.105	0.330 ± 0.222
Logistic [$S = b/(c+A^{-z})$]	20.236	9.498	14.91	0.006	0.680 ± 1.165

The species-area relationship was expressed in power function model as follows (see also Figure 5.1):

$S = 50.91 \times A^{0.12}$, where S = number of bird species breeding, A = area in sq. km., slope of the curve (z) = 0.12, and intercept (c) = 50.91 [see Table 5.2 for goodness-of-fit statistics].

Figure 5.1. Species-area relationship in breeding birds of Central Indian Highlands. The dashed line is the observed species-area curve, while the solid line is the power function curve fitted to the data (N = 9).

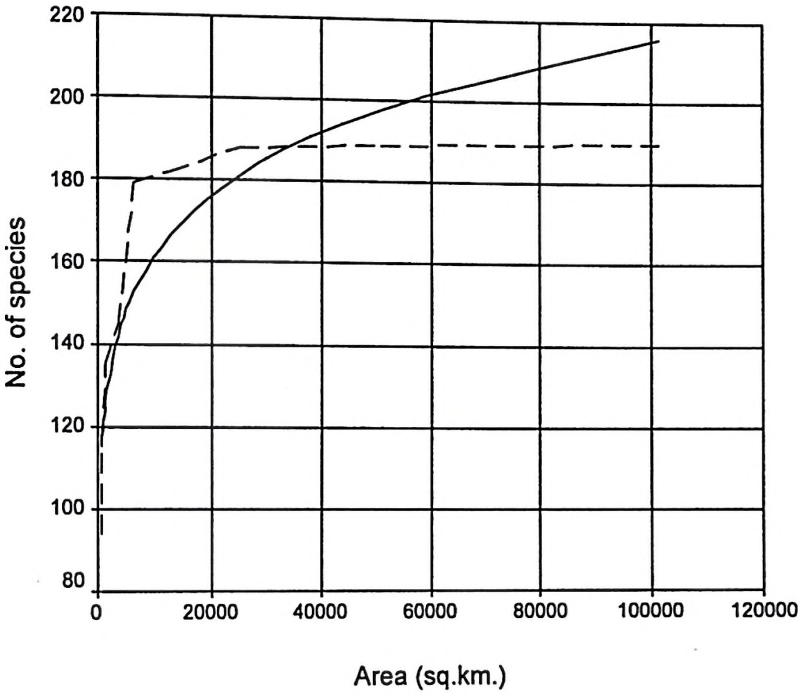


Table 5.2. Regression parameters of species-area relationships for Central Indian birds as described by power function model ($S = cA^z$).

I. Analysis of Variance

Source	SS	df	F	P	$R^2 \pm 1$ SE
Regression	0.415	1	28.57	0.001	0.803 ± 0.120
Residual	0.102	7			
Total	0.517	8			

II. Parameter Estimates

Parameter ± 1 SE	t	P
z = 00.12 ± 00.023	5.34	0.001
c = 50.91 ± 10.709	4.75	0.002

When species-area curves were generated separately for habitat-specialists and generalists using power-function model, slope of the curve was found to be much higher in specialists (z = 0.23) than among generalists (z = 0.05). See Figure 5.2 for a comparative illustration of species-area curves for both the assemblages. Further, an inspection of y-intercept values revealed that the minimum expected number of bird species breeding in a quadrat (715 km^2) was around 54 for habitat-generalists and 8 for habitat-specialists (Table 5.3).

Figure 5.2. Species-area curves for the breeding birds of Central Indian Highlands, partitioned into habitat-specialists and generalists and expressed by power function in log-log space. The hollow squares refer to generalists while the solid squares represent habitat-specialists.

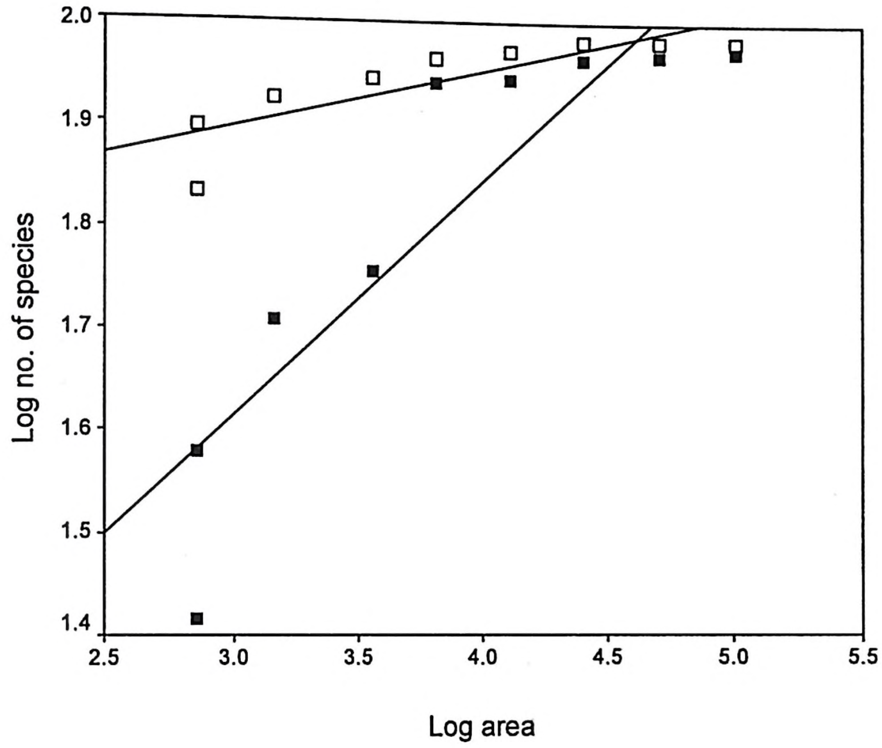


Table 5.3. Regression parameters of species-area relationships for habitat-specialists and generalists as described by power function model among central Indian avifauna ($S = cA^z$).

Habitat-generalists

I. Analysis of Variance

Source	SS	df	F	P	$R^2 \pm 1$ SE
Regression	0.080	1	19.66	0.003	0.737 ± 0.064
Residual	0.029	7			
Total	0.109	8			

II. Parameter Estimates

Parameter ± 1 SE	t	P
z = 00.05 ± 0.012	4.43	0.003
c = 53.87 ± 6.017	8.95	<0.0001

Habitat-specialists

I. Analysis of Variance

Source	SS	df	F	P	$R^2 \pm 1$ SE
Regression	1.398	1	26.83	0.001	0.793 ± 0.228
Residual	0.365	7			
Total	1.763	8			

II. Parameter Estimates

Parameter ± 1 SE	t	P
z = 0.23 ± 0.044	5.18	0.001
c = 8.42 ± 3.355	2.51	0.040

5.3.2. Species-accumulation curve & species density

On examining the species-accumulation curve plotted for 11 regions (Figure 5.3), two among them, viz., Satpura Plateau and Betul Plateau, emerged as regions of high avian diversity as reflected by their position in the biplot with respect to both the line of mean bird species richness and the line of species-area regression predicted by the power-function model. Though some of the other regions did appear to stand out in the scatter-plot, they were however found to be wanting on one or the other account. For example, the region of Nimar Hills, though figured prominently above the species-accumulation curve, was downgraded in the prioritization exercise, as its species pool was much lower than that of the mean value of the Highlands. On the contrary, East Maikal Range and Seoni-Chhindwara Plateau were characterized by a species pool richer than the mean value, but they were again deselected as they had fewer bird species given their large geographical area (Table 5.4).

Figure 5.3. Species-accumulation curve of breeding land birds vis-à-vis 11 regions of Central Indian Highlands. The dashed line corresponds to the overall mean bird species richness across all regions. The vertically slanted line represented the power function curve of species-area relationship. Satpura Plateau and Betul Plateau emerge as regions of high species diversity as they lie above both the mean richness line and the power-function curve. Note the overlap on both axes between two regions viz., Malwa Plateau and Lower Narmada Valley.

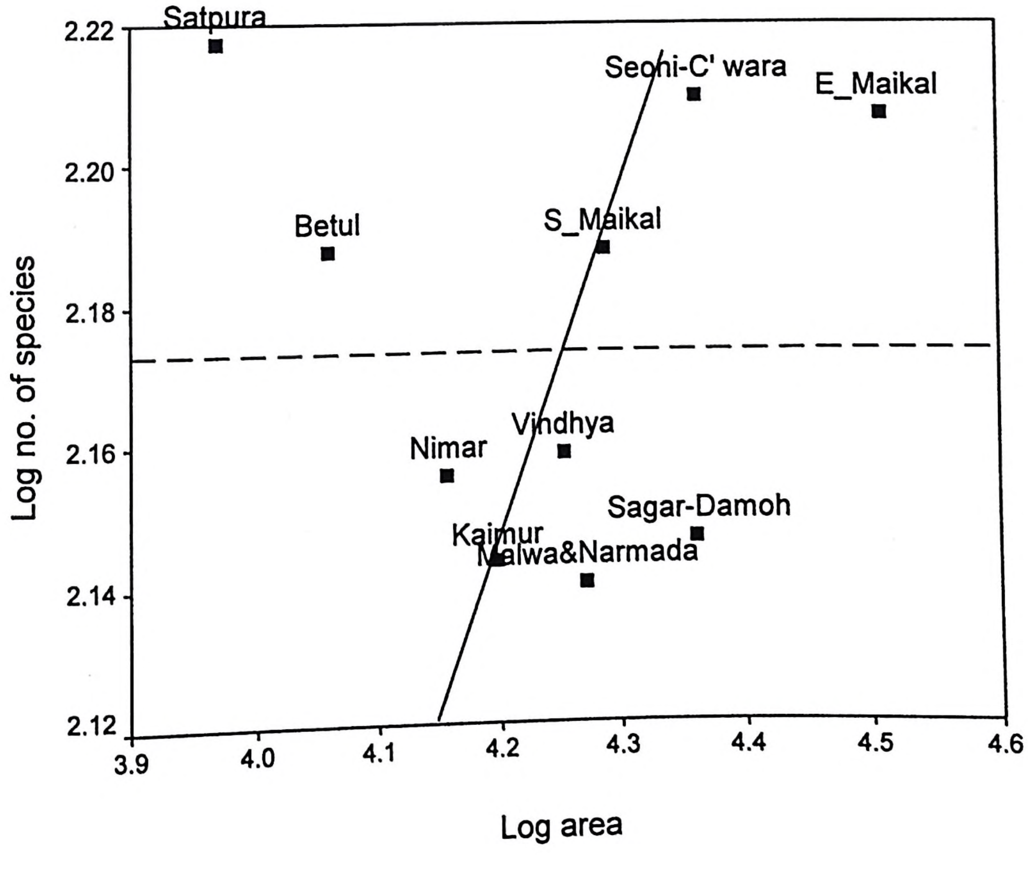


Table 5.4. Total area and number of breeding bird species of each region in Central Indian Highlands.

Sl.No.	Region	No. of grids	Total area (km^2)	Number of bird species
1	Malwa Plateau	26	18590	138
2	Nimar Hills	20	14300	143
3	Lower Narmada Valley	26	18590	138
4	Betul Plateau	16	11440	154
5	Sagar-Damoh Plateau	32	22880	140
6	Satpura Plateau	13	9295	165
7	Seoni-Chhindwara Plateau	32	22880	162
8	Vindhya Scarplands	25	17875	144
9	Kaimur Hills	22	15730	139
10	East Maikal Range	45	32175	161
11	South Maikal Range	27	19305	154

The species-accumulation curve was described by a slope of 0.12 and an intercept of 50.91. While ranking regions for their ornithological significance on the basis of their bird species density (computed using the slope and intercept values of the species-accumulation curve), Satpura Plateau was observed to be the only region with a positive integer value implying high bird species density, followed closely by Betul Plateau (Table 5.5). The regions in the west and north-west of Central Indian Highlands (e.g., Malwa Plateau, Lower Narmada Valley, and Sagar-Damoh Plateau) were typically marked by a relatively low number of bird species breeding per unit area.

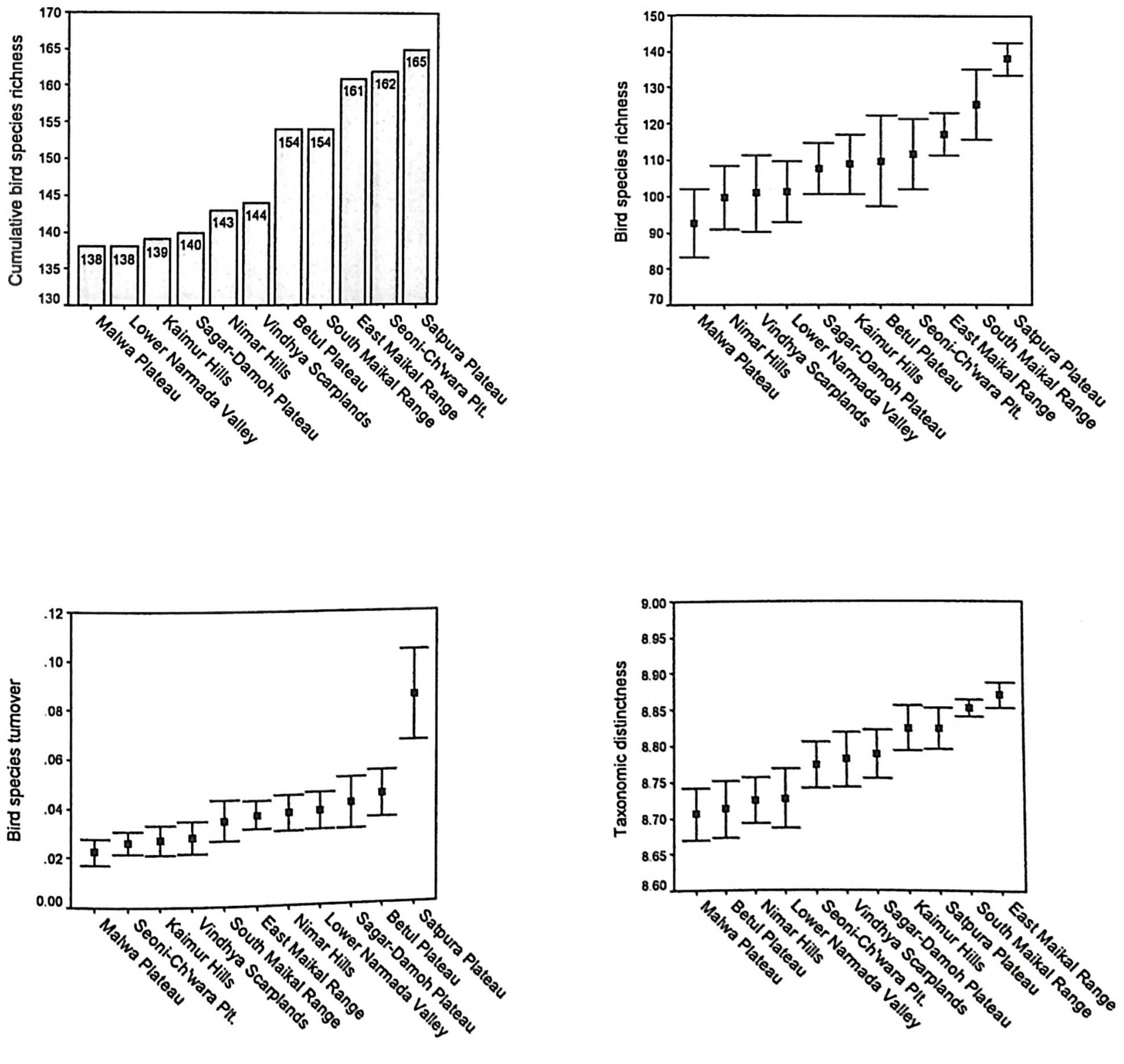
Table 5.5. Ranking of regions of Central Indian Highlands in terms of bird species density (α), as computed from the power function model of species-accumulation curve.

Region	α value
Satpura Plateau	0.034
Betul Plateau	-0.006
Seoni-Chhindwara Plateau	-0.020
South Maikal Range	-0.034
East Maikal Range	-0.041
Nimar Hills	-0.050
Vindhya Scarplands	-0.059
Kaimur Hills	-0.067
Malwa Plateau	-0.079
Lower Narmada Valley	-0.079
Sagar-Damoh Plateau	-0.084

5.3.3. Species diversity, species turnover, & taxonomic distinctness

A region-wise comparison of species distribution attributes in central Indian avifauna revealed that alpha and gamma diversity were the highest in Satpura Plateau and the lowest in Malwa Plateau. Trends in bird species turnover were noted to be nearly similar to that of species richness, though Seoni-Chhindwara Plateau and Lower Narmada Valley showed contradictory patterns. The variations, among the regions, in taxonomic distinctness were nonetheless observed to be only marginal with the Malwa Plateau and Maikal ranges representing the lowest and highest limits of the gradient (Figure 5.4).

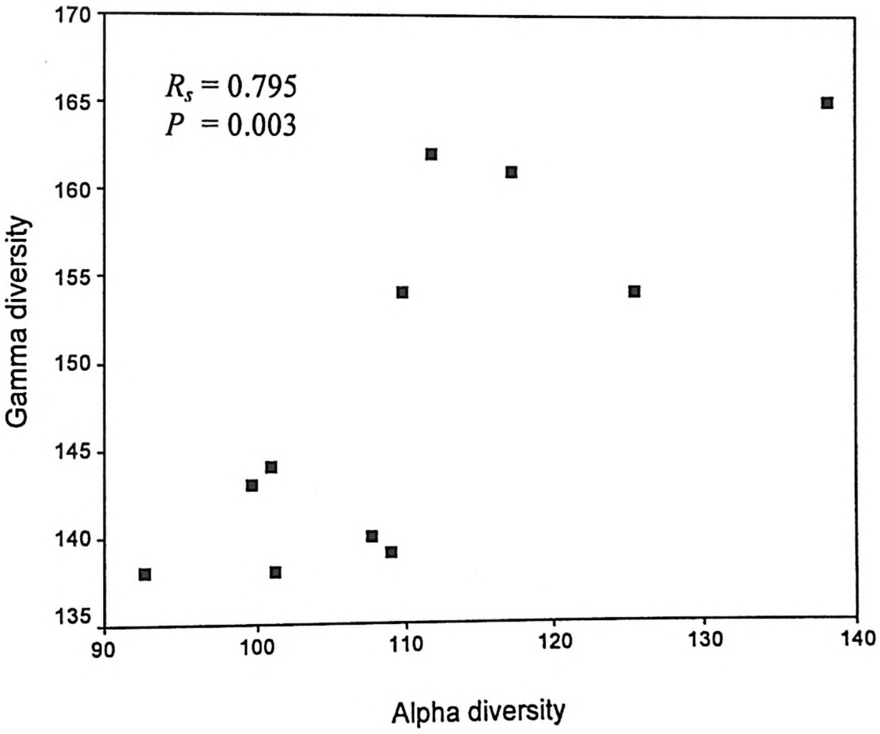
Figure 5.4. Regions of Central Indian Highlands arranged on an increasing gradient of species distribution attributes of breeding birds: a) cumulative species richness (gamma diversity), b) mean species richness (alpha diversity), c) species turnover, and d) taxonomic distinctness. The error bars correspond to 95 % CI about the mean.



Among the regions, gamma diversity was found to increase significantly with alpha diversity of birds ($R_s = 0.795$, $P = 0.003$, N = 11). In other words, regional species pool varied as a function of mean local species richness in central Indian avifauna (Figure 5.5).

Bird species turnover was unrelated to both alpha ($R_s = 0.336$, $P = 0.312$, n = 11) and gamma diversity ($R_s = 0.265$, $P = 0.431$, N = 11). Likewise, taxonomic distinctness of avian assemblages also showed no relationship with gamma ($R_s = 0.406$, $P = 0.215$, N = 11), but a statistically weak positive association with alpha diversity ($R_s = 0.682$, $P = 0.021$, N = 11). [See Figure 5.6].

Figure 5.5. Relationship between alpha and gamma diversity in central Indian birds (N = 11).



No significant correlation was detected between species turnover and species richness among breeding land birds of Central Indian Highlands, when the attributes were analyzed at the level of quadrats ($R = 0.084$, $P = 0.160$, N = 284). However, a close inspection of the scatter plot (Figure 5.7) revealed that species-rich quadrats (i.e., S > 90) might show different patterns of relationship in comparison to species-poor quadrats (i.e., S < 90). In a subsequent re-analysis, a weak yet significant positive relationship between species richness and species turnover was noted independently for species-poor quadrats ($R = 0.377$, $P = 0.002$, N = 65) and species-rich quadrats ($R = 0.205$, $P = 0.002$, N = 219).

Figure 5.6. Scatterplots showing Spearman's rank correlations among alpha, gamma, species turnover, and taxonomic distinctness in birds of Central Indian Highlands (N = 11).

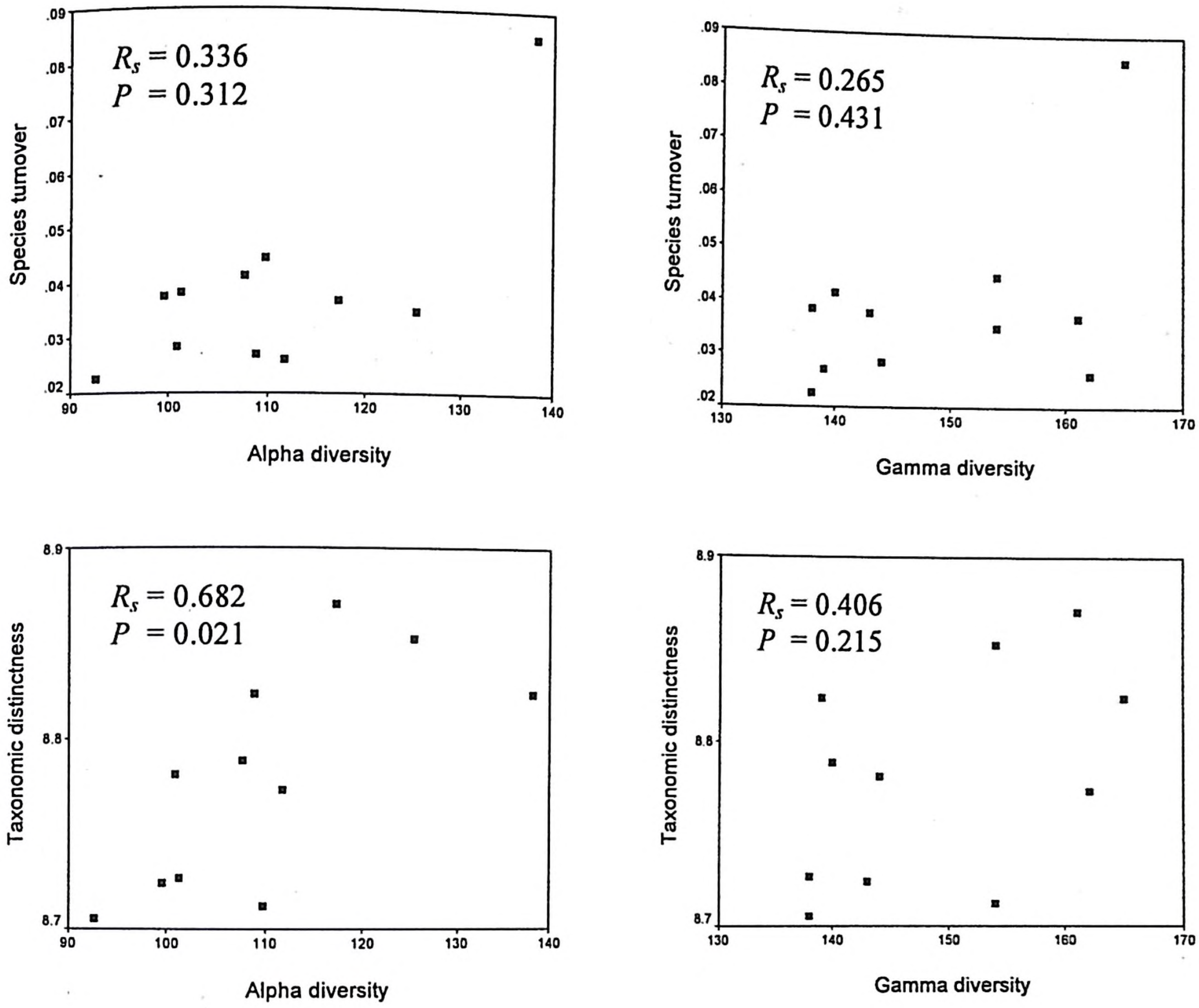
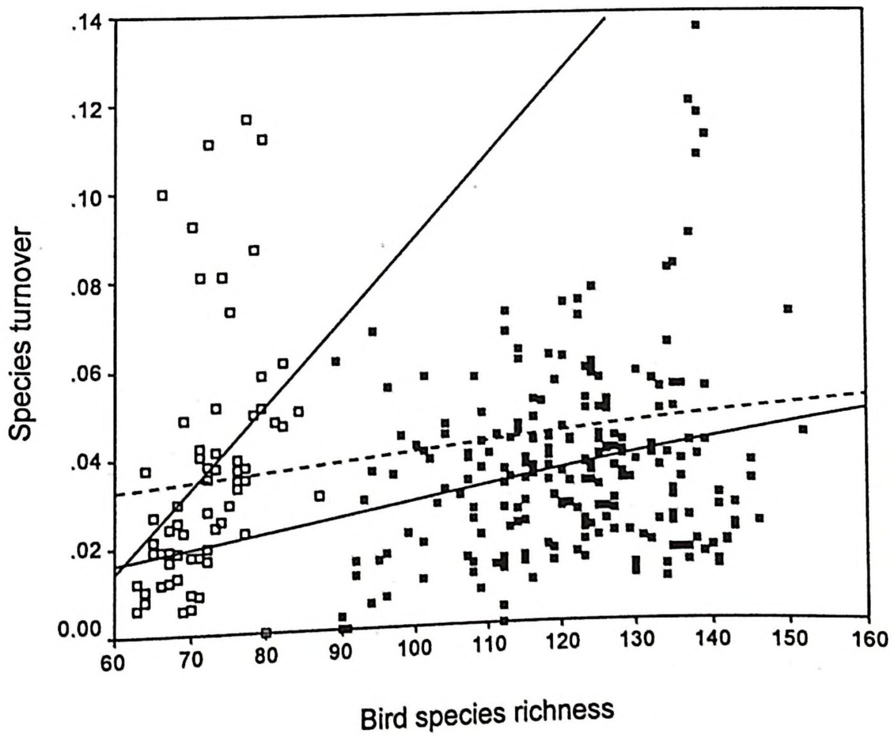
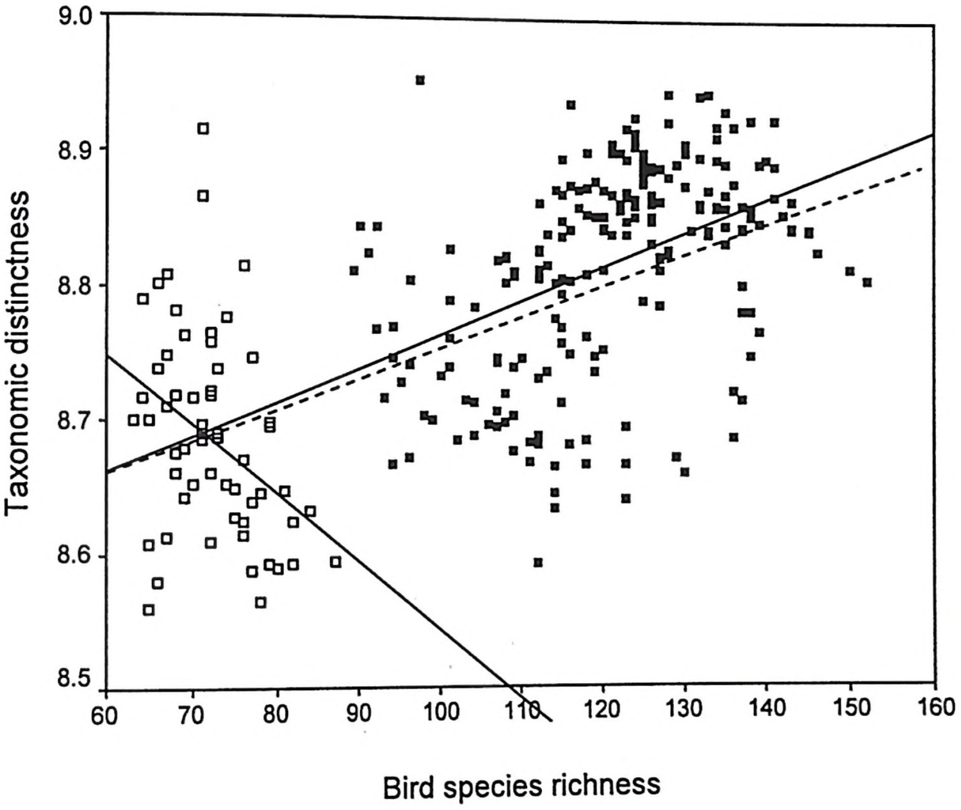


Figure 5.7. Relationship between species richness and species turnover among breeding birds of Central Indian Highlands. Note that hollow squares represent species-poor quadrats (S<90) and solid squares represent species-rich quadrats (S>90). The dashed line is the linear fit to overall relationship between species richness and species turnover.



In another related investigation of quadrats, taxonomic distinctness was found to increase significantly with bird species richness ($R = 0.644$, $P < 0.0001$, N = 284). But a re-analysis of data, following a visual examination of the scatter plot (Figure 5.8), yielded an inverse relationship among species-poor quadrats ($R = -0.379$, $P = 0.002$, N = 65) while species-rich quadrats continued to show positive association as the combined data ($R = 0.443$, $P < 0.0001$, N = 219).

Figure 5.8. Relationship between species richness and taxonomic distinctness among breeding birds of Central Indian Highlands. Hollow squares represent species-poor quadrats (S< 90) and solid squares represent species-rich quadrats (S > 90). The dotted line is the linear fit to overall relationship between species richness and taxonomic distinctness.



5.4. DISCUSSION

The species-area relationship as shown by the breeding land birds of Central Indian Highlands was best described by a power-function curve. Though power-function is the most popular model used in species-area studies, it is often used unquestioningly with no empirical evidence, and this apriorism has drawn considerable flak from ecologists (e.g., Martin, 1981). Ideally, the selection of the regression model should be guided by data and not by any precedent. When I applied the three contemporary species-area models to Central Indian birds and assessed their goodness-of-fit, power-function emerged as the best fit, though logistic curve was also found to be statistically significant. This is not entirely surprising, as it has been recognized that the extent of sampling area and spatial scale play a major role in determining the shape of species-area curves (Martin, 1981; He & Legendre, 1996; Scheiner, 2003; Tjørve, 2003; Turner & Tjørve, 2005). In other words, species-area relationship is expected to take exponential curve in small areas, power-function in areas of intermediate size, and logistic for large areas (He & Legendre, 1996). The recognition of sampling areas as small, medium, or large is not always unequivocal and may depend on the size of the organisms and their assemblages under study. For example, Central Indian Highlands with a total area of about 2,00,000 km^2 are certainly too large for exponential curve to describe the species-area association in adequate terms. But, the vastness of the geographical area is ambiguous enough to deter any categorical classification of the region as either a landscape (large area) or a province (intermediate area), and this is well reflected in the findings of the species-area analysis in which both power function and logistic curves were found to be statistically significant and regression parameters had to be examined to ascertain the best fit.

The slope of the power function curve was observed to be 0.12, which is well in accordance with the widely held view that the slope of the species-area curve for a biogeographically homogeneous region in mainland would always be between 0.1 and 0.2, varies between 0.25 and 0.55 for islands, and should be the greatest for areas straddling different continents with a range of 0.60-1.15 (Rosenzweig, 2003). The slope of the curve also falls short of the much-acclaimed 'Preston's canonical *z*-value' of 0.262 (the limits of which are given as 0.17 and 0.33). This canonical range is presumed to be characteristic of 'climactic equilibrium communities' (Preston, 1960), and a log-normal distribution of animal abundances is usually considered as an evidence of such equilibrium state as inferred from the slope of species-area curves. But it is not feasible to corroborate this proposition with the present study in the absence of abundance data, nor is it appropriate given the fact that the sampling units of the study are in reality geographically defined quadrats and not distinct habitat types that would otherwise characterize true communities. In any case, the notion that canonical range of slope values signifies equilibrium communities has been severely criticized elsewhere (see Williamson, 1988). Though ecological interpretations of species-area curves and their coefficients are, for the most part, denounced by a section of ecologists (e.g., Connor & McCoy, 1979; Martin, 1981; He & Legendre, 1996; Lomolino, 2001; Scheiner, 2004), it is useful to consider the significance of the observed slope of 0.12 in view of some of the more passable explanations. For example, Martin (1981) contended that species-area curves with unusually low slopes might arise as a result of species saturation of local assemblages vis-à-vis source species pool. This has also been recently indicated in a study on Czech birds (Storch *et al.*, 2003). An analysis of local-regional richness plots has already demonstrated that birds of Central Indian Highlands are indeed made up of saturated assemblages (see Chapter 4) and an extremely low value of slope as observed in the species-area curve of central Indian avifauna is consistent with the species-saturation hypothesis. This slope is also much closer to a value (0.15) typical of Stage II of the endemism gradient (Ricklefs & Cox, 1972), implying a low endemism among local species pool of breeding birds. Unlike slope, y-intercept values in species-area curves remain underutilized in ecology barring some tentative attempts to equate intercept with local (alpha) diversity (MacArthur, 1965) and with the minimum size of species pool in untransformed power models (e.g. Connor & McCoy, 1979; Lomolino, 2001). It then follows from the intercept of the species-area curve of central Indian birds that around 51 species of land birds can be expected, at the minimum, to breed in a quadrat of c.715 km^2 area in Central Indian Highlands. Predictably, this is less than one-third of the total species pool of central Indian birds and is amply remindful of the species impoverishment of the local avifauna. Since the species-area relationship is described by a non-linear curve, this number is also observed to level off soon with increasing area. In central India, the plateau in species richness is reached no sooner than a cumulative addition of around 30 quadrats (see Figure 5.1). To sum up, a combination of historical factors is believed to have given rise to low species-area slope and intercept that characterize central Indian birds: relatively homogeneous landscape of the Central Highlands with shared biogeographical history, a generally impoverished avifauna, low species turnover in space, high species-saturation of local assemblages, and an extremely low level of endemism.

Though a large number of hypotheses have been proposed and tested, increasing heterogeneity in environmental resources with area is the most celebrated ecological mechanism for species-area relationships (e.g., Williamson, 1988; Rosenzweig, 1995; Storch *et al.*, 2003). The observation in central Indian birds that the number of habitat-specialists increases with area at a much higher rate ($z = 0.23$) in comparison to generalists ($z = 0.05$) clearly points to a greater role of environmental heterogeneity, expressed here as habitat diversity, in giving rise to species-area curves. In spite of adoption of a coarse set of classification criteria for habitat occupancy patterns at the landscape level, the difference in the slope of the curves between habitat-specialists and generalists is stark enough to imply the plausibility of the habitat diversity hypothesis. This also concurs with the scale-dependent mechanisms of species-area relationships as propounded by Shmida & Wilson (1985); according to this view, niche relations at local scale, habitat diversity at regional scale, mass effect at meso-scale, and ecological equivalency at continental scale are believed to determine the shape of species-area curves. Another interesting observation pertains to the striking difference in the intercept of the species-area curves of habitat-specialists and generalists among central Indian avifauna. While the intercept was about 54 for generalists, it was a mere eight in the case of habitat-specialists. It means, in terms of proportions, that a minimum of 56 % of generalist species could be expected from a sampling quadrat (c. 715 km^2) and it is only 8.5 % in the case of habitat-specialists. The sizable representation of habitat-generalists in the minimum area of sampling and the early peaking of species-area curve probably elicit the generally lukewarm response among conservation planners and Protected Area managers towards Central Indian avifauna, despite the region being the stronghold of some of the threatened and restricted-range species like Malabar Pied Hornbill (*Anthracoceros coronatus*), Forest Owlet (*Heteroglaux blewitti*), White-bellied Minivet (*Pericrocotus erythropygius*), Spotted Creeper (*Salpornis spilonotus*), and Green Avadavat (*Amandava formosa*). In fact, some parts of Central Indian Highlands did emerge as regions of high conservation significance when their species-accumulation curves were compared. In particular, Satpura Plateau stood out from the rest for its exceptional array of bird diversity despite its small geographical extent.

Satpura Plateau, nestled amidst the Mahadeo Hills of the Satpura Range, is floristically unique, being the only eco-climatic region in the whole of peninsular India with extensive patches of broad-leaved semi-evergreen forest and the region's landscape is dotted with some of the tallest peaks of Central Highlands (e.g., Dhupgarh at 1348 m). Several species of montane avifauna showing typically insular patterns of breeding distribution in central India are found in good numbers in Satpura Plateau. These include Blue-bearded Bee-eater (*Nyctyornis athertoni*), Alpine Swift

(*Tachymarptis melba*), Spot-bellied Eagle Owl (*Bubo nipalensis*), Crested Goshawk (*Accipiter trivirgatus*), Malabar Whistling Thrush (*Myophonus horsfiedii*), Grey-headed Canary Flycatcher (*Culicicapa ceylonensis*), Black-crested Bulbul (*Pycnonotus melanicterus*), and Brown-cheeked Fulvetta (*Alcippe poioicephala*). Not surprisingly, analyses of both the species-accumulation curve and the species-density rankings identified Satpura Plateau as a prime 'diversity hotspot' for central Indian avifauna. It may be noted from Table 5.4 that three other regions viz., Seoni-Chhindwara Plateau, East Maikal Range, and South Maikal Range are also marked by a fairly large species pool exceeding 150 species (c. 80 % of total number of bird species that breed in Central Indian Highlands). Yet, the fact that their bird species richness is inconsistent with their large geographical area weighs heavily against their inclusion as regions of conservation importance. A simple species-area ratio would not suffice here in ranking regions for their diversity value, for it would overlook two key aspects of species-area relationships: i) number of bird species found in unit area ('*minimum expected number of species*') is a function of biogeographical history of the region, and cannot be assumed constant over different regions, and ii) rate of increase in species numbers with area is invariably non-linear and strongly subject to both historical and contemporary forces. For these reasons, species-accumulation curves as described in appropriate regression models are immensely preferable to simple index-based approach while identifying areas of conservation importance (e.g., Pomeroy, 1993; Veech, 2000; Hobohm, 2003). In this regard, it is also useful to study interactions between bird species diversity, species turnover, and species composition as they are known to influence choice of areas in such prioritization exercise (Veech, 2000). These interactions also serve as macroecological indicators that reflect evolutionary past of the region's avifauna.

Among the avian assemblages of central India, alpha and gamma diversity components were found to be strongly related. A linear relationship between local and regional species diversity is customarily presumed to signify non-saturation of ecological communities (see Chapter 4); this argument, however, cannot be sustained here as the sampling units are simply too large to assume any significant species interactions, a prerequisite for testing species saturation of local assemblages. Therefore, the positive association observed between alpha and gamma components would, at best, be explained as a mathematical artefact. In a related observation, species turnover of birds was found to remain unaffected by either alpha or gamma diversity. The indifference of species turnover to changes in alpha is predictable, as the turnover was measured using a symmetrical form of Simpson's similarity index (Lennon *et al.*, 2001) and β_{sim} is known to be statistically independent of species richness. However, it is intriguing to note that species turnover is also not influenced by the size of the regional species pool (gamma), as one would normally expect the rate of species replacement to increase with the cumulative species richness. The finding that it is not to be so suggests importance of local ecological factors, vis-à-vis historical forces, in maintaining species trajectories of central Indian avifauna. It is also borne out by the observation that phylogenetic diversity of bird species composition, expressed as taxonomic distinctness of assemblages, is unrelated to gamma diversity of birds. This could possibly arise as a result of the widespread phenomenon of geographical substitution of congeneric species within a region often along ecological boundaries. Such species-replacement within a genus with nearly non-overlapping ranges tends to conserve the taxonomic integrity of assemblages. For example, the following species-pairs among the central Indian avifauna show prominent patterns of parapatric distributions within Central Highlands, contributing significantly to the observed narrow range of taxonomic diversity values:

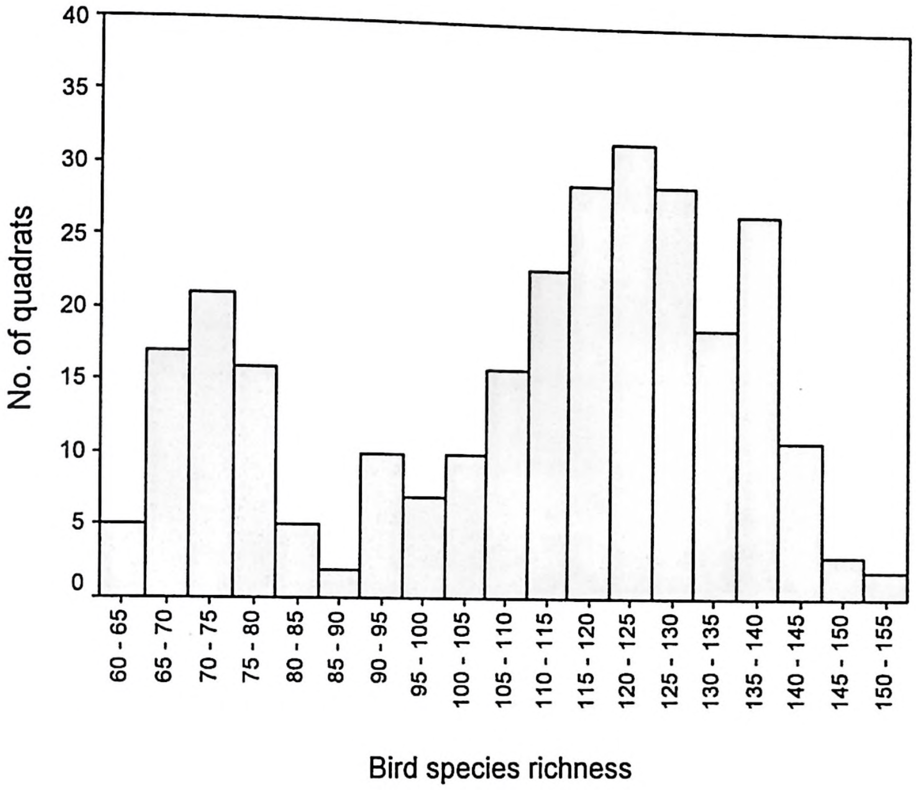
- Rock Bush Quail (*Perdicula argoondah*) & Painted Bush Quail (*P. erythrorhyncha*)
- Red Spurfowl (*Galloperdix spadicea*) & Painted Spurfowl (*G. lunulata*)
- Red Junglefowl (*Gallus gallus*) & Grey Junglefowl (*G. sonneratii*)
- Eurasian Eagle Owl (*Bubo bubo*) & Dusky Eagle Owl (*B. coromandus*)
- Peregrine Falcon (*Falco peregrinus*) & Laggar Falcon (*F. jugger*)
- Scarlet Minivet (*Pericrocotus flammeus*) & White-bellied Minivet (*P. erythropygius*)
- White-browed Bulbul (*Pycnonotus luteolus*) & Red-whiskered Bulbul (*P. jocosus*)
- Singing Bushlark (*Mirafra cantillans*) & Bengal Bushlark (*M. assamica*)

The response of taxonomic distinctness of assemblages to alpha diversity, however, remains equivocal. Though the weak linear correlation was statistically significant, a careful re-examination of the scatter plot (Figure 5.6c) revealed that phylogenetic diversity might increase with alpha diversity up to a point and then start declining with further increments in alpha, suggesting a quadratic response. When quadratic model was subsequently fitted to the relationship, the fit was indeed found to be statistically significant but as weak as the linear trend ($R^2 \pm 1SE = 0.59 \pm. 0.04$,

$p = 0.02$, n = 11). Therefore, no final conclusion could be drawn on the nature of relationship between alpha and taxonomic diversity in the absence of strong evidence. But if the curvilinear trend turns out to be consistent in further independent investigations, it implies that the local assemblages of central Indian avifauna require about 115 species of birds to reach their maximum taxonomic diversity highlighting the role of biogeographical and phylogenetic constraints on the evolution of species diversity in a region. Additionally, the alpha value at which taxonomic distinctness peaks, may then be considered as an empirical measure of '*phylogenetic stock / reservoir*' of ecological communities [i.e., the minimum number of species required to maintain the taxonomic integrity of local assemblages]. As such, it can be used as a potential optimality indicator in biodiversity assessment and monitoring surveys.

When relationships between bird species richness, species turnover, and taxonomic distinctness were examined at the level of sampling quadrats, the biplots incidentally revealed a curious pattern in which the quadrats were grouped neatly into two clusters: species-rich ($S > 90$) and species-poor ($S < 90$). The nature of relationships among the species distribution attributes was also found to vary between these two clusters. For example, there was a positive association between bird species richness and species turnover detected independently for both species-rich and species-poor quadrats, but the correlation became insignificant when the quadrats were pooled. More intriguing was the relationship between bird species richness and taxonomic distinctness – a strong positive association for the combined data, but an evidently inverse relationship in the case of species-poor quadrats. Popularly known in statistical literature as Simpson's Paradox (Scheiner *et al.*, 2000), this phenomenon can be further illustrated by means of frequency distribution of bird species richness of all the quadrats in Central Indian Highlands (see Figure 5.9). A distinct bimodality was observed in species richness gradient with a marked discontinuity between 85 and 95, and the frequency polygon seemed to peak at two class-intervals – first at 70-75, and then again at 120-125. Bimodal response of species richness towards an environmental gradient is sometimes thought to be fallout of existence of disparate biogeographical boundaries within a given region (e.g., Johst & Huth, 2005). But the fact that quadrats belonging to disjunct regions were grouped together in the biplots made this proposition untenable. This led me to consider land use/cover patterns of the quadrats as a possible mediator of bimodality since landscape characteristics, next to biogeography, are known to limit the number of species found in a region (e.g., Waltert *et al.*, 2004).

Figure 5.9. Histogram showing the bimodal frequency distribution of quadrats in Central Indian Highlands with respect to bird species richness.

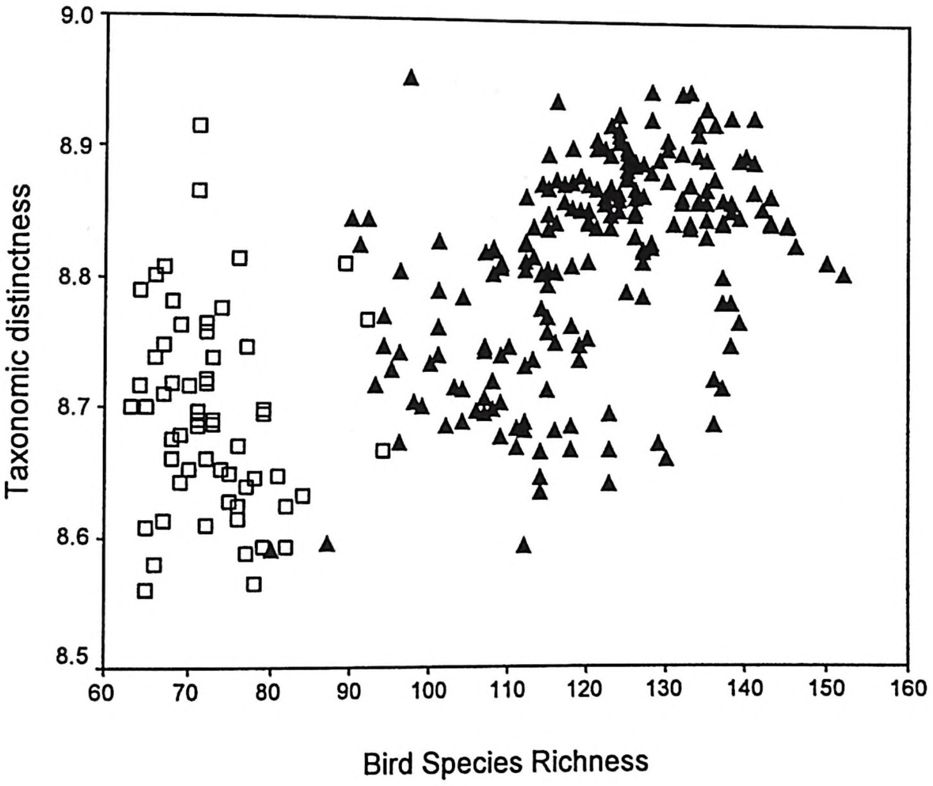


I partitioned the quadrats into two categories, viz., forested and non-forested, on the basis of the predominance of land use/cover type. All the quadrats in which forests and other forms of natural vegetation dominated the landscape were classified as 'forested' and quadrats with an overbearing presence of agricultural and urban environments were labelled as 'non-forested'. Summary statistics of bird species richness indicated that the mean number of bird species in non-forested and forested quadrats were around 72 and 121 respectively, which exactly matched the class-intervals about which the frequency polygon of species richness gradient peaked earlier (Table 5.6). Further, when the bird species richness-taxonomic distinctness biplot was reproduced with these land-cover labels on, the two clusters of quadrats corresponded very well with the categories of forested and non-forested landscapes (see Figure 5.10). These results give rise to the speculation that species diversity of forest and non-forest elements of central Indian avifauna may not be following similar trajectories and are probably governed by independently evolved regulatory mechanisms.

Table 5.6. Summary statistics of bird species richness for forested and non-forested quadrats in Central Indian Highlands.

Quadrat Cluster	N	Bird Species Richness			
		Minimum	Maximum	Mean	Median
Forested Quadrats	218	80	152	121.00	122.50
Non-forested Quadrats	66	63	94	72.73	72.00

Figure 5.10. Replotting the relationship between species richness and taxonomic distinctness among breeding birds of Central Indian Highlands with explicit labeling of quadrats on the basis of forest cover. Note that quadrats seem to neatly group into two clusters, viz., forested (solid triangles, ▲) and non-forested (hollow squares, □).



To understand why the putative relationships between bird species richness, turnover, and composition change in response to species richness gradients, it is pertinent to examine some of the statistical properties of the measures used to derive species distribution attributes. A case in point would be the species turnover, as expressed in Simpson's similarity index (β_{sim}). It can be theoretically partitioned into three components: i) species gain (species present in neighbouring quadrat but absent from focal quadrat), ii) species loss (species present in focal quadrat but absent from neighbouring quadrat), and iii) species continuity (species common to both quadrats). Among them, both species continuity and species loss are known to increase with species richness while species gain shows inverse relationship (Lennon *et al.*, 2001).

In other words, the contribution of species loss would be perceptibly high in species turnovers measured across species-rich quadrats, while species gain would characterize turnover in species-poor quadrats. Any deviation from these generalities would result in a pattern different from that shown by the pooled data. It then follows that there is less than expected rate of species-gain among non-forested quadrats and greater than expected rate of species-loss among forested quadrats in breeding birds of Central Indian Highlands. While this is a matter of conjecture inferred on the statistical premise of the turnover measure, it remains to be tested with empirical data in future investigations. Unlike species turnover, the change in direction of relationship between taxonomic distinctness and species richness from species-rich forested quadrats to species-poor non-forested quadrats may not be of any ecological significance and, in all probability, represents a classic case of Simpson's Paradox involving sampling artefact (Cartron *et al.*, 2000; Scheiner *et al.*, 2000). This, however, brings to the fore the importance of spatial scale while eliciting ecological patterns. For example, when the analysis of relationship between taxonomic distinctness and species richness was moved up in spatial scale from regions to quadrats, the nature of association was observed to be inconsistent. Though the current study draws on mathematical models like power function and measures like β_{sim} both of which are said to be scale-invariant (Gisiger, 2001; Lennon *et al*, 2001), a need for multi-scale investigations is strongly indicated in the findings of the probe. Scarcity of studies on spatial patterns in species richness and taxonomic diversity from tropical regions seriously hampers our efforts to derive generalizations in macroecology (Gaston & Williams, 1996), and these patterns are the cornerstones of conservation planning at regional and landscape-level.

5.5. SUMMARY

1. I investigated, in this chapter, the spatial patterns of species diversity in breeding land birds of Central Indian Highlands. I first examined the species-area relationship and tested if the increase in species numbers with area was due to habitat heterogeneity by comparing the slopes of the species-area curves of habitat-specialists and generalists. This was followed by a regional level analysis of the relationships among the three spatial components of species diversity (α, β, & γ). Then, I analyzed the associations between bird species richness, species turnover, and taxonomic distinctness at the scale of both regions and quadrats. I also sought to rank the regions of Central Indian Highlands for their conservation value using species-accumulation curve and species-density measure.
2. The study area was divided into 11 regions on the basis of topography, natural vegetation, and eco-climatology. All the regions were then gridded into quarter-degree cells (15′ X 15′) called '*quadrats*' (c. 27 X 26.5 km size), which were treated as the basic sampling units. Primary data on distribution of breeding land birds were collected for each quadrat using a spatially-hierarchical multi-pronged sampling scheme. In total, distribution of 190 species of birds was mapped at the level of 284 quarter-degree quadrats.
3. Species-area curve was generated by using 'sequential addition of randomized quadrats' design and non-linear regression was carried out to ascertain the best fit among the three popular models tested viz., power function, exponential, and logistic. Birds were classified into habitat-specialists and generalists based on the extent of their occupancy of seven habitat types recognized at a broader landscape level. Species-area curves were then derived separately for habitat-specialists and generalists and their slopes were compared to test the habitat diversity hypothesis. Species-accumulation curve of birds for 11 regions was produced using power function model and the resultant regression coefficients were used to compute bird species density for each region. The regions were, subsequently, ranked for their conservation value by means of their species-density values. Alpha, beta, and gamma diversity components were derived for all the regions following Whittaker (1972) and their relationships with species turnover and taxonomic diversity were explored at the level of both regions and quadrats. Species turnover was calculated using symmetrical form of Simpson's similarity index and taxonomic distinctness of assemblages was computed following Clarke & Warwick (1998).
4. Among the regression models tested, power function was found to be the best descriptor of the species-area curve of central Indian birds. The slope of the curve was 0.12 and intercept 50.91. The slope of habitat-specialists (0.23) was much higher than generalists (0.05), but the intercept was very low for habitat-specialists (8.42) in comparison to generalists (53.87). Both species-accumulation curve and species-density rankings identified Satpura Plateau and Betul Plateau as 'diversity hotspots' for central Indian

avifauna. At the level of regions, species turnover was found unrelated to both alpha and gamma diversities; taxonomic distinctness was also observed to be independent of gamma, but showed a weak positive association with alpha. At a finer spatial scale of quadrats, no significant relationship was detected between bird species richness and species turnover, but taxonomic distinctness was shown to increase with species richness. Examination of the biplots revealed that the quadrats tended to segregate into two distinct clusters as species-rich ($S > 90$) and species-poor ($S < 90$), reflecting forested and non-forested landscapes. Re-analysis of the relationships between species distribution attributes yielded different patterns for forested and non-forested quadrats with evidences of Simpson's Paradox.

5. The acutely low slope of species-area curve observed among central Indian birds is consistent with the view that Central Indian Highlands are characterized by a generally depauperate avifauna. It was also reaffirmed by an equally low intercept value which meant that only about 51 species of birds were to be expected at the minimum to breed in a sampling quadrat as large as c. 715 km^2 in area. The habitat diversity hypothesis of species-area relationships was strongly supported by the data; while the minimum number of generalist bird species expected from a quadrat was around 54, only 8 habitat-specialists were to be found breeding in a quadrat. The lack of dependence of both species turnover and taxonomic distinctness on gamma diversity may suggest a greater role for ecological factors, vis-à-vis historical forces, in maintaining species trajectories in central Indian avifauna. On the other hand, the strong demonstration of bimodality in species richness gradient of central Indian birds in response to forest-cover dichotomy may signify that species diversity of forest and non-forest birds are governed by independently evolved regulatory mechanisms. Further, the Simpson's Paradox observed in species richness-species turnover relationships implies that there is less than expected rate of species-gain among non-forested quadrats and greater than expected rate of species-loss among forested quadrats in breeding birds of Central Indian Highlands. Thus, the overall findings of the study tend to emphasize the importance of spatial scale in eliciting macroecological patterns.

Chapter 6. Environmental Determinants of Bird Species Richness

6.1. INTRODUCTION

One of the fundamental questions in biogeography relates to why some areas are richer in species diversity than others. Factors driving species richness are usually classified either as ecological or historical and what contributes more, between them, to biodiversity (termed as '*MacArthur's Paradox*' in Herzog & Kessler, 2006) has always been a subject of much debate (Currie, 1991). In general, studies in community ecology focus on local ecological phenomena like competition, co-existence, density compensation, and other forms of species interactions (Wiens, 1989) and investigations into role of environmental factors (as a function of history) in determining upper limit to number of species (henceforth termed '*species-environment relationships*' in this chapter) forms the central tenet of macroecology (Brown, 1999). The fact that environment can be described and measured in n-dimensional axes means that there is a possibility of deriving an infinite number of environmental factors as correlates of species richness. In fact, the search for a general law in explaining species richness gradients has given rise to more than one hundred hypotheses till now (Rahbek and Graves 2001). These multitudes of explanations can, however, be reduced to a few environmental dimensions representing independent mechanisms like topography, water-energy balance (climate), primary productivity, landscape patterns, and human factors.

The relationship between species richness and environment was first formally proposed as '*species-energy hypothesis*', which stated that the number of species was a function of energy availability in the environment (Connell & Orias, 1964; Wright, 1983; Turner *et al.*, 1988). In other words, high ambient energy means more energy to spend on productivity (rather than on fighting 'environmental challenges'), which, in turn, gives rise to more individuals and ultimately to more species (Connell & Orias, 1964). Though Orians (1969) proposed independently that primary productivity was the chief environmental predictor of species richness, a large number of subsequent studies treated energy availability and primary productivity interchangeably as correlates of species richness (e.g., Currie, 1991; Rosenzweig & Abramsky, 1993; Wright *et al.*, 1993; Waide *et al.*, 1999; Bailey *et al.*, 2004). This is, in part, attributable to species-energy hypothesis which in its original form explicitly presumed that increase in species richness with energy availability was mediated through increased productivity (Connell & Orias, 1964). But this no longer holds true, as a recent review of species-energy relationships has identified nine other possible pathways through which high energy can give rise to greater species diversity (Evans *et al.*, 2005; also see Srivastava & Lawton, 1998 for empirical evidence against 'more individuals' hypothesis of primary productivity). The fact that these hypotheses are largely independent of mechanisms of productivity-diversity relationships reviewed elsewhere (Rosenzweig & Abramsky, 1993) warrants a great deal of caution before energy availability and primary productivity can be considered as two sides of the same coin. In addition, lack of uniformity over the choice of environmental measures to be used as surrogates of either productivity or energy availability has impaired our understanding of species-environment relationships to a considerable extent (see Waide *et al.*, 1999; Whittaker *et al.*, 2001). See Table 6.1 for some selected works which have used same sets of environmental variables as measures of productivity and ambient energy.

Table 6.1. Examples for inconsistent use of environmental variables as measures/surrogates of energy availability and primary productivity in species-environment studies.

Explanatory mechanism of species richness gradients	**Environmental variable**	**References**
Energy availability	AET[1]	Wright, 1983; Evans *et al.*, 2005;
	PET[2]	Currie, 1991; O'Brien, 1998; Stephenson, 1998;
	NDVI[3]	Bailey *et al.*, 2004
Primary productivity	AET	Currie, 1991; Mönkkönen *et al.*, 2006
	NDVI	Cihlar *et al.*, 1991; Lo Seen Chong *et al.*, 1993; H-Acevedo & Currie, 2003; Hawkins *et al.*, 2003; Bailey *et al.*, 2004; Lee *et al.*, 2004; Storch *et al.*, 2005

[1] Actual Evapotranspiration
[2] Potential Evapotranspiration
[3] Normalized Difference Vegetation Index

In a major review of conceptual issues in species richness-environment studies, Hawkins *et al.* (2003) propose that climatic parameters be distinguished into water-related variables (e.g., precipitation, wet-day frequency, relative humidity), and energy-related parameters (e.g., temperature, actual and potential evapotranspitaion, and solar radiation), while NDVI (Normalized Difference Vegetation Index) may be used as a surrogate of primary productivity. This suggestion was mainly in response to growing empirical support for 'water-energy balance' as a strong correlate of species richness along latitudinal gradients. The 'water-energy balance' theory predicts that energy is the limiting factor for species richness in colder regions at higher latitudes, while water availability determines species richness in warmer tracts at lower latitudes. It was Stephenson (1990) who first observed this phenomenon in plant species richness of Sierra Nevada. Though Currie's (1991) analysis of the North American tree and vertebrate richness did point to such latitudinal shift, it was not known until Kerr & Packer (1997) reanalyzed his findings and found evidences for water-energy balance in Currie's data. They found that vertebrate species richness in North America increased with PET up to about 1000 mm after which the richness either declined or remained independent of PET. They also concluded that 45°- 48° latitude was the boundary along which temperature or PET (energy-related variable) was replaced by rainfall (a measure of water availability) as the major environmental predictor of species diversity. Subsequent studies have strongly corroborated these findings (O'Brien, 1998; Stephenson, 1998; Andrews & O'Brien, 2000; H-Acevedo & Currie, 2003; Hawkins *et al.*, 2003; Bini *et al.*, 2004). Specifically for bird species richness, Hawkins *et al.* (2003) have found that the latitudinal limit for water-energy interchange is around 46° N in North America and 50° N in the Palaearctic, and the cutoff value of PET beyond which the number of bird species may start declining is 541 mm in North America and 423 mm in the Palaearctic; of course, climatic parameters describing water-energy balance also follow strong latitudinal gradients (H-Acevedo & Currie, 2003).

But it is not clear if the influence of water-energy balance or productivity over number of species is direct or mediated through a common factor. Turner *et al.* (1988) observed that seasonal changes in species richness of insectivorous birds were in accordance with parallel changes in available solar energy from winter to summer, suggesting a direct mechanistic role. But this was disputed by Lennon *et al.* (2000) who claimed that summer temperature explained both winter and summer bird species richness equally well and there was a residual effect of summer climate over winter bird communities. However, recent studies have demonstrated a stronger seasonality in species richness-environment relationships, implying direct role for productivity and energy balance; for example, it has been observed that change in species richness of North American birds in response to NDVI is consistent across seasons (H-Acevedo & Currie, 2003; Hurlbert & Haskell, 2003).

Latitude or season may not also be the sole descriptors of how energy or productivity influences species-richness gradient. For example, Waide *et al.* (1999), in a review of about 200 studies, found that the shape of the productivity-diversity curve has been far from consistent with the observation of nearly an equal proportion of linear and hump-shaped relationships. They concluded that spatial scale, biome, choice of measure, and taxon were some of the important covariates in productivity-diversity relationships, besides latitude. Mittelbach *et al.* (2001) noted that productivity-diversity curves were predominantly hump-shaped when plant biomass was used as measure of primary productivity and linear associations were more common in studies that used climate as surrogate. In a reflection of similar patterns, Evans *et al.* (2005) observed that species richness-energy curves might be either monotonic or unimodal depending on the spatial grain of sampling; in general, plot-based studies returned unimodal relationships, while grid-based studies tended to show linear correlations. Among the vertebrate taxa, species richness-environment relationships were found to be strongest in reptiles and mammals in comparison to birds (Boone & Krohn, 2000), and there were also evidences for within-taxa differences in response of species richness to environmental gradients [see Pino *et al.* (2000) for forest *vs.* non-forest birds, Jetz & Rahbek (2002) for wide-ranging *vs.* restricted-range birds, Bailey *et al.* (2004) for resident *vs.* migratory birds, Bini *et al.* (2004) for differences among avian orders, Ruggiero & Kitzberger (2004) for wide-ranging *vs.* restricted-range mammals, Mönkkönen *et al.* (2006) for breeding *vs.* non-breeding birds, and Herzog & Kessler (2006) for differences between birds of humid forests and dry forests].

Apart from climatic models which invoke water-energy balance as a strong predictor of number of species, other environmental factors have also been known to contribute significantly to observed species richness. These include topography (e.g., Rahbek & Graves, 2001; Jetz & Rahbek, 2002; Diniz-Filho *et al.*, 2003; Kaboli *et al.*, 2006), habitat heterogeneity (e.g., Böhning-Gaese, 1997; Fraser, 1998; Lennon *et al.*, 2000; van Rensburg *et al.*, 2002), natural vegetation (e.g., Cueto & de Casenave, 1999; Andrews & O'Brien, 2000; Herzog & Kessler, 2006), landscape metrics (Jones *et al.*, 2000; Gillespie & Walter, 2001; Fairbanks, 2004; Titeux *et al.*, 2004), urbanization (e.g., Findlay & Houlahan, 1997; Cam *et al.*, 2000; Lee *et al.*, 2004), and human population (e.g., Evans & Gaston, 2005). Though some studies recognize only climate as the global predictor of species richness (e.g., Turner *et al.*, 1988; Boone & Krohn, 2000; Oindo *et al.*, 2001; Francis & Currie, 2003), the importance of other environmental variables to species diversity becomes more apparent in multiple scale investigations.

The overbearing influence of spatial scale on species-environment relationships has always been recognized as one of the theoretical challenges in macroecology (Blackburn & Gaston, 2002; Foody, 2004). The impact of scale can manifest in two ways: i) on the mathematical nature of relationships, and ii) on the explanatory power of different environmental models in predicting species richness. For example, both species-energy (e.g., Wright *et al.*, 1993) and productivity-diversity relationships (e.g., Chase & Leibold, 2002) have been observed to be linear at large scale but distinctly hump-shaped at local scale. Similarly, a large number of studies have found that climate and productivity are usually strong predictors of species richness at coarse scale, while topography and habitat diversity become significant correlates at much finer spatial resolution (Böhning-Gaese, 1997; van Rensburg *et al.*, 2002; Hawkins *et al.*, 2003). Some studies have, however, found the reverse to be true (e.g., Rahbek & Graves, 2001; Hurlbert & Haskell, 2003; Foody, 2004). The importance of scale in species-environment relationships also brings up the spatial nature of environmental data and its attendant statistical and conceptual issues.

Macroecological investigations into how environment influences species richness are invariably conducted over spatially contiguous, gridded quadrats. Understandably, this incurs problems of spatial autocorrelation (Legendre, 1993; Lennon, 2000; Selmi & Boulinier, 2001; Legendre *et al.*, 2002; Fleishman & Mac Nally, 2006) and spatially structured multicollinearity (Diniz-Filho *et al.*, 2003; Heikkinen *et al.*, 2004) among the environmental variables. Spatial autocorrelation refers to the property of an environmental variable between a pair of quadrats at a given distance being more similar or less similar than expected between a random pair of quadrats (Legendre, 1993; Lennon, 2000). The lack of independence between pairs of observations over given lags of spatial or temporal units unduly inflates the number of degrees of freedom and therefore seriously underestimates the Type I error, leading to spurious correlations (Diniz-Filho *et al.*, 2003). In particular, environmental variables like climate and topography are more prone to spatial autocorrelation (van Rensburg, 2002; Diniz-Filho *et al.*, 2003). In fact, this probably explains why a large number of studies in the past, which did not address explicitly the issue of spatial variation in environmental data, would invariably come up with climate as strong predictor of species richness (e.g., Crowe & Crowe, 1982; Currie, 1991; O'Brien, 1998; Cueto & de Casenave, 1999; Oindo *et al.*, 2001).

Some of the common practices to deal with spatial autocorrelation in species-environment studies include examination of regression residuals for homoscedasticity (e.g., Currie, 1991), inclusion of latitude and longitude as independent predictors (e.g., Lennon *et al.*, 2000), ranking of predictors in a regression on the basis of F-ratios of ANOVA rather than P-values (e.g., Rahbek & Graves, 2001), and a priori reduction of number of degrees of freedom (e.g., Dale & Fortin, 2002; H-Acevedo & Currie, 2003). But these measures are, at best, ameliorative, and ecologists are strongly advised to employ statistical techniques that take into account the underlying spatial structure in environmental data in an explicit manner (see the discussion in Lennon, 2000). Since Borcard *et al.* (1992) used canonical ordination to partition the variation in regression coefficient into spatial and environmental components, variance-partitioning became a dominant tool in species-environment studies (e.g., Boone & Krohn, 2000; Bini *et al.*, 2004; Kaboli *et al.*, 2006). Another straightforward approach to develop spatially structured models involves partial regressions constrained by nth order polynomial function of geographical coordinates (e.g., Legendre, 1993; van Rensburg *et al.*, 2002). Sometimes, spatial autoregressive models are used (e.g., Jetz & Rahbek, 2002; Keitt *et al.*, 2002; Lichstein *et al.*, 2002; Hurlbert & Haskell, 2003), though their popularity is limited by computational rigour of the analysis. A promising procedure underutilized in macroecological investigations is the Dutilleul's method of reducing the number of degrees of freedom commensurate with the magnitude of spatial autocorrelation in both predictor and response variables (Legendre *et al.*, 2002). A more recent trend is the use of generalized least squares (GLS) regression [often known as 'geographically weighted' or 'kriging' regression], a robust geostatistical technique that seeks to describe species-environment relationships after modeling the spatial structure in the environmental data by means of semivariograms and incorporating the spatial autocorrelation terms directly into regression residuals (see Cressie, 1993 for details). Despite instances of early application of GLS regression in spatial ecology (e.g., Pearson & Carroll, 1998), it became popular in species-environment studies only recently (e.g., Selmi & Boulinier, 2001; Diniz-Filho *et al.*, 2003; Foody, 2004; Evans & Gaston, 2005; Storch *et al.*, 2005). Spatial autocorrelation in environmental data is usually detected by examining spatial correlogram, a scatter graph in which a measure of autocorrelation [very often Moran's I and rarely Geary's C (e.g., Dutilleul & Legendre, 1993)] is plotted along a series of distance classes (Selmi & Boulinier, 2001).

Though ecological literature is rife with commentaries that underscore the importance of incorporating spatial autocorrelation in statistical analyses (e.g., Sokal & Oden, 1978; Legendre, 1993; Lennon, 2000; Keitt *et al.*, 2002; Lichstein *et al.*, 2002; Perry *et al.*, 2002), a recent review has concluded that it is perhaps overemphasized especially in species-environment studies (Diniz-Filho *et al.*, 2003), in view of the following considerations: i) In a multiple regression model of species-environment relationships, the fact that predictor variables usually operate at different scales would render residuals reasonably free of spatial dependence, and ii) spatial variation in environmental data may not be entirely superfluous or inadmissible as it is often made out to be, but may actually reflect the role of history in structuring species diversity-environment relationships. Hence Diniz-Filho *et al.* (2003) contend that both conventional and spatial regression models should be examined simultaneously to understand regional and local factors that drive species diversity gradients.

With the advent of cost-effective technologies like remote sensing and aerial photogrammetry, there has been a marked increase in the availability of reliable, high-resolution datasets measuring various environmental layers over a range of spatial scales (Gould, 2000; Turner *et al.*, 2003). This has led to a phenomenal growth in number of studies on species richness-environment relationships, and the first three years of 21st century alone has produced more than 100 papers (Evans *et al.*, 2005). But comparable investigations on bird species richness of tropical Asia are very scanty (e.g., Pearson & Carroll, 1998; Lee *et al.*, 2004; Kaboli *et al.*, 2006), and this seriously hampers our efforts to predict impacts of anthropogenic changes in physical and human environment on biological diversity.

In this chapter, I intend to explore the relationships between environmental variables and species richness of breeding birds in Central Indian Highlands. In particular, I seek to study the influence of various spatial layers viz., topography, climate, primary productivity, landscape heterogeneity, forest cover, human population, and urbanization on bird species richness. First, I investigated the presence of spatial autocorrelation in all the predictor variables and correspondingly assessed the strength of relationship between bird species richness and each of the environmental variables. Then I developed a spatially structured regression model to predict the number of bird species that breed in a given area using a set of environmental parameters that are found to be of high significance to bird species richness. While it would return factors that act at local scale as determinants of bird species diversity, a spatially independent model was also developed alongside to identify environmental correlates at regional scale. The models were followed by a brief discussion over implications of these findings on long-term conservation of forest birds in Central Indian Highlands.

6.2. METHODS

6.2.1. Study area

The study was conducted in Central Indian Highlands in Madhya Pradesh, which comprise the Satpura and the Vindhya Ranges and extend over an area of about 200,000 sq. km. The landscape is predominantly covered with tropical dry- and moist-deciduous forests, dominated by associations of teak (*Tectona grandis*) in western and central parts, and sal (*Shorea robusta*) in the east. The mean elevation of the hill ranges varies between 200-800 m, while some of the peaks in western and central ranges exceed 1000 m.

I divided the study area, a priori, into 11 conterminous landscape units ('regions') on the basis of natural vegetation, drainage, topography, and eco-climatic attributes, as follows: Malwa Plateau, Nimar Hills, Lower Narmada Valley, Betul Plateau, Sagar-Damoh Plateau, Satpura Plateau, Seoni-Chhindwara Plateau, Vindhya Scarplands, Kaimur Hills, East Maikal Range, and South Maikal Range [see Appendix 5.1 for a brief description of these regions]. All the regions were, then, gridded into quarter-degree cells (15′X 15′) or 'quadrats' (corresponding to Survey of India's 1:50,000 scale toposheets), with each quadrat measuring about 27 X 26.5 km in size (c. 715 sq. km. area). This generated 284 contiguous quadrats, in total, from the entire study area, and these quadrats formed the primary sampling units at which bird species richness and environmental variables were measured.

6.2.2. Birds

Data on species richness of land birds that were known to breed in each quadrat were collected between April and July during 2002-04. As the study area was too expansive to cover within a short period, I adopted a spatially hierarchical sampling protocol which had the following components: i) identification and mapping of key vegetation types in all the quadrats of each region, ii) inventory-survey of breeding birds in each of the key vegetation types, and iii) interpolating species occurrence for all the quadrats of the region from both these information layers (See Section 5.2.2 for a comprehensive description of the bird sampling methodology and the underlying assumptions and limitations).

Though the field-surveys targeted all the land bird species that were known to breed regularly in Central Indian Highlands, several species were excluded from the final analysis owing to insufficient data. These included all the three species of buttonquail (*Turnix* spp.), Asian Palm Swift (*Cypsiurus balasiensis*), Brahminy Kite (*Haliastur indus*), Forest Owlet (*Heteroglaux blewitti*), Ashy Woodswallow (*Artamus fuscus*), White-bellied Minivet (*Pericrocotus erythropygius*), Spotted Creeper (*Salpornis spilonotus*), and Green Avadavat (*Amandava formosa*). In total, 190 species of land birds for which I had adequate data were included in the analysis. [See Appendix 5.3 for a region-wise list of the breeding land birds of Central Indian Highlands].

6.2.3. Environment

Data on environmental parameters that represent different spatial themes, viz., topography, climate, primary productivity, landscape heterogeneity, forest cover, human population, and urbanization were compiled from a variety of sources including remotely sensed data from satellite imageries, databases with national government agencies, and rasterized global datasets of international organizations. See Table 6.2 for list of variables along with metadata information describing data characterization, format, spatial resolution, temporal coverage, ownership, and access. It may be noted that the original spatial resolution of data in all the cases was finer than quarter-degree scale (15′X 15′) of the sampling quadrats, and values of environmental parameters were therefore aggregated to 15-minute scale. Though coefficient of variation (CV) in climatic variables and NDVI has been used as a measure of environmental stability in some studies (e.g., Oindo, 2002), it is not used here as it would require inter-annual CV to be quantified and within-year variation among the quadrats in a biogeographically homogeneous landscape as Central Indian Highlands would be too insignificant to be of any heuristic value.

Table 6.2. Spatial themes and environmental variables used as correlates of bird species richness in Central Indian Highlands along with metadata information.

Spatial theme	**Variables & units of measurement**	**Spatial resolution of original data**	**Data description**	**Data source & access**
TOPOGRAPHY	• Elevation (mean, minimum, maximum, and range) [m]	1 km (30″ X 30″)	NOAA/NGDC-GLOBE DEM	Hastings *et al.*, 2000 http://www.ngdc.noaa.gov/mgg/topo/globe.html (Accessed on: 27 June, 2006)
	• Drainage length [km]	10 km (DCW) & 15′ X 15′ (SoI)	ESRI-Digital Chart of the World, 1993 & SoI 1:50,000 scale toposheets	ESRI, 1993 http://www.maproom.psu.edu/dcw/ (Accessed on 20 June, 2006) & Survey of India
CLIMATE	• Precipitation [mm/year] • Wet-day frequency[1] [days/year] • Temperature (mean, minimum, & maximum) [°C] • Diurnal temperature range[2] [°C] • Relative humidity [%] • Sunshine duration [no. of hours/day] • Wind speed [3] [m/sec]	10′ X 10′	CRU High-Resolution Surface Climatology (1961-1990 monthly climatic normals)	New *et al.*, 2002 http://www.cru.uea.ac.uk/cru/data/tmc.htm (Accessed on: 25 June, 2006)
	• Day length [no. of hours/day]	Calibrated for each 15′ latitude	US Naval Observatory Solar/Lunar data	USNO, 2006 http://aa.usno.navy.mil/data/docs/RS_OneYear.html#formb (Accessed on: 27 June, 2006)
	• Potential Evapotranspiration [mm/year][4]	15′ X 15′	Derived using Thornthwaite formula	Thornthwaite, 1948
	• Moisture availability [%][5]	15′ X 15′	Derived as ratio of total annual rainfall to PET	Oindo *et al.*, 2001

Spatial theme	**Variables & units of measurement**	**Spatial resolution of original data**	**Data description**	**Data source & access**
PRIMARY PRODUCTIVITY	• Monthly NDVI	1.1 km [Final calibrated data 8 km]	GIMMS-AVHRR data of NOAA-16 [intercalibrated with MODIS & SPOT data] (Monthly means from January – December 2002)	Tucker *et al.*, 2005 http://islscp2.sesda.com/ISLSCP2_1/html_pages/islscp2_home.html (Accessed on: 6 June, 2006)
LANDSCAPE HETEROGENEITY	UMD land use/cover classes [6]: • Class 06 • Class 07 • Class 08 • Class 09 • Class 10 • Class 11 • Landscape diversity [7]	1 km	AVHRR data of NOAA/NESDIS [Land-cover classes of University of Maryland Global Land Cover Classification, used in International Geosphere-Biosphere Programme]	Hansen *et al.*, 2000 http://islscp2.sesda.com/ISLSCP2_1/html_pages/islscp2_home.html (Accessed on: 7 June, 2006)
	• Crop-fields [sq. km] [8]	1 km (UMD) & 23.5 m (IRS 1D)	From UMD & IRS 1D LISS III Data	Hansen *et al.*, 2000 & National Remote Sensing Agency
FOREST COVER [9]	• Scrub jungle [sq. km] • Open forest [sq. km] • Dense forest [sq. km] • Total forest [sq. km]	23.5 m (IRS 1D) & 15′ X 15′ (FSI)	IRS 1D-LISS III & FSI 1:50,000 scale toposheets	National Remote Sensing Agency & Forest Survey of India

Spatial theme	Variables & units of measurement	Spatial resolution of original data	Data description	Data source & access
HUMAN POPULATION	• Total population (1995) • Population density (1995) [persons/sq. km] • GDP (1990)	Point data aggregated to 15′ X 15′ grids	Gridded Population of the World (GPW) Data, Version 2. [UN's 1995 projections of 1990 census data after correction against the country-wise national agencies' census data]	GPW, 2000 http://islscp2.sesda.com/ISLSCP2_1/html_pages/islscp2_home.html (Accessed on: 7 June, 2006)
URBANIZATION	• Night light area [sq. km]	2.7 X 2.7 km	DMSP/OLS data	NGDC, 2006 http://www.ngdc.noaa.gov/dmsp/global_composites_v2.html (Accessed on: 21 July, 2006)
	• Road length [km]	10 X 10 km (DCW) & 15′ X 15′ (SoI)	ESRI-Digital Chart of the World, 1993 & SoI 1:50,000 scale toposheets	ESRI, 1993 http://www.maproom.psu.edu/dcw/ (Accessed on 20 June, 2006) & Survey of India

[1] No. of days with precipitation ≥ 1 mm

[2] Difference between daily maximum and minimum temperature

[3] Mean wind speed at a height of 10 m from ground

[4] Thornthwaite formula for estimating PET in a month is given as:

$PET = PE^{*}(h/12)(D/30)$

PE^{*} = Unadjusted PET, h = Mean day length, and D = No. of days in the month

$PE^{*} = 1.6(10T/J)^{a}$

T = mean monthly temperature, J = annual heat index, and a = cubic function of annual heat index, J

$J = \sum i$, where $i = (T/5)^{1.514}$ and J takes values of i for 12 months

$a = 0.000000675\,J^3 - 0.0000771\,J^2 + 0.01792\,J + 0.49239$

[5] Moisture availability, MO in % = (mean annual rainfall / mean annual PET)*100

[6] UMD-IGBP Global Land Cover Classification

Class 06:	Forests, dominated by trees with 40-60 % canopy cover & exceeding 5 m in height
Class 07:	Current & old fallows with sparse tree cover of 10-40 %

Class 08:	Dense scrub and thickets with >40 % canopy & not exceeding 5 m in height; trees with <10 % canopy cover may be present
Class 09:	Open scrublands with canopy cover of 10-40 % & not exceeding 2 m in height; no or negligible tree cover
Class 10:	Grasslands with <10 % tree canopy cover
Class 11:	Standing crop-fields with >80 % cover
	Note that Classes 01-05 not applicable to Central India, and area under Class 12 (barren exposed land) and Class 13 (urban built-up area) negligible

[7] Landscape diversity (LD) was computed using Shannon index as follows:

$$LD = - \Sigma P_i * \ln P_i$$

where Pi = Proportion of area under the i^{th} land cover/use class, and six categories of UMD classification scheme (from Class 06 to Class 11) were used in the calculation

[8] Area under crop-fields is estimated as sum of proportional areas of Class 07 and Class 11 of UMD-GLCF land cover classification. Class 11 signifies standing crop-fields and Class 07 current fallows. But this is an overestimate, as Class 07 also includes open countryside, degraded grazing lands with sparse tree cover, and parks and gardens. To rectify this anomaly, the sum area of Class 07 and 11 is compared with the total non-forested land area as estimated by using IRS 1D LISS III data and corrected for total land area excluding water bodies.

[9] FSI Classification of forest cover

Scrub jungle:	Secondary jungle and thickets with canopy density < 10 %
Open forests:	Forests with canopy density of 10-40 %
Dense forests:	Forests with canopy density exceeding 40 %
Total forests:	Sum of area under open and dense forests

6.2.4. Analysis

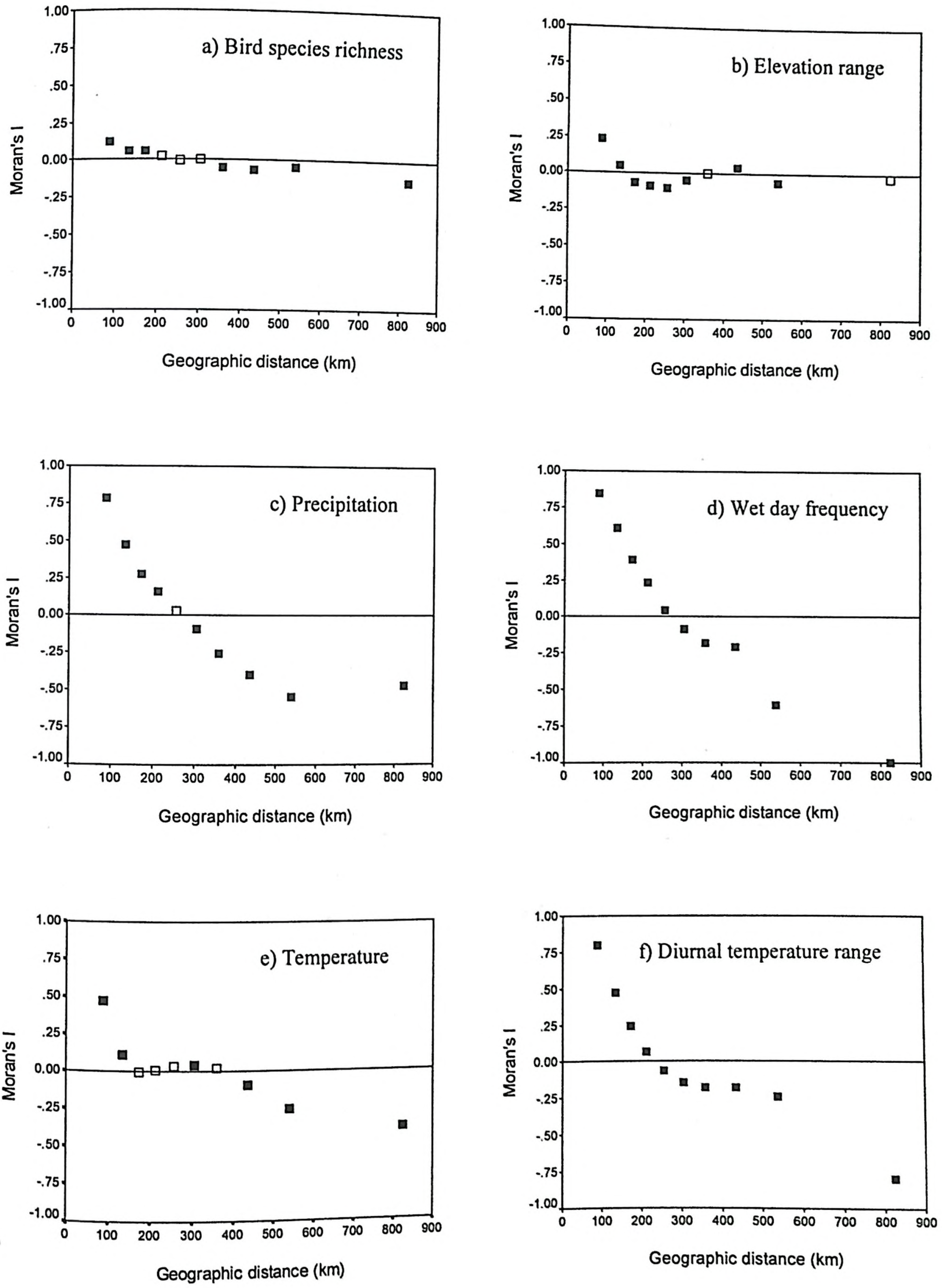
Presence of spatial autocorrelation in both bird species richness and each of the environmental variables was examined by means of spatial correlograms in which Moran's *I* coefficients of spatial autocorrelation, computed for each distance class, were plotted on y-axis against 10 distance classes along x-axis (after Legendre, 1993; Selmi & Boulinier, 2001; Diniz-Filho *et al.*, 2003). A variable is considered as spatially autocorrelated at a given significance level α if Moran's *I* coefficients are statistically significant at α/k (Bonferroni sequential correction) for at least any one of the *k* distance classes (Diniz-Filho *et al.*, 2003). Accordingly, a correlogram was deemed to be significant at $P \leq 0.05$, when Moran's *I* coefficients were found to be significant at $P \leq 0.0005$ for a minimum of one distance class. Since all the variables showed significant degree of spatial structure in data [see Figure 6.1a-n for spatial correlograms], further investigations of interactions between bird species richness and environmental correlates were carried out using spatial statistical techniques.

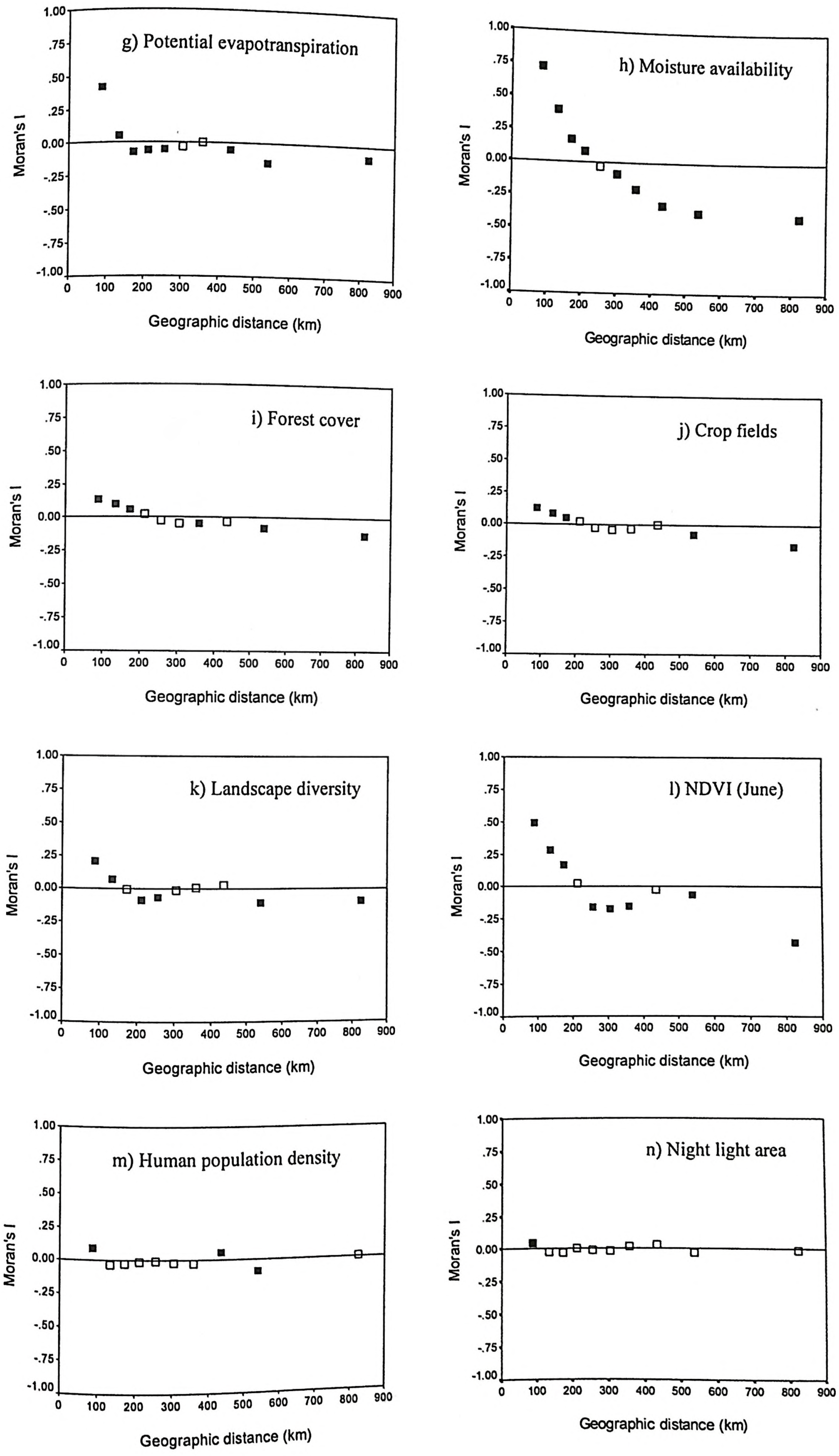
The relationship between bird species richness and each of the environmental variables was examined through partial regressions after the spatial components were modeled using second-order polynomial function of the latitude and longitude of sampling quadrats (after Legendre, 1993; van Rensburg *et al.*, 2002). In total, twenty environmental variables representing seven spatial themes (refer to Table 6.2) were analyzed separately. The partial regression coefficients were assessed for statistical significance at $P \leq 0.0025$ after Bonferroni correction for non-independence of environmental parameters. Total variation in bird species richness (R^2) was partitioned into four components, expressed as relative contributions of: a) environmental variable only, b) environment + space, c) space only, and d) unexplained factors. Environmental variables that were observed to explain more than 10 % of variation in bird species richness after the spatial effects were partialled out (i.e., sum of components a and b), were selected as predictor variables for building the final model.

The final integrated environmental model to predict the number of bird species was developed using generalized least squares (GLS) regression, a geostatistical technique that builds spatially-explicit regression models by quantifying spatial structure present in the environmental data and incorporating autocorrelation terms into regression residuals (after Selmi & Boulinier, 2001; Diniz-Filho *et al.*, 2003; Evans & Gaston, 2005). Spatial covariance in GLS regression was modeled by means of semivariograms in which the empirical values of semivariance, estimated for a given set of distance classes, were fitted with three theoretical models -spherical, exponential, and Gaussian by iterating the values of the three components of semivariograms, viz., nugget effect, partial sill, and range under restricted maximum likelihood criterion. The best fit among the models was chosen by both visual examination and AIC (Akaike Information Criterion) value. Prior to the final model, variables that showed high levels of multicollinearity were excluded from the analysis by carrying out a series of GLS regressions and examining the corresponding changes in the significance of t-statistic with every step (Haining, 1990). Between two competing models with comparable regression coefficients, the model with the smaller AIC value was selected (after Burnham & Anderson, 2002). An ordinary least squares (OLS) regression was also carried out using the same set of original environmental variables and a final OLS model was constructed after covariance among the variables was detected and eliminated in multiple stepwise regressions (Zar, 1999). This spatially-independent model was, then, contrasted with the spatially-structured GLS model to compare the regional and local scale predictors of bird species richness in Central Indian Highlands (following Diniz-Filho *et al.*, 2003).

All the spatial analyses were performed using the statistical program SAM (Spatial Analysis in Macroecology) version 1.1 (Rangel *et al.*, 2006).

Figure 6.1. Spatial correlograms showing the presence of spatial autocorrelation in some key variables measured across Central Indian Highlands at the level of quarter-degree grids (15' X 15'). The spatial autocorrelation is measured as Moran's *I* coefficients over a series of 10 distance classes. Note that solid squares represent significant presence of spatial autocorrelation while hollow squares represent lack of it for the particular distance class. Statistical significance was estimated at P<0.005 after Bonferroni correction (α/k) at P = 0.05.



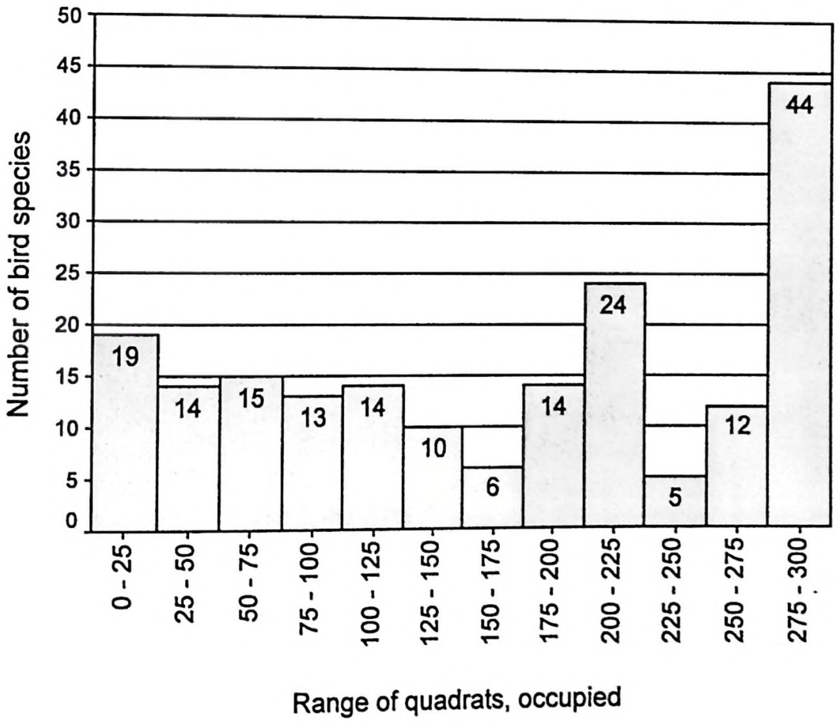

g) Potential evapotranspiration
h) Moisture availability
i) Forest cover
j) Crop fields
k) Landscape diversity
l) NDVI (June)
m) Human population density
n) Night light area
Moran's I
1.00
.75
.50
.25
0.00
-.25
-.50
-.75
-1.00
0
100
200
300
400
500
600
700
800
900
Geographic distance (km)

6.3. RESULTS

6.3.1. Bird species richness

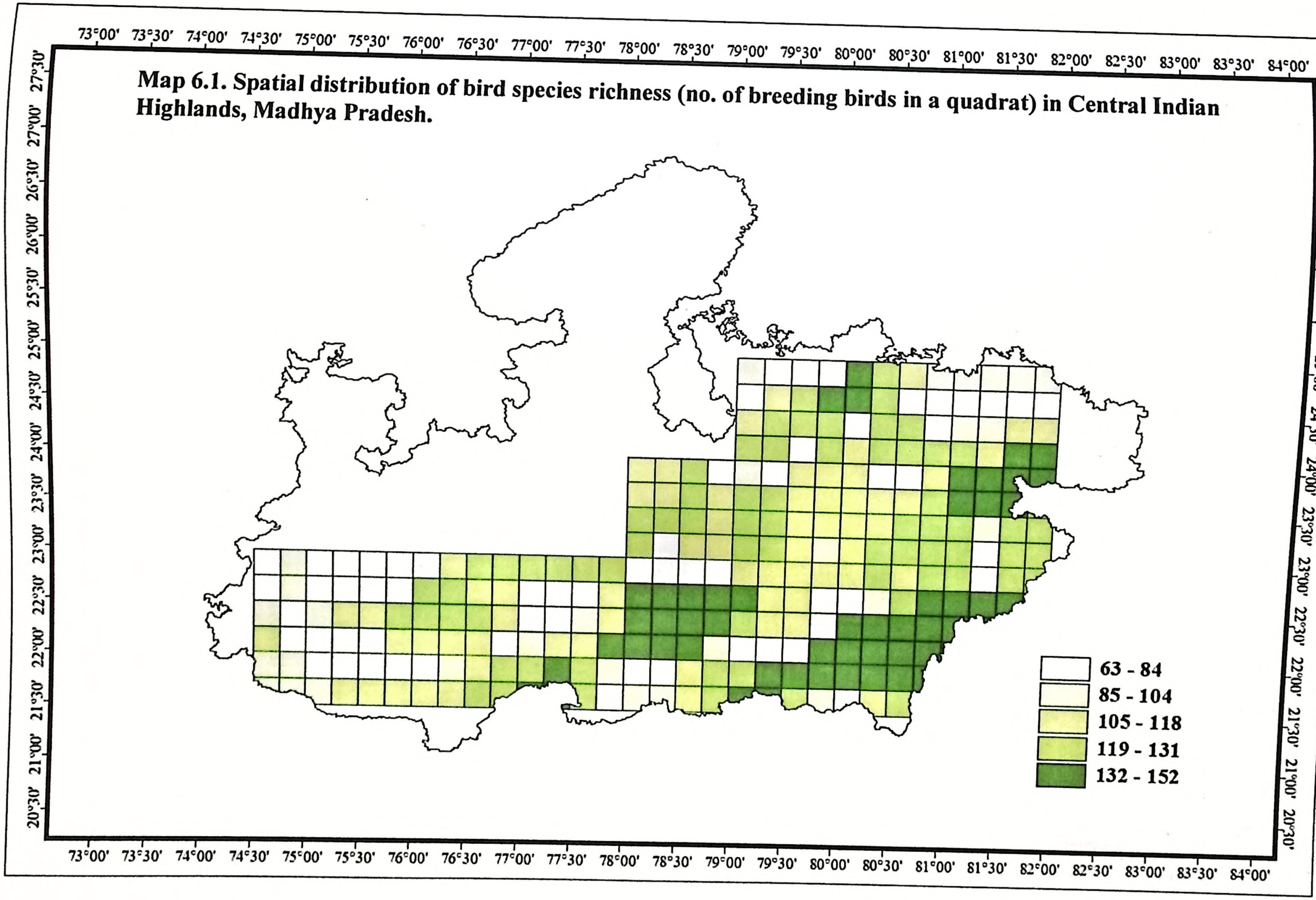
Of 190 species of birds for which the distribution data were collected and analyzed, 44 species were observed to occur in all the 284 quadrats and 19 occurred in less than 25 quadrats (Figure 6.2). The mean bird species richness was found to be 109.8 ± 23.9 SD, with the minimum of 63 (recorded from two quadrats in Vindhya Scarplands) and maximum of 152 species (from one quadrat in Satpura Plateau). In general, bird species richness was highest in central and south-eastern parts while lowest in western and northern ranges of the study area. [See Map 6.1 for species richness gradients in breeding birds of Central Indian Highlands.].

Figure 6.2. Geographical range size in breeding birds of Central Indian Highlands expressed as number of quadrats occupied by bird species in the study area.



6.3.2. Environmental variables

The quadrats were found to be relatively homogeneous in climate and primary productivity (with CV < 50 %), but evinced a high variability in other environmental layers; in particular, distribution of forest cover and urbanization parameters were noted to be extremely polarized in the area with CV exceeding 75 to 100 %. However, area under crop-fields was observed to be fairly uniform across the quadrats with low variation, though landscape diversity and topography showed mixed patterns (see Table 6.3).



Map 6.1. Spatial distribution of bird species richness (no. of breeding birds in a quadrat) in Central Indian Highlands, Madhya Pradesh.

Table 6.3. Summary statistics of environmental variables measured across quarter-degree quadrats of Central Indian Highlands (n = 284).

Sl.No.	Spatial themes & variables	Unit	Mean ± SD	CV (%)	Min.	Max.
	Topography					
1	Mean elevation	m	447.29 ± 141.3	31.6	158.17	873.35
2	Elevation range	m	309.02 ± 155.2	50.2	58	861
3	Drainage length	km	32.70 ± 027.8	84.9	0	153.97
	Climate					
4	Precipitation	mm/year	1162.76 ± 180.3	15.5	659.5	1611.1
5	Wet-day frequency	days/year	52.21 ± 008.7	16.6	36.4	73.1
6	Mean temperature	°C	25.48 ± 000.8	3.1	23.2	27.3
7	Diurnal temperature range	°C	13.03 ± 000.8	5.8	11.4	14.5
8	PET	mm/year	1748.95 ± 174.5	10.0	1320	2158
9	Moisture availability	%	67.62 ± 014.6	21.5	31.1	106.8
	Primary Productivity					
10	Mean NDVI		0.36 ± 000.1	13.9	0.219	0.539
11	June NDVI		0.24 ± 000.1	29.2	0.1	0.44
	Landscape Heterogeneity					
12	Landscape diversity		0.38 ± 000.2	63.2	0	0.907
13	Crop-fields	sq. km	480.80 ± 156.6	32.6	50	716
	Forest Cover					
14	Scrub jungle	sq. km	6.02 ± 009.6	159.8	0	71
15	Open forest	sq. km	77.11 ± 066.1	85.7	0	355
16	Dense forest	sq. km	129.01 ± 125.9	97.6	0	553
17	Total forest cover	sq. km	206.12 ± 156.8	76.1	0	633
	Human Population					
18	Population density	persons/sq. km	164.26 ± 098.9	60.2	37	1157
	Urbanization					
19	Night light area	sq. km	32.72 ± 057.3	175.2	0	414
20	Road length	km	17.87 ± 019.0	106.2	0	78.79

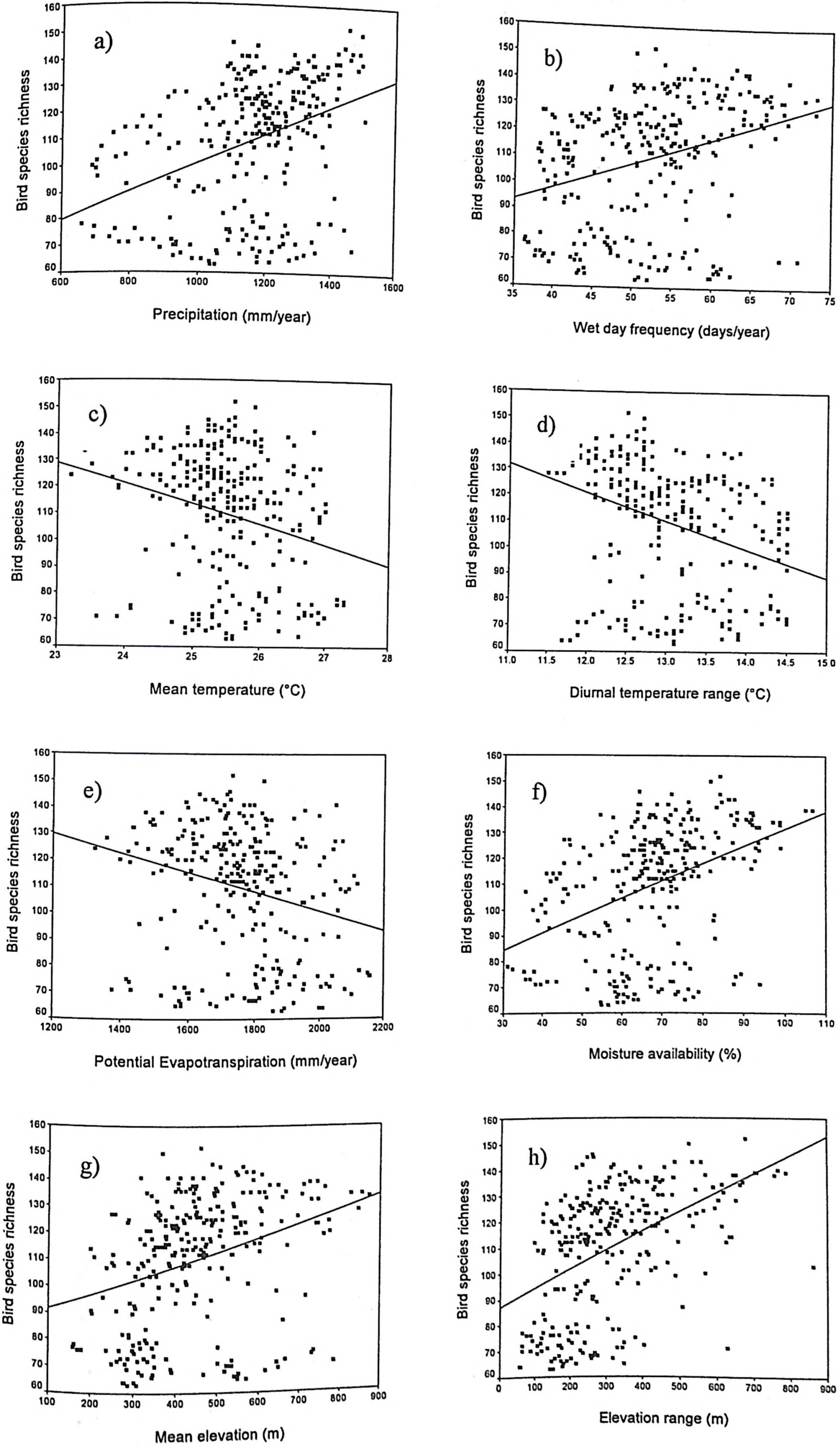
6.3.3. Relationships between bird species richness & environment

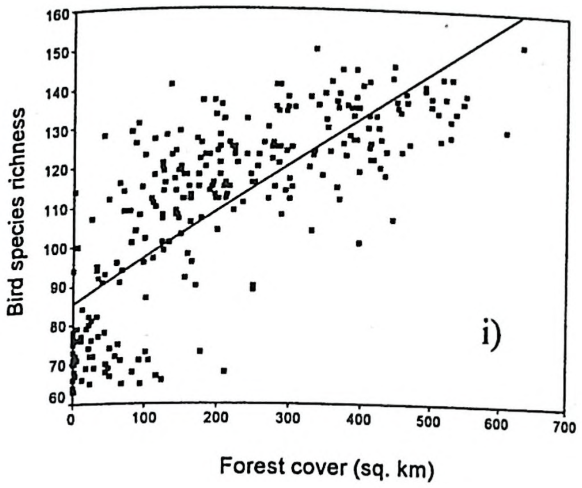
Bird species richness was found to be significantly related to all the environmental variables ($P < 0.0001$), although the direction and magnitude of relationship varied much among the spatial layers. For example, bird species richness was positively associated with rainfall-related parameters, landscape diversity, and forest cover, but decreased with increasing values of temperature-related climatic variables and human environment; the relationship was also observed to be stronger with respect to variables that described land use and land cover patterns (see R^2 values in Table 6.4 & scatter-plots in Figure 6.3a-p). However, subsequent results of partial regressions showed that the relative contributions of environmental factors alone (after discounting spatial effects) to bird species richness were insignificant in the case of climate, human population, and urbanization (c.1-7 %). On the contrary, topography, primary productivity, landscape heterogeneity, and forest cover continued to explain a large part of variation in bird species richness (c. 18-44 %) even after contributions from spatial components were partialled out.

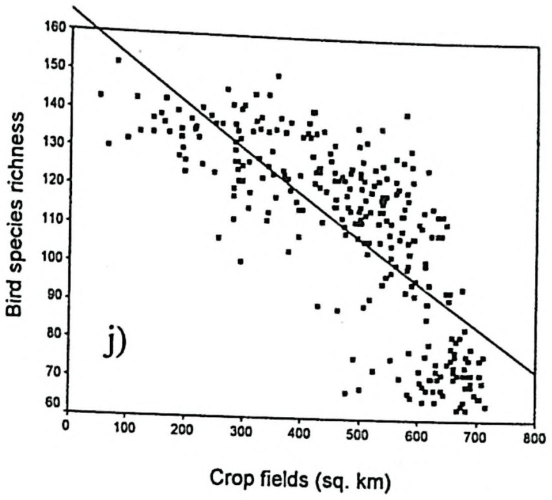
Table 6.4. Results of partial OLS regressions modeled with 2nd order polynomials of geographical coordinates between each of the environmental variables and bird species richness in Central Indian Highlands. The variation in bird species richness (R^2) is partitioned into four components: a) environmental variable only, b) environmental variable + space, c) space only, and d) unexplained variation. Note that all the partial regression coefficients were evaluated for statistical significance using sequential Bonferroni correction. [***P < 0.0001].

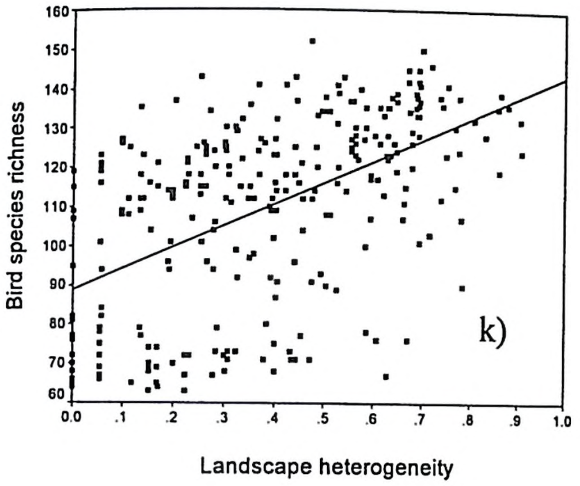
		% of variation in bird species richness			
Environmental variable	R^2	**Environment only**	**Environment + space**	**Space only**	**Unexplained component**
Topography					
Mean elevation	0.186***	1.9	7.9	8.8	81.4
Elevation range	0.356***	18.8	3.7	13.0	64.4
Drainage length	0.168***	0.0	0.4	16.4	83.2
Climate					
Precipitation	0.188***	2.1	14.0	2.7	81.2
Wet-day frequency	0.172***	0.5	11.9	4.8	82.8
Mean temperature	0.179***	1.1	5.1	11.6	82.1
Diurnal temperature range	0.168***	0.0	11.5	5.2	83.2
Potential evapotranspiration	0.182***	1.5	5.6	11.1	81.7
Moisture availability	0.195***	2.8	13.9	2.8	80.5
Primary Productivity					
Mean NDVI	0.261***	10.2	12.3	4.4	73.0
June NDVI	0.429***	26.2	9.4	7.3	57.0
Landscape Heterogeneity					
Landscape diversity	0.392***	22.5	6.5	10.2	60.8
Crop-fields	0.586***	41.9	14.6	2.1	41.4
Forest Cover					
Scrub jungle	0.183***	1.5	-0.4	17.1	81.7
Open forest	0.415***	24.7	3.7	13.0	58.5
Dense forest	0.503***	33.5	12.8	3.9	49.7
Total forest cover	0.607***	43.9	15.6	1.1	39.3
Human Population					
Population density	0.205***	3.8	3.7	13.0	79.4
Urbanization					
Night light area	0.238***	7.1	2.2	14.5	76.2
Road length	0.184***	1.7	-1.4	18.2	81.6

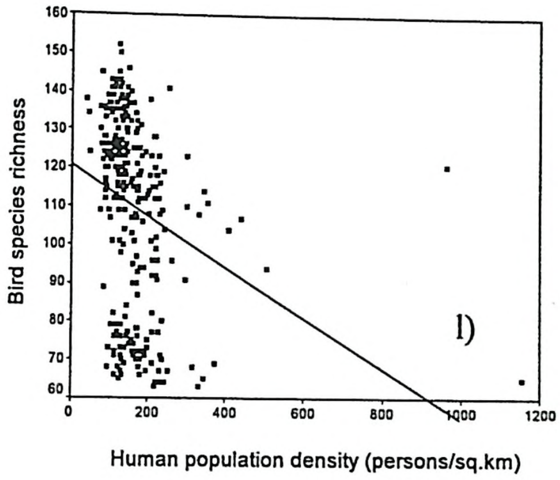
Figure 6.3. Scatterplots showing linear relationships between species richness of breeding birds and environmental / landscape variables in Central Indian Highlands (n = 284).

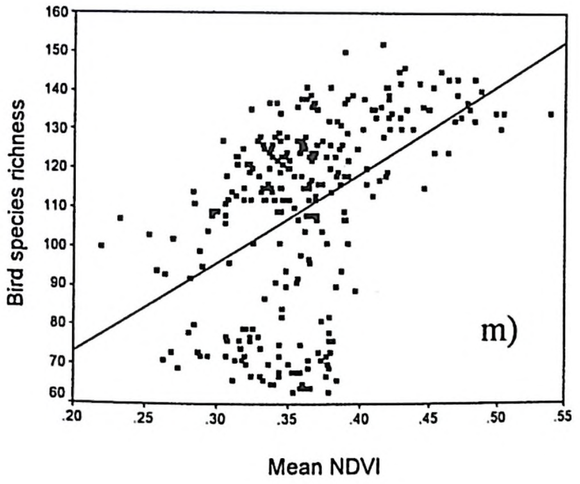


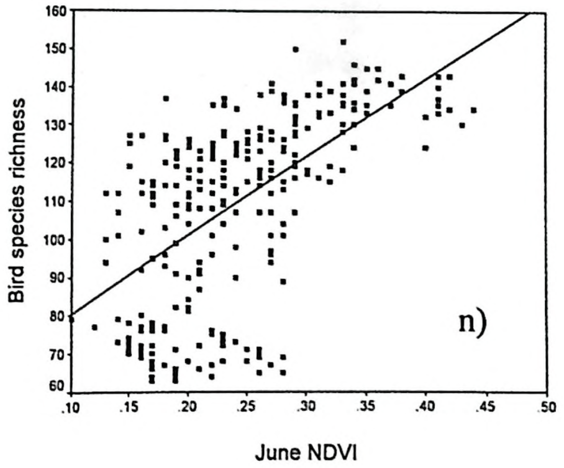

Bird species richness
160
150
140
130
120
110
100
90
80
70
60
0
100
200
300
400
500
600
700
i)
Forest cover (sq. km)

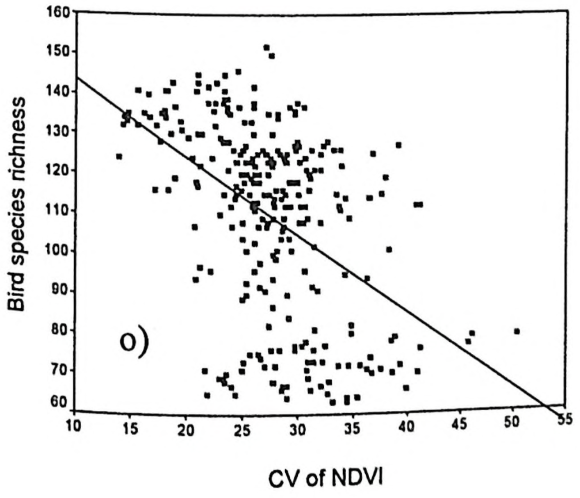

Bird species richness
160
150
140
130
120
110
100
90
80
70
60
0
100
200
300
400
500
600
700
800
j)
Crop fields (sq. km)


Bird species richness
160
150
140
130
120
110
100
90
80
70
60
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
k)
Landscape heterogeneity


Bird species richness
160
150
140
130
120
110
100
90
80
70
60
0
200
400
600
800
1000
1200
l)
Human population density (persons/sq.km)


Bird species richness
160
150
140
130
120
110
100
90
80
70
60
.20
.25
.30
.35
.40
.45
.50
.55
m)
Mean NDVI


Bird species richness
160
150
140
130
120
110
100
90
80
70
60
.10
.15
.20
.25
.30
.35
.40
.45
.50
n)
June NDVI


Bird species richness
160
150
140
130
120
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20
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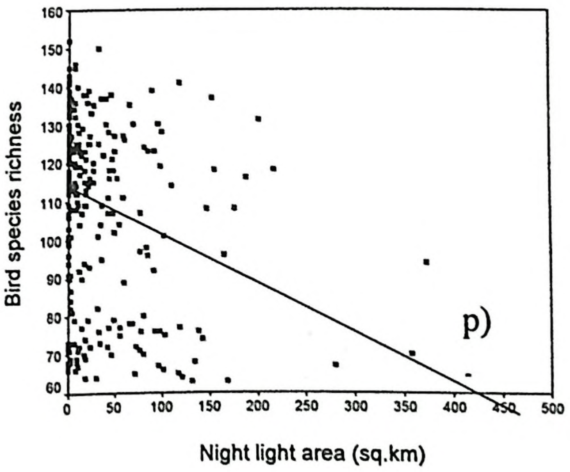
35
40
45
50
55
o)
CV of NDVI


Bird species richness
160
150
140
130
120
110
100
90
80
70
60
0
50
100
150
200
250
300
350
400
450
500
p)
Night light area (sq.km)

6.3.4. Environmental models of bird species richness

6.3.4a. GLS regression for spatially-structured model

The following environmental variables were considered for spatial GLS regression on the basis of their significant contributions to variation in bird species richness in partial regressions [i.e., sum of components a & b > 10 % in Table 6.4]: elevation range, precipitation, wet day frequency, diurnal temperature range, moisture availability, mean NDVI, June NDVI, landscape diversity, crop-fields, open forest, dense forest, and total forest cover. Repeated regression procedures, however, revealed a heavy presence of multicollinearity among these variables, and after examining changes in the statistical significance of t-statistics, the following three parameters were finally selected as independent predictors:

- Elevation range
- Landscape diversity
- Total forest cover

Spatial covariance in the environmental data was quantified using a spherical model of semivariogram function (see Figure 6.4), which was preferred to the other two models viz., exponential and Gaussian on account of lower AIC value. Maximum convergence was achieved between the empirical observations of semivariance and the estimated values in the spherical model when the semivariogram was fitted with the following components:

$$\mathbf{SV}(d) = C_0 + (C_1 * (1 - (1.5 * (d/a)) + (0.5 * ((d/a)^{\wedge}3)))), \text{ as } 0 < d \leq a$$

where distance (d) = 75, nugget effect (C_0) = 190, partial sill (C_1) = 40, & range (a) = 590.

The final, spatially-structured GLS model had a prediction accuracy of 71.7 % and was expressed as follows:

Bird species richness = [(Elevation range * 0.025) + (Landscape diversity * 13.759) + (Forest cover * 0.091) + 75.3340)

See Table 6.5 for summary statistics of the GLS model and Figure 6.5 for a comparison of observed *versus* predicted values of bird species richness in Central Indian Highlands.

Figure 6.4. Spherical model of semivariogram fitted in GLS regression of bird species richness against environmental variables along 16 distance classes. Hollow squares relate to empirical observations while the solid squares were the fitted semivariogram functions.

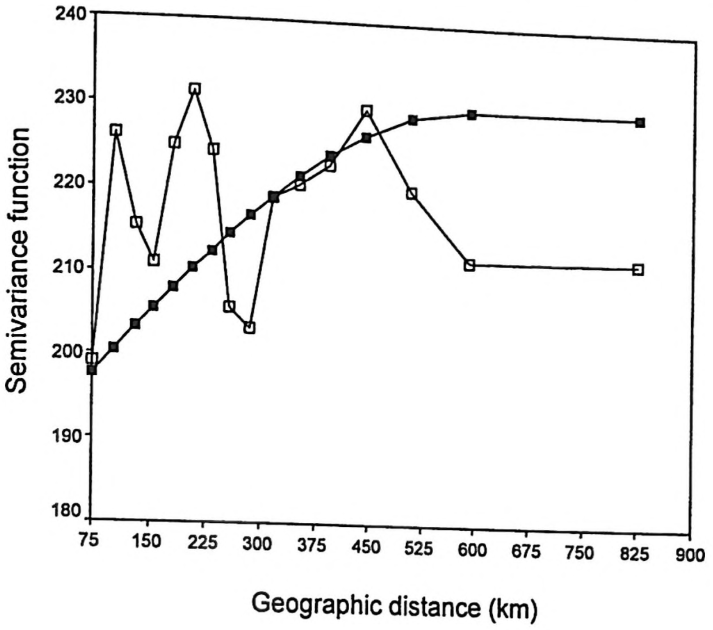
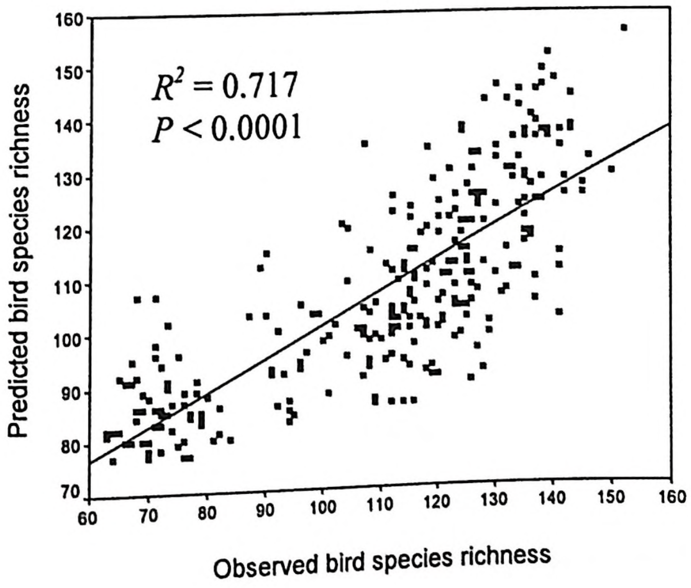


Table 6.5. Summary of GLS regression model for bird species richness in Central Indian Highlands (N=284).

Regression Model	*R*	R^2	AIC	*F*	*P*
GLS (Predictors)	0.846	0.717	1459.20	236.141	< 0.0001
GLS (Predictors + Space)	0.808	0.653	1517.06		

Variable	Regression coefficient	SE	*t*	*P*
Constant	75.334	4.282	17.592	< 0.0001
Elevation range	0.025	0.007	3.617	< 0.0001
Landscape diversity	13.759	4.938	2.786	0.006
Forest cover	0.091	0.007	12.054	< 0.0001

Figure 6.5. Scatterplot comparing observed bird species richness with the predicted values, which were estimated using the spatial GLS regression model.



6.3.4b. OLS regression for spatially-independent model

All the twenty environmental factors (refer to Table 6.3) were included in the OLS multiple regression and those variables showing collinearity were removed from the final analysis in a stepwise procedure [probability of F to remove was 0.1 and to enter in the model 0.05]. The final model had four explanatory variables, viz., precipitation, elevation range, landscape diversity, and forest cover and they together explained about 62 % of variation in bird species richness (see Table 6.6). The OLS model was given as:

Bird species richness = [(Precipitation * 0.011) + (Elevation range * 0.018) + (Landscape diversity * 11.358) + (Forest cover * 0.094) + 67.859]

Table 6.6. Summary of OLS regression model for bird species richness in Central Indian Highlands (N=284).

Regression Model	*R*	R^2	SE	*F*	*P*
OLS	0.791	0.625	14.741	116.39	< 0.0001

Variable	Regression coefficient	SE	*t*	*P*
Constant	67.859	6.125	11.078	< 0.0001
Precipitation	0.011	0.005	2.007	0.046
Elevation range	0.018	0.007	2.630	0.009
Landscape diversity	11.358	4.768	2.382	0.018
Forest cover	0.094	0.008	12.474	< 0.0001

A comparison of GLS and OLS regressions of bird species richness revealed that three environmental predictor variables were common to both spatial and aspatial models: elevation range, landscape diversity, and total forest cover. However, total annual precipitation emerged as an additional explanatory variable in OLS regression implying a greater role for precipitation in determining bird species richness at regional scale.

6.4. DISCUSSION

Bird species richness in Central Indian Highlands is found to respond positively to environmental variables that describe water availability (like precipitation and wet day frequency), and is negatively associated with energy-related climatic parameters (like mean temperature, diurnal temperature range, and PET). This is consistent with the predictions of the 'water-energy balance' theory of latitudinal gradients in species richness (O'Brien, 1998; Stephenson, 1998; Hawkins *et al.*, 2003). It may be argued that if available energy is indeed copious, it should translate into more species as species diversity is expected to increase with productivity according to species-energy hypothesis (see Connell & Orias, 1964; Wright *et al.*, 1993). In terms of climatic surrogates, it then follows that increasing temperature or PET should return more species. In fact, this was the dominant idea in species-environment studies till water-energy balance mechanism was proposed and a growing number of investigations at global scale reveal that productivity cannot increase infinitely with solar radiation as temperature would curtail water availability due to negative feedback (e.g., O'Brien, 1998; H-Acevedo & Currie, 2003).

Surprisingly, water as a key ecological factor for primary productivity was seriously underrated in early works (e.g., Turner *et al.*, 1988; Currie, 1991) as these studies were carried out in largely temperate regions where energy would be the limiting factor. But it is also true that temperature does not simply cease to be influential at lower latitudes as suggested by the water-energy balance theory; it probably continues to govern species diversity gradients in warmer latitudes as well in conjunction with precipitation, though the latter has clearly a larger role. Because of a sizable degree of interaction between temperature and rainfall in the tropics, species richness may sometimes increase with temperature as long as there is plentiful rainfall (see H-Acevedo & Currie, 2003). For example, mean daily temperature and annual precipitation in Central India were observed to be non-independent with significant inverse relationship ($R = -0.47$, $P < 0.0001$, $N = 284$). A strong covariation, like this, probably prompted some of the recent studies to use the ratio of rainfall to PET ('moisture availability') as an environmental predictor of bird species richness (e.g., Oindo *et al.*, 2001) and this can also be a good measure of climatic 'water-energy balance' in the tropics. Number of bird species, in Central Indian Highlands, is indeed found to increase significantly with moisture availability and the magnitude of its contribution to bird species richness is marginally greater than that of precipitation or PET alone. It is suspected that this ratio may also explain why high rainfall areas like Eastern Himalayas and Western Ghats are marked by an exceptional number of endemic species of birds in comparison to Central Indian Highlands (see Table 6.7), as strong relationships between abiotic components of environment and species richness of endemic avifauna have been demonstrated elsewhere (e.g., Foody, 2004). High moisture availability is likely to promote development of structural complexity in forest vegetation, which in turn gives rise to greater niche diversification leading to evolution of specialized resource consumers and endemism (see Waltert *et al.*, 2004). In fact, it has been shown in tropical deciduous forests that precipitation, more than any other environmental factor, influences vegetation structure (Lerdau *et al.*, 1991).

Table 6.7. Comparison of three biogeographic zones with respect to water-energy balance and number of endemic birds.

Biogeographic Zone	Rainfall (mm/year)	PET (mm/year)	Moisture Availability	Number of endemic land birds[4]
Eastern Himalayas[1]	1594	716	223 %	19
Western Ghats[2]	1740	685	254 %	15
Central India[3]	1163	1749	67 %	2

[1] Climate data for Ziro, Lower Subansiri, Arunachal Pradesh (IMD, 1999).
[2] Climate data for Kodaikanal, Palni Hills, Tamil Nadu (IMD, 1999).
[3] Climate data averaged across all the quadrats in the study area (New *et al.*, 2002).
[4] Source for Eastern Himalayas (Lower Subansiri district) and Western Ghats (Palni Hills): Stattersfield *et al.*, 1998. The two species now considered as endemic to Central India (Rasmussen & Anderton, 2005) include: Forest Owlet (*Heteroglaux blewitti*) and Green Munia (*Amandava formosa*).

But inadequacy of water-energy balance to predict species diversity across spatial scales on account of a high degree of spatial structure in climate data makes it less of a robust predictor than it is generally assumed. It is therefore frequently suggested that spatial autocorrelation in environmental data be investigated using correlograms prior to species-environment analysis (Dutilleul & Legendre, 1993; van Rensberg *et al.*, 2002; Diniz-Filho *et al.*, 2003). Examination of spatial correlograms also yields interesting insights into geographical gradients in environmental variables that may aid regional characterization (Selmi & Boulinier, 2001). For example, climate parameters like precipitation, wet day frequency, diurnal temperature range, and moisture availability are observed to follow a strongly linear and isotropic gradient in Central Indian Highlands with a positive autocorrelation as far as c.250 km distance after which there is a marked negative autocorrelation. In other words, quadrats within 250 km radius tend to be more similar and those lying beyond 250 km are more dissimilar than a random set of quadrats in terms of these climate variables.

In contrast, temperature and PET show positive autocorrelation till about 120 km beyond which the quadrats are relatively free of any spatial covariance. This is probably a reflection of the geographical patterns in topography of the region (see Diniz-Filho *et al.*, 2003), as elevation range also shows similar spatial distribution in central India and both temperature and PET are observed to drop significantly with increasing elevation ($R_{\mathrm{PET.ELEV}} = -0.94$, $P < 0.0001$ & $R_{\mathrm{TEMP.ELEV}} = -0.85$, $P < 0.0001$, N = 284). In the case of land cover classes, forests and crop-fields show strong positive autocorrelation up to 200 km followed by a weak negative trend till 400 km after which no significant structure is evident. Incidentally, human population density is marked by a near-absence of spatial autocorrelation, implying a more or less equable distribution of human settlements in Central Indian Highlands. This is surprising given the interstitial nature of the region's landscape in which belts of intensively used lands often alternate with vast tracts of forests. This paradox can be explained by some of the demographic features unique to the region: relatively sparse population (with a population density of 164 against the national average of 274), a low degree of urbanization (only 11 quadrats out of 284 having an urban built-up area of ≥ 1 % of the quadrat area: Hansen *et al.*, 2000), and a predominance of tribal population with forest-dependent sustenance (c. 20 % against the national average of 8 %).

Spatial structure in species richness can also be a potential tool in characterizing geographical distribution of taxa and inferring macroecological hypotheses to explain gradients of species diversity in space. For example, Selmi & Boulinier (2001) found from spatial correlograms that introduced species of birds tended to be more patchy in distribution in comparison to native taxa in Southern Ocean islands. On the contrary, species richness of breeding birds in central India shows a weak linear trend in spatial autocorrelation. This is typically shown when a region's avifauna is characterized by a combination of low species turnover in space (as demonstrated in Chapter 5) and primarily checkerboard patterns of distribution (see the discussion in Chapter 4). The muted response of species richness gradients to spatial variation, as observed in the study, has also been noted elsewhere (e.g., Selmi & Boulinier, 2001; Diniz-Filho *et al.*, 2003; Kaboli *et al.*, 2006; but see van Rensburg *et al.*, 2002 for a strong presence of spatial autocorrelation in South African birds). Nonetheless, it is the spatial structure in predictor variables rather than response variable that is considered a serious problem meriting application of geostatistical techniques (Lennon, 2000).

Though studies in macroecology often highlight spatial nonstationarity of the nature of species-environment relationships (e.g., Rahbek & Graves, 2001; Foody, 2004), recent evidences indicate only marginal differences between analyses that take spatial effect into account and those which do not (e.g., Selmi & Boulinier, 2001; Diniz-Filho *et al.*, 2003). This is also borne out by the findings of the present study in which both spatially-structured and spatially-independent models of bird species richness in Central Indian Highlands converge on three environmental factors: elevation range, landscape diversity, and forest cover. However, precipitation emerges as a significant additional predictor, when spatial variations in data are ignored in the conventional regression model. As Diniz-Filho *et al.* (2003) sum up, spatially-structured models tend to emphasize the role of environmental parameters that vary at local scale while non-spatial regression models select variables only on the basis of the magnitude of regression coefficients regardless of the spatial scale at which the variables may be functional. This view has also been shared by several other independent investigations (e.g., Boone & Krohn, 2000; van Rensburg *et al.*, 2002; Hawkins *et al.*, 2003; but see Foody, 2004). The inconsistency among past studies in their choice of statistical approach (between spatially-explicit and nonspatial models) severely undermines our efforts to generalize predictors of bird species richness at multiple scales. For example, among the studies that did not take spatial autocorrelation into account, a majority underscored greater role for habitat diversity or topography at local scale (e.g., Tellería *et al.*, 1992; Böhning-Gaese, 1997; Cueto & de Casenave, 1999) while a few others found climate as equally significant (e.g., Rahbek & Graves, 2001).

Conventionally, investigations into relationships between species richness of land birds and environment include all the species of birds known to occur in sampling quadrats. But this practice has been questioned on the grounds that response of different groups of birds to a given environmental gradient may not be identical (e.g., Jones *et al.*, 2000; Jetz & Rahbek, 2002; Herzog & Kessler, 2006; Mönkkönen *et al.*, 2006); in particular, species richness of forest *versus* non-forest birds is known to vary in a notably dissimilar fashion (e.g., Askins *et al.*, 1987; Pino *et al.*, 2000). Though breeding birds in Central India do seem to segregate neatly into forest and non-forest species (see the discussion in Chapter 5), they are not treated here separately as: a) forest birds are naturally expected to respond more to land use and land cover patterns and separating them from other abiotic components in the environment as independent factors would be statistically untenable, and b) partitioning the response variables into 'a posteriori' subsets would only serve to increase the accuracy of prediction models at the cost of model parsimony and universality of applications.

Another recurring problem in studies on species-environment relationships is the degree of multicollinearity among the predictor variables, which increases as a function of number of environmental variables used as correlates of species diversity (Diniz-Filho *et al.*, 2003). Multicollinearity is recognized as a grave issue in regression analysis (Zar, 1999), and it is particularly exacerbated, in species-environment models, by spatially-structured covariations in data (Lennon, 2000). Though there are a number of tests and measures available to detect collinearity and rank variables accordingly, they frequently do not concur in their choice of variables (see Heikkinen *et al.*, 2004). For this reason, geostatistical techniques, which can deal with multicollinearity arising out of both circumstances, are recommended for analysis of species richness-environment relationships (Haining, 1990; Legendre, 1993; Lennon, 2000; Selmi & Boulinier, 2001). They employ a hybrid procedure in which variables showing high degree of collinearity are removed on the basis of significance of t-statistic and the final competing models are evaluated by means of AIC parameter. The usefulness of this approach is amply demonstrated in the present study. In central India, bird species richness is found be significantly related to all the environmental variables even after the spatial components have been partitioned and discounted from the regressions (see Boone & Krohn, 2000; Oindo *et al.*, 2001; Rahbek & Graves, 2001; Foody, 2004; for similar results). But examination of GLS statistics reveals a great deal of multicollinearity among all the correlates and only three variables for which regression coefficients are statistically significant are retained in the final model. In addition, models with comparable explanatory power are also assessed for redundancy and ranked using AIC values.

The finding that elevation range, landscape diversity, and forest cover together predict about 72 % of the total number of breeding birds in Central Indian Highlands at local scale and 61 % at regional level has several far-reaching implications for the conservation of forest birds in the region. In particular, landscape diversity and forest cover are vulnerable to human activities and impacts of expanding agriculture and other forms of land use patterns on this fragile equation can be quite heavy; in extreme scenario, landscape diversity may become effectively nil with 100 % area under crop-fields. In fact, 45 quadrats in the study area currently have more than 90 % area under intensive farming. It is also observed that every 10 sq. km. increase in the cropping area would result in loss of one species of forest birds (Table 6.8).

Table 6.8. Regression of bird species richness against area under crop-fields in Central Indian Highlands (N = 284). Note that spatial autocorrelation in the data was minimized through partial model with the first order polynomial function of latitude and longitude.

Regression model	***R***	***R^2***	**AIC**	***F***	***P***
Partial Regression	0.75	0.57	1574.29	123.15	< 0.0001

Variable	**Regression coefficient**	**Standardized coefficient**	**SE**	***t***	***P***
Constant	106.92	0.00	38.831	2.75	0.006
Cropping area	-0.11	-0.73	0.006	-16.86	< 0.0001
Longitude	0.85	0.07	0.572	1.49	0.137
Latitude	-0.48	-0.02	1.196	-0.40	0.689

As total forest cover in central India is strongly an inverse function of area under crop-fields ($R^2_{\text{FOREST.CROP}} = 0.94$, $P < 0.0001$, N = 284), this loss is presumably mediated through deforestation as brought about by expanding agriculture. As only 13 % of the total forest area of 58,500 sq. km is protected in Central Indian Highlands, the magnitudes of loss in forest cover and subsequent local extinctions in birds will be immense unless an integrated land use policy is evolved and implemented.

It may be recalled here that precipitation emerges as a significant determinant of bird species richness in central India at the regional scale. As it represents the role of history in the evolution of local species diversity, the ecological significance of precipitation may be considered in the light of global climate change and long-term changes in precipitation are known to affect birds in more than one way (e.g., Thomas & Lennon, 1999 for range extensions & contractions in British birds; Crick & Sparks, 1999 for changes in the timing of onset of breeding). Though rise in ambient temperature is often the focus of climate change studies (with warming trend over

India estimated as 0.57°C over next 100 years: Rupakumar *et al.*, 1994), the effects of global warming over tropical India become readily apparent in concomitant changes in monsoon trends and increase in interannual variability of mean daily rainfall (Lal *et al.*, 2001). Though long-term trends in precipitation in the Subcontinent are unclear, decadal departures in mean annual rainfall are noted to be markedly above and below long-time average in the last three decades alternately (Kothyari & Singh, 1996). This can affect reproductive success of bird populations over the years and threatened species are particularly at high risk as breeding cycles in Indian avifauna are known to be closely regulated by periodicity of the south-west monsoon (Padmanabhan & Yom-Tov, 2000). Further, any prolonged deviations in rainfall patterns may cause irreversible changes in both floristics and structure of tropical forests especially in hilly and mountainous regions (Lal *et al.* 2001), which are home to more than half of the total forest birds in Central Indian Highlands including Malabar Pied Hornbill (*Anthracoceros coronatus*), Blue-bearded Bee-eater (*Nyctyornis athertoni*), Oriental Scops Owl (*Otus sunia*), Crested Goshawk (*Accipiter trivirgatus*), Asian Brown Flycatcher (*Muscicapa dauurica*), Black-crested Bulbul (*Pycnonotus melanicterus*), Brown-cheeked Fulvetta (*Alcippe poioicephala*), and Puff-throated Babbler (*Pellorneum ruficeps*).

Thus, the models of species-environment relationships have a promising role in theoretical predictions and mapping of species richness gradients, and environmental forecasting of possible impacts of human activities on regional species diversity. Future studies should focus on species distributions at finer spatial resolution (ideally with quadrat size < 100 km^2), which will aid us to develop species-environment models at multiple scales with more accuracy. It is also important to extend the scope of these investigations to other organisms (including plants) to draw inferences that would cut across taxa, as discovering general laws signifies maturation of ecology both as a science and conservation tool (Lawton, 1999).

6.5. SUMMARY

1. In this chapter, I studied the relationships between bird species richness and environment in Central Indian Highlands. First, I investigated the magnitude and direction of the influence of each of the environmental variables on species richness of breeding birds after taking into account spatial structure in the data. Then, an integrated environmental model was developed in a spatially explicit manner to predict the number of bird species that occur in a given area in Central Indian Highlands.
2. The study area was divided into 11 regions on the basis of topography, natural vegetation, and eco-climatology. All the regions were then gridded into quarter-degree cells (15′ X 15′) or '*quadrats*' (c. 27 X 26.5 km size), which were treated as the basic sampling units. Primary data on distribution of breeding land birds were collected for each quadrat using a spatially-hierarchical sampling scheme. In total, distribution of 190 species of birds was mapped at the level of 284 quarter-degree quadrats. Data on a set of twenty environmental variables that represented seven spatial themes, viz., topography, climate, productivity, landscape heterogeneity, forest cover, human population, and urbanization were extracted from various sources including satellite imageries, government agencies, and international organizations.
3. Examination of Moran's I spatial correlograms revealed a high degree of spatial structure in most of the environmental variables. Therefore, all further analyses were carried out using spatial statistical techniques. The relationship between each of the environmental variables and bird species richness was explored using partial regressions with 2nd order polynomial function of the latitude and longitude of quadrats. All the variables that showed significant correlations with bird species richness were selected to build the integrated environmental model. But they were tested for multicollinearity before the final set of predictor variables could be chosen. Then, a spatially structured model was developed using generalized least squares (GLS) regression to predict the number of bird species that breed in a given area, after the spatial autocorrelation terms were modeled using semivariograms. While GLS would return factors that act at local scale as determinants of bird species diversity, a spatially independent model was also developed in conventional ordinary least squares (OLS) regression to identify environmental correlates at regional scale.
4. Bird species richness was found to be significantly related to all the environmental variables. Among climate, species richness increased with variables that described water availability (i.e., rainfall, wet day frequency, and moisture availability), but showed inverse relationship with energy-related parameters (i.e. temperature, diurnal temperature range, and PET). Elevation range, landscape diversity, and forest cover emerged as the

environmental predictors of bird species richness in both GLS and OLS models, though precipitation showed up as an additional predictor in the OLS regression. The GLS spatial model was able to explain 72 % of variation in bird species richness, while accuracy of the OLS regression was observed to be 62 %.

5. The findings of the study support the '*water-energy balance*' hypothesis of species richness gradients which states that temperature limits number of species at higher latitudes and rainfall determines species richness at warm lower latitudes. The fact that bird species richness in Central Indian Highlands is found to be a function of nearly the same set of environmental predictors (comprising elevation range, landscape diversity, and forest cover) at both local and regional scales indicates that spatial autocorrelation may not be a serious flaw in species-environment studies as long as a good number of independent factors acting at multiple scales are included in the analysis.
6. Among the environmental predictors, landscape diversity and forest cover show extreme vulnerability to human activities. Changing proportions of different land use and land cover patterns and contractions in forest cover in response to expanding agriculture are a serious threat to forest birds in the region, and it is borne out by our estimation that every 10 sq. km. increase in cropping area would result in loss of one species of forest birds in Central Indian Highlands.

Chapter 7. Assessing the Adequacy of Protected Area Network Using Patterns of Geographical Distribution in Breeding Birds

7.1. INTRODUCTION

How to conserve biological diversity in an increasingly fragmented landscape of natural areas has always been a central challenge faced by conservationists and policy makers (Burbidge & Wallace, 1995). Creation of a network of Protected Areas (PAs) that are relatively free from external interference remains the most efficient strategy (Balmford *et al.*, 2002; Trombulak *et al.*, 2004; Locke & Dearden, 2005), though alternative paradigms such as community participation and joint forest management are also being experimented with conflicting results (Mehta & Kellert, 1998; Attwell & Cotterill, 2000; Berkes, 2004; Kiss, 2004). But PA network cannot be infinitely large in size in a landscape like Central Indian Highlands where a sizable number of native people directly depend on forestry resources for sustenance, and demand for land is growing fast to meet their economic and livelihood needs (Shah, 2005). Therefore, conservationists prescribe that an optimal portion of wilderness area be brought under PA network to ensure protection of maximum biodiversity at a minimal socioeconomic cost (Trombulak *et al.*, 2004). How much area would make up this optimum has been a matter of much debate and discussion. For example, World Commission on Protected Areas of IUCN set a target of 10 % area of each of the major biomes on the earth in its fourth World Parks Congress at Caracas in 1993 (Locke & Dearden, 2005), and European Union has a reserve policy by which a minimum of 15 % area of all the key ecosystems are to be legally protected (Rey Benayas & de la Montaña, 2003).

Identification of ecologically significant biomes or ecosystems in a landscape and prioritization of sites in each biome pose an uphill task. Most often, occurrence of surrogate taxa like an umbrella species or a flagship species prompts declaration of a site as a protected area. Though surrogate taxa have an admirable role in garnering political and public support for setting aside exclusive areas for conservation (Walpole & Leader-Williams, 2002), this approach is known to overlook other important species leaving several gaps in the protection network (see Caro & O'Doherty, 1999; Coppolillo *et al.*, 2004; Roberge & Angelstam, 2004). Therefore, a multi-species analysis is strongly recommended in identifying biomes or ecosystems and in ranking sites for their conservation value (Reyers *et al.*, 2002; Roberge & Angelstam, 2004; Rodrigues *et al.*, 2004; McCarthy *et al.*, 2006). Investigating the patterns of geographical distribution of taxa in a region forms the core of such multiple species approach in PA network assessment.

Birds have always been the most sought-after taxa in studies on application of biogeographical principles in developing a rational PA network and reserve selection criteria. This can be attributed to several factors that favour avifauna: a relatively stable lower-level taxonomy, availability of high-quality distribution data, feasibility of large-scale surveys to collect primary data on population status in a short span of time, presence of non-random assemblages with a strong degree of allegiance to biomes / ecosystems, strong response in species numbers to environmental gradients, a high surrogacy value for biodiversity assessment, and widespread popularity. Some of the prominent studies that have used geographical distribution of birds in site prioritization exercise are summarized in the Table 7.1.

Table 7.1. Some prominent examples of studies in the past that have used geographical distribution of birds in identification of biomes for PA network analysis.

Region	Spatial resolution	Reference
Tropical Africa	4° X 4°	Crowe & Crowe, 1982
Uttar Kannada, India	Point data	Daniels *et al.*, 1991
Southern Africa	15′ X 15′	Harrison & Martinez, 1995
Kenya	15′ X 15′	Muriuki *et al.*, 1997
Northern Senegal	3 X 3 km	Nøhr & Jørgensen, 1997
Tropical Africa	1° X 1°	Williams *et al.*, 1999
Bioko Island, West Africa	Point data	Lenton *et al.*, 2000
Quebec, Canada	0.1° - 1°	Garson *et al.*, 2002
Southern Africa	15′ X 15′	Reyers *et al.*, 2002
French Guiana	Point data	Thiollay, 2002
Hong Kong, China	1 X 1 km	Yip *et al.*, 2004

Biomes are normally identified by classifying sites into distinct clusters based on their similarity in species composition. Data on presence/absence of species in each of the sampling units (usually spatially contiguous grids at various scales) are analyzed using a classification technique like cluster analysis (e.g., Crowe & Crowe, 1982; Muriuki *et al.*, 1997; Orrock *et al.*, 2000) or ordination methods (e.g., Reyers *et* *al.*, 2002). A thorny issue in such multivariate approach is the uncertainty over the optimal number of clusters ('*biomes*') to be extracted for further investigations. In an attempt to overcome this problem, Dufrêne and Legendre (1997) developed Indicator Species Analysis in which indicator values of all the species for each biome were computed along with their associated *P*-values at different cluster levels, and the 'most significant' number of clusters would be the one at which the mean *P*-value was observed to be the lowest. This has also been successfully adopted in some of the recent studies to identify unique sets of ecological communities and assemblages and their indicator species (e.g., Orrock *et al.*, 2000; Heino *et al.*, 2003; Venier & Pearce, 2005). Once the biomes are identified, they are mapped along with the existing PA network to assess how much area of each biome is legally protected. If a biome is indeed found to be under-represented, new sites in the biome have to be identified and prioritized for inclusion in the PA network, using principles of reserve selection algorithms.

Though the need for developing a more representative network of PAs using site-based norms was recognized earlier (e.g., Kirkpatrick, 1983; Margules *et al.*, 1988; Vane-Wright *et al.*, 1991), it was Pressey *et al.* (1993) who formulated an analytical framework for rationalizing PA network with the establishment of three key principles of reserve selection criteria: *complementarity* ('sites selected should complement the existing PA network in their coverage of species and ecosystems, thus maximizing the representativeness of conservation network'), *irreplaceability* ('sites selected should possess the highest conservation value measured as the inverse of the number of equally valuable alternative sites'), and *flexibility* ('sites selected should feature maximum diversity of species, showing a high degree of congruence across taxa'). But it is not always possible to apply all the three criteria, especially when flexibility requires data on species distribution of multiple taxa. Most of the studies, therefore, choose complementarity and irreplaceability as measures of conservation assessment in systematic reserve selection (e.g., Harrison & Martinez, 1995; Csuti *et al.*, 1997; Muriuki *et al.*, 1997; Ferrier *et al.*, 2000; Tsuji & Tsubaki, 2004).

While complementarity is evaluated by simply examining the degree of spatial overlap between existing PA network and ecological biomes, computation of irreplaceability of sites is not so straightforward. In general, three families of algorithms are employed to measure irreplaceability of sites for prioritization: species richness-based greedy algorithms, rarity-based heuristic algorithms, and linear programming-based branch-and-bound algorithms (see Csuti *et al.*, 1997 for a comprehensive review). Though linear optimization tools return the best results, they are computationally intensive and take unduly longer time with large datasets. Therefore, a combination of richness and rarity-based algorithms is usually recommended as an alternative (e.g., Briers, 2002; Tsuji & Tsubaki, 2004), and such a hybrid approach has also been known to yield surprisingly near-optimal solutions (Csuti *et al.*, 1997; Sarkar *et al.*, 2004; but see Rodrigues & Gaston, 2002b). Another recent trend is the use of probabilistic models in reserve selection procedures that aim to achieve solutions close to that of linear programming yet as expeditious as greedy algorithms (e.g., Ferrier *et al.*, 2000; Polasky *et al.*, 2000). But these probabilistic models suffer from the untenability of two of their key assumptions: i) occurrence of a species in a site is independent of its occurrence in other sites and ii) occurrence of a species in a site is independent of other species in the site. There are also attempts to develop systematic protocols for rationalizing reserve network with spatially explicit algorithms that assume nonlinear species distribution models (e.g., Moilanen, 2005).

The reserve selection algorithms are, however, not universally accepted and they are sometimes disapproved on the following grounds:

- They tend to ignore population viability, conservation threats, and other key ecological information while choosing sites (Goldstein, 1999; Reyers *et al.*, 2002).
- They do not take into account connectivity between sites (Briers, 2002).
- They do not always reflect local expert knowledge (Cowling *et al.*, 2003; Lindh & Martin, 2004).
- They are equivocal about the locally rare but globally common populations at their range-peripheries (Hunter & Hutchinson, 1994; Lessica & Allendorf, 1995; but see Csuti *et al.*, 1997).
- They do not consider phylogenetic diversity (Rodrigues & Gaston, 2002a).

A further issue that warrants caution would be the conflicting evidences on the presumed congruence across taxa in spatial patterns of species diversity, an important premise in one of the reserve selection criteria, i.e., flexibility. In fact, some authors contend that flexibility should be accorded primacy over complementarity or irreplaceability while prioritizing sites for PA network (see Caro & O'Doherty, 1999;

Hopkinson *et al.*, 2001). Even as several investigations found little support for such a spatial congruence across taxa (e.g., Prendergast *et al.*, 1993; Hopkinson *et al.*, 2001; Rey Benayas & de la Montaña, 2003; Yip *et al.*, 2004), a nearly equal number of studies have observed a reasonably strong concordance among different taxa in geographical distribution of species richness or endemism (e.g., Williams *et al.*, 1997; Garson *et al.*, 2002; Negi & Gadgil, 2002).

Despite these limitations, principles of systematic reserve selection have been hugely successful in designing a rational network of Protected Areas that aims to maximize protection of key species and biomes against overriding political and socio-economic considerations (Reyers *et al.*, 2002; Whittaker *et al.*, 2005). In this chapter, I intend to apply some of these principles to assess the efficacy of the existing PA network in Central Indian Highlands using birds as reference taxa. First, geographical patterns in species richness and composition of breeding birds are examined at quarter-degree grid cells to identify and extract major 'avian biomes' of the region by means of a combination of hierarchical clustering and indicator species analysis. All the biomes are, then, assessed for their extent of coverage in the current PA network. The adequacy of area under protection in each biome is evaluated against the IUCN's 10 % biome-area target. In case of a shortfall, new sites are identified and proposed for inclusion in the PA network after the sites are ranked and prioritized within the biome using a rarity and richness-based hybrid algorithm. Such a systematic approach to spatial conservation planning is especially pertinent for a region like central India where biodiversity conservation ought to be weighed against the largely forest-based livelihood options of the tribal societies.

7.2. METHODS

7.2.1. Study area

The study was conducted in Central Indian Highlands in Madhya Pradesh, which comprise the Satpura and the Vindhya Ranges and extend over an area of about 200,000 sq. km. The mean elevation of the hill ranges varies between 200-800 m, while some of the peaks in western and central ranges exceed 1000 m. The natural vegetation is predominantly made up of tropical dry- and moist-deciduous forests, characterized by associations of teak (*Tectona grandis*) in western and central parts, and sal (*Shorea robusta*) in the east. These forests cover about 29 % of the total land area (Source: IRS 1D-LISS III & FSI). There are 20 Protected Areas (i.e., 6 National Parks + 14 Wildlife Sanctuaries) in the landscape and they occupy about 13 % of the total forest area [see Appendix 2.2 for a list of PAs in Central Indian Highlands].

The entire study area was gridded into quarter-degree cells (15′X 15′) or '*quadrats*' (corresponding to Survey of India's 1:50,000 scale toposheets), with each quadrat measuring about 27 X 26.5 km in size (c. 715 sq. km.). This generated 284 contiguous grid-cells in total, and these quadrats formed the primary sampling units at which bird species richness and composition were mapped. To facilitate systematic bird surveys, these quadrats were grouped, a priori, into 11 conterminous landscape units ('*regions*') on the basis of natural vegetation, drainage, topography, and eco-climatic attributes, as follows: Malwa Plateau, Nimar Hills, Lower Narmada Valley, Betul Plateau, Sagar-Damoh Plateau, Satpura Plateau, Seoni-Chhindwara Plateau, Vindhya Scarplands, Kaimur Hills, East Maikal Range, and South Maikal Range [see Appendix 5.1 for a brief description of these regions].

7.2.2. Birds

Data on species richness and composition of land birds that were known to breed in each quadrat were collected between April and July during 2002-04. As the study area was too expansive to cover within a short period, I adopted a spatially hierarchical sampling protocol which had the following components: i) identification and mapping of key vegetation types in all the quadrats of each region, ii) inventory-survey of breeding birds in each of the key vegetation types, and iii) interpolating species occurrence for all the quadrats of the region from both these information layers [See Section 5.2.2 for a comprehensive description of the bird sampling methodology and the underlying assumptions and limitations].

Though the field-surveys targeted all the land bird species that were known to breed regularly in Central Indian Highlands, several species were excluded from the final analysis owing to insufficient data. These included all the three species of buttonquail (*Turnix* spp.), Asian Palm Swift (*Cypsiurus balasiensis*), Brahminy Kite (*Haliastur indus*), Forest Owlet (*Heteroglaux blewitti*), Ashy Woodswallow (*Artamus fuscus*), White-bellied Minivet (*Pericrocotus erythropygius*), Spotted Creeper (*Salpornis spilonotus*), and Green Avadavat (*Amandava formosa*). In total, 190 species of land birds for which I had adequate data were included in the analysis. [See

Appendix 5.3 for a region-wise list of the breeding land birds of Central Indian Highlands].

7.2.3. Analysis

The data matrix describing the occurrence of 190 species of birds in 284 quadrats was first subjected to hierarchical clustering to classify the quadrats into categorical biomes. As the data was binary in nature (i.e., presence/absence of species), Sørenson's distance measure was used in conjunction with flexible beta linkage (β = -0.25) to extract the clusters. This combinatorial strategy is often recommended as it turns out to be the most space-conserving clustering algorithm for binary data (McCune & Grace, 2002). However, the actual number of statistically significant clusters present in the dataset would still remain unresolved, and I concurrently used Indicator Species Analysis (ISA) to choose the optimal number of biomes from the cluster dendrogram (following Dufrêne & Legendre, 1997; McCune & Grace, 2002).

ISA is a non-parametric, intuitive technique in which indicator value of a species for a given biome is computed as the product of '*faithfulness*' (proportion of sites/samples within the biome in which the species is present) and '*exclusivity*' (inverse of the total number of biomes in which the species occurs), expressed as percentage. The values range from zero (poorest indicator) to 100 % (perfect indicator). The statistical significance of indicator values is estimated by means of Monte Carlo randomizations. In order to ascertain the number of significant clusters to be extracted from the classification output, multiple runs of cluster analyses are carried out over a specified range of cluster-levels (usually from a few clusters higher than the 'expected level' down to two clusters). At each level of clustering, indicator values and their associated *P*-values of all the bird species are calculated and averaged across the biomes. The optimal number of clusters would then be determined as the one at which either the mean indicator value is noted to be the highest or the mean *P*-value is observed to be the lowest. [See McCune & Grace (2002) for further details].

Accordingly, I ran a series of clustering [from 15 to 2 clusters] to classify the quadrats into biomes, and means of both indicator values and *P*-values [with 999 randomizations] were computed at each cluster level. The lowest *P*-value was used as the criterion to set the number of biomes to be identified and extracted. Both the cluster analysis and ISA were performed in the statistical program PC-ORD Version 4.0 (McCune & Mefford, 1999).

Quadrats representing different biomes were, then, mapped along with the existing PA network to calculate the proportion of area in each biome that is currently under legal protection. For this, the area of PA network in each biome was computed and contrasted with the total biome area [i.e., area under 'dense forest cover' across all the quadrats of the biome, estimated from UMD-GLCF data (Hansen *et al.*, 2000) and FSI toposheets]. If a PA was to be found extending over more than one quadrat, the area of the PA in each quadrat would be calculated separately. This was necessary, as PA might sometimes stretch across two quadrats which were assigned to two different biomes in the cluster analysis. I applied the IUCN's target of 10 % area (Locke & Dearden, 2005) as the minimum benchmark for assessing the adequacy of PA network in each biome. In case a biome was to be found under-protected, quadrats containing potential sites for addition to the PA network would be selected by means of reserve selection algorithms.

I developed a richness and rarity-based hybrid algorithm to rank quadrats for their conservation value expressed as irreplaceability, which was calculated as follows:

$$\text{Irreplaceability of a quadrat } q\ (\%) = [\Sigma\Phi * S_q / S^2_{max}] * 100$$

where, S = bird species richness, and Φ = normalized rarity score (0-1), an additive function of geographical range size, habitat specialization, and population size.

The eight rarity classes as developed by Rabinowitz *et al.* (1986) were adopted with modifications to compute rarity score for each bird species. See Table 7.2 for the definitions and scores of different rarity criteria used in the algorithm. [Also see Appendix 7.1 for a list of bird species of the Central Indian Highlands along with their rarity scores].

In the end, connectivity of quadrats within a biome was used to break the ties between sites with equal irreplaceability values (after Briers, 2002). Sites selected were then proposed for PA status to complement the existing PA network in the region.

Table 7.2. Rarity classes along with their definitions and scores adopted in the study from Rabinowitz *et al.* (1986) for the breeding land birds of Central Indian Highlands (CIH).

Geographical range within CIH [1]	**Habitat choice in CIH** [2]	**Population size within CIH**	**Rarity score**	**No. of bird species**
WIDE (>33 % grid occupancy)	BROAD (≥ 4 habitats)	Somewhere LARGE	1	82
		Everywhere SMALL	2	4
	RESTRICTED (≤ 3 habitats)	Somewhere LARGE	3	34
		Everywhere SMALL	4	13
NARROW (<33 % grid occupancy)	BROAD (≥ 4 habitats)	Somewhere LARGE	5	5
		Everywhere SMALL	6	5
	RESTRICTED (≤ 3 habitats)	Somewhere LARGE	7	32
		Everywhere SMALL	8	15

[1] Out of the total number of 284 quadrats, occupancy of 93 quadrats and less was counted as 'narrow' range & occupancy of 94 quadrats and above was defined as 'wide' range.

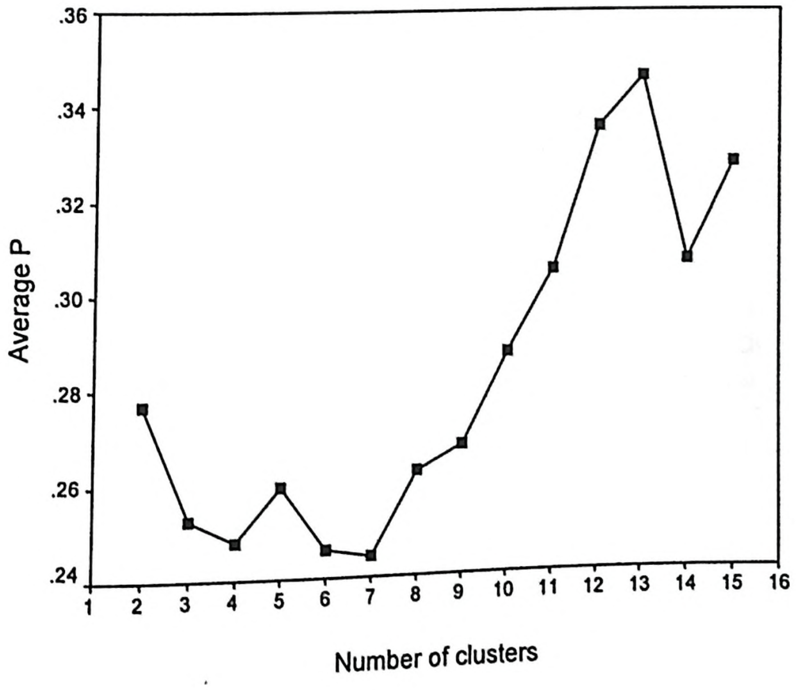
[2] Seven broad habitat types were considered : i) dry-deciduous forests, ii) moist-deciduous forests, iii) bamboo-dominant forests, iv) open grasslands, cultivation, and glades in forested tracts, v) scrub jungle, vi) agricultural fields, villages, and open countryside, and vii) urban environments.

7.3. RESULTS

7.3.1. Classification of avian biomes

When average *P*-values associated with the indicator values of bird species as computed by ISA were examined against the number of cluster-levels of quadrats, the lowest *P*-value was obtained for seven clusters (Figure 7.1).

Figure 7.1. Scatterplot showing the change in mean *P*-values of indicator values of bird species in response to different levels of clusters of quadrats in Central Indian Highlands. Note that the optimal number of clusters was found to be seven as the lowest *P*-value was obtained at this level.



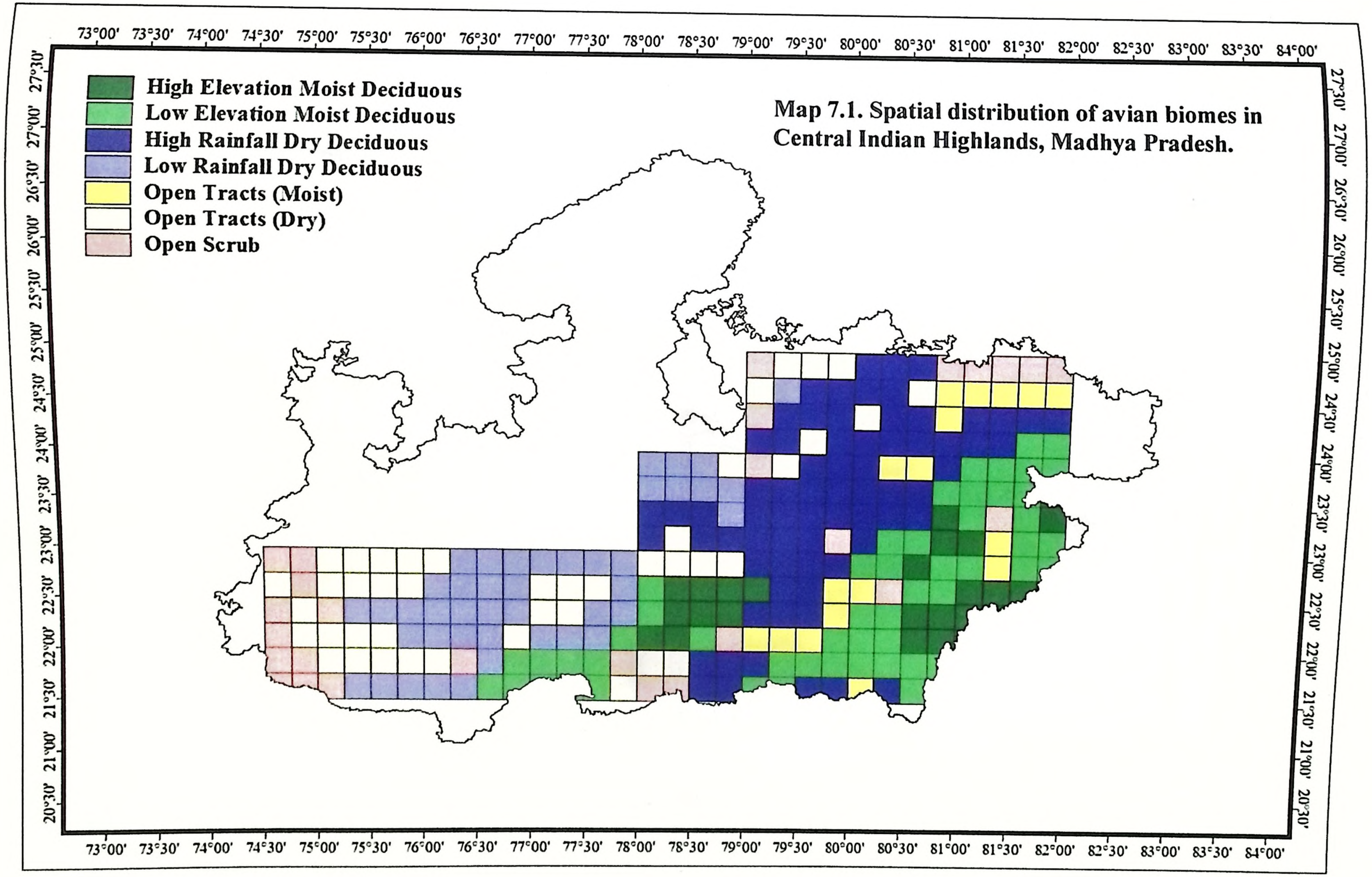
Correspondingly, a final run of cluster analysis with a solution of seven clusters was carried out [see Figure 7.2 for the resultant dendrogram]. It could be seen from the dendrogram that the quadrats were classified into seven distinct groups falling under the following four vegetation types (as deduced from UMD-GLCF land use data):

1. Open tracts-I & II
2. Scrub jungle
3. Dry deciduous forests-I & II
4. Moist deciduous forests-I & II

To aid further construction of the clusters, the relative positions of these groups along some environmental gradients were examined by comparison of group-means and degree of overlaps in 95 % confidence intervals about the mean. The clusters were observed to differ significantly along either rainfall or elevation (Figure 7.3), yielding the following biomes (see Map 7.1):

1. Open moist tracts
2. Open semiarid tracts
3. Scrub jungle
4. Low-rainfall dry deciduous forests
5. High-rainfall dry deciduous forests
6. Low-elevation moist deciduous forests
7. High-elevation moist deciduous forests

Out of these seven avian biomes, only the four forest-biomes were considered for further investigations into adequacy of PA network. Open tracts and scrub jungle were omitted from analysis as they were essentially human-modified environments and were found to be less useful as reserve selection criteria being dominated by generalist birds in great abundance.



Map 7.1. Spatial distribution of avian biomes in Central Indian Highlands, Madhya Pradesh.

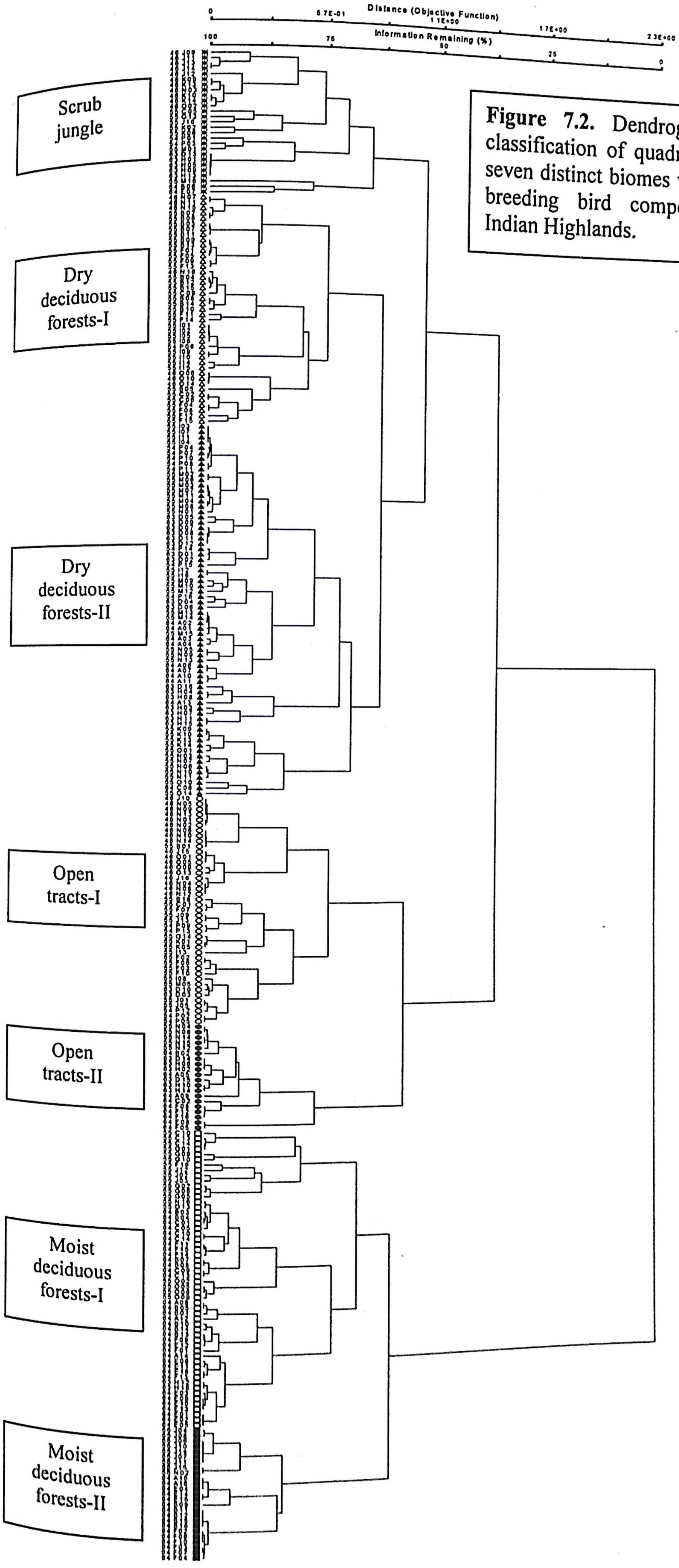
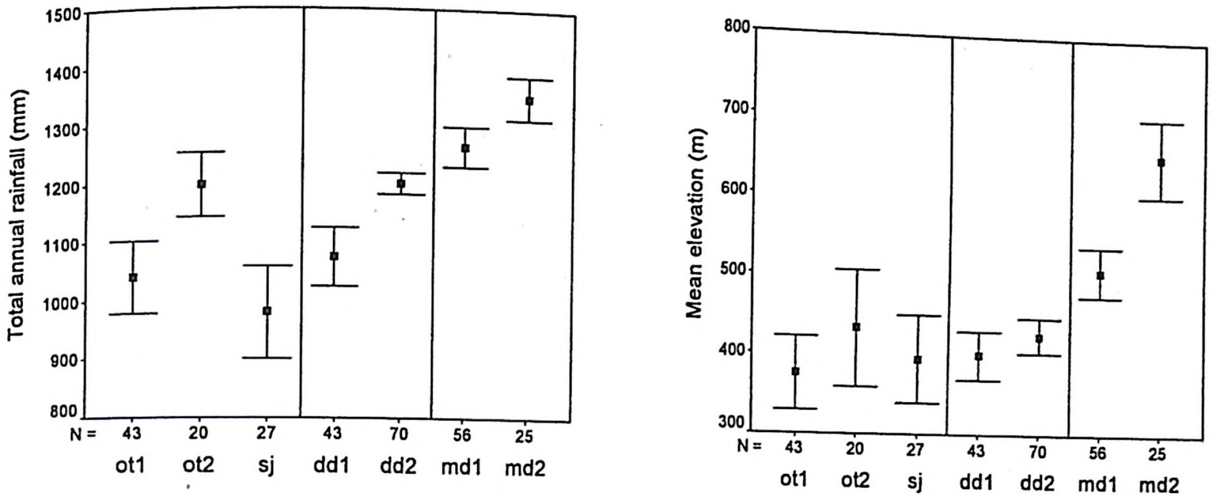


Figure 7.2. Dendrogram showing the classification of quadrats (N = 284) into seven distinct biomes with respect to their breeding bird composition in Central Indian Highlands.

Figure 7.3. Comparison of environmental attributes of the seven biomes as obtained in the hierarchical clustering of quadrats in Central Indian Highlands based on bird distribution. The error bars correspond to lower and upper 95% CI about the mean. The abbreviations of biomes are as following: ot = open tracts, sj = scrub jungle, dd = dry deciduous forests, and md = moist deciduous forests. Note that two classes of open tracts and that of dry deciduous forests segregate along rainfall, and the two groups of moist deciduous forests differ along elevational gradients.



7.3.2. Indicator species of avian biomes

Indicator values (IV) of all the bird species were computed in ISA for each biome and only those species with statistically significant values (P < 0.01) were regarded for further screening. Among them, species were assigned as indicator taxa to a biome for which the IV was observed to be the largest. Of all biomes, high-elevation moist deciduous forests were characterized by species with very high indicator values. On the contrary, both the biomes of dry deciduous forests were marked by generally low mean indicator values [see Table 7.3 for complete a list of major indicator taxa for each of the four avian biomes].

Table 7.3. Major indicator birds of the four forest-biomes of Central Indian Highlands along with their indicator values (IV) and associated *P*-values as estimated by ISA.

Avian Biome	Indicator Species	IV	*P*
High-elevation moist deciduous forests	1. Emerald Dove *Chalcophaps indica*	62	0.001
	2. Brown Hawk Owl *Ninox scutulata*	62	0.001
	3. Spangled Drongo *Dicrurus hottentottus*	61	0.001
	4. Puff-throated Babbler *Pellorneum ruficeps*	60	0.001
	5. Oriental Scops Owl *Otus sunia*	58	0.001
	6. Brown-cheeked Fulvetta *Alcippe poioicephala*	58	0.001
	7. Indian Scimitar Babbler *Pomatorhinus horsfieldii**	58	0.001
	8. Malabar Pied Hornbill *Anthracoceros coronatus**	58	0.001
	9. White-throated Fantail *Rhipidura albicollis*	57	0.001
	10. Rufous Woodpecker *Celeus brachyurus*	56	0.001

Avian Biome	Indicator Species	IV	P
	11. Streak-throated Woodpecker *Picus xanthopygaeus*	56	0.001
	12. Bonelli's Eagle *Hieraaetus fasciatus*	54	0.001
	13. Oriental Turtle Dove *Streptopelia orientalis*	54	0.001
	14. Malabar Whistling Thrush *Myophonus horsfieldii**	53	0.001
	15. Ashy Drongo *Dicrurus leucophaeus*	52	0.001
	16. Bar-winged Flycatcher-shrike *Hemipus picatus*	52	0.001
	17. Lesser Yellownape *Picus chlorolophus*	51	0.001
	18. Velvet-fronted Nuthatch *Sitta frontalis*	49	0.001
	19. Banded Bay Cuckoo *Cacomantis sonneratii*	48	0.001
	20. Scarlet Minivet *Pericrocotus flammeus*	46	0.001
	21. Red-whiskered Bulbul *Pycnonotus jocosus*	36	0.001
	22. Crested Goshawk *Accipiter trivirgatus*	34	0.001
	23. Grey-headed Flycatcher *Culicicapa ceylonensis*	26	0.001
	24. White-rumped Shama *Copsychus malabaricus*	25	0.001
Low-elevation moist deciduous forests	1. Greater Racket-tailed Drongo *Dicrurus paradiseus*	42	0.001
	2. Golden-fronted Leafbird *Chloropsis aurifrons*	41	0.001
	3. Pale-billed Flowerpecker *Dicaeum erythrorhynchos**	40	0.001
	4. Orange-headed Thrush *Zoothera citrina*	37	0.001
	5. Black-naped Monarch *Hypothymis azurea*	37	0.001
	6. Drongo Cuckoo *Surniculus lugubris*	36	0.001
	7. Changeable Hawk Eagle *Spizaetus cirrhatus*	35	0.001
	8. Black-hooded Oriole *Oriolus xanthornus*	35	0.001
	9. Red Junglefowl *Gallus gallus*	34	0.001
	10. Crested Serpent Eagle *Spilornis cheela*	32	0.001
	11. Grey Nightjar *Caprimulgus indicus*	32	0.001
	12. Alexandrine Parakeet *Psittacula eupatria*	32	0.001
	13. Chestnut-bellied Nuthatch *Sitta castanea*	31	0.001
	14. Chestnut-tailed Starling *Sturnus malabaricus*	30	0.001
	15. Indian Cuckoo *Cuculus micropterus*	29	0.001
High-rainfall dry deciduous forests	1. Collared Scops Owl *Otus bakkamoena*	27	0.001
	2. Jungle Owlet *Glaucidium radiatum*	27	0.001
	3. White-naped Woodpecker *Chrysocolaptes festivus**	26	0.001
	4. Pallas's Fish Eagle *Haliaeetus leucoryphus*	26	0.001
	5. Indian Pitta *Pitta brachyura**	26	0.001
	6. Indian Grey Hornbill *Ocyceros birostris**	23	0.001
	7. Plum-headed Parakeet *Psittacula cyanocephala**	22	0.001
	8. White-bellied Drongo *Dicrurus caerulescens**	22	0.001
	9. Yellow-crowned W'pecker *Dendrocopos mahrattensis*	20	0.001
	10. Grey-bellied Cuckoo *Cacomantis passerinus**	20	0.001
	11. Crested Treeswift *Hemiprocne coronata*	20	0.001
	12. Yellow-footed Green Pigeon *Treron phoenicoptera*	20	0.001
	13. Blue-winged Leafbird *Chloropsis cochinchinensis*	20	0.001
	14. Large Cuckooshrike *Coracina macei*	20	0.001

Avian Biome	Indicator Species	IV	*P*
Low-rainfall dry deciduous forests	1. Tawny-bellied Babbler *Dumetia hyperythra**	26	0.001
	2. Oriental Honey Buzzard *Pernis ptilorhyncus*	24	0.001
	3. Jungle Prinia *Prinia sylvatica**	23	0.001
	4. Mottled Wood Owl *Strix ocellata**	21	0.001
	5. White-eyed Buzzard *Butastur teesa*	21	0.001
	6. Jungle Bush Quail *Perdicula asiatica**	20	0.001
	7. Brown-capped Pygmy W'pecker *Dendrocopos nanus**	20	0.001
	8. Black-headed Cuckooshrike *Coracina melanoptera*	20	0.001
	9. Small Minivet *Pericrocotus cinnamomeus*	20	0.001
	10. White-browed Fantail *Rhipidura aureola*	20	0.001

* Endemic to the Indian subcontinent

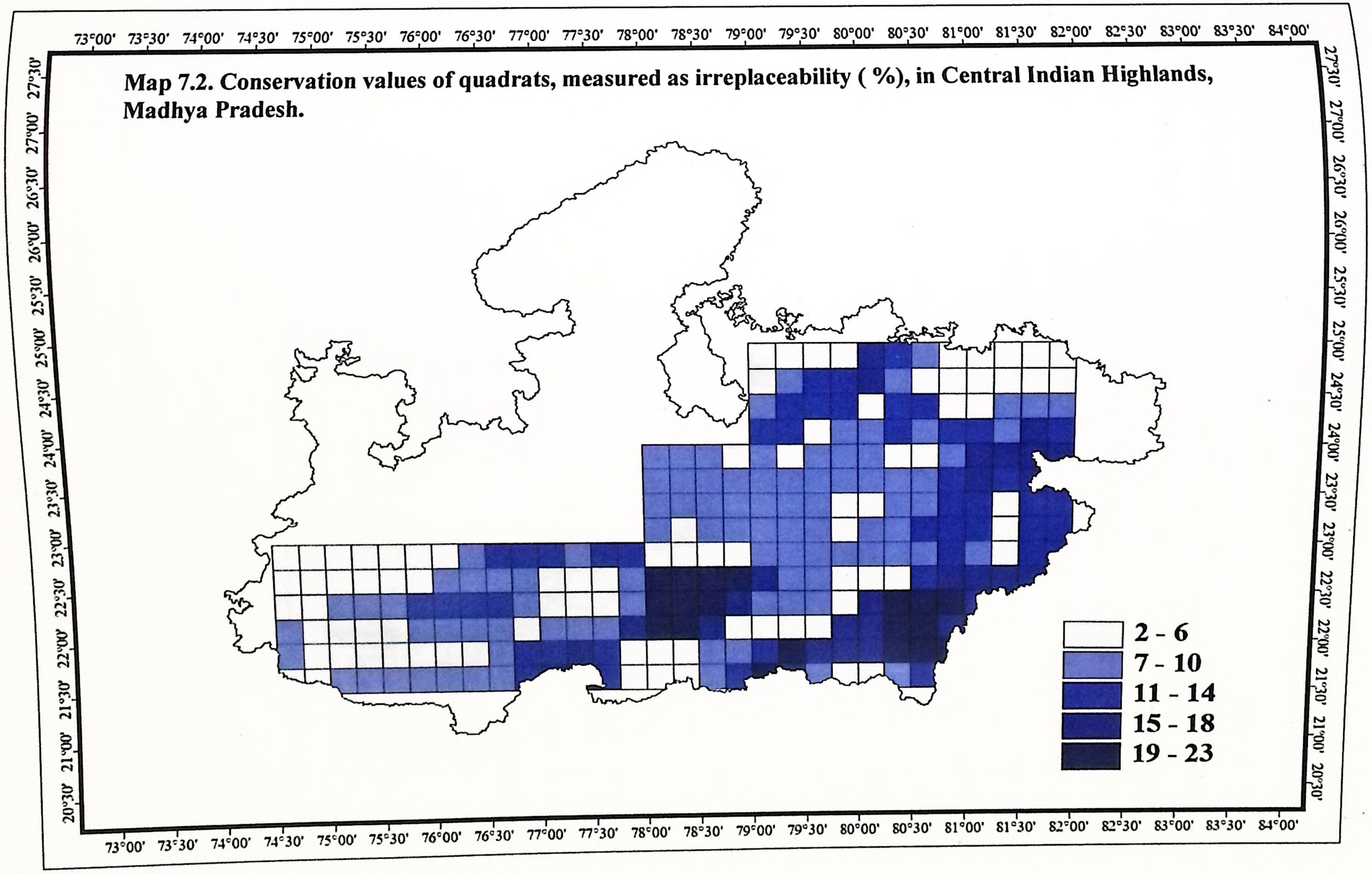
7.3.3. Adequacy of PA network

When the boundaries of the existing PAs, comprising National Parks and Wildlife Sanctuaries, were overlaid on the map of quadrats representing the four avian biomes, it was observed that all the biomes were adequately covered with PA network (i.e., > 10 % of area) barring the low-rainfall dry deciduous forests with a shortfall of about 3 % area as per IUCN norms. In contrast, the high-elevation moist deciduous forests had a fairly large proportion of area (c. 20 %) under protection (Table 7.4). Refer to Appendix 7.2 for quadrat and biome-wise distribution of PAs in Central Indian Highlands.

Table 7.4. The proportion of area under PA network in each of the four forest-biomes of Central Indian avifauna. Note that the low-rainfall dry deciduous forest biome is under-represented with less than 10 % of area under legal protection.

Avian biome	Total forest area (sq. km.)	Forest area under PAs (sq. km.)	% Area under PA network
High-elevation moist deciduous forests	9512	1876	19.72 %
Low-elevation moist deciduous forests	18741	2256	12.04 %
High-rainfall dry deciduous forests	16501	1975	11.97 %
Low-rainfall dry deciduous forests	8883	607	6.83 %

Map 7.2. Conservation values of quadrats, measured as irreplaceability (%), in Central Indian Highlands, Madhya Pradesh.



7.3.4. Site prioritization using reserve selection algorithm

As low-rainfall dry deciduous forest was found to be the only under-protected biome for central Indian avifauna, the quadrats within this biome were assessed and ranked using irreplaceability values to identify new sites for addition to the PA network [refer to Map 7.2 showing different classes of quadrats with respect to their irreplaceability values over the entire Central Indian Highlands]. Interestingly, the first four quadrats that were prioritized as having top-ranking sites for low-rainfall dry deciduous forest biome were found to lie outside the existing PA network, though quadrats of subsequent ranks did house two protected forests as wildlife sanctuaries (Table 7.5). Among these four quadrats, the first three were selected for proposal of a new PA owing to their connectivity. It was also prompted by the fact that the provisional Choral Wildlife Sanctuary as proposed by Rodgers & Panwar (1988) was located in these quadrats.

Table 7.5. Ranking of quadrats within 'low-rainfall dry deciduous forest' biome for their conservation values estimated using rarity-based reserve selection algorithm in Central Indian Highlands. Note that the first four quadrats that top in their irreplaceability values are actually outside the existing PA network.

Conservation rank	Grid Id	Irreplaceability (%)	Area under PA (sq. km.)	Name of the PA/RF
1	55B/03	12.42		Choral (*Proposed*) WLS
2	55B/07	12.20		Nimanpur RF
3	55B/11	11.23		Chandgarh RF
4	55B/09	11.10		Narpakheri RF
5	55F/09	10.97	288	**Ratapani WLS**
6	55F/13	10.93	172	**Ratapani WLS**
7	55B/13	10.93	123	**Kheoni WLS**

7.4. DISCUSSION

The study amply demonstrates the potential of Indicator Species Analysis (ISA) in eliciting the structure and composition of biomes for a given taxon in a landscape, and how these biomes can be objectively used in assessing the adequacy of conservation efforts in the region. Analysis of geographical distribution of the breeding land birds in Central Indian Highlands using hierarchical clustering and ISA has revealed presence of seven distinct ecological units, and accordingly the quadrats are grouped into seven parallel sets of biomes. These biomes representing unique assemblages of central Indian avifauna are evidently organized along three environmental gradients: vegetation physiognomy, elevation, and rainfall. The role of environment in structuring vegetation communities and secondarily the associated faunal assemblages has been acknowledged as one of the unfailing patterns in macroecology (Brown, 1999; Hawkins *et al.*, 2003; Whittaker *et al.*, 2005), and such species-environment relationships have been successfully applied in delineating biogeographical boundaries among a region's avifauna (e.g., Crowe & Crowe, 1982; O'Connor *et al.*, 1996; Williams *et al.*, 1999).

The tropical seasonal forests of central India show a marked gradient of moisture ranging from extremely dry forests in the west (e.g., Malwa Plateau) to wet forests in the south-east (e.g., Maikal Ranges), heavily influencing the composition and proportion of floristic associations alongside. For example, sal (*Shorea robusta*) dominates the climax vegetation of the moist deciduous forests in the east and south-eastern parts of Madhya Pradesh, and teak (*Tectona grandis*) forms core of the vegetation associations among the dry deciduous forests in central and western parts of the state. These changes in floristic composition are often accompanied by corresponding changes in bird composition as well, sometimes mediated through species replacements within closely related taxa [e.g., Red Junglefowl (*Gallus gallus*) in the sal and Grey Junglefowl (*Gallus sonneratii*) in the teak biotopes; also see sections 3.4 & 5.4). Not surprisingly, forest physiognomy is observed in the study as the key ecological factor that primarily defines the avian biomes of Central Indian Highlands. In succession, birds of moist deciduous forests show two distinct assemblages in response to elevational gradient, and differences in rainfall seem to describe the two biomes of dry deciduous forests.

Of the four forest-biomes of central Indian avifauna, high-elevation moist deciduous forests are characterized by bird species with extraordinarily high indicator values (Mean $IV_{(n=190)}$ = 20.31 %), signifying the uniqueness of the biome with a large number of biome-specialists (IV > 50 % for 17 species). These include Malabar Pied Hornbill (*Anthrococeros coronatus*), Oriental Scops Owl (*Otus sunia*), Ashy Drongo (*Dicrurus leucophaeus*), Malabar Whistling Thrush (*Myophonus horsfieldii*), Velvet-fronted Nuthatch (*Sitta frontalis*), Red-whiskered Bulbul (*Pycnonotus jocosus*), Puff-throated Babbler (*Pellorneum ruficeps*), Indian Scimitar Babbler (*Pomatorhinus horsfieldii*), and Brown-cheeked Fulvetta (*Alcippe poioicephala*). Biogeographically, birds of high-elevation moist deciduous forest biome are significant as they represent remnants of the avifauna of wet humid montane forests in the past which acted as dispersal highway for Indo-Malayan fauna from the Eastern Himalayas to the Western Ghats according to the '*Satpura Hypothesis*' (Ali, 1949; Hora, 1949; see Karanth, 2003 for a recent review).

The low-elevation moist deciduous biome is noteworthy for its regional importance as it is by far the most dominant in area of extent in Central Indian Highlands. Though the cumulative mean indicator value of the biome is marginally less than its high-elevation counterpart (Mean $IV_{(n=190)}$ = 15.37 %), some species of birds do show a great degree of affinity with indicator values exceeding 40 %. Prominent among the birds that almost exclusively breed in low-elevation moist deciduous forests are Red Junglefowl (*Gallus gallus*), Drongo Cuckoo (*Surniculus lugubris*), White-rumped Needletail Swift (*Zoonavena sylvatica*), Changeable Hawk Eagle (*Spizaetus cirrhatus*), Golden-fronted Leafbird (*Chloropsis aurifrons*), Black-naped Monarch (*Hypothymis azurea*), and Chestnut-bellied Nuthatch (*Sitta castanea*).

Unlike the avifauna of moist-deciduous forests, both the high- and low-rainfall biomes of dry deciduous forests are generally marked by bird species with moderate indicator values (Mean $IV_{(n=190)}$ = c. 11 %). However, they form one of the most ubiquitous assemblages of birds that one encounters in the central Indian landscape. In fact, high-rainfall dry deciduous forests are second only to low-elevation moist deciduous forests in geographical extent, covering over an area of nearly 16,000 sq. km. An interesting feature common to indicator birds of both the dry deciduous forest biomes is that they shelter a good proportion of species endemic to the Indian Subcontinent [e.g., White-naped Woodpecker (*Chrysocolaptes festivus*), Indian Grey Hornbill (*Ocyceros birostris*), Indian Pitta (*Pitta brachyura*), White-bellied Drongo (*Dicrurus caerulescens*) among the breeding birds of high-rainfall dry deciduous biome, and Jungle Bush Quail (*Perdicula asiatica*), Brown-capped Pygmy Woodpecker (*Dendrocopus nanus*), Mottled Wood Owl (*Strix ocellata*), Jungle Prinia (*Prinia sylvatica*), and Tawny-bellied Babbler (*Dumetia hyperythra*) in low-rainfall dry deciduous forest biome]. This is probably a reflection of the fact that forests in the Subcontinent are chiefly dry deciduous in nature. If it were to be believed so historically too (as inferred from the remarkable number of endemic birds in the indicator taxa), it would lend little support to the vicariance hypothesis of the occurrence of wet-zone taxa in Western Ghats rendering the dispersal along the peninsular hills as the more plausible and parsimonious model (see Karanth, 2003). Thus, the preponderance of endemic species as indicator taxa makes both high- and low-rainfall biomes of dry deciduous forests biologically significant and calls for adequate conservation measures.

Indicator Species Analysis is a promising tool in macroecological applications, and is being increasingly used in place of classification and ordination methods (e.g., Dufrêne & Legendre, 1997; Orrock *et al.*, 2000; Heino *et al.*, 2003; Venier & Pearce, 2005). One of the reasons for its popularity is that ISA is relatively free of many of the key assumptions and data-constraints traditionally associated with multivariate techniques; for example, assignment of a species to a biome in ISA is independent of other members of the biome unlike TWINSPAN (Dufrêne & Legendre, 1997), and ordination method like Canonical Correspondence Analysis would require unimodal response of species to environmental gradients, an assumption often difficult to meet with ecological data (McCune & Grace, 2002; Reyers *et al.*, 2002). Some of the other emergent properties of ISA that favour its widespread use are: straightforwardness of distribution algorithms, flexibility with presence/absence data, tractability of computations, use of objective criteria to identify and retrieve indicator species, incorporation of randomization methods to evaluate statistical significance of indicator scores, and compatibility with spatial data. The present study has also demonstrated the usefulness of ISA in determining the cutoff level in a dendrogram to extract meaningful clusters, as originally proposed by Dufrêne and Legendre (1997) in their landmark paper.

Identification of biomes using multiple taxa is immensely preferable to single-species approach (e.g., umbrella or flagship species) as the latter frequently fails to ensure adequate protection for several key species and ecosystems (Roberge & Angelstam, 2004; Rodrigues *et al.*, 2004; McCarthy *et al.*, 2006). This is well illustrated by the findings of the current investigation in which 'low-rainfall dry deciduous forests' emerge as the only avian biome in Central Indian Highlands that is under-represented in PA network. Nearly restricted to western Madhya Pradesh, these forests have been overlooked for long by PA managers evidently because they do not hold any significant populations of tiger, a species that almost solely inspires and drives conservation planning and reserve network in central India. It was, therefore, a revelation that when the critically endangered Forest Owlet (*Hetroglaux blewitti*) - a species endemic to Central India, was rediscovered in 1997 after a gap of 113 years (King & Rasmussen, 1998), these low-rainfall dry deciduous forests were found to be its core habitat [contrary to original descriptions of 19th century records]. The fact that eight out of ten sites which are currently holding the fragmented populations of Forest Owlet lie outside PA network highlights the severe bias in reserve planning in Central Indian Highlands. Though the landscape boasts of 13 % forest area under protected forests, they are not equitably distributed across different biomes. For example, high-elevation moist deciduous forests, in contrast to low-rainfall dry deciduous forest biome, have a remarkably high proportion of about 20 % area under PA network exceeding the IUCN's target. It is also to be noted here that all the PAs in this biome including Kanha and Bori-Satpura Conservation Areas were created almost exclusively for the cause of tiger, and these PAs are marked by areas (c.1500 & 1050 km^2 respectively) much larger than the average area of PAs (383.2 km^2) in central India. Despite this prejudice, it is heartening to find that all the biomes of central Indian avifauna, barring low-rainfall dry deciduous forests, are adequately protected with more than 10 % of area in each biome currently under PA network. Ironically, this is again attributed to the creditable role played by charismatic taxa like tiger. It serves to highlight the political relevance of flagship species in our conservation efforts even as we begin to recognize the need for multi-species approach (see Walpole & Leader-Williams, 2002).

When the PA network in low-rainfall dry deciduous forest biome was found in the study to be short of 3 % by IUCN standards, reserve selection algorithms were developed to identify new sites for addition to the PA network. This was achieved by computing irreplaceability values with which quadrats were assessed and ranked for prioritization. This did produce some surprising results. There are no protected forests in any of the first four top-ranking quadrats (all lying in Malwa Plateau), though subsequent quadrats are found to house PAs (i.e., Ratapani WLS and Kheoni WLS). Curiously, the quadrat that emerges as the topmost priority in terms of conservation value in the analysis also turns out to be the intuitive choice of Rodgers & Panwar (1988), who proposed Choral WLS from the same quadrat. The findings of reserve selection analysis for low-rainfall dry deciduous forest biome indeed offer two choices: either an extended sanctuary by combining Choral with the contiguous

Nimanpur RF in the neighbouring quadrat which is ranked next in irreplaceability value, or creation of two small disjunct PAs – Choral in the quadrat 55B/03 and Narpakheri from 55B/09. Though the SLOSS (‘*single large or several small*’) debate is one of the long-standing issues in studies on optimal reserve design (e.g., Diamond, 1975b; Simberloff, 1982; Worthen, 1996), it still eludes consensus among biogeographers (Whittaker *et al.*, 2005). In the mean time, connectivity between sites has been strongly recommended for long-term maintenance of viable populations, even if it means a trade-off in ‘representativeness’ of reserve network (e.g., Nicholls & Margules, 1993; Rothley, 1999; Briers, 2002). It, then, follows that a larger Choral WLS would be the best bet for complementing the existing PA network in low-rainfall dry deciduous forest biome. The fact that the reserve selection algorithm used in the study and an independent biogeographical review of PA network in India (i.e., Rodgers & Panwar, 1988) converge on the same site within the biome as their choice of new PA, testifies to the comprehensiveness of the evaluation criteria used in building the algorithm. They are largely drawn from the rarity classes of Rabinowitz *et al.* (1986), by which a species is assigned a rarity score on the basis of its geographical range size, habitat breadth, and population status. These classes are, however, redefined in the study keeping in view the aims and scope of the investigation (see Humphries *et al.*, 1995); for example, range size is computed here as the number of quadrats occupied by a species within the study area and this ensures that globally common but locally rare populations receive equal weights in the algorithm on par with other rarity classes (following Hunter & Hutchinson, 1994; Lessica & Allendorf, 1995). Though it can, by no means, be claimed as a complete algorithm, it is shown in the study to return near-optimal solutions with considerable economy of efforts and resources.

The application of Indicator Species Analysis in conjunction with reserve selection algorithms has gained widespread approval for its biome-oriented approach to rationalization of PA network. Nevertheless, lack of awareness about these spatial conservation tools along with a general antipathy towards 'prescriptive' approaches to wildlife and reserve management explain why these techniques are consistently under-utilized by conservation planners and field managers (Prendergast *et al.*, 1999). A conceptual issue at stake would, however, be its efficiency, when the entire analysis is restricted to a particular taxon. This is because congruence across different taxa in spatial patterns of species diversity and endemism is not always supported by empirical data (e.g., Prendergast *et al*., 1993; Hopkinson *et al*., 2001; Rey Benayas & de la Montaña, 2003). Future studies should, therefore, strive to reach solutions universally applicable to all major taxa by investigating into conditions under which cross-taxa congruence becomes evident. This would also require data on distribution of multiple taxa from a landscape and concerted efforts are to be in place to achieve these aims.

7.5. SUMMARY

1. I examined, in this chapter, how adequate was the existing PA network in Central Indian Highlands using patterns of geographical distribution in breeding land birds of the region. To begin with, ecologically distinct biomes were identified on the basis of bird species composition and each biome was then assessed independently for the proportion of area under PA network. If a biome was to be found under-protected, new sites were identified and prioritized for addition to PA network using reserve selection algorithms.
2. The study area was gridded into quarter-degree cells (15′ X 15′) or '*quadrats*' (c. 27 X 26.5 km size), and primary data on distribution of breeding land birds were collected for each quadrat using a spatially-hierarchical sampling scheme. In total, distribution of 190 species of birds was mapped for all the 284 quadrats. I employed hierarchical clustering to classify the quadrats into categorical groups with respect to their bird species composition. In conjunction with clustering, Indicator Species Analysis was carried out to determine the optimal number of clusters ('*biomes*') to be extracted and to identify indicator birds for each of the avian biomes recognized in Central Indian Highlands. The proportion of forest area under PA network was then estimated for all the biomes and adequacy of PA network was assessed for each biome against IUCN's target of 10 % area. In case of shortcomings, new sites within the biome were identified and proposed for addition to PA network after the quadrats were ranked and prioritized by means of irreplaceability values. These values were computed using a reserve selection algorithm that took into consideration multiple criteria including the geographical range size, habitat width, and population status of bird species. In the end, connectivity between sites was used to choose between quadrats with comparable rankings.
3. The avifauna of central Indian Highlands was found to be composed of seven biomes along the gradients of vegetation physiognomy, elevation, and rainfall: open tracts (moist & semiarid), scrub jungle, dry deciduous forests (high & low-rainfall), and moist deciduous forests (high & low-elevation). Among the four forest-biomes, both low-elevation moist deciduous forests and high-rainfall dry deciduous forests were observed to be the most dominant in the region in geographical extent. On the other hand, high-elevation moist deciduous forests, despite occupying a smaller area, were characterized by bird species with very high indicator values, signifying a notable presence of biome-specialists.
4. In the analysis of spatial coverage of PA network, the low-rainfall dry deciduous forests emerged as the only under-protected biome in Central Indian Highlands with just 6 % area under PA network, while the remaining three forest-biomes had more than 10 % area currently enjoying legal protection. In particular, the high-elevation moist deciduous forest biome had a fairly high proportion of area (c. 20 %) under PA network. The

subsequent assessment of sites in low-rainfall dry deciduous forest biome revealed that the first four top-ranking quadrats, all lying within Malwa Plateau, were marked by a complete absence of PAs. The reserve selection algorithm, therefore, selected Choral RF from the highest ranking quadrat as the topmost prioity site for addition to the existing PA network. Interestingly, Rodgers & Panwar (1998) had earlier proposed PA status for Choral RF in their biogeographical review of PA network in India.

5. The findings of the study clearly illustrate the bias in PA network that a single-species approach can potentially bring about. The tiger-centric conservation planning in central India is amply evident from the fact that three out of four biomes in Central Indian Highlands have an impressive coverage of PA network but a biome like low-rainfall dry deciduous forests which do not hold any significant populations of tiger remains grossly under-protected. The recent rediscovery of the critically endangered Forest Owlet from these low-rainfall dry deciduous forests highlights the importance of extending adequate protection to all major biomes and the need for multi-species approach in design and maintenance of an efficient PA network in a landscape.

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Appendix 2.1. Distribution, floristics, and classification of major forest types in Central Indian Highlands according to Champion & Seth (1968). Note that the codes and notations are as given in the source.

Group 2. TROPICAL SEMI-EVERGREEN FORESTS

Subgroup 2B. *Northern Tropical Semi-evergreen Forests*

Type 2B/E_3. **Moist bamboo brakes**

Locally throughout moist-deciduous forests in Satpura Plateau and Maikal Ranges

- Bamboo (*Dendrocalamus strictus*)

Group 3. TROPICAL MOIST DECIDUOUS FORESTS

Subgroup 3B. *South Indian Moist Deciduous Forests*

Type 3B/C_{1b}. **Moist teak forest**

North Betul & Hoshangabad divisions

- Teak, *Terminalia alata*, *Adina cordifolia*, *Pterocarpus marsupium*, *Diospyros melanoxylon*, *Miliusa velutina*, *Careya arborea*, & *Schleichera trijuga*
- Bamboo (*D. strictus*)
- *Milletia auriculata* & *Bauhinia vahlii*
- *Helicteres isora*

Type 3B/C_{1c}. **Slightly moist teak forest**

Betul & other parts of southern M.P.

- Teak, *Lagerstroemia parviflora*, *Terminalia alata*, *Anogeissus latifolia*, *Buchanania lanzan*, *Flacourtia indica*, *Lannea coromandelica*, & *Schleichera trijuga*
- Bamboo (*D. strictus*)
- *Butea superba*
- *Grewia hirsuta*

Type 3B/C_2. **Southern moist mixed deciduous forest**

Moist-deciduous forests of southern M.P. in the teak biome (teak occasionally present)

- *Pterocarpus marsupium*, *Bombax ceiba*, *Anogeissus latifolia*, *Dalbergia latifolia*, *Terminalia alata*, *Madhuca indica*, *Garuga pinnata*, *Lannea coromandelica*, & occasional teak
- *Cleistanthus collinus*, *Miliusa velutina*, *Grewia tilaefolia*, & *Diospyros montana*

Subgroup 3C. *North Indian Moist Deciduous Forests*

Type 3C/$C_{2e(i)}$. **Moist peninsular high level sal**

In south-east M.P on undulating hills of 650-820 m (e.g., Kanha, Supkhar)

- Sal, *Syzygium cumini*, *Pterocarpus marsupium*, *Terminalia alata*, *Wendlandia exerta*, *Kydia calycina*, *Ougeinia ougeinensis*, *Bridelia squamosa*, *Terminalia chebula*, & *Bauhinia malabarica*
- *Phoenix acaulis*
- *Bauhinia vahlii*

Type 3C/$C_{2e(ii)}$. **Moist peninsular low level sal**

Eastern M.P mostly about or below 600m

- Sal, *Terminalia alata*, *Pterocarpus marsupium*, *Madhuca indica*, *Emblica officinalis*, *Buchanania lanzan*, & *Diospyros melanoxylon*
- Bamboo (*D. strictus*)

Type 3/E_1. ***Terminalia tomentosa*** **forest**

In eastern M.P, often as the transition zone of vegetation to sal biome

- *Terminalia alata*, Sal & *Syzygium cumini*
- *Mallotus philippinensis*
- *Clerodendrum viscosum*

Group 5. TROPICAL DRY DECIDUOUS FORESTS

Subgroup 5A. *Southern Tropical Dry Deciduous Forests*

Type 5A/C_{ib}. **Dry teak forest**

Most parts of dry-deciduous forests in western and southern M.P between 300-750 m (e.g., Seoni, Indore, & Kannod)

- Teak, *Anogeissus latifolia*, *Diospyros melanoxylon*, *Lagerstroemia parviflora*, *Dalbergia latifolia*, *Emblica officinalis*, & *Aegle marmelos*
- Bamboo (*D. strictus*)

Type 5A/C_3. **Southern dry mixed deciduous forest**

Throughout the dry forests of M.P.

- *Terminalia alata*, *Anogeissus latifolia*, *Boswellia serrata*, *Madhuca indica*, *Emblica officinalis*, *Chloroxylon swietenia*, *Sterculia urens*, *Cassia fistula*, & *Butea monosperma*
- *Adhatoda vasica*, *Grewia* spp., *Holarrhena antidysenterica*, & *Lantana camara*
- *Cassia tora*

Subgroup 5B. *Northern Tropical Dry Deciduous Forests*

Type 5B/C_{1c}. **Dry peninsular sal forest**

In south-central and eastern M.P (Pachmarhi Plateau is the higher limit)

- Sal, *Chloroxylon swietenia, Terminalia tomentosa, Lagerstroemia parviflora, Anogeissus latifolia, & Buchanania lanzan*
- *Holarrhena antidysenterica & Dodonea viscosa*
- *Clematis* spp.

Type 5/E_2. **Dry deciduous *Boswellia* forest**

Western M.P (higher reaches of Nimar Hills) & southern M.P (Seoni)

- *Boswellia serrata, Tectona grandis, Hardwickia binata, Sterculia urens, Cochlospermum religiosum, & Lannea coromandelica*
- Bamboo (*D. strictus*)

Type 5/E_4. **Dry deciduous *Hardwickia* forest**

Western M.P (Barwani in Khargone division of Nimar Hills & Kannod division in Malwa Plateau)

- *Hardwickia binata, Boswellia serrata, Anogeissus latifolia, Lannea coromandelica, & Albizzia lebbek*
- Bamboo (*D. strictus*)

Type 5/E_5. **Dry deciduous *Butea* forest**

Locally throughout the region esp. as village forests / community grazing areas

- *Butea monosperma*, sometimes with sparse cover of *Terminalia alata, Syzygium cumini*, and *Madhuca indica*

Type 5/E_9. **Dry bamboo brakes**

Locally in dry-deciduous forest belt

- Bamboo (*D. strictus*), *Boswellia serrata, Sterculia urens, & Cochlospermum religiosum*

Type 5/1S_1. **Southern dry tropical riverain forest**

Forested riverine stretches in hilly country (e.g. Wainganga in south-eastern M.P)

- *Terminalia arjuna, Mitragyna parvifolia, Holoptelea integrifolia, Bauhinia malabarica, Mallotus philippinensis, & Syzygium cumini*
- *Helicteres isora*

Type 5/2S_1. **Secondary dry deciduous forest**

Chiefly in western M.P & some parts of north-central M.P

- *Prosopis spicigera, Terminalia alata, & Butea monosperma*
- *Lantana camara / Holarrhena antidysenterica*
- *Cassia tora*

Group 6. TROPICAL THORN FORESTS

Subgroup 6A. *Southern Tropical Thorn Forests*

Type 6A/C_1. **Southern thorn forest**

In isolated patches on plateaus in southern M.P

- *Acacia nilotica / A. leucophloea & Ziziphus mauritiana*
- *Heteropogon contortus*

Group 8. SUBTROPICAL BROADLEAVED HILL FORESTS

Subgroup 8A. *Southern Subtropical Broadleaved Hill Forests*

Type 8A/C_3. **Central Indian subtropical hill forest**

Hill-tops over 1000 m in Betul & Satpura Plateaus (e.g., Chikaldhara, Pachmarhi)

- *Manilkara hexandra, Mangifera indica, Syzygium cumini,* & *Ficus* spp.
- *Mallotus philippinensis*

Appendix 2.2. List of Protected Areas (National Parks & Wildlife Sanctuaries) in Central Indian Highlands, Madhya Pradesh.

Sl. No.	Name of the Protected Area	Biogeographical Region	Districts	Geographical area (km^2)	Year of estt.
1	Bandhavgarh NP	East Maikal Range	Umaria & Jabalpur	448.85	1982
2	Kanha NP	South Maikal Range	Mandla & Balaghat	940.00	1955
3	Panna NP	Vindhya Scarplands	Chhatarpur & Panna	542.67	1973
4	Pench NP	Seoni-Chhindwara Plateau	Chhindwara & Seoni	292.85	1975
5	Sanjay NP	East Maikal Range	Sidhi	466.88	1981
6	Satpura NP	Satpura Plateau	Hoshangabad	585.17	1981
7	Bori WLS	Satpura Plateau	Hoshangabad	485.72	1977
8	Ken Gharial WLS	Vindhya Scarplands	Chhatarpur & Panna	45.20	1981
9	Kheoni WLS		Dewas & Sehore	122.70	1982
10	Nauradehi WLS	Sagar-Damoh Plateau	Sagar, Damoh & Narsimhapur	1194.67	1984
11	Pachmarhi WLS	Satpura Plateau	Hoshangabad	417.78	1977
12	Panpatha WLS	East Maikal Range	Shahdol	245.84	1983
13	Pench WLS	Seoni-Chhindwara Plateau	Seoni	118.47	1975
14	Phen WLS	South Maikal Range	Mandla	110.74	1983
15	Ralamandal WLS	Malwa Plateau	Indore	2.34	1989
16	Ratapani WLS	Lower Narmada Valley	Raisen	823.84	1978
17	Sanjay Dubri WLS	East Maikal Range	Sidhi	364.59	1975
18	Sardarpur WLS	Malwa Plateau	Dhar	348.12	1983
19	Son Gharial WLS	Kaimur Hills & East Maikal Range	Sidhi, Shahdol, & Satna	83.60	1981
20	Veerangna Durgawati WLS	Kaimur Hills	Damoh	23.97	1997

Source: *National Wildlife Database Cell, WII*

Appendix 3.1. *List of sampling sites with their attributes used in the study in Central Indian Highlands, Madhya Pradesh. The vegetation measurements are mean values averaged across vegetation plots of 100* m^2 area.

Sl.No.	Vegetation type	Site code	Locality	Tree sp. richness	Tree abund.	GBH	Canopy cover	Tree height diversity	Shrub abund.	Snag abund.	Bamboo abund.	Protection status*
1	Teak mixed plantation	CHP 1	Seoni-Chhindwara Plateau	5.8	11.0	38.8	77.74	0.66	3.2	0.2	0.2	RF
2	Dry-deciduous lowland forest	CHP 2	Seoni-Chhindwara Plateau	7.2	12.3	47.4	90.29	1.01	11.7	0.2	0.0	RF-PA
3	Dry-deciduous hill forest	CHP 3	Seoni-Chhindwara Plateau	6.2	14.3	47.0	90.38	0.98	3.5	0.0	1.2	RF
4	*Butea* scrub jungle	CHP 4	Seoni-Chhindwara Plateau	1.2	3.2	53.5	16.07	0.13	5.0	0.0	0.0	Nil
5	Dry-deciduous *garari* forest (Unprotected)	CHP 5	Seoni-Chhindwara Plateau	5.2	25.0	29.6	86.39	0.78	1.0	0.0	0.0	RF
6	Dry-deciduous teak forest	CHP 6	Seoni-Chhindwara Plateau	3.5	14.8	40.1	85.66	0.92	10.7	1.7	0.2	PA
7	Moist-deciduous bamboo forest	CHP 7	Seoni-Chhindwara Plateau	4.3	12.0	55.6	94.45	0.80	9.3	0.0	5.7	PA
8	Dry-deciduous *garari* forest (Protected)	CHP 8	Seoni-Chhindwara Plateau	3.0	15.5	44.1	89.04	0.42	0.0	1.5	0.0	PA
9	Non-teak mixed hill forest	CHP 9	Seoni-Chhindwara Plateau	7.3	13.3	41.0	85.01	0.89	9.5	1.3	0.0	PA
10	Open deciduous mixed forest	SMR 1	South Maikal Range	5.8	15.7	40.3	87.35	0.85	13.3	0.0	0.0	RF
11	Young mixed regeneration forest	SMR 2	South Maikal Range	10.3	29.5	21.9	72.57	0.36	12.0	0.0	0.0	RF
12	Moist-deciduous *sal* forest	SMR 3	South Maikal Range	2.0	10.2	68.7	90.47	0.89	0.5	0.0	0.0	RF
13	Dry-deciduous mixed forest	SMR 4	South Maikal Range	9.0	21.5	34.7	78.25	0.82	5.0	1.2	1.3	RF
14	*Butea-Lagerstroemia* scrub jungle	SMR 5	South Maikal Range	0.9	0.9	44.6	11.31	0.00	12.9	0.0	0.0	Nil
15	Moist-deciduous *sal*+bamboo forest	SMR 6	South Maikal Range	3.7	8.7	76.6	96.45	1.09	21.7	0.2	2.0	PA
16	Bamboo-clad ravine jungle	SMR 7	South Maikal Range	4.4	13.0	70.4	90.64	0.95	8.6	0.2	8.0	PA
17	Open mixed bamboo forest	EMR 1	East Maikal range	3.7	7.3	86.6	82.36	0.98	1.2	0.2	2.7	PA
18	Moist-deciduous *sal* forest (Protected)	EMR 2	East Maikal range	1.7	5.8	99.1	94.93	0.74	0.0	0.3	0.0	PA
19	*Sal*+bamboo mixed forest	EMR 3	East Maikal range	4.0	9.7	56.9	83.23	0.83	4.2	0.0	4.0	PA
20	*Sal*+*Lantana* open mixed forest	EMR 4	East Maikal range	1.8	4.5	92.1	79.63	0.88	17.0	0.3	0.2	RF
21	Moist-deciduous *sal* forest (Unprotected)	EMR 5	East Maikal range	1.8	5.7	83.5	86.52	0.91	14.2	0.2	0.0	RF
22	Bamboo-dominant mixed valley forest	EMR 6	East Maikal range	5.3	10.8	83.1	91.77	0.94	8.2	0.0	4.7	PA
23	Open scrub jungle	EMR 7	East Maikal range	3.2	5.3	62.5	18.13	0.26	5.2	0.0	0.8	Nil
24	Mixed deciduous hill forest + Bamboo	BTP 1	Betul Plateau	4.5	7.5	71.1	84.18	0.46	16.5	0.3	1.5	RF
25	Teak-dominant deciduous hill forest	BTP 2	Betul Plateau	2.8	5.8	66.7	82.67	0.81	7.7	0.0	0.0	RF
26	Teak-dominant moist foothill forest	BTP 3	Betul Plateau	2.2	9.0	60.9	80.76	0.69	14.5	0.0	0.0	RF

Sl.No.	Vegetation type	Site code	Locality	Tree sp. richness	Tree abund.	GBH	Canopy cover	Tree height diversity	Shrub abund.	Snag abund.	Bamboo abund.	Protection status*
27	Teak+bamboo plantation	BTP 4	Betul Plateau	3.0	9.5	62.0	92.68	0.91	6.7	1.2	1.7	RF
28	Open mixed bamboo hill forest	BTP 5	Betul Plateau	3.8	10.2	59.3	87.30	0.87	7.7	0.2	3.3	RF
29	Old coffee plantation	BTP 6	Betul Plateau	6.2	9.5	61.4	97.75	0.84	13.3	0.0	0.0	Nil
30	Moist-deciduous mixed forest (non-teak)	STP 1	Satpura Plateau	5.3	8.3	86.9	87.09	1.04	6.8	0.0	1.3	PA
31	Dry-deciduous bamboo forest	STP 2	Satpura Plateau	6.0	20.8	33.1	86.18	0.52	5.5	1.5	6.8	PA
32	Teak-*Lagerstroemia* secondary forest	STP 3	Satpura Plateau	2.7	11.5	42.8	75.69	0.80	4.2	4.2	0.0	PA
33	Dry-deciduous mixed forest (non-bamboo)	STP 4	Satpura Plateau	5.2	12.8	49.8	84.49	1.06	29.2	2.7	0.0	PA
34	Moist-deciduous secondary forest	STP 5	Satpura Plateau	4.3	10.0	58.9	88.34	0.83	11.2	0.5	0.0	PA
35	Dry-deciduous hill forest	STP 6	Satpura Plateau	4.3	9.0	42.4	76.99	1.02	5.0	1.0	0.3	PA
36	*Lantana* scrub jungle	STP 7	Satpura Plateau	5.7	12.5	25.5	35.82	0.44	33.0	1.0	0.0	PA

* Protection status: PA: Protected Area, RF: Reserve Forest, Nil: Revenue land

Appendix 3.2. List of bird species recorded from all the 36 sampling sites in Central Indian Highlands along with the number of sites in which each species was found and foraging guilds (either insectivorous or phytophagous) to which they were assigned.

Sl.No.	Common name	Scientific name	No. of sites, occupied	Guild
1	Jungle Babbler	*Turdoides striatus*	35	Insectivorous
2	Red-vented Bulbul	*Pycnonotus cafer*	34	Others
3	Black-rumped Flameback	*Dinopium benghalense*	33	Insectivorous
4	Rufous Treepie	*Dendrocitta vagabunda*	32	Others
5	Plum-headed Parakeet	*Psittacula cyanocephala*	29	Phytophagous
6	Oriental Magpie Robin	*Copsychus saularis*	28	Insectivorous
7	Common Woodshrike	*Tephrodornis pondicerianus*	28	Insectivorous
8	Oriental White-eye	*Zosterops palpebrosus*	28	Others
9	Purple Sunbird	*Nectarinia asiatica*	27	Phytophagous
10	Rose-ringed Parakeet	*Psittacula krameri*	27	Phytophagous
11	Spotted Dove	*Streptopelia chinensis*	27	Phytophagous
12	Common Iora	*Aegithina tiphia*	25	Insectivorous
13	Common Myna	*Acridotheres tristis*	24	Others
14	Jungle Owlet	*Glaucidium radiatum*	24	Others
15	Chestnut-shouldered Petronia	*Petronia xanthocollis*	24	Phytophagous
16	Indian Pitta	*Pitta brachyura*	24	Insectivorous
17	Large Cuckooshrike	*Coracina macei*	23	Others
18	Greater Racket-tailed Drongo	*Dicrurus paradisaeus*	22	Insectivorous
19	Common Tailorbird	*Orthotomus sutorius*	22	Others
20	Tickell's Blue Flycatcher	*Cyornis tickelliae*	21	Insectivorous
21	Common Hawk Cuckoo	*Hierococcyx varius*	21	Insectivorous
22	Grey-breasted Prinia	*Prinia hodgsonii*	21	Insectivorous
23	Indian Cuckoo	*Cuculus micropterus*	20	Insectivorous
24	Black-hooded Oriole	*Oriolus xanthornus*	20	Others
25	White-throated Kingfisher	*Halcyon smyrnensis*	19	Insectivorous
26	Brown-headed Barbet	*Megalaima zeylanica*	18	Phytophagous
27	Great Tit	*Parus major*	18	Insectivorous
28	Brahminy Starling	*Sturnus pagodarum*	18	Others
29	Small Minivet	*Pericrocotus cinnamomeus*	17	Insectivorous
30	Thick-billed Flowerpecker	*Dicaeum agile*	16	Phytophagous
31	Eurasian Golden Oriole	*Oriolus oriolus*	16	Others
32	Indian Roller	*Coracias benghalensis*	15	Insectivorous
33	White-bellied Drongo	*Dicrurus caerulescens*	15	Insectivorous
34	Ashy Drongo	*Dicrurus leucophaeus*	15	Insectivorous
35	Asian Koel	*Eudynamys scolopacea*	15	Phytophagous
36	Coppersmith Barbet	*Megalaima haemacephala*	15	Phytophagous
37	White-browed Fantail	*Rhipidura aureola*	15	Insectivorous
38	Large-billed Crow	*Corvus macrorhynchos*	13	Others
39	Indian Peafowl	*Pavo cristatus*	13	Others
40	Greater Coucal	*Centropus sinensis*	12	Others
41	Orange-headed Thrush	*Zoothera citrina*	12	Others
42	Shikra	*Accipiter badius*	11	Others
43	Black Drongo	*Dicrurus macrocercus*	11	Insectivorous
44	White-naped Woodpecker	*Chrysocolaptes festivus*	10	Insectivorous
45	Brown-capped Pygmy Woodpecker	*Dendrocopos nanus*	9	Insectivorous
46	Drongo Cuckoo	*Surniculus lugubris*	9	Insectivorous
47	Yellow-crowned Woodpecker	*Dendrocopos mahrattensis*	8	Insectivorous
48	Red Junglefowl	*Gallus gallus*	8	Others
49	Black-naped Monarch	*Hypothymis azurea*	8	Insectivorous

Sl.No.	Common name	Scientific name	No. of sites, occupied	Guild
50	Indian Grey Hornbill	*Ocyceros birostris*	8	Phytophagous
51	Alexandrine Parakeet	*Psittacula eupatria*	8	Phytophagous
52	Grey-bellied Cuckoo	*Cacomantis passerinus*	7	Insectivorous
53	Puff-throated Babbler	*Pellorneum ruficeps*	7	Insectivorous
54	Indian Scimitar Babbler	*Pomatorhinus horsfieldii*	7	Insectivorous
55	Indian Robin	*Saxicoloides fulicata*	7	Insectivorous
56	Asian Paradise-flycatcher	*Terpsiphone paradisi*	7	Insectivorous
57	Grey Junglefowl	*Gallus sonneratii*	6	Others
58	Yellow-footed Green Pigeon	*Treron phoenicoptera*	6	Phytophagous
59	Brown-cheeked Fulvetta	*Alcippe poioicephala*	5	Insectivorous
60	Black-headed Cuckooshrike	*Coracina melanoptera*	5	Others
61	Eurasian Cuckoo	*Cuculus canorus*	5	Insectivorous
62	Tawny-bellied Babbler	*Dumetia hyperythra*	5	Insectivorous
63	Red-whiskered Bulbul	*Pycnonotus jocosus*	5	Others
64	Chestnut-tailed Starling	*Sturnus malabaricus*	5	Others
65	White-eyed Buzzard	*Butastur teesa*	4	Others
66	Golden-fronted Leafbird	*Chloropsis aurifrons*	4	Others
67	Bar-winged Flycatcher-shrike	*Hemipus picatus*	4	Insectivorous
68	Green Bee-eater	*Merops orientalis*	4	Insectivorous
69	Black-lored Tit	*Parus xanthogenys*	4	Insectivorous
70	White-throated Fantail	*Rhipidura albicollis*	4	Insectivorous
71	Eurasian Collared Dove	*Streptopelia decaocto*	4	Phytophagous
72	Eurasian Blackbird	*Turdus merula*	4	Others
73	House Swift	*Apus affinis*	3	Insectivorous
74	Pale-billed Flowerpecker	*Dicaeum erythrorynchos*	3	Phytophagous
75	Grey Francolin	*Francolinus pondicerianus*	3	Others
76	Bay-backed Shrike	*Lanius vittatus*	3	Insectivorous
77	Scarlet Minivet	*Pericrocotus flammeus*	3	Insectivorous
78	Chestnut-bellied Nuthatch	*Sitta castanea*	3	Insectivorous
79	Oriental Turtle Dove	*Streptopelia orientalis*	3	Phytophagous
80	Laughing Dove	*Streptopelia senegalensis*	3	Phytophagous
81	Barred Buttonquail	*Turnix suscitator*	3	Others
82	Spotted Owlet	*Athene brama*	2	Others
83	White-rumped Shama	*Copsychus malabaricus*	2	Insectivorous
84	Spangled Drongo	*Dicrurus hottentottus*	2	Insectivorous
85	Red Spurfowl	*Galloperdix spadicea*	2	Others
86	Long-tailed Shrike	*Lanius schach*	2	Insectivorous
87	Velvet-fronted Nuthatch	*Sitta frontalis*	2	Insectivorous
88	Yellow-legged Buttonquail	*Turnix tanki*	2	Others
89	Rufous-tailed Lark	*Ammomanes phoenicurus*	1	Others
90	Malabar Pied Hornbill	*Anthracoceros coronatus*	1	Phytophagous
91	Painted Francolin	*Francolinus pictus*	1	Others
92	Crested Treeswift	*Hemiprocne coronata*	1	Insectivorous
93	Indian Bushlark	*Mirafra erythroptera*	1	Others
94	Malabar Whistling Thrush	*Myophonus horsfieldii*	1	Others
95	Jungle Bush Quail	*Perdicula asiatica*	1	Others
96	Oriental Honey Buzzard	*Pernis ptilorhyncus*	1	Insectivorous
97	Streak-throated Woodpecker	*Picus xanthopygaeus*	1	Insectivorous
98	Rufous-fronted Prinia	*Prinia buchanani*	1	Insectivorous
99	Crested Serpent Eagle	*Spilornis cheela*	1	Others
100	Common Babbler	*Turdoides caudatus*	1	Insectivorous
101	White-rumped Needletail	*Zoonavena sylvatica*	1	Insectivorous

Appendix 3.3. List of woody plant species recorded from sampling plots in five study localities in Central Indian Highlands and their abundance proportions (%). The abbreviations of the regions are as follows: SCP - Seoni Chhindwara Plateau, SMR - South Maikal Range, EMR - East Maikal Range, BTP - Betul Plateau, and STP - Satpura Plateau.

Sl.No.	Woody Plant Species	Food value for birds	SCP	SMR	EMR	BTP	STP
1	*Acacia catechu*		2.5	0.0	0.0	0.0	2.5
2	*Acacia leucophloea*		0.1	0.0	0.0	0.0	0.0
3	*Aegle marmelos*	Fruit	0.1	0.0	0.0	0.0	5.7
4	*Albizzia lebbek*	Nectar	0.0	0.3	0.3	2.3	0.0
5	*Albizzia procera*	Nectar	0.0	0.0	0.0	0.0	0.4
6	*Anogeissus latifolia*		1.5	14.6	4.4	1.3	0.8
7	*Bauhinia malabarica*	Nectar	0.0	0.3	0.0	0.0	0.0
8	*Bauhinia racemosa*	Nectar	3.2	0.2	0.0	1.3	2.2
9	*Bauhinia vahlii*	Seed	0.0	0.0	0.3	0.6	0.0
10	*Bombax ceiba*	Nectar, Seed	0.0	0.0	0.0	0.6	0.2
11	*Boswellia serrata*		1.1	1.4	0.3	0.0	0.0
12	*Bridelia squamosa*	Fruit	0.7	0.3	0.3	0.0	0.6
13	*Buchanania lanzan*	Fruit	0.7	4.5	5.4	0.3	0.6
14	*Butea monosperma*	Nectar	2.8	0.5	0.7	0.0	0.8
15	*Butea superba*	Nectar	0.1	0.0	0.0	0.0	1.0
16	*Careya arborea*	Nectar	0.0	0.3	0.0	0.3	1.0
17	*Carissa spinarum*	Fruit	0.0	0.2	0.0	0.0	0.0
18	*Casearia elliptica*		0.0	1.2	1.0	1.9	0.0
19	*Cassia fistula*	Fruit	0.7	1.4	0.7	1.0	1.0
20	*Chloroxylon swietenia*		1.1	0.3	0.0	0.0	5.3
21	*Cleistanthus collinus*		25.9	0.0	0.0	0.0	0.0
22	*Dalbergia latifolia*		0.1	1.7	0.0	0.0	0.0
23	*Dalbergia paniculata*		0.4	0.3	0.0	0.0	1.2
24	*Dendrocalamus strictus*	Seed	6.0	10.3	25.1	12.6	10.0
25	*Diospyros melanoxylon*	Fruit	6.7	7.0	4.4	0.0	9.6
26	*Emblica officinalis*	Fruit	2.8	1.4	1.0	0.6	2.0
27	*Ficus microcarpa*	Fruit	0.0	0.2	0.0	0.0	0.0
28	*Ficus racemosa*	Fruit	0.0	0.0	0.0	1.3	0.0
29	*Ficus religiosa*	Fruit	0.1	0.0	0.0	0.0	0.0
30	*Flacourtia indica*	Fruit	0.0	0.0	0.7	0.0	0.0
31	*Gardenia latifolia*		0.1	0.0	0.3	0.0	0.0
32	*Grevillea robusta*	Nectar	0.0	0.0	0.0	1.0	0.0
33	*Grewia hirsuta*	Fruit	0.0	0.0	0.0	0.3	0.0
34	*Grewia tiliaefolia*	Fruit	2.2	0.2	0.0	0.0	0.4
35	*Kydia calycina*		0.1	0.2	0.7	1.0	0.0
36	*Lagerstroemia parviflora*	Fruit	11.0	5.7	1.0	1.6	10.0
37	*Lannea coromandelica*	Fruit	1.3	1.5	0.3	0.0	0.2
38	*Madhuca indica*	Nectar	1.0	2.6	1.0	0.0	1.8
39	*Mangifera indica*	Fruit	0.0	0.0	0.0	1.0	0.0
40	*Miliusa velutina*		2.8	0.5	0.0	0.6	1.6
41	*Millettia auriculata*		0.0	0.0	0.0	0.3	0.6
42	*Mitragyna parvifolia*		0.1	0.0	0.0	0.0	0.2
43	*Ougeinia ougeinensis*		0.3	0.9	0.0	9.1	1.2
44	*Pterocarpus marsupium*		0.0	1.0	0.3	0.0	0.0
45	*Schleichera trijuga*	Seed	0.1	0.0	0.3	0.3	0.0
46	*Schrebera swietenioides*		0.0	0.2	0.0	0.0	0.0
47	*Semecarpus anacardium*		0.8	0.2	0.7	0.0	0.0

Sl.No.	Woody Plant Species	Food value for birds	SCP	SMR	EMR	BTP	STP
48	*Shorea robusta*		0.0	13.7	44.1	0.0	0.0
49	*Soymida febrifuga*		0.1	0.0	0.0	0.0	0.0
50	*Syzygium cumini*	Fruit	0.0	1.4	1.0	4.9	3.1
51	*Tectona grandis*		15.5	4.5	0.0	38.8	22.7
52	*Terminalia alata*		2.0	15.2	1.4	1.6	7.3
53	*Terminalia arjuna*		0.1	0.0	0.0	0.0	0.0
54	*Terminalia belerica*		0.0	0.0	0.0	0.3	0.6
55	*Terminalia chebula*		0.0	0.0	0.0	0.3	0.0
56	*Ventilago maderaspatana*		0.4	0.0	0.0	0.0	0.2
57	*Ziziphus mauritiana*	Fruit	0.0	1.2	0.0	0.3	0.0
58	*Ziziphus oenoplia*	Fruit	0.1	0.0	0.3	0.0	0.0
59	*Ziziphus xylopyra*	Fruit	1.1	1.4	0.3	1.0	2.4
..	Unidentified species		3.6	3.4	3.4	13.3	3.1

Appendix 4.1. List of regions and sampling sites used for studying local-regional richness patterns in Central Indian Highlands and the number of bird species recorded in each site.

Sl. No.	Forest type in the sampling site	Region	Protection status*	No. of bird species, recorded
1	Teak mixed plantation	Seoni-Chhindwara Plateau	RF	29
2	Dry-deciduous lowland forest	Seoni-Chhindwara Plateau	RF-PA	44
3	Dry-deciduous hill forest	Seoni-Chhindwara Plateau	RF	38
4	Dry-deciduous *garari* forest (Unprotected)	Seoni-Chhindwara Plateau	RF	27
5	Dry-deciduous teak forest	Seoni-Chhindwara Plateau	PA	41
6	Moist-deciduous bamboo forest	Seoni-Chhindwara Plateau	PA	33
7	Dry-deciduous *garari* forest (Protected)	Seoni-Chhindwara Plateau	PA	28
8	Non-teak mixed hill forest	Seoni-Chhindwara Plateau	PA	40
9	Open deciduous mixed forest	South Maikal Range	RF	37
10	Young mixed regeneration forest	South Maikal Range	RF	22
11	Moist-deciduous *sal* forest	South Maikal Range	RF	16
12	Dry-deciduous mixed forest	South Maikal Range	RF	43
13	Moist-deciduous *sal*+bamboo forest	South Maikal Range	PA	23
14	Bamboo-clad ravine jungle	South Maikal Range	PA	37
15	Open mixed bamboo forest	East Maikal range	PA	33
16	Moist-deciduous *sal* forest (Protected)	East Maikal range	PA	24
17	*Sal*+bamboo mixed forest	East Maikal range	PA	37
18	*Sal*+*Lantana* open mixed forest	East Maikal range	RF	42
19	Moist-deciduous *sal* forest (Unprotected)	East Maikal range	RF	25
20	Bamboo-dominant mixed valley forest	East Maikal range	PA	28
21	Mixed deciduous hill forest + Bamboo	Betul Plateau	RF	32
22	Teak-dominant deciduous hill forest	Betul Plateau	RF	29
23	Teak-dominant moist foothill forest	Betul Plateau	RF	25
24	Teak+bamboo plantation	Betul Plateau	RF	19
25	Open mixed bamboo hill forest	Betul Plateau	RF	39
26	Old coffee plantation forest	Betul Plateau	RF	36
27	Moist-deciduous mixed forest (non-teak)	Satpura Plateau	PA	38
28	Dry-deciduous bamboo forest	Satpura Plateau	PA	36
29	Teak-*Lagerstroemia* secondary forest	Satpura Plateau	PA	36
30	Dry-deciduous mixed forest (non-bamboo)	Satpura Plateau	PA	33
31	Moist-deciduous secondary forest	Satpura Plateau	PA	27
32	Dry-deciduous hill forest	Satpura Plateau	PA	35
33	Dry-deciduous mixed forest	Sagar-Damoh Plateau	PA	32
34	Open dry-deciduous mixed forest	Sagar-Damoh Plateau	PA	27
35	Secondary dry-deciduous jungle	Sagar-Damoh Plateau	PA	38

* Protection status: PA: Protected Area, RF: Reserve Forest.

Appendix 4.2. List of bird species recorded on transects during sampling of 35 sites in six regions in Central Indian Highlands. [The regions are abbreviated as follows:- CHP: Seoni-Chhindwara Plateau, SMR: South Maikal Range, EMR: East Maikal Range, BTP: Betul Plateau, STP: Satpura Plateau, & SDP: Sagar-Damoh Plateau].

Sl. No.	Common name	Scientific name	CHP	SMR	EMR	BTP	STP	SDP
1	Shikra	*Accipiter badius*	1	1	0	0	1	1
2	Common Myna	*Acridotheres tristis*	1	1	1	1	1	1
3	Common Iora	*Aegithina tiphia*	1	1	1	1	1	1
4	Brown-cheeked Fulvetta	*Alcippe poioicephala*	0	1	1	1	1	0
5	Malabar Pied Hornbill	*Anthracoceros coronatus*	1	0	0	0	0	0
6	House Swift	*Apus affinis*	0	0	1	0	0	0
7	White-eyed Buzzard	*Butastur teesa*	1	1	0	0	0	0
8	Grey-bellied Cuckoo	*Cacomantis passerinus*	1	1	1	0	0	1
9	Greater Coucal	*Centropus sinensis*	1	1	1	0	1	1
10	Golden-fronted Leafbird	*Chloropsis aurifrons*	0	1	0	0	1	0
11	White-naped Woodpecker	*Chrysocolaptes festivus*	1	1	1	1	1	0
12	White-rumped Shama	*Copsychus malabaricus*	0	1	0	0	0	0
13	Oriental Magpie Robin	*Copsychus saularis*	1	1	1	1	1	1
14	Indian Roller	*Coracias benghalensis*	1	1	1	0	1	1
15	Large Cuckooshrike	*Coracina macei*	1	1	1	1	1	0
16	Black-headed Cuckooshrike	*Coracina melanoptera*	0	1	1	0	0	1
17	Large-billed Crow	*Corvus macrorhynchos*	1	1	1	1	0	1
18	Eurasian Cuckoo	*Cuculus canorus*	1	1	1	0	0	1
19	Indian Cuckoo	*Cuculus micropterus*	1	1	1	0	1	1
20	Tickell's Blue Flycatcher	*Cyornis tickelliae*	1	1	1	1	1	1
21	Rufous Treepie	*Dendrocitta vagabunda*	1	1	1	1	1	1
22	Yellow-crowned Woodpecker	*Dendrocopos mahrattensis*	1	1	1	1	1	1
23	Brown-capped Pygmy Woodpecker	*Dendrocopos nanus*	1	1	1	1	1	0
24	Thick-billed Flowerpecker	*Dicaeum agile*	1	1	1	1	0	0
25	Pale-billed Flowerpecker	*Dicaeum erythrorynchos*	0	1	0	0	0	0
26	White-bellied Drongo	*Dicrurus caerulescens*	1	1	0	1	1	1
27	Spangled Drongo	*Dicrurus hottentottus*	1	0	0	0	1	0
28	Ashy Drongo	*Dicrurus leucophaeus*	1	1	1	0	1	0
29	Black Drongo	*Dicrurus macrocercus*	1	1	1	0	1	1
30	Greater Racket-tailed Drongo	*Dicrurus paradisaeus*	1	1	1	0	1	0
31	Black-rumped Flameback	*Dinopium benghalense*	1	1	1	1	1	1
32	Tawny-bellied Babbler	*Dumetia hyperythra*	1	1	0	1	0	0
33	Asian Koel	*Eudynamys scolopacea*	1	1	1	0	1	1
34	Grey Francolin	*Francolinus pondicerianus*	0	0	0	0	0	1
35	Red Spurfowl	*Galloperdix spadicea*	1	1	0	0	0	0
36	Red Junglefowl	*Gallus gallus*	1	1	1	0	0	0
37	Grey Junglefowl	*Gallus sonneratii*	0	0	0	1	1	0
38	Jungle Owlet	*Glaucidium radiatum*	1	1	1	1	1	0
39	White-throated Kingfisher	*Halcyon smyrnensis*	1	1	1	1	1	1
40	Crested Treeswift	*Hemiprocne coronata*	0	0	0	1	0	1
41	Bar-winged Flycatcher-shrike	*Hemipus picatus*	0	1	0	1	1	0
42	Common Hawk Cuckoo	*Hierococcyx varius*	1	1	1	1	1	1
43	Black-naped Monarch	*Hypothymis azurea*	1	1	1	1	1	0
44	Long-tailed Shrike	*Lanius schach*	1	0	1	0	0	0
45	Bay-backed Shrike	*Lanius vittatus*	0	0	1	0	0	1
46	Coppersmith Barbet	*Megalaima haemacephala*	1	1	1	1	1	1
47	Brown-headed Barbet	*Megalaima zeylanica*	1	1	1	1	1	0
48	Green Bee-eater	*Merops orientalis*	0	0	0	1	1	1

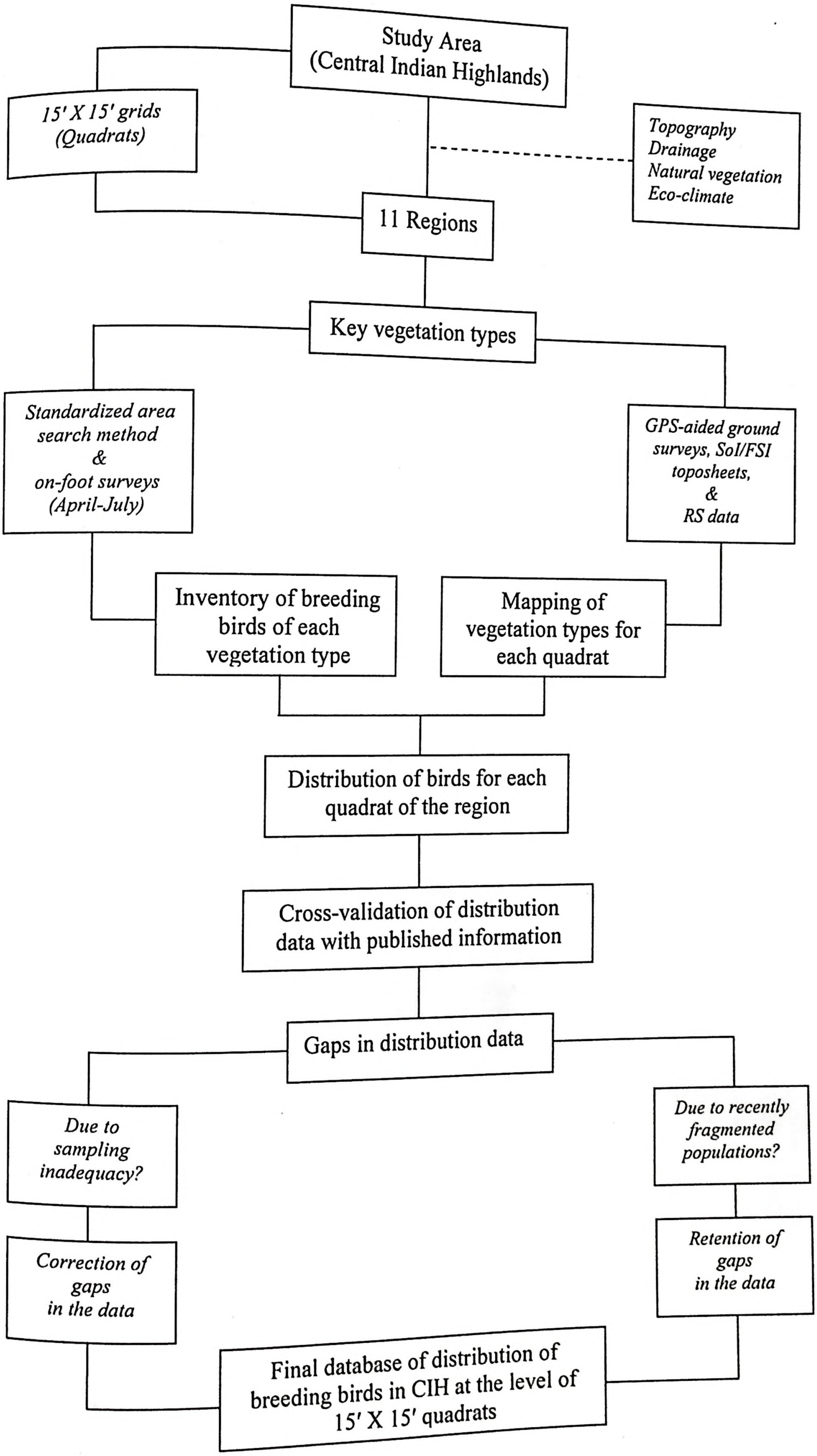
Sl. No.	Common name	Scientific name	CHP	SMR	EMR	BTP	STP	SDP
49	Indian Bushlark	*Mirafra erythroptera*	0	0	0	0	0	1
50	Malabar Whistling Thrush	*Myophonus horsfieldii*	0	0	0	1	0	0
51	Purple Sunbird	*Nectarinia asiatica*	1	1	1	1	1	1
52	Indian Grey Hornbill	*Ocyceros birostris*	1	0	1	1	1	0
53	Eurasian Golden Oriole	*Oriolus oriolus*	1	1	1	1	1	0
54	Black-hooded Oriole	*Oriolus xanthornus*	1	1	1	1	1	0
55	Common Tailorbird	*Orthotomus sutorius*	1	1	1	1	1	1
56	Great Tit	*Parus major*	1	1	1	1	1	1
57	Black-lored Tit	*Parus xanthogenys*	0	0	0	1	1	0
58	Indian Peafowl	*Pavo cristatus*	1	1	1	0	1	0
59	Puff-throated Babbler	*Pellorneum ruficeps*	0	1	1	1	1	0
60	Jungle Bush Quail	*Perdicula asiatica*	0	0	0	0	1	0
61	Small Minivet	*Pericrocotus cinnamomeus*	1	1	1	1	1	1
62	Scarlet Minivet	*Pericrocotus flammeus*	0	1	0	0	1	0
63	Oriental Honey Buzzard	*Pernis ptilorhyncus*	1	0	0	0	0	0
64	Chestnut-shouldered Petronia	*Petronia xanthocollis*	1	1	0	1	1	1
65	Streak-throated Woodpecker	*Picus xanthopygaeus*	0	0	0	0	1	0
66	Indian Pitta	*Pitta brachyura*	1	1	1	0	1	1
67	Indian Scimitar Babbler	*Pomatorhinus horsfieldii*	0	1	1	1	1	0
68	Grey-breasted Prinia	*Prinia hodgsonii*	1	1	1	1	1	1
69	Plum-headed Parakeet	*Psittacula cyanocephala*	1	1	1	1	1	1
70	Alexandrine Parakeet	*Psittacula eupatria*	1	1	1	0	1	0
71	Rose-ringed Parakeet	*Psittacula krameri*	1	1	1	1	1	1
72	Red-vented Bulbul	*Pycnonotus cafer*	1	1	1	1	1	1
73	Red-whiskered Bulbul	*Pycnonotus jocosus*	0	0	0	1	1	0
74	White-throated Fantail	*Rhipidura albicollis*	0	1	0	1	1	0
75	White-browed Fantail	*Rhipidura aureola*	1	0	1	1	1	1
76	Spotted Creeper	*Salpornis spilonotus*	0	0	0	0	0	1
77	Indian Robin	*Saxicoloides fulicata*	0	0	1	1	0	1
78	Chestnut-bellied Nuthatch	*Sitta castanea*	0	1	1	1	0	0
79	Velvet-fronted Nuthatch	*Sitta frontalis*	0	0	0	1	0	0
80	Crested Serpent Eagle	*Spilornis cheela*	0	0	0	1	0	1
81	Spotted Dove	*Streptopelia chinensis*	1	1	1	1	1	1
82	Eurasian Collared Dove	*Streptopelia decaocto*	0	1	1	0	0	0
83	Oriental Turtle Dove	*Streptopelia orientalis*	0	1	1	0	0	0
84	Laughing Dove	*Streptopelia senegalensis*	0	0	1	1	0	0
85	Chestnut-tailed Starling	*Sturnus malabaricus*	1	0	0	0	1	0
86	Brahminy Starling	*Sturnus pagodarum*	1	0	1	1	1	1
87	Drongo Cuckoo	*Surniculus lugubris*	1	1	1	0	0	1
88	Common Woodshrike	*Tephrodornis pondicerianus*	1	1	1	1	1	1
89	Asian Paradise-Flycatcher	*Terpsiphone paradisi*	1	0	1	1	1	1
90	Yellow-footed Green Pigeon	*Treron phoenicoptera*	1	0	0	1	0	0
91	Jungle Babbler	*Turdoides striatus*	1	1	1	1	1	1
92	Eurasian Blackbird	*Turdus merula*	0	0	0	1	0	0
93	Barred Buttonquail	*Turnix suscitator*	0	0	1	0	1	0
94	Yellow-legged Buttonquail	*Turnix tanki*	1	0	0	1	0	0
95	White-rumped Needletail	*Zoonavena sylvatica*	1	0	0	0	0	0
96	Orange-headed Thrush	*Zoothera citrina*	1	1	1	1	1	0
97	Oriental White-eye	*Zosterops palpebrosus*	1	1	1	1	1	1

Appendix 5.1. Biogeographical regions of Central Indian Highlands and their attributes.

Sl.No.	Region	Approx. Area (km^2)	Districts, covered	Major forest types	Major rivers	Important breeding birds
1	Malwa Plateau	18,590	Jhabua, Dhar, Indore, and Dewas	Tropical dry-deciduous forest (teak-mixed) and Tropical dry-deciduous forest (mixed)	Chambal, Sipra	Lesser Florican, Asian Brown Flycatcher, and Southern Grey Shrike
2	Nimar Hills	14,300	Barwani, West Nimar, and East Nimar	Tropical dry-deciduous forest (teak-mixed) and Tropical dry-deciduous forest (mixed)	Beda, Chota Tawa	Grey Junglefowl, Banded Bay Cuckoo, and Southern Grey Shrike
3	Lower Narmada Valley	18,590	West Nimar, Dewas, Harda, Sehore, and Hoshangabad	Tropical dry-deciduous forest (mixed)	Narmada	Asian Brown Flycatcher, Southern Grey Shrike, and Striated Grassbird
4	Betul Plateau	11,440	Betul	Tropical dry-deciduous forest (teak dominant), Tropical dry-deciduous forest (teak-mixed), and Tropical dry-deciduous forest (mixed)	Tapti	Grey Junglefowl, Bar-winged Flycatcher-shrike, Malabar Whistling Thrush, Red-whiskered Bulbul, and Purple-rumped Sunbird
5	Sagar-Damoh Plateau	22,880	Sagar and Damoh	Tropical dry-deciduous forest (mixed)	Dhasan, Bearma, Narmada	Spotted Creeper, and Marshall's Iora
6	Satpura Plateau	9,295	Hoshangabad, Betul, and Chhindwara	Tropical dry-deciduous forest (teak dominant), Tropical dry-deciduous forest (teak-mixed), Tropical moist-deciduous forest (sal dominant), Tropical moist-deciduous forest (sal-mixed), and Subtropical broad-leaved hill forest	Tawa, Dudhi	Grey-headed Canary Flycatcher, Black-crested Bulbul, Blue-bearded Bee-eater, Malabar Whistling Thrush, Bar-winged Flycatcher-shrike, Malabar Pied Hornbill, Brown-cheeked Fulvetta, and Ashy Drongo

Sl.No.	Region	Approx. Area (km^2)	Districts, covered	Major forest types	Major rivers	Important breeding birds
7	Seoni-Chhindwara Plateau	22,880	Chhindwara, Narsimhapur, and Seoni	Tropical dry-deciduous forest (teak dominant), Tropical dry-deciduous forest (teak-mixed), and Tropical dry-deciduous forest (mixed)	Kanhan, Pench, Wainganga	White-browed Bulbul, Spot-bellied Eagle Owl, Red Junglefowl, White-rumped Needletail, Malabar Pied Hornbill, and Ashy Drongo,
8	Vindhya Scarplands	17,875	Chhatarpur, Panna, and Satna	Tropical dry-deciduous forest (teak dominant), and Tropical dry-deciduous forest (teak-mixed)	Ken	Marshall's Iora, White-bellied Minivet, Pallas's Fish Eagle, Long-billed Vulture, and Striated Grassbird
9	Kaimur Hills	15,730	Jabalpur, Katni, Satna, and Rewa	Tropical dry-deciduous forest (teak-mixed)	Hiran, Katni, Mahanadi	Pallas's Fish Eagle, Striated Grassbird, Painted Spurfowl, and Indian Spotted Eagle
10	East Maikal Range	32,175	Shahdol, Umaria, Katni, and Sidhi	Tropical moist-deciduous forest (sal dominant) and Tropical moist-deciduous forest (sal-mixed)	Son, Banas	Bengal Bushlark, Painted Bushquail, Blue-bearded Bee-eater, Large-tailed Nightjar, Red Junglefowl, Malabar Whistling Thrush, Spangled Drongo, Puff-throated Babbler, and Malabar Pied Hornbill
11	South Maikal Range	19,305	Mandla, Balaghat, and Dindori	Tropical moist-deciduous forest (sal dominant) and Tropical moist-deciduous forest (sal-mixed)	Narmada, Banjar, Wainganga	White-rumped Shama, Red Junglefowl, Malabar Pied Hornbill, Bar-winged Flycatcher-shrike, Jungle Myna, Painted Bushquail, Crested Goshawk, Puff-throated Babbler, Brown-cheeked Fulvetta, Indian Scimitar Babbler, and Scarlet Minivet

Appendix 5.2. Schematic diagram of the hierarchical sampling design adopted in the study to develop distribution database of breeding birds in Central Indian Highlands.



Appendix 5.3. List of breeding birds of Central Indian Highlands included in the final analysis and their occurrence in different regions. The abbreviations of regions are as follows:- MLP: Malwa Plateau, NMH: Nimar Hills, LNV: Lower Narmada Valley, BTP: Betul Plateau, SDP: Sagar-Damoh Plateau, STP: Satpura Plateau, SCP: Seoni-Chhindwara Plateau, VNS: Vindhya Scarplands, KMH: Kaimur Hills, EMR: East Maikal Range, and SMR: South Maikal Range.

Sl. No.	Common Name	Scientific Name	MLP	NMH	LNV	BTP	SDP	STP	SCP	VNS	KMH	EMR	SMR
1	Painted Francolin	*Francolinus pictus*	1	1	1	1	1	1	1	1	1	1	1
2	Grey Francolin	*Francolinus pondicerianus*	1	1	1	1	1	1	1	1	1	1	1
3	Rain Quail	*Coturnix coromandelica*	1	1	1	1	1	1	1	1	1	1	1
4	Jungle Bush Quail	*Perdicula asiatica*	1	1	1	1	1	1	1	1	1	1	1
5	Rock Bush Quail	*Perdicula argoondah*	1	1	1	1	1	1	0	1	1	0	0
6	Painted Bush Quail	*Perdicula erythrorhyncha*	0	0	0	0	0	0	0	0	0	1	1
7	Red Spurfowl	*Galloperdix spadicea*	1	1	1	1	0	1	1	0	0	0	1
8	Painted Spurfowl	*Galloperdix lunulata*	0	0	0	0	1	1	1	1	1	1	0
9	Red Junglefowl	*Gallus gallus*	0	0	0	0	0	0	1	0	0	1	1
10	Grey Junglefowl	*Gallus sonneratii*	0	1	0	1	0	1	0	0	0	0	0
11	Indian Peafowl	*Pavo cristatus*	1	1	1	1	1	1	1	1	1	1	1
12	Brown-capped Pygmy W'pecker	*Dendrocopos nanus*	1	1	1	1	1	1	1	1	1	1	1
13	Yellow-crowned Woodpecker	*Dendrocopos mahrattensis*	1	1	1	1	1	1	1	1	1	1	1
14	Rufous Woodpecker	*Celeus brachyurus*	0	0	0	0	0	1	1	0	0	1	1
15	Lesser Yellownape	*Picus chlorolophus*	0	0	0	0	0	1	1	0	0	0	1
16	Streak-throated Woodpecker	*Picus xanthopygaeus*	0	0	0	1	0	1	1	0	0	1	1
17	Black-rumped Flameback	*Dinopium benghalense*	1	1	1	1	1	1	1	1	1	1	1
18	White-naped Woodpecker	*Chrysocolaptes festivus*	1	1	1	1	1	1	1	1	1	1	1
19	Brown-headed Barbet	*Megalaima zeylanica*	1	1	1	1	1	1	1	1	1	1	1
20	Coppersmith Barbet	*Megalaima haemacephala*	1	1	1	1	1	1	1	1	1	1	1
21	Indian Grey Hornbill	*Ocyceros birostris*	1	1	1	1	1	1	1	1	1	1	1
22	Malabar Pied Hornbill	*Anthracoceros coronatus*	0	0	0	0	0	1	1	0	0	1	1
23	Common Hoopoe	*Upupa epops*	1	1	1	1	1	1	1	1	1	1	1
24	Indian Roller	*Coracias benghalensis*	1	1	1	1	1	1	1	1	1	1	1
25	Common Kingfisher	*Alcedo atthis*	1	1	1	1	1	1	1	1	1	1	1
26	Stork-billed Kingfisher	*Halcyon capensis*	1	1	1	1	1	1	1	1	1	1	1
27	White-throated Kingfisher	*Halcyon smyrnensis*	1	1	1	1	1	1	1	1	1	1	1
28	Pied Kingfisher	*Ceryle rudis*	1	1	1	1	1	1	1	1	1	1	1
29	Blue-bearded Bee-eater	*Nyctyornis athertoni*	0	0	0	0	0	1	0	0	0	1	0
30	Green Bee-eater	*Merops orientalis*	1	1	1	1	1	1	1	1	1	1	1
31	Pied Cuckoo	*Clamator jacobinus*	1	1	1	1	1	1	1	1	1	1	1
32	Common Hawk Cuckoo	*Hierococcyx varius*	1	1	1	1	1	1	1	1	1	1	1
33	Indian Cuckoo	*Cuculus micropterus*	1	1	1	1	1	1	1	1	1	1	1
34	Eurasian Cuckoo	*Cuculus canorus*	1	1	1	1	1	1	1	1	1	1	1
35	Banded Bay Cuckoo	*Cacomantis sonneratii*	0	1	0	1	0	1	0	0	0	0	1
36	Grey-bellied Cuckoo	*Cacomantis passerinus*	1	1	1	1	1	1	1	1	1	1	1
37	Drongo Cuckoo	*Surniculus lugubris*	0	0	0	1	1	1	1	1	1	1	1
38	Asian Koel	*Eudynamys scolopacea*	1	1	1	1	1	1	1	1	1	1	1
39	Sirkeer Malkoha	*Phaenicophaeus leschenaultii*	1	1	1	1	1	1	1	1	1	1	1
40	Greater Coucal	*Centropus sinensis*	1	1	1	1	1	1	1	1	1	1	1
41	Alexandrine Parakeet	*Psittacula eupatria*	1	1	1	1	1	1	1	1	1	1	1
42	Rose-ringed Parakeet	*Psittacula krameri*	1	1	1	1	1	1	1	1	1	1	1
43	Plum-headed Parakeet	*Psittacula cyanocephala*	1	1	1	1	1	1	1	1	1	1	1
44	White-rumped Needletail	*Zoonavena sylvatica*	0	0	0	0	0	0	1	0	0	1	1

Sl. No.	Common Name	Scientific Name	MLP	NMH	LNV	BTP	SDP	STP	SCP	VNS	KMH	EMR	SMR
45	Alpine Swift	*Tachymarptis melba*	0	0	0	0	0	1	0	0	0	0	0
46	House Swift	*Apus affinis*	1	1	1	1	1	1	1	1	1	1	1
47	Crested Treeswift	*Hemiprocne coronata*	1	1	1	1	1	1	1	1	1	1	1
48	Barn Owl	*Tyto alba*	1	1	1	1	1	1	1	1	1	1	1
49	Oriental Scops Owl	*Otus sunia*	0	0	0	1	0	1	1	0	0	1	1
50	Collared Scops Owl	*Otus bakkamoena*	1	1	1	1	1	1	1	1	1	1	1
51	Eurasian Eagle Owl	*Bubo bubo*	1	1	1	1	1	1	1	1	1	1	1
52	Forest Eagle Owl	*Bubo nipalensis*	0	0	0	0	0	1	1	0	0	0	0
53	Dusky Eagle Owl	*Bubo coromandus*	1	1	1	0	1	0	0	1	1	1	0
54	Brown Fish Owl	*Ketupa zeylonensis*	1	1	1	1	1	1	1	1	1	1	1
55	Mottled Wood Owl	*Strix ocellata*	1	1	1	0	1	0	0	1	1	1	0
56	Jungle Owlet	*Glaucidium radiatum*	1	1	1	1	1	1	1	1	1	1	1
57	Spotted Owlet	*Athene brama*	1	1	1	1	1	1	1	1	1	1	1
58	Brown Hawk Owl	*Ninox scutulata*	0	0	0	0	0	1	1	1	0	1	1
59	Grey Nightjar	*Caprimulgus indicus*	1	1	1	1	1	1	1	1	1	1	1
60	Large-tailed Nightjar	*Caprimulgus macrurus*	0	0	0	0	0	0	0	0	0	1	1
61	Indian Nightjar	*Caprimulgus asiaticus*	1	1	1	1	1	1	1	1	1	1	1
62	Savanna Nightjar	*Caprimulgus affinis*	1	1	1	1	1	1	1	1	1	1	1
63	Rock Pigeon	*Columba livia*	1	1	1	1	1	1	1	1	1	1	1
64	Oriental Turtle Dove	*Streptopelia orientalis*	0	0	0	1	0	1	1	0	0	1	1
65	Laughing Dove	*Streptopelia senegalensis*	1	1	1	1	1	1	1	1	1	1	1
66	Spotted Dove	*Streptopelia chinensis*	1	1	1	1	1	1	1	1	1	1	1
67	Red Collared Dove	*Streptopelia tranquebarica*	1	1	1	1	1	1	1	1	1	1	1
68	Eurasian Collared Dove	*Streptopelia decaocto*	1	1	1	1	1	1	1	1	1	1	1
69	Emerald Dove	*Chalcophaps indica*	0	0	0	0	0	1	1	0	0	1	1
70	Yellow-footed Green Pigeon	*Treron phoenicoptera*	1	1	1	1	1	1	1	1	1	1	1
71	Lesser Florican	*Sypheotides indica*	1	0	0	0	0	0	0	0	0	0	0
72	Oriental Honey Buzzard	*Pernis ptilorhyncus*	1	1	1	1	1	1	1	1	1	1	1
73	Black-shouldered Kite	*Elanus caeruleus*	1	1	1	1	1	1	1	1	1	1	1
74	Black Kite	*Milvus migrans*	1	1	1	1	1	1	1	1	1	1	1
75	Pallas's Fish Eagle	*Haliaeetus leucoryphus*	0	0	0	0	1	0	0	1	1	1	0
76	Grey-headed Fish Eagle	*Ichthyophaga ichthyaetus*	1	0	1	0	1	1	1	1	1	1	0
77	Egyptian Vulture	*Neophron percnopterus*	1	1	1	1	1	1	1	1	1	1	1
78	White-rumped Vulture	*Gyps bengalensis*	1	1	1	1	1	1	1	1	1	1	1
79	Long-billed Vulture	*Gyps indicus*	1	1	1	1	1	1	1	1	1	1	1
80	Red-headed Vulture	*Sarcogyps calvus*	1	1	1	1	1	1	1	1	1	1	1
81	Short-toed Snake Eagle	*Circaetus gallicus*	1	1	1	1	1	1	1	1	1	1	0
82	Crested Serpent Eagle	*Spilornis cheela*	1	1	1	1	1	1	1	1	1	1	1
83	Crested Goshawk	*Accipiter trivirgatus*	0	0	0	0	0	1	0	0	0	0	1
84	Shikra	*Accipiter badius*	1	1	1	1	1	1	1	1	1	1	1
85	White-eyed Buzzard	*Butastur teesa*	1	1	1	1	1	1	1	1	1	1	1
86	Indian Spotted Eagle	*Aquila hastata*	1	0	1	0	1	0	0	1	1	1	0
87	Tawny Eagle	*Aquila rapax*	1	1	1	1	1	0	1	1	1	1	0
88	Bonelli's Eagle	*Hieraaetus fasciatus*	0	0	0	1	0	1	1	1	1	1	1
89	Changeable Hawk Eagle	*Spizaetus cirrhatus*	1	1	1	1	1	1	1	1	1	1	1
90	Red-necked Falcon	*Falco chicquera*	1	1	1	1	1	0	0	1	1	1	0
91	Laggar Falcon	*Falco jugger*	1	1	1	1	1	1	1	1	1	1	1
92	Peregrine Falcon	*Falco peregrinus*	1	1	1	1	1	1	1	1	1	1	1
93	Indian Pitta	*Pitta brachyura*	1	1	1	1	1	1	1	1	1	1	1
94	Blue-winged Leafbird	*Chloropsis cochinchinensis*	1	1	1	1	1	1	1	1	1	1	1
95	Golden-fronted Leafbird	*Chloropsis aurifrons*	0	1	0	1	0	1	1	0	0	1	1

Sl. No.	Common Name	Scientific Name	MLP	NMH	LNV	BTP	SDP	STP	SCP	VNS	KMH	EMR	SMR
96	Bay-backed Shrike	*Lanius vittatus*	1	1	1	1	1	1	1	1	1	1	1
97	Long-tailed Shrike	*Lanius schach*	1	1	1	1	1	1	1	1	1	1	1
98	Southern Grey Shrike	*Lanius meridionalis*	1	1	1	0	1	0	0	1	0	0	0
99	Rufous Treepie	*Dendrocitta vagabunda*	1	1	1	1	1	1	1	1	1	1	1
100	House Crow	*Corvus splendens*	1	1	1	1	1	1	1	1	1	1	1
101	Large-billed Crow	*Corvus macrorhynchos*	1	1	1	1	1	1	1	1	1	1	1
102	Eurasian Golden Oriole	*Oriolus oriolus*	1	1	1	1	1	1	1	1	1	1	1
103	Black-hooded Oriole	*Oriolus xanthornus*	0	1	0	1	1	1	1	1	1	1	1
104	Large Cuckooshrike	*Coracina macei*	1	1	1	1	1	1	1	1	1	1	1
105	Black-headed Cuckooshrike	*Coracina melanoptera*	1	1	1	1	1	1	1	1	1	1	1
106	Small Minivet	*Pericrocotus cinnamomeus*	1	1	1	1	1	1	1	1	1	1	1
107	Scarlet Minivet	*Pericrocotus flammeus*	0	0	0	1	0	1	1	0	0	0	1
108	Bar-winged Flycatcher-shrike	*Hemipus picatus*	0	0	0	1	0	1	0	0	0	0	1
109	White-throated Fantail	*Rhipidura albicollis*	0	0	0	1	0	1	0	0	0	0	1
110	White-browed Fantail	*Rhipidura aureola*	1	1	1	1	1	1	1	1	1	1	1
111	Black Drongo	*Dicrurus macrocercus*	1	1	1	1	1	1	1	1	1	1	1
112	Ashy Drongo	*Dicrurus leucophaeus*	0	0	0	0	0	1	1	0	0	1	1
113	White-bellied Drongo	*Dicrurus caerulescens*	1	1	1	1	1	1	1	1	1	1	1
114	Spangled Drongo	*Dicrurus hottentottus*	0	0	0	0	0	1	1	0	0	1	1
115	Greater Racket-tailed Drongo	*Dicrurus paradiseus*	0	1	0	1	0	1	1	0	0	1	1
116	Black-naped Monarch	*Hypothymis azurea*	1	1	1	1	0	1	1	0	0	1	1
117	Asian Paradise-flycatcher	*Terpsiphone paradisi*	1	1	1	1	1	1	1	1	1	1	1
118	Common Iora	*Aegithina tiphia*	1	1	1	1	1	1	1	1	1	1	1
119	Marshall's Iora	*Aegithina nigrolutea*	0	0	0	0	1	0	0	1	0	0	0
120	Common Woodshrike	*Tephrodornis pondicerianus*	1	1	1	1	1	1	1	1	1	1	1
121	Malabar Whistling Thrush	*Myophonus horsfieldii*	0	0	0	1	0	1	0	0	0	1	0
122	Orange-headed Thrush	*Zoothera citrina*	0	0	0	1	0	1	1	1	1	1	1
123	Eurasian Blackbird	*Turdus merula*	1	1	0	1	0	1	1	0	0	1	1
124	Asian Brown Flycatcher	*Muscicapa dauurica*	1	0	1	1	0	0	0	0	0	0	0
125	Tickell's Blue Flycatcher	*Cyornis tickelliae*	1	1	1	1	1	1	1	1	1	1	1
126	Grey-headed Canary Flycatcher	*Culicicapa ceylonensis*	0	0	0	0	0	1	0	0	0	0	0
127	Oriental Magpie Robin	*Copsychus saularis*	1	1	1	1	1	1	1	1	1	1	1
128	White-rumped Shama	*Copsychus malabaricus*	0	0	0	0	0	0	1	0	0	0	1
129	Indian Robin	*Saxicoloides fulicata*	1	1	1	1	1	1	1	1	1	1	1
130	Pied Bushchat	*Saxicola caprata*	0	1	0	1	1	1	1	1	1	1	1
131	Brown Rock-chat	*Cercomela fusca*	1	1	1	0	1	0	0	1	1	1	0
132	Chestnut-tailed Starling	*Sturnus malabaricus*	0	0	0	0	1	1	1	1	1	1	1
133	Brahminy Starling	*Sturnus pagodarum*	1	1	1	1	1	1	1	1	1	1	1
134	Asian Pied Starling	*Sturnus contra*	0	0	1	1	1	1	1	1	1	1	1
135	Common Myna	*Acridotheres tristis*	1	1	1	1	1	1	1	1	1	1	1
136	Bank Myna	*Acridotheres ginginianus*	1	1	1	1	1	1	1	1	1	1	0
137	Jungle Myna	*Acridotheres fuscus*	0	0	0	0	0	0	0	0	0	0	1
138	Chestnut-bellied Nuthatch	*Sitta castanea*	1	1	1	1	0	1	1	0	0	1	1
139	Velvet-fronted Nuthatch	*Sitta frontalis*	0	0	0	1	0	1	1	0	0	0	1
140	Great Tit	*Parus major*	1	1	1	1	1	1	1	1	1	1	1
141	Black-lored Tit	*Parus xanthogenys*	1	1	1	1	1	1	1	0	0	0	1
142	Plain Martin	*Riparia paludicola*	1	1	1	1	1	0	1	1	1	1	1
143	Dusky Crag Martin	*Hirundo concolor*	1	1	1	1	1	1	0	1	1	1	0
144	Wire-tailed Swallow	*Hirundo smithii*	1	1	1	1	1	1	1	1	1	1	1
145	Red-rumped Swallow	*Hirundo daurica*	1	1	1	1	1	1	1	1	1	1	1
146	Streak-throated Swallow	*Hirundo fluvicola*	1	1	1	0	1	1	1	1	1	1	0

Sl. No.	Common Name	Scientific Name	MLP	NMH	LNV	BTP	SDP	STP	SCP	VNS	KMH	EMR	SMR
147	Black-crested Bulbul	*Pycnonotus melanicterus*	0	0	0	0	0	1	0	0	0	0	0
148	Red-whiskered Bulbul	*Pycnonotus jocosus*	0	0	0	1	0	1	0	0	0	0	1
149	Red-vented Bulbul	*Pycnonotus cafer*	1	1	1	1	1	1	1	1	1	1	1
150	White-browed Bulbul	*Pycnonotus luteolus*	0	0	0	0	0	0	1	0	0	0	0
151	Zitting Cisticola	*Cisticola juncidis*	1	1	1	1	1	1	1	1	1	1	1
152	Rufous-fronted Prinia	*Prinia buchanani*	1	1	1	1	1	0	1	1	0	1	0
153	Grey-breasted Prinia	*Prinia hodgsonii*	1	1	1	1	1	1	1	1	1	1	1
154	Jungle Prinia	*Prinia sylvatica*	1	1	1	1	1	1	1	1	1	1	1
155	Ashy Prinia	*Prinia socialis*	1	1	1	1	1	1	1	1	1	1	1
156	Plain Prinia	*Prinia inornata*	1	1	1	1	1	1	1	1	1	1	0
157	Oriental White-eye	*Zosterops palpebrosus*	1	1	1	1	1	1	1	1	1	1	1
158	Common Tailorbird	*Orthotomus sutorius*	1	1	1	1	1	1	1	1	1	1	1
159	Striated Grassbird	*Megalurus palustris*	0	0	1	0	1	0	1	1	1	0	0
160	Puff-throated Babbler	*Pellorneum ruficeps*	0	0	0	1	0	1	0	0	0	1	1
161	Indian Scimitar Babbler	*Pomatorhinus horsfieldii*	0	0	0	1	0	1	1	1	1	1	1
162	Tawny-bellied Babbler	*Dumetia hyperythra*	1	1	1	1	1	1	1	1	1	1	1
163	Yellow-eyed Babbler	*Chrysomma sinense*	1	1	1	1	1	1	1	1	1	1	1
164	Common Babbler	*Turdoides caudatus*	1	1	1	1	1	1	1	1	1	1	0
165	Large Grey Babbler	*Turdoides malcolmi*	1	1	1	1	1	1	1	1	1	1	1
166	Jungle Babbler	*Turdoides striatus*	1	1	1	1	1	1	1	1	1	1	1
167	Brown-cheeked Fulvetta	*Alcippe poioicephala*	0	1	0	1	0	1	1	0	0	1	1
168	Singing Bushlark	*Mirafra cantillans*	1	1	1	1	0	1	1	0	0	0	1
169	Indian Bushlark	*Mirafra erythroptera*	1	1	1	1	1	1	1	1	1	0	0
170	Bengal Bushlark	*Mirafra assamica*	0	0	0	0	0	0	0	0	0	1	0
171	Ashy-crowned Sparrow Lark	*Eremopterix grisea*	1	1	1	1	1	1	1	1	1	1	1
172	Rufous-tailed Lark	*Ammomanes phoenicurus*	1	1	1	1	1	1	1	1	1	1	1
173	Sand Lark	*Calandrella raytal*	1	1	1	0	1	0	1	1	1	1	0
174	Sykes's Lark	*Galerida deva*	1	1	1	1	1	0	1	1	0	0	0
175	Oriental Skylark	*Alauda gulgula*	1	1	1	1	1	1	1	1	1	1	1
176	Thick-billed Flowerpecker	*Dicaeum agile*	1	1	1	1	1	1	1	1	1	1	1
177	Pale-billed Flowerpecker	*Dicaeum erythrorhynchos*	0	1	0	1	0	1	1	0	0	1	1
178	Purple-rumped Sunbird	*Nectarinia zeylonica*	0	0	0	1	0	1	1	0	0	0	0
179	Purple Sunbird	*Nectarinia asiatica*	1	1	1	1	1	1	1	1	1	1	1
180	House Sparrow	*Passer domesticus*	1	1	1	1	1	1	1	1	1	1	1
181	Chestnut-shouldered Petronia	*Petronia xanthocollis*	1	1	1	1	1	1	1	1	1	1	1
182	White-browed Wagtail	*Motacilla maderaspatensis*	1	1	1	1	1	1	1	1	1	1	1
183	Paddyfield Pipit	*Anthus rufulus*	1	1	1	1	1	1	1	1	1	1	1
184	Baya Weaver	*Ploceus philippinus*	1	1	1	1	1	1	1	1	1	1	1
185	Red Avadavat	*Amandava amandava*	1	1	1	1	1	1	1	1	1	1	1
186	Indian Silverbill	*Lonchura malabarica*	1	1	1	1	1	1	1	1	1	1	1
187	White-rumped Munia	*Lonchura striata*	0	1	0	1	0	1	1	1	1	1	1
188	Scaly-breasted Munia	*Lonchura punctulata*	1	1	1	1	1	1	1	1	1	1	1
189	Black-headed Munia	*Lonchura malacca*	0	0	0	0	0	0	1	0	0	0	1
190	Crested Bunting	*Melophus lathami*	1	1	1	1	1	1	1	1	1	1	0

Appendix 5.4. List of breeding birds of Central Indian Highlands along with their habitat occupancy patterns. Habitat abbreviations are as follows:- DDF: Dry-deciduous forests, MDF: Moist-deciduous forests, BMF: Bamboo-dominant forests, GRF: open grasslands, cultivation, and glades in forested tracts, SCJ: Scrub jungle, AGR: Agricultural fields, villages, and open countryside, and URB: urban environments. The last column refers to the two habitat categories (HC), viz., habitat-specialists (HS) and habitat-generalists (HG).

S. No.	Common Name	Scientific Name	DDF	MDF	BMF	GRF	SCJ	AGR	URB	HC
1	Painted Francolin	*Francolinus pictus*	0	0	0	1	1	0	0	HS
2	Grey Francolin	*Francolinus pondicerianus*	0	0	0	1	1	1	1	HG
3	Rain Quail	*Coturnix coromandelica*	0	0	0	1	1	1	0	HS
4	Jungle Bush Quail	*Perdicula asiatica*	1	0	1	1	1	0	0	HG
5	Rock Bush Quail	*Perdicula argoondah*	0	0	0	1	1	0	0	HS
6	Painted Bush Quail	*Perdicula erythrorhyncha*	0	1	1	1	1	0	0	HG
7	Red Spurfowl	*Galloperdix spadicea*	1	1	1	0	0	0	0	HS
8	Painted Spurfowl	*Galloperdix lunulata*	1	0	1	0	1	0	0	HS
9	Red Junglefowl	*Gallus gallus*	0	1	1	0	1	0	0	HS
10	Grey Junglefowl	*Gallus sonneratii*	1	0	1	0	1	0	0	HS
11	Indian Peafowl	*Pavo cristatus*	1	1	1	1	1	1	0	HG
12	Brown-capped Pygmy W'pecker	*Dendrocopos nanus*	1	1	1	0	1	0	0	HG
13	Yellow-crowned Woodpecker	*Dendrocopos mahrattensis*	1	1	1	0	1	0	0	HG
14	Rufous Woodpecker	*Celeus brachyurus*	0	1	1	0	0	0	0	HS
15	Lesser Yellownape	*Picus chlorolophus*	1	1	0	0	0	0	0	HS
16	Streak-throated Woodpecker	*Picus xanthopygaeus*	1	1	0	0	0	0	0	HS
17	Black-rumped Flameback	*Dinopium benghalense*	1	1	1	0	1	1	1	HG
18	White-naped Woodpecker	*Chrysocolaptes festivus*	1	1	1	0	0	0	0	HS
19	Brown-headed Barbet	*Megalaima zeylanica*	1	1	1	0	0	1	1	HG
20	Coppersmith Barbet	*Megalaima haemacephala*	1	1	1	0	0	1	1	HG
21	Indian Grey Hornbill	*Ocyceros birostris*	1	1	1	0	0	0	0	HS
22	Malabar Pied Hornbill	*Anthracoceros coronatus*	0	1	0	0	0	0	0	HS
23	Common Hoopoe	*Upupa epops*	1	0	1	1	1	1	1	HG
24	Indian Roller	*Coracias benghalensis*	1	0	0	1	1	1	1	HG
25	Common Kingfisher	*Alcedo atthis*	0	0	0	1	0	1	1	HS
26	Stork-billed Kingfisher	*Halcyon capensis*	1	1	1	0	0	0	0	HS
27	White-throated Kingfisher	*Halcyon smyrnensis*	1	1	1	1	1	1	1	HG
28	Pied Kingfisher	*Ceryle rudis*	0	0	0	1	0	1	1	HS
29	Blue-bearded Bee-eater	*Nyctyornis athertoni*	0	1	1	0	0	0	0	HS
30	Green Bee-eater	*Merops orientalis*	1	0	1	1	1	1	1	HG
31	Pied Cuckoo	*Clamator jacobinus*	1	0	1	0	1	1	1	HG
32	Common Hawk Cuckoo	*Hierococcyx varius*	1	1	1	0	1	1	1	HG
33	Indian Cuckoo	*Cuculus micropterus*	1	1	1	0	0	0	0	HS
34	Eurasian Cuckoo	*Cuculus canorus*	1	1	1	0	1	0	0	HG
35	Banded Bay Cuckoo	*Cacomantis sonneratii*	1	1	0	0	0	0	0	HS
36	Grey-bellied Cuckoo	*Cacomantis passerinus*	1	0	0	0	1	1	0	HS
37	Drongo Cuckoo	*Surniculus lugubris*	0	1	0	0	0	0	0	HS
38	Asian Koel	*Eudynamys scolopacea*	1	1	1	0	1	1	1	HG
39	Sirkeer Malkoha	*Phaenicophaeus leschenaultii*	1	0	1	0	1	0	0	HS
40	Greater Coucal	*Centropus sinensis*	1	0	1	0	1	1	1	HG
41	Alexandrine Parakeet	*Psittacula eupatria*	1	1	1	0	0	0	0	HS
42	Rose-ringed Parakeet	*Psittacula krameri*	1	1	1	0	1	1	1	HG
43	Plum-headed Parakeet	*Psittacula cyanocephala*	1	1	1	0	1	1	1	HG
44	White-rumped Needletail	*Zoonavena sylvatica*	1	1	1	1	0	0	0	HG

S. No.	Common Name	Scientific Name	DDF	MDF	BMF	GRF	SCJ	AGR	URB	HC
45	Alpine Swift	*Tachymarptis melba*	1	1	0	0	0	0	0	HS
46	House Swift	*Apus affinis*	1	0	1	1	1	1	1	HG
47	Crested Treeswift	*Hemiprocne coronata*	1	1	1	0	0	0	0	HS
48	Barn Owl	*Tyto alba*	0	0	0	1	1	1	1	HG
49	Oriental Scops Owl	*Otus sunia*	1	1	0	0	0	0	0	HS
50	Collared Scops Owl	*Otus bakkamoena*	1	1	1	0	0	0	0	HS
51	Eurasian Eagle Owl	*Bubo bubo*	1	1	1	0	0	0	0	HS
52	Spot-bellied Eagle Owl	*Bubo nipalensis*	0	1	0	0	0	0	0	HS
53	Dusky Eagle Owl	*Bubo coromandus*	1	1	0	0	0	0	0	HS
54	Brown Fish Owl	*Ketupa zeylonensis*	1	1	0	0	0	1	0	HS
55	Mottled Wood Owl	*Strix ocellata*	1	1	0	0	0	1	0	HS
56	Jungle Owlet	*Glaucidium radiatum*	1	1	1	0	1	1	0	HG
57	Spotted Owlet	*Athene brama*	1	0	0	0	1	1	1	HG
58	Brown Hawk Owl	*Ninox scutulata*	0	1	1	0	0	0	0	HS
59	Grey Nightjar	*Caprimulgus indicus*	1	1	1	1	0	0	0	HG
60	Large-tailed Nightjar	*Caprimulgus macrurus*	0	1	1	1	0	0	0	HS
61	Indian Nightjar	*Caprimulgus asiaticus*	1	0	0	1	1	1	1	HG
62	Savanna Nightjar	*Caprimulgus affinis*	0	0	0	1	1	0	0	HS
63	Rock Pigeon	*Columba livia*	0	0	0	1	1	1	1	HG
64	Oriental Turtle Dove	*Streptopelia orientalis*	0	1	1	1	0	0	0	HS
65	Laughing Dove	*Streptopelia senegalensis*	0	0	0	1	1	1	1	HG
66	Spotted Dove	*Streptopelia chinensis*	1	1	1	1	1	1	1	HG
67	Red Collared Dove	*Streptopelia tranquebarica*	0	0	0	1	1	1	0	HS
68	Eurasian Collared Dove	*Streptopelia decaocto*	0	0	0	1	1	1	1	HG
69	Emerald Dove	*Chalcophaps indica*	0	1	1	0	0	0	0	HS
70	Yellow-footed Green Pigeon	*Treron phoenicoptera*	1	1	1	0	0	0	0	HS
71	Lesser Florican	*Sypheotides indica*	0	0	0	1	0	0	0	HS
72	Oriental Honey Buzzard	*Pernis ptilorhyncus*	1	1	1	0	1	0	0	HG
73	Black-shouldered Kite	*Elanus caeruleus*	0	0	0	1	1	1	1	HG
74	Black Kite	*Milvus migrans*	0	0	0	1	1	1	1	HG
75	Pallas's Fish Eagle	*Haliaeetus leucoryphus*	1	1	0	0	0	0	0	HS
76	Grey-headed Fish Eagle	*Ichthyophaga ichthyaetus*	1	1	0	0	0	0	0	HS
77	Egyptian Vulture	*Neophron percnopterus*	0	0	0	1	1	1	1	HG
78	White-rumped Vulture	*Gyps bengalensis*	1	0	0	1	0	1	1	HG
79	Long-billed Vulture	*Gyps indicus*	1	0	0	1	0	1	0	HS
80	Red-headed Vulture	*Sarcogyps calvus*	1	1	0	1	0	0	0	HS
81	Short-toed Snake Eagle	*Circaetus gallicus*	1	0	0	1	1	1	0	HG
82	Crested Serpent Eagle	*Spilornis cheela*	1	1	0	0	0	0	0	HS
83	Crested Goshawk	*Accipiter trivirgatus*	0	1	0	0	0	0	0	HS
84	Shikra	*Accipiter badius*	1	1	1	0	1	1	1	HG
85	White-eyed Buzzard	*Butastur teesa*	1	0	1	1	1	0	0	HG
86	Indian Spotted Eagle	*Aquila hastata*	1	1	0	0	0	0	0	HS
87	Tawny Eagle	*Aquila rapax*	0	0	0	1	1	1	1	HG
88	Bonelli's Eagle	*Hieraaetus fasciatus*	1	1	0	0	0	0	0	HS
89	Changeable Hawk Eagle	*Spizaetus cirrhatus*	1	1	1	0	0	0	0	HS
90	Red-necked Falcon	*Falco chicquera*	0	0	0	1	1	1	0	HS
91	Laggar Falcon	*Falco jugger*	0	0	0	1	0	1	0	HS
92	Peregrine Falcon	*Falco peregrinus*	0	0	0	1	0	1	1	HS
93	Indian Pitta	*Pitta brachyura*	1	1	1	0	1	0	0	HG
94	Blue-winged Leafbird	*Chloropsis cochinchinensis*	1	0	1	0	1	1	0	HG
95	Golden-fronted Leafbird	*Chloropsis aurifrons*	1	1	1	0	0	0	0	HS

S. No.	Common Name	Scientific Name	DDF	MDF	BMF	GRF	SCJ	AGR	URB	HC
96	Bay-backed Shrike	*Lanius vittatus*	0	0	0	0	1	1	1	HS
97	Long-tailed Shrike	*Lanius schach*	1	1	1	0	0	0	0	HS
98	Southern Grey Shrike	*Lanius meridionalis*	0	0	0	1	1	1	1	HG
99	Rufous Treepie	*Dendrocitta vagabunda*	1	1	1	0	1	1	1	HG
100	House Crow	*Corvus splendens*	0	0	0	1	1	1	1	HG
101	Large-billed Crow	*Corvus macrorhynchos*	1	1	1	1	1	1	0	HG
102	Eurasian Golden Oriole	*Oriolus oriolus*	1	0	1	0	1	1	1	HG
103	Black-hooded Oriole	*Oriolus xanthornus*	1	1	1	0	0	1	1	HG
104	Large Cuckooshrike	*Coracina macei*	1	1	1	0	1	0	0	HG
105	Black-headed Cuckooshrike	*Coracina melanoptera*	1	1	1	0	1	0	0	HG
106	Small Minivet	*Pericrocotus cinnamomeus*	1	1	1	0	1	1	0	HG
107	Scarlet Minivet	*Pericrocotus flammeus*	0	1	1	0	0	0	0	HS
108	Bar-winged Flycatcher-shrike	*Hemipus picatus*	0	1	1	0	0	0	0	HS
109	White-throated Fantail	*Rhipidura albicollis*	0	1	1	0	0	0	0	HS
110	White-browed Fantail	*Rhipidura aureola*	1	0	1	0	1	1	0	HG
111	Black Drongo	*Dicrurus macrocercus*	1	0	1	1	1	1	1	HG
112	Ashy Drongo	*Dicrurus leucophaeus*	1	1	1	0	0	0	0	HS
113	White-bellied Drongo	*Dicrurus caerulescens*	1	1	1	0	0	0	0	HS
114	Spangled Drongo	*Dicrurus hottentottus*	0	1	1	0	0	0	0	HS
115	Greater Racket-tailed Drongo	*Dicrurus paradiseus*	1	1	1	0	0	0	0	HS
116	Black-naped Monarch	*Hypothymis azurea*	1	1	1	0	1	0	0	HG
117	Asian Paradise-flycatcher	*Terpsiphone paradisi*	1	1	1	0	1	0	0	HG
118	Common Iora	*Aegithina tiphia*	1	1	1	0	1	1	1	HG
119	Marshall's Iora	*Aegithina nigrolutea*	1	0	1	0	1	1	0	HG
120	Common Woodshrike	*Tephrodornis pondicerianus*	1	0	1	0	1	0	0	HS
121	Malabar Whistling Thrush	*Myophonus horsfieldii*	0	1	1	0	0	0	0	HS
122	Orange-headed Thrush	*Zoothera citrina*	1	1	1	0	1	0	0	HG
123	Eurasian Blackbird	*Turdus merula*	1	1	1	0	1	0	0	HG
124	Asian Brown Flycatcher	*Muscicapa dauurica*	1	0	1	0	1	0	0	HS
125	Tickell's Blue Flycatcher	*Cyornis tickelliae*	1	1	1	0	1	0	0	HG
126	Grey-headed Canary Flycatcher	*Culicicapa ceylonensis*	0	1	1	0	0	0	0	HS
127	Oriental Magpie Robin	*Copsychus saularis*	1	0	1	0	1	1	1	HG
128	White-rumped Shama	*Copsychus malabaricus*	0	1	1	0	0	0	0	HS
129	Indian Robin	*Saxicoloides fulicata*	0	0	0	1	1	1	1	HG
130	Pied Bushchat	*Saxicola caprata*	1	0	0	1	1	1	0	HG
131	Brown Rock-chat	*Cercomela fusca*	0	0	0	0	1	1	1	HS
132	Chestnut-tailed Starling	*Sturnus malabaricus*	1	1	1	0	0	0	0	HS
133	Brahminy Starling	*Sturnus pagodarum*	1	0	1	1	1	1	1	HG
134	Asian Pied Starling	*Sturnus contra*	0	0	0	1	1	1	1	HG
135	Common Myna	*Acridotheres tristis*	1	0	1	1	1	1	1	HG
136	Bank Myna	*Acridotheres ginginianus*	0	0	0	1	1	1	1	HG
137	Jungle Myna	*Acridotheres fuscus*	0	1	1	0	0	0	0	HS
138	Chestnut-bellied Nuthatch	*Sitta castanea*	1	1	1	0	0	0	0	HS
139	Velvet-fronted Nuthatch	*Sitta frontalis*	1	1	1	0	0	0	0	HS
140	Great Tit	*Parus major*	1	1	1	0	1	0	0	HG
141	Black-lored Tit	*Parus xanthogenys*	1	1	1	0	0	0	0	HS
142	Plain Martin	*Riparia paludicola*	0	0	0	1	1	1	1	HG
143	Dusky Crag Martin	*Hirundo concolor*	0	0	0	1	1	1	1	HG
144	Wire-tailed Swallow	*Hirundo smithii*	0	0	0	1	1	1	1	HG
145	Red-rumped Swallow	*Hirundo daurica*	1	1	1	1	0	0	0	HG
146	Streak-throated Swallow	*Hirundo fluvicola*	0	0	0	1	1	1	1	HG

S. No.	Common Name	Scientific Name	DDF	MDF	BMF	GRF	SCJ	AGR	URB	HC
147	Black-crested Bulbul	*Pycnonotus melanicterus*	0	1	0	0	0	0	0	HS
148	Red-whiskered Bulbul	*Pycnonotus jocosus*	1	1	1	0	1	0	0	HG
149	Red-vented Bulbul	*Pycnonotus cafer*	1	1	1	1	1	1	1	HG
150	White-browed Bulbul	*Pycnonotus luteolus*	1	0	0	0	1	1	1	HG
151	Zitting Cisticola	*Cisticola juncidis*	0	0	0	1	1	1	0	HS
152	Rufous-fronted Prinia	*Prinia buchanani*	0	0	0	1	1	1	0	HS
153	Grey-breasted Prinia	*Prinia hodgsonii*	1	1	1	1	1	0	0	HG
154	Jungle Prinia	*Prinia sylvatica*	0	0	1	1	1	0	0	HS
155	Ashy Prinia	*Prinia socialis*	1	0	1	1	1	1	1	HG
156	Plain Prinia	*Prinia inornata*	0	0	0	1	1	1	1	HG
157	Oriental White-eye	*Zosterops palpebrosus*	1	1	1	0	1	1	0	HG
158	Common Tailorbird	*Orthotomus sutorius*	1	1	1	1	1	1	1	HG
159	Striated Grassbird	*Megalurus palustris*	0	0	0	1	1	1	0	HS
160	Puff-throated Babbler	*Pellorneum ruficeps*	0	1	1	0	0	0	0	HS
161	Indian Scimitar Babbler	*Pomatorhinus horsfieldii*	0	1	1	0	0	0	0	HS
162	Tawny-bellied Babbler	*Dumetia hyperythra*	1	0	1	0	1	0	0	HS
163	Yellow-eyed Babbler	*Chrysomma sinense*	0	0	0	1	1	1	0	HS
164	Common Babbler	*Turdoides caudatus*	0	0	0	1	1	1	0	HS
165	Large Grey Babbler	*Turdoides malcolmi*	0	0	0	1	1	1	1	HG
166	Jungle Babbler	*Turdoides striatus*	1	1	1	1	1	1	1	HG
167	Brown-cheeked Fulvetta	*Alcippe poioicephala*	0	1	1	0	0	0	0	HS
168	Singing Bushlark	*Mirafra cantillans*	0	0	0	0	1	1	0	HS
169	Indian Bushlark	*Mirafra erythroptera*	0	0	0	1	1	1	1	HG
170	Bengal Bushlark	*Mirafra assamica*	0	0	0	0	1	1	0	HS
171	Ashy-crowned Sparrow Lark	*Eremopterix grisea*	0	0	0	1	1	1	1	HG
172	Rufous-tailed Lark	*Ammomanes phoenicurus*	0	0	0	1	1	1	1	HG
173	Sand Lark	*Calandrella raytal*	0	0	0	1	0	1	0	HS
174	Sykes's Lark	*Galerida deva*	0	0	0	1	1	1	0	HS
175	Oriental Skylark	*Alauda gulgula*	0	0	0	1	1	1	0	HS
176	Thick-billed Flowerpecker	*Dicaeum agile*	1	1	1	0	1	1	1	HG
177	Pale-billed Flowerpecker	*Dicaeum erythrorhynchos*	1	1	1	0	0	0	0	HS
178	Purple-rumped Sunbird	*Nectarinia zeylonica*	1	0	0	0	1	1	1	HG
179	Purple Sunbird	*Nectarinia asiatica*	1	1	1	0	1	1	1	HG
180	House Sparrow	*Passer domesticus*	0	0	0	1	1	1	1	HG
181	Chestnut-shouldered Petronia	*Petronia xanthocollis*	1	0	1	1	1	1	0	HG
182	White-browed Wagtail	*Motacilla maderaspatensis*	0	0	0	1	1	1	1	HG
183	Paddyfield Pipit	*Anthus rufulus*	0	0	0	1	1	1	1	HG
184	Baya Weaver	*Ploceus philippinus*	0	0	0	1	1	1	1	HG
185	Red Avadavat	*Amandava amandava*	1	0	1	1	1	0	0	HG
186	Indian Silverbill	*Lonchura malabarica*	0	0	0	1	1	1	0	HS
187	White-rumped Munia	*Lonchura striata*	0	0	0	1	1	1	0	HS
188	Scaly-breasted Munia	*Lonchura punctulata*	1	0	1	1	1	0	0	HG
189	Black-headed Munia	*Lonchura malacca*	0	0	0	1	1	1	0	HS
190	Crested Bunting	*Melophus lathami*	0	0	0	1	1	0	0	HS

Appendix 7.1. List of breeding birds of Central Indian Highlands along with their rarity scores computed as an additive function of geographical range size, habitat specialization, and population size. The scores range in their values from 8 ('extremely rare') to 1 ('extremely common').

Common name	Scientific name	Rarity Score
Malabar Pied Hornbill	*Anthracoceros coronatus*	8
Blue-bearded Bee-eater	*Nyctyornis athertoni*	8
Banded Bay Cuckoo	*Cacomantis sonneratii*	8
Alpine Swift	*Tachymarptis melba*	8
Spot-bellied Eagle Owl	*Bubo nipalensis*	8
Lesser Florican	*Sypheotides indica*	8
Pallas's Fish Eagle	*Haliaeetus leucoryphus*	8
Crested Goshawk	*Accipiter trivirgatus*	8
Indian Spotted Eagle	*Aquila hastata*	8
Red-necked Falcon	*Falco chicquera*	8
Malabar Whistling Thrush	*Myophonus horsfieldii*	8
Asian Brown Flycatcher	*Muscicapa dauurica*	8
Jungle Myna	*Acridotheres fuscus*	8
Black-crested Bulbul	*Pycnonotus melanicterus*	8
Striated Grassbird	*Megalurus palustris*	8
Red Spurfowl	*Galloperdix spadicea*	7
Painted Spurfowl	*Galloperdix lunulata*	7
Red Junglefowl	*Gallus gallus*	7
Grey Junglefowl	*Gallus sonneratii*	7
Rufous Woodpecker	*Celeus brachyurus*	7
Lesser Yellownape	*Picus chlorolophus*	7
Streak-throated Woodpecker	*Picus xanthopygaeus*	7
Oriental Scops Owl	*Otus sunia*	7
Dusky Eagle Owl	*Bubo coromandus*	7
Mottled Wood Owl	*Strix ocellata*	7
Brown Hawk Owl	*Ninox scutulata*	7
Large-tailed Nightjar	*Caprimulgus macrurus*	7
Oriental Turtle Dove	*Streptopelia orientalis*	7
Emerald Dove	*Chalcophaps indica*	7
Grey-headed Fish Eagle	*Ichthyophaga ichthyaetus*	7
Bonelli's Eagle	*Hieraaetus fasciatus*	7
Golden-fronted Leafbird	*Chloropsis aurifrons*	7
Scarlet Minivet	*Pericrocotus flammeus*	7
Bar-winged Flycatcher-shrike	*Hemipus picatus*	7
White-throated Fantail	*Rhipidura albicollis*	7
Ashy Drongo	*Dicrurus leucophaeus*	7
Spangled Drongo	*Dicrurus hottentottus*	7
Grey-headed Canary Flycatcher	*Culicicapa ceylonensis*	7
White-rumped Shama	*Copsychus malabaricus*	7
Chestnut-bellied Nuthatch	*Sitta castanea*	7
Velvet-fronted Nuthatch	*Sitta frontalis*	7
Puff-throated Babbler	*Pellorneum ruficeps*	7
Indian Scimitar Babbler	*Pomatorhinus horsfieldii*	7
Brown-cheeked Fulvetta	*Alcippe poioicephala*	7
Bengal Bushlark	*Mirafra assamica*	7

Common name	Scientific name	Rarity Score
Sand Lark	*Calandrella raytal*	7
Black-headed Munia	*Lonchura malacca*	7
Painted Bush Quail	*Perdicula erythrorhyncha*	6
Marshall's Iora	*Aegithina nigrolutea*	6
Plain Martin	*Riparia paludicola*	6
White-browed Bulbul	*Pycnonotus luteolus*	6
Purple-rumped Sunbird	*Nectarinia zeylonica*	6
White-rumped Needletail	*Zoonavena sylvatica*	5
Southern Grey Shrike	*Lanius meridionalis*	5
Eurasian Blackbird	*Turdus merula*	5
Streak-throated Swallow	*Hirundo fluvicola*	5
Red-whiskered Bulbul	*Pycnonotus jocosus*	5
Rock Bush Quail	*Perdicula argoondah*	4
Drongo Cuckoo	*Surniculus lugubris*	4
Red Collared Dove	*Streptopelia tranquebarica*	4
Long-billed Vulture	*Gyps indicus*	4
Laggar Falcon	*Falco jugger*	4
Black-lored Tit	*Parus xanthogenys*	4
Rufous-fronted Prinia	*Prinia buchanani*	4
Jungle Prinia	*Prinia sylvatica*	4
Common Babbler	*Turdoides caudatus*	4
Singing Bushlark	*Mirafra cantillans*	4
Sykes's Lark	*Galerida deva*	4
Pale-billed Flowerpecker	*Dicaeum erythrorhynchos*	4
White-rumped Munia	*Lonchura striata*	4
Painted Francolin	*Francolinus pictus*	3
Rain Quail	*Coturnix coromandelica*	3
White-naped Woodpecker	*Chrysocolaptes festivus*	3
Indian Grey Hornbill	*Ocyceros birostris*	3
Common Kingfisher	*Alcedo atthis*	3
Stork-billed Kingfisher	*Halcyon capensis*	3
Pied Kingfisher	*Ceryle rudis*	3
Indian Cuckoo	*Cuculus micropterus*	3
Grey-bellied Cuckoo	*Cacomantis passerinus*	3
Sirkeer Malkoha	*Phaenicophaeus leschenaultii*	3
Alexandrine Parakeet	*Psittacula eupatria*	3
Crested Treeswift	*Hemiprocne coronata*	3
Collared Scops Owl	*Otus bakkamoena*	3
Eurasian Eagle Owl	*Bubo bubo*	3
Brown Fish Owl	*Ketupa zeylonensis*	3
Savanna Nightjar	*Caprimulgus affinis*	3
Yellow-footed Green Pigeon	*Treron phoenicoptera*	3
Red-headed Vulture	*Sarcogyps calvus*	3
Crested Serpent Eagle	*Spilornis cheela*	3
Changeable Hawk Eagle	*Spizaetus cirrhatus*	3
Peregrine Falcon	*Falco peregrinus*	3
Bay-backed Shrike	*Lanius vittatus*	3
Long-tailed Shrike	*Lanius schach*	3
White-bellied Drongo	*Dicrurus caerulescens*	3
Greater Racket-tailed Drongo	*Dicrurus paradiseus*	3

Common name	Scientific name	Rarity Score
Common Woodshrike	*Tephrodornis pondicerianus*	3
Brown Rock-chat	*Cercomela fusca*	3
Chestnut-tailed Starling	*Sturnus malabaricus*	3
Zitting Cisticola	*Cisticola juncidis*	3
Tawny-bellied Babbler	*Dumetia hyperythra*	3
Yellow-eyed Babbler	*Chrysomma sinense*	3
Oriental Skylark	*Alauda gulgula*	3
Indian Silverbill	*Lonchura malabarica*	3
Crested Bunting	*Melophus lathami*	3
Eurasian Cuckoo	*Cuculus canorus*	2
White-rumped Vulture	*Gyps bengalensis*	2
Tawny Eagle	*Aquila rapax*	2
Black-headed Cuckooshrike	*Coracina melanoptera*	2
Grey Francolin	*Francolinus pondicerianus*	1
Jungle Bush Quail	*Perdicula asiatica*	1
Indian Peafowl	*Pavo cristatus*	1
Brown-capped Pygmy W'pecker	*Dendrocopos nanus*	1
Yellow-crowned Woodpecker	*Dendrocopos mahrattensis*	1
Black-rumped Flameback	*Dinopium benghalense*	1
Brown-headed Barbet	*Megalaima zeylanica*	1
Coppersmith Barbet	*Megalaima haemacephala*	1
Common Hoopoe	*Upupa epops*	1
Indian Roller	*Coracias benghalensis*	1
White-throated Kingfisher	*Halcyon smyrnensis*	1
Green Bee-eater	*Merops orientalis*	1
Pied Cuckoo	*Clamator jacobinus*	1
Common Hawk Cuckoo	*Hierococcyx varius*	1
Asian Koel	*Eudynamys scolopacea*	1
Greater Coucal	*Centropus sinensis*	1
Rose-ringed Parakeet	*Psittacula krameri*	1
Plum-headed Parakeet	*Psittacula cyanocephala*	1
House Swift	*Apus affinis*	1
Barn Owl	*Tyto alba*	1
Jungle Owlet	*Glaucidium radiatum*	1
Spotted Owlet	*Athene brama*	1
Grey Nightjar	*Caprimulgus indicus*	1
Indian Nightjar	*Caprimulgus asiaticus*	1
Rock Pigeon	*Columba livia*	1
Laughing Dove	*Streptopelia senegalensis*	1
Spotted Dove	*Streptopelia chinensis*	1
Eurasian Collared Dove	*Streptopelia decaocto*	1
Oriental Honey Buzzard	*Pernis ptilorhyncus*	1
Black-shouldered Kite	*Elanus caeruleus*	1
Black Kite	*Milvus migrans*	1
Egyptian Vulture	*Neophron percnopterus*	1
Short-toed Snake Eagle	*Circaetus gallicus*	1
Shikra	*Accipiter badius*	1
White-eyed Buzzard	*Butastur teesa*	1
Indian Pitta	*Pitta brachyura*	1
Blue-winged Leafbird	*Chloropsis cochinchinensis*	1

Common name	Scientific name	Rarity Score
Rufous Treepie	*Dendrocitta vagabunda*	1
House Crow	*Corvus splendens*	1
Large-billed Crow	*Corvus macrorhynchos*	1
Eurasian Golden Oriole	*Oriolus oriolus*	1
Black-hooded Oriole	*Oriolus xanthornus*	1
Large Cuckooshrike	*Coracina macei*	1
Small Minivet	*Pericrocotus cinnamomeus*	1
White-browed Fantail	*Rhipidura aureola*	1
Black Drongo	*Dicrurus macrocercus*	1
Black-naped Monarch	*Hypothymis azurea*	1
Asian Paradise-flycatcher	*Terpsiphone paradisi*	1
Common Iora	*Aegithina tiphia*	1
Orange-headed Thrush	*Zoothera citrina*	1
Tickell's Blue Flycatcher	*Cyornis tickelliae*	1
Oriental Magpie Robin	*Copsychus saularis*	1
Indian Robin	*Saxicoloides fulicata*	1
Pied Bushchat	*Saxicola caprata*	1
Brahminy Starling	*Sturnus pagodarum*	1
Asian Pied Starling	*Sturnus contra*	1
Common Myna	*Acridotheres tristis*	1
Bank Myna	*Acridotheres ginginianus*	1
Great Tit	*Parus major*	1
Dusky Crag Martin	*Hirundo concolor*	1
Wire-tailed Swallow	*Hirundo smithii*	1
Red-rumped Swallow	*Hirundo daurica*	1
Red-vented Bulbul	*Pycnonotus cafer*	1
Grey-breasted Prinia	*Prinia hodgsonii*	1
Ashy Prinia	*Prinia socialis*	1
Plain Prinia	*Prinia inornata*	1
Oriental White-eye	*Zosterops palpebrosus*	1
Common Tailorbird	*Orthotomus sutorius*	1
Large Grey Babbler	*Turdoides malcolmi*	1
Jungle Babbler	*Turdoides striatus*	1
Indian Bushlark	*Mirafra erythroptera*	1
Ashy-crowned Sparrow Lark	*Eremopterix grisea*	1
Rufous-tailed Lark	*Ammomanes phoenicurus*	1
Thick-billed Flowerpecker	*Dicaeum agile*	1
Purple Sunbird	*Nectarinia asiatica*	1
House Sparrow	*Passer domesticus*	1
Chestnut-shouldered Petronia	*Petronia xanthocollis*	1
White-browed Wagtail	*Motacilla maderaspatensis*	1
Paddyfield Pipit	*Anthus rufulus*	1
Baya Weaver	*Ploceus philippinus*	1
Red Avadavat	*Amandava amandava*	1
Scaly-breasted Munia	*Lonchura punctulata*	1

Appendix 7.2. Quadrat and biome-wise distribution of Protected Areas (National Parks & Wildlife Sanctuaries) in Central Indian Highlands, Madhya Pradesh.

Quadrat	Biome & PA	Forest area under PA (sq. km.)	Conservation value (%)
	High-elevation moist deciduous forests		
55/J07	Bori WLS + Satpura NP + Pachmarhi WLS	309	20.45
55/J06	Bori WLS + Satpura NP + Pachmarhi WLS	393	20.06
64/B11	Kanha NP	423	18.69
64/B12	Kanha NP	47	18.69
64/B16	Kanha NP	329	18.32
64/F04	Kanha NP	19	16.90
64/B15	Kanha NP + Phen WLS	122	18.69
64/F03	Kanha NP + Phen WLS	92	17.31
55/J11	Pachmarhi WLS	17	20.45
55/J10	Pachmarhi WLS	125	19.54
	Low-elevation moist deciduous forests		
64/E02	Bandhavgarh NP	337	18.36
64/A14	Bandhavgarh NP + Panpatha WLS	114	13.05
55/J03	Bori WLS	364	22.54
55/J02	Bori WLS	73	20.54
64/B07	Kanha NP	19	20.99
64/E01	Panpatha WLS	135	18.36
55/O02	Pench NP	29	19.01
55/O06	Pench NP	59	17.92
55/O05	Pench NP + Pench WLS	206	19.54
55/O09	Pench WLS	89	17.81
64/E09	Sanjay NP (incl. Sanjay Dubri WLS)	166	15.87
64/E13	Sanjay NP (incl. Sanjay Dubri WLS)	416	15.22
63/H12	Sanjay NP (incl. Sanjay Dubri WLS)	166	15.12
63/H16	Sanjay NP (incl. Sanjay Dubri WLS)	83	14.26
	High-rainfall dry deciduous forests		
55/M06	Nauradehi WLS	299	10.32
55/M04	Nauradehi WLS	48	10.16
55/M08	Nauradehi WLS	12	10.16
55/M02	Nauradehi WLS	119	9.82
55/M07	Nauradehi WLS	239	9.82
55/M03	Nauradehi WLS	426	9.07
63/D02	Panna NP	244	14.79
54/P14	Panna NP	244	13.88
54/P15	Panna NP	49	11.89
63/D01	Panna NP	50	14.89
64/A13	Panpatha WLS	108	9.37
55/O01	Pench NP	29	11.68
63/H04	Son Gharial WLS	38	10.91
63/H08	Son Gharial WLS	21	9.32
63/H11	Son Gharial WLS	4	8.45
63/H15	Son Gharial WLS	0	7.63
63/H07	Son Gharial WLS	21	7.48
55/M10	Veerangna Durgawati WLS	13	8.65
55/M14	Veerangna Durgawati WLS	11	6.77

Quadrat	Biome & PA	Forest area under PA (sq. km.)	Conservation value (%)
	Low-rainfall dry deciduous forests		
55/F15	Bori WLS	24	7.72
55/B13	Kheoni WLS	123	10.97
55/F13	Ratapani WLS	172	10.97
55/F09	Ratapani WLS	288	10.93