

**A GEOSPATIAL FRAMEWORK TO ASSESS ECOLOGICAL CONNECTIVITY
& THEIR PERSISTENCE FOR CENTRAL INDIAN LANDSCAPE**

**THESIS
SUBMITTED TO THE
FOREST RESEARCH INSTITUTE UNIVERSITY
DEHRADUN, UTTARAKHAND
FOR
THE AWARD OF THE DEGREE OF
DOCTOR OF PHILOSOPHY IN FORESTRY
(FOREST ECOLOGY & ENVIRONMENT)**



BY

SWATI SAINI

**UNDER THE SUPERVISION OF
PROF. QAMAR QURESHI
DR. Y.V. JHALA**

**WILDLIFE INSTITUTE OF INDIA
DEHRADUN, UTTARAKHAND**

2019




भारतीय वन्यजीव संस्थान
Wildlife Institute of India

CERTIFICATE

This is to certify that the thesis entitled "A Geospatial framework to assess ecological connectivity & their persistence for Central India Landscape" submitted by Ms. Swati Saini (Reg. no. 11Ph.D178) to Forest Research Institute (Deemed) University, Dehradun, for the award of the degree of **Doctor of Philosophy in Forestry (Forest Ecology and Environment)**, is a record of bonafide research work carried out by her under my supervision. No part of this thesis has been submitted for any other degree and it fulfills all the requirements laid down in the ordinance of Forest Research Institute University, Dehradun for this purpose.

Place: Dehradun
Date: 27th Aug., 2018


Qamar Qureshi
[Supervisor]



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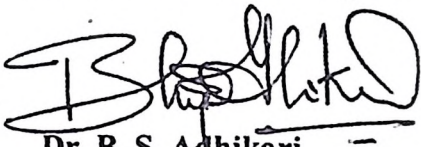
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Y. V. Jhala,
[Co-Supervisor]

Place: Dehradun
Date: 27th Aug., 2018

Forest Research Institute (Deemed) University, Dehradun

This is to certify that Ms. Swati Saini, enrolment no 11Ph.D178 carried out research work under the supervision of Prof. Qamar Qureshi, Scientist-G & HoD and Co-Supervision of Dr. Y.V. Jhala, Scientist-G Wildlife Institute of India, Dehradun. The topic of the research registered with Forest Research Institute (Deemed) University, Dehradun was "A Geospatial framework to assess ecological connectivity & their persistence for Central India Landscape". The scholar presented her work in the pre-thesis submission seminar held on 08.01.2018 and the Research Advisory Committee 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 Forest Research Institute (Deemed) University.



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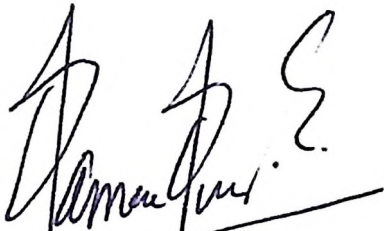
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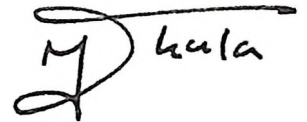
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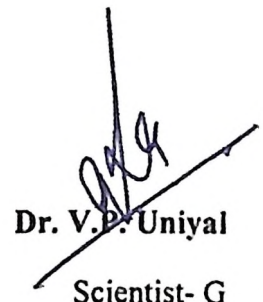
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To,

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C/o Dr. Kumar Qureshi, Scientist-F,
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4. The Topic of research approved by the FRI University: "A Geospatial framework to assess Ecological connectivity & their persistence for Central Indian Landscape".
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(ii) Name of Co-Supervisor :- Dr. Y.V. Jhala
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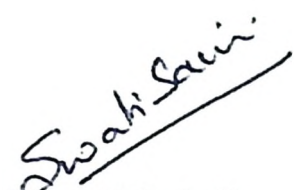
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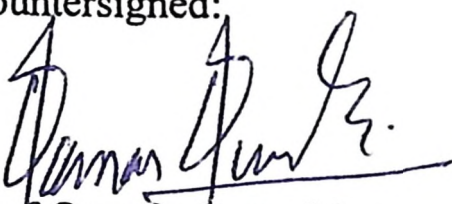
I hereby declare that the thesis entitled "A Geospatial framework to assess ecological connectivity & their persistence for Central India Landscape" submitted by Ms. Swati Saini (Reg. no. 11Ph.D178) to Forest Research Institute (Deemed) University, Dehradun, for the award of the degree of **Doctor of Philosophy in Forestry (Forest Ecology and Environment)**, is a record of original research work carried out by me under the supervision of Prof. Qamar Qureshi and co-supervision of Dr. Y.V. Jhala, Scientist-G, Wildlife Institute of India, Dehradun and it has not formed the basis for the award of any other degree or diploma. I also declare that the thesis embodies my own work, observation and analysis and in that respects the investigation appears to advance knowledge in the subject.

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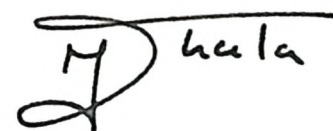

[Swati Saini]

Countersigned:


Prof Qamar Qureshi,

Scientist-G & HoD

[Supervisor]



Dr. Y. V. Jhala,

Scientist-G

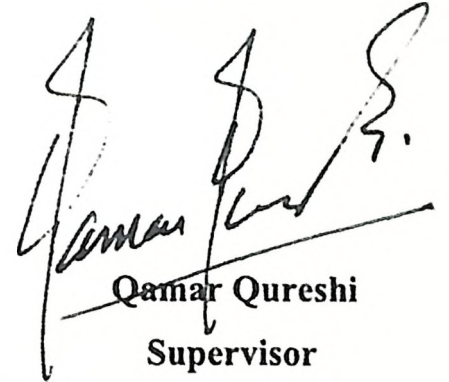
[Co-Supervisor]



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Qamar Qureshi
Supervisor

Place: Dehradun

Date: 03 October, 2019

Prioritizing Tiger Conservation through Landscape Genetics and Habitat Linkages

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Abstract

Even with global support for tiger (*Panthera tigris*) conservation their survival is threatened by poaching, habitat loss and isolation. Currently about 3,000 wild tigers persist in small fragmented populations within seven percent of their historic range. Identifying and securing habitat linkages that connect source populations for maintaining landscape-level gene flow is an important long-term conservation strategy for endangered carnivores. However, habitat corridors that link regional tiger populations are often lost to development projects due to lack of objective evidence on their importance. Here, we use individual based genetic analysis in combination with landscape permeability models to identify and prioritize movement corridors across seven tiger populations within the Central Indian Landscape. By using a panel of 11 microsatellites we identified 169 individual tigers from 587 scat and 17 tissue samples. We detected four genetic clusters within Central India with limited gene flow among three of them. Bayesian and likelihood analyses identified 17 tigers as having recent immigrant ancestry. Spatially explicit tiger occupancy obtained from extensive landscape-scale surveys across 76,913 km² of forest habitat was found to be only 21,290 km². After accounting for detection bias, the covariates that best explained tiger occupancy were large, remote, dense forest patches; large ungulate abundance, and low human footprint. We used tiger occupancy probability to parameterize habitat permeability for modeling habitat linkages using least-cost and circuit theory pathway analyses. Pairwise genetic differences (F_{ST}) between populations were better explained by modeled linkage costs ($r > 0.5$, $p < 0.05$) compared to Euclidean distances, which was in consonance with observed habitat fragmentation. The results of our study highlight that many corridors may still be functional as there is evidence of contemporary migration. Conservation efforts should provide legal status to corridors, use smart green infrastructure to mitigate development impacts, and restore habitats where connectivity has been lost.

Citation: Yumnam B, Jhala YV, Qureshi Q, Maldonado JE, Gopal R, et al. (2014) Prioritizing Tiger Conservation through Landscape Genetics and Habitat Linkages. PLoS ONE 9(11): e111207. doi:10.1371/journal.pone.0111207

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Data Availability: The authors confirm that all data underlying the findings are fully available without restriction. Data is available from Dryad with the following data identifier: doi: 10.5061/dryad.c7v41.

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Introduction

By virtue of being at the top of the food chain, large carnivores occur at low densities, have large home ranges and therefore require vast areas to harbor viable populations [1]. Since historical times, large carnivores have been in conflict with humans for food and resources, often resulting in their demise [2]. Habitat destruction, excessive hunting by humans and the use of body parts for traditional medicine have extirpated many populations [3,4,5] while severely reducing, fragmenting, and isolating most others to varying degrees [6,7]. Small and isolated populations are prone to local extirpation [8,9]. Managing such populations in a metapopulation framework [10,11] by connecting them through habitat corridors [12,13] so that individuals have the opportunity to disperse, establish residency and reproduce, reduces the overall risk of extinction [1,14]. Much of the global conservation policy on endangered species is centered on land allocation schemes for

securing source populations [15], promoting and maintaining connectivity between fragmented populations [16,17]. Land is one of the most prized resources, and a major challenge to this conservation approach is the difficulty in convincing governments and policy makers on its allocation for conservation purposes. This problem is further compounded when objective criteria for delineating corridor habitats or documenting their functionality based on rigorous scientific data are lacking. As a result, conservation relies heavily on expert opinion and models of corridor connectivity that have little empirical validation.

The tiger (*Panthera tigris*) acts as a flagship species for the conservation of forested ecosystems throughout its range in Asia [18]. Conserving the tiger typifies the prospects and challenges inherent in the current paradigm of fragmented small populations and landscape based conservation models in large carnivores [19]. Extant tiger populations are confined to less than seven percent of their historical range in patchily distributed habitats across a range

of twelve regional tiger conservation landscapes (TCLs) in southern and north-eastern Asia [20]. Six global priority TCLs of long-term tiger conservation significance are present in the Indian subcontinent. These Indian TCLs are important for global tiger recovery as they harbor over 50% of the estimated global population of ~3,000 wild tigers [21,22], and >60% of the global genetic variation in the species [23]. The high genetic variation seen in Indian tigers could be attributed to historically high population sizes, numbering about 50,000 individuals until *c.* 200 years ago, and habitat contiguity that permitted genetic exchange between the various regional tiger populations in the area [23]. Due to change in land ownership and forest use policy in the mid nineteenth century during British rule and again during the early years of India's independence a century later, much of the forest was cleared for timber and agricultural needs [24,25]. This change in land use combined with organized trophy hunting and bounty driven extermination resulted in severe decline, fragmentation and isolation of tiger populations throughout India [25,26]. Tiger conservation and subsequent population recovery in India began during the 1970s with the creation of a number of protected areas (Tiger Reserves) under the Project Tiger network in 1973 [18], and aided by comprehensive wildlife legislation (Wildlife Protection Act 1972, [27]). Under Project Tiger, the tiger was used as a flagship and umbrella species for conserving the biodiversity of India's forested ecosystems. However, even though extensive areas have been added to the protected area network, the future of tigers is under severe threat from commercial poaching, and extensive habitat fragmentation within the last two decades [15,18,21]. The rise in human-wildlife conflict and issues dealing with land rights of forest-based dwellers, as people are present both inside and outside tiger reserves, further vexes grass-roots conservation especially at a landscape-scale, and negatively impacts tiger dispersal capability and survival within TCLs [28]. These factors have precipitated the systematic decline in tiger and prey populations from both outside and inside reserves, as attested by the recent local extirpations in few areas [5,29].

Currently in India, the once contiguous tiger population is now fragmented with source populations primarily restricted to tiger reserves. A tiger reserve is legally mandated to designate a critical core area wherein human habitation and resource extraction is not permitted (Wildlife Protection Act 1972, amendment 2005 [30]). This core is surrounded by a buffer zone, which is essentially a multiple use area, wherein conservation objectives are to be given precedence over other land uses. Breeding populations of tigers are mostly located in the core area of tiger reserves, while the buffers usually serve as population sinks [22,28,31]. The size of these tiger reserves vary between 344 km² to 3,150 km² (average 1,321 km²), with tiger densities ranging from about 0.1 to 20 individuals per 100 km² [22,31,32]. For a demographically viable tiger population, a minimum of 20 to 25 breeding units are believed to be essential [15,32,33]. As such, many extant tiger populations are by themselves inadequate for long-term persistence [33,34], either because of habitats harboring a low number of breeding tigers, small size of the protected area and/or ecological isolation from other populations. High spatial genetic structuring and small population size observed in today's Indian tiger populations [35] dictates preserving them in a metapopulation framework wherein individual populations are connected through a permeable habitat matrix and can occasionally exchange individuals [36,37]. This would result in re-colonization of suitable habitat patches where tigers have become locally extinct and 'rescue' declining local populations from extinction by immigrants [37,38]. Understanding and managing the metapopulation framework of extant tiger populations is an important strategy for ensuring their long-term

conservation. This approach entails strict preservation of source populations in protected areas and informed conservation strategies across tiger landscapes.

Due to the relatively high *K* selected life history traits of the tiger in comparison to other large cats, dispersal and immigration play a vital role in long-term viability of tiger populations [32]. Incidentally, it was likely due to the 'rescue effect' by immigrants from high-density populations and intact habitat corridors in the vicinity of Chitwan National Park, Nepal, which enabled the tiger population in the park during the 1930s to recover, even after heavy trophy hunting, to pre-decline levels in only three years [32]. In recent times, tigers have successfully recolonized Rajaji National Park, India, in the Shivalik-Gangetic Plain landscape, from connected source populations further east, within a decade of having completely disappeared from the area [39]. Small tiger populations that become isolated are likely to face extinction due to demographic stochasticity, inbreeding depression [40] and deterministic factors such as poaching [32,33], as witnessed in the small and isolated Indian tiger reserves of Sariska and Panna which recently suffered from local extinction events, although tigers were later re-introduced [5,29]. Habitat connectivity is integral to sustaining regional populations of tigers, as they require contiguous forest connectivity for dispersal and genetic exchange between populations [41]. Currently, within the six tiger occupied landscapes of India, habitat contiguity varies extensively, with the best being within the Western Ghats and the North East, while fragmentation is highest in the Shivalik-Gangetic Plain and the Central Indian Landscapes [42]. Most of the connecting habitats in these landscapes are not within the legal domain of protected areas and are often lost to burgeoning development demands of a growing economy and attrition by human consumptive uses. In India, the transfer of forest-land to other land uses requires approval from the Federal Government as outlined in the Forest (Conservation) Act 1980 [43]. Since Federal Government approvals are usually sought on a case-by-case basis, and rarely are the cumulative impacts of projects or landscape scale conservation significance of forest patches factored into decision making, such permissions are frequently granted [44]. However, when the Supreme Court of India and Federal Government Committees were presented with concrete scientific evidence on the significance of conserving these forest patches, development projects even of national interests have been stalled [45,46,47]. Unfortunately, scientific data rarely exist to substantiate the landscape-level conservation significance of forest patches that constitute habitat corridors, and crucial areas are often lost. Studies on spatial dispersal and gene flow to detect population units and migration between patches can provide a quantitative and formal assessment of corridor function and identify priority populations for conservation action.

Assessing gene flow in species across populations in complex fragmented habitats is critical to understand how landscapes structure genetic variation and maintain metapopulation connectivity. Unfortunately, the traditional validation of habitat connectivity through the direct observation of individual animal movement is logistically difficult as it would entail following the fates of many radio-collared or camera trapped individuals over a regional scale and spanning multiple generations. As a result, alternative genetic assignment methods based on individual clustering approaches [48,49] have gained popularity [7,50]. The integration of metapopulation genetic models with spatial analytic tools in a landscape genetics framework provides a quantitative approach for understanding the role of geography, habitat and land-use features either as barriers or facilitators to gene flow among natural populations [51]. Though initially

restricted to analyses correlating with linear distances [51,52], the developing field of landscape genetics has now advanced to include more complicated connectivity modeling incorporating ways in which habitats are actually traversed in nature. The use of landscape heterogeneity patterns and habitat permeability obtained from Geographical Information Systems (GIS) layers to model habitat connectivity by least-cost pathway (LCP) analysis [53] and circuit theory based isolation-by-resistance (IBR) model [54,55] that permit gene-flow between populations provide an objective criteria for delineating and prioritizing habitat corridors. There is a small but rapidly growing body of literature investigating the relationship between genetic and corridor connectivity, with both LCP and IBR models finding promise in gene flow studies on taxa with lower dispersal capabilities and that readily form visible metapopulations such as amphibians (tiger salamanders, *Ambystoma sp.* [56,57]), to wide-ranging carnivore species (cougar, *Puma concolor* [58]; bobcat, *Lynx rufus* [59]; wolverine, *Gulo gulo* [60]; black bear, *Ursus americanus* [61]). Where available, researchers have incorporated information from animal habitat use and movement behavior in the cost parameterization schemes to approximate realistic paths of least resistance, as in Reding *et al.* [59]. However, such data are not readily obtainable, and hence the vast majority of studies rely on expert opinion and *a priori* assumptions on animal presence to assign cost schemes and parameterize landscape resistance to gene flow. Although informative, the parameterization schemes used in landscape resistance surfaces to model movement paths and the assignment of cost schemes to grids in GIS rasters could easily introduce biases which may be more reflective of habitats as perceived by humans rather than by animals [62,63]. Incorporating information obtained from fine-scale species and landscape-specific ground data on suitable habitat, cover, prey availability, disturbance and threats in considering the attribute of surrounding cells, is one way which could help reduce subjectivity involved when assessing resistance or cost of a cell and the likelihood of path usage [63].

In this study, we investigate patterns of landscape heterogeneity and spatial genetic structuring to identify barriers and minimal habitat corridors for gene flow between populations within the fragmented tiger habitats in Central India. The Central Indian landscape is a globally recognized area for tiger conservation, with significant potential for long-term persistence of the species [15,31]. The area supports one of the largest global concentrations of tiger populations (~20% of an estimated 1,700 adult Indian tigers, [31]) in patchily connected habitats. Although the populations were historically connected, rapid infrastructural development and urbanization in recent years threaten to form permanent barriers to dispersing tigers by isolating tenuously connected small populations, thereby effectively reducing long-term metapopulation persistence. Recent population and spatial genetic studies have observed low genetic structure among populations indicative of gene flow [64,65] and long-range dispersal which are affected by increasing urbanization in the area [66]. Although tigers can move huge distances in undisturbed habitats [67], the complex fragmented habitat mosaic in the area, interspersed with high density human settlements and increasingly urbanized centers, have generally been thought to limit long-range dispersal [41]. Dispersal in tigers, like in lions (*Panthera leo* [19]) is male biased, as female offspring tend to reside and breed close to their maternal ranges, while male offspring disperse long distances and establish home ranges far from their natal areas [41]. This study explores a strategy that utilizes genetic assignment methods to detect population genetic structuring and determine which populations are in migratory contact, extensive occupancy

modeling and GIS analysis to delineate structural connectivity between populations, and a correlation process between landscape connectivity versus population pairwise genetic distances to determine which of the movement cost schemes and modeled corridors best explain the observed genetic structuring in the area.

We extensively and intensively collected scat and a few tissue samples across seven tiger reserves in the Central Indian Landscape and first identify tiger individuals by genotyping the DNA extracts using eleven autosomal microsatellite loci. Next we assessed spatial genetic structuring and gene flow in the identified individuals through individual clustering methods. We use likelihood based [49] and Bayesian [48,68] assignment methods to detect first and second generation migrants between the identified genetic population clusters. Since resident tigers do not occur outside of forested habitat, we surveyed all of the forested area (76,913 km²) within 185,100 km² of Central India. Based on our understanding of tiger ecology, we predicted *a priori* that tigers should occur in vast, undisturbed, productive forest patches, with high density of large wild ungulate prey, which would be negatively impacted by human disturbances [20,31,41,67]. We tested these *a priori* hypotheses by spatially explicit modeling of tiger occupancy that accounted for imperfect detections, using covariates obtained by remote sensing and ground surveys covering all forest patches within our study area. We then used this spatially explicit information of tiger occupancy as a resource selection probability function [69,70] to model habitat corridors joining tiger populations using LCP [71] and circuit theory [72] analyses in a GIS setting. With genetic data we tested if the observed population structure and dispersal between populations is in concordance with ground reality of tiger occupancy and existing habitat connectivity. Our comprehensive study highlights the importance of particular tiger source populations and intervening forest corridors for maintaining metapopulation structure within Central India. It provides a basis to formulate conservation policy and assist informed decision making for land-use planning at the landscape scale.

Materials and Methods

Ethics Statement

The majority of field sampling was conducted non-invasively from tiger scat, without animal capture and handling. Permits for collection of tiger scat samples were obtained from the National Tiger Conservation Authority and the State Forest Departments. Capture and radio collaring of tigers required the approval of the Ministry of Environment and Forests, Government of India and the Chief Wildlife Warden, Madhya Pradesh State, under the Wildlife (Protection) Act 1972. The permissions define the conditions required for capture of tigers, which include an approved protocol and participation by a Park Official and supervision by a qualified veterinarian in the capture and collaring exercise. Both these permissions were obtained and strictly adhered to. Capture operations were conducted by trained veterinarians and wildlife biologists as per the protocols of the Wildlife Institute of India and the National Tiger Conservation Authority. A tiger tissue sample was obtained from Satpura Tiger Reserve where the tiger died due to natural causes (was killed by another tiger in a territorial strife). This research project was conceived and radio collaring reported in this paper was done prior to the formation of an animal ethics committee at the Wildlife Institute of India.

Study Area

The present study was carried out in the global priority tiger conservation landscape of Central India within the states of Madhya Pradesh, Maharashtra, and Chhattisgarh (Figure 1). A forested area of 76,913 km² (20.1–23.5°N and 76.5–81.5°E) covering the seven tiger reserves of Melghat, Satpura, Pench, Kanha, Tadoba, Achanakmar, and Bandhavgarh along with their buffer zones, corridor habitats and adjoining forested habitats were sampled. Sampled sites covered different types of tiger habitats found in Central India ranging from the tropical moist-deciduous Sal (*Shorea robusta*) forests in Kanha and Bandhavgarh to tropical dry-deciduous teak (*Tectona grandis*) dominated forests in Pench, Tadoba and Melghat. The topography varied from about 200 meters above sea level (m a.s.l.) in the low-lying hills to the *dadar* plateaus and meadows in Kanha (500 m a.s.l.) and the rugged Satpura ranges (highest elevation 1,352 m a.s.l.). The rainfall, primarily restricted to the monsoon season (late June to September end) ranged between 1,000 to 2,200 mm per year. The large mammal fauna found in the region included tigers (*Panthera tigris*), leopards (*P. pardus*), sloth bears (*Melursus ursinus*), dholes (*Cuon alpinus*), gaurs (*Bos gaurus*), wild pigs (*Sus scrofa*), sambar deer (*Rusa unicolor*), chital deer (*Axis axis*), barking deer (*Muntiacus muntjak*), swamp deer (*Rucervus duvaucelii*) and nilgai antelopes (*Boselaphus tragocamelus*).

Genetic Sampling and Laboratory Work

Blood from 16 radio-collared tigers, one tissue sample from a dead individual and 587 putative tiger scat (faeces) samples were collected between 2006 and 2011 from the seven Tiger Reserves, and at a few intervening forest corridors in the area (Figure 1 and Table 1). The number of samples obtained was largely proportional to the population size of tigers in that region. However, due to logistical constraints the Tadoba population was under sampled. Scats were stored, either dry with silica or in 75% ethanol, and kept at ambient temperature, prior to laboratory analysis. For each scat, a Global Positioning System (GPS) reading was taken and transferred into a GIS. Scat DNA extractions were performed in a room dedicated to low-copy DNA extraction, using the guanidine isothiocyanate - silica extraction protocol [73]. For every extraction, negative controls composed of reagent only without the scat sample were included to monitor contamination. Extractions from blood and tissue samples were carried out using the DNeasy blood and tissue kit (QIAGEN, Germany).

Tiger scats were identified from among the field collected scats through PCR and *Bam*HI restriction enzyme digestion of the mitochondrial DNA cytochrome *b* gene (Figure S1; see Methods S1 and Tables S10 and S11 for details on protocols and reference species used for PCR). Unambiguously assigned tiger scats and blood and tissue samples were individually identified using a panel of eleven microsatellite loci, derived from domestic cat [74] and tiger [75,76]. The loci consisted of three dinucleotide (Fca304, Fca954, 6Hdz700), three trinucleotide (Pati01, Pati09, Pati15) and five tetranucleotide repeat markers (Fca441, F85, F53, F124, Pati18), variously labeled at the 5' end of each forward primer with 6 FAM, PET, VIC and NED dyes. Gender identification in individual tigers was carried out by amplifying the Y chromosome linked SRY gene and an X chromosome microsatellite locus Fca651. PCR amplifications were carried out in 10 µl reactions with a multiple panel of 3 to 4 loci using the Multiplex PCR kit (QIAGEN) according to the manufacturer's instructions. Amplified products were resolved on the ABI 3130 Genetic Analyzer and GENEMAPPER 3.7 (Applied Biosystems, USA) was used to score allele sizes. To limit genotyping error due to allelic dropout (nonamplification of one allele in a heterozy-

gote), multiple PCR replicates were conducted as in Navidi *et al.* [77]. Heterozygotes were confirmed with at least two independent replicates and homozygotes with five replicates. The genotype data were checked on MICROCHECKER [78] for identifying and correcting genotyping errors such as those that arose from stuttering patterns, null alleles and small-allele dominance.

Identification of Individuals and Descriptive Statistics

In order to investigate the power of the eleven microsatellite loci to distinguish among closely related individuals in the same population, the conservative sibling probability of identity (*PI sib*) statistic [79,80] was computed in GIMLET 1.1 [81]. Unique multilocus genotypes were identified using the *Identity* analysis option in CERVUS 3.0 [82,83]. Samples that showed mismatches at up to two loci were re-examined for possible genotyping errors and allelic drop-out, and again amplified thrice in order to confirm the multilocus genotypes before assigning them as unique individuals. Multiple replicates of the same individual from the same locality were discarded and only unique multilocus genotypes were used for all further analyses. We used CERVUS 3.0, GENEPOP 4.1 [84,85], GENALEX 6.3 [86] and FSTAT 2.9.3 [87] to calculate the following descriptive statistics: (i) number of alleles per locus, (ii) observed and expected heterozygosity, (iii) tests for deviation from Hardy-Weinberg Equilibrium (HWE), (iv) significance values for linkage disequilibrium (LD) among all pairs of loci, and (v) estimates of population pair-wise F_{ST} [88] and R_{ST} [89] values. Loci with null alleles were flagged by MICROCHECKER, and we tested for deviation from HWE using both null allele adjusted and unadjusted (observed allele frequencies) genotypes. We also tested for associations between genetic variation and estimated population size through Spearman's rank correlation using the *pspearman* package [90] in R (<http://cran.r-project.org>).

Population Genetic Structure

We used two types of individual-based analyses to assess genetic differences among individuals and assignment patterns of tigers to populations. First, a Principal Coordinates analysis (PCoA) based on pair-wise Phi_{PT} genetic distances [91] was carried out in GENALEX and the scatter of population-wise individual assignments was plotted on the first three PCo axes using NCSS (www.ncss.com) to understand broad spatial patterns of populations structure in the landscape. Next, we used the Bayesian individual clustering approach in STRUCTURE 2.3.3 [48] to detect population structure among sampled localities in the area by assigning sampled individuals into a number of clusters (*K*) based on the multilocus genotype data alone. The clustering process ensures that for identified population clusters, deviations from Hardy Weinberg and linkage equilibrium are minimized. We analyzed our data in STRUCTURE by using the admixed model and correlated allele frequencies option to carry out thirty independent simulations at each *K* (*K* = 1 to 10), with a burn-in length of one million Monte Carlo Markov Chain (MCMC) steps and data collection phase of five million MCMC iterations. These run times were sufficient to ensure convergence of the Markov chains, and all runs were carried out both with (*locprior* = 1) and without (*locprior* = 0) using prior sampling locality information. The true *K* or most likely number of population clusters in the dataset was inferred from (i) the *ad hoc* parameter of log-likelihood change in probability of individual assignments to *K* clusters ($Ln P(K)$, [48]), and (ii) the second order rate of change in the likelihood of *K* values (ΔK , [92]). Both these values were computed from the STRUCTURE output using the program STRUCTURE HARVESTER v0.6.91 [93]. We also carried out

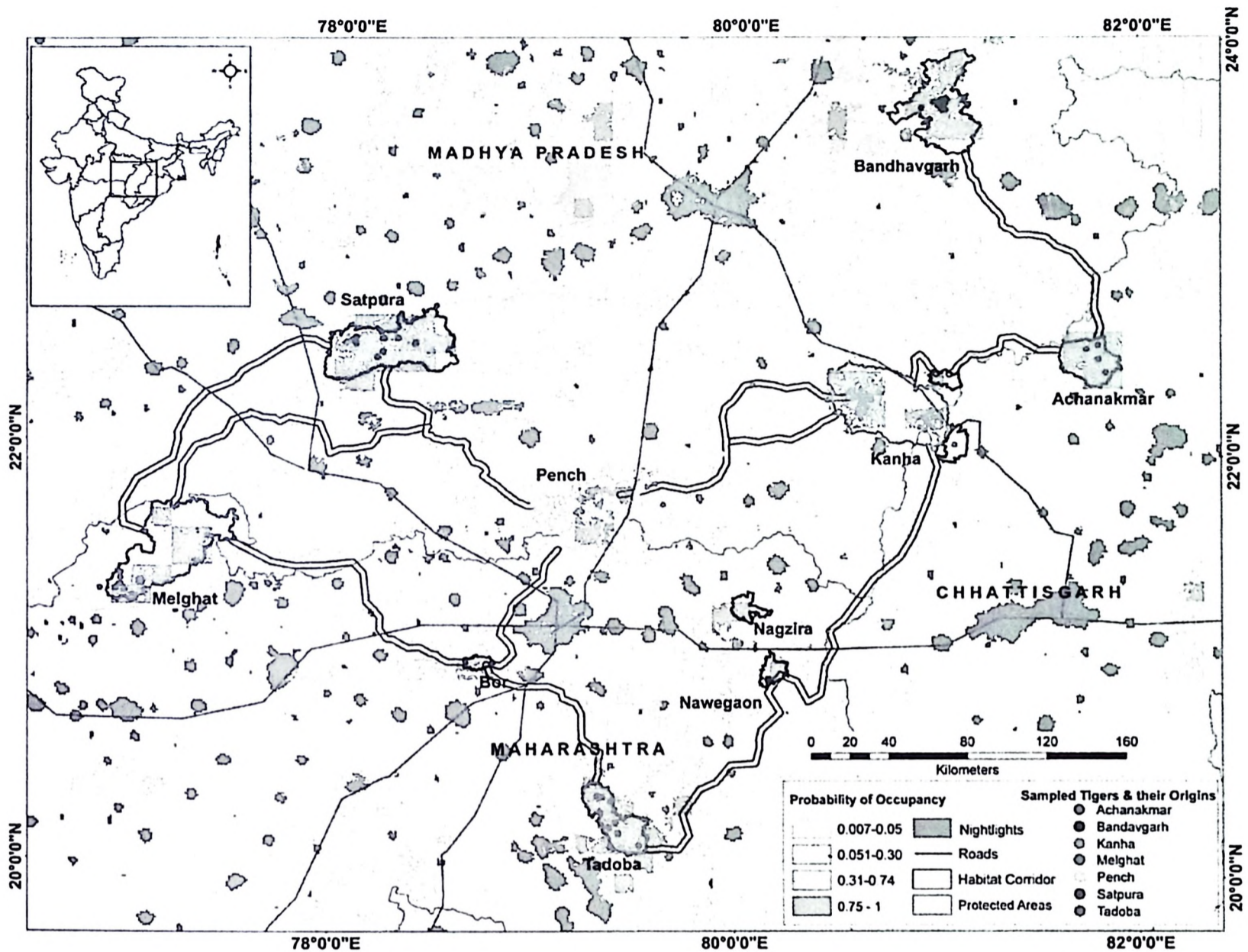


Figure 1. Study area map showing sampled sites, genotype locations and habitat connectivity. The study area of Central India spanning the states of Madhya Pradesh, Maharashtra and Chhattisgarh, showing tiger habitat (forest cover) coded with tiger occupancy probability, protected areas, human habitation (night lights), major roads and least-cost habitat corridors connecting tiger reserves. Individually genotyped tigers ($n = 165$) are shown as color coded dots at their sampled locations with their colors matching their genetically assigned population. doi:10.1371/journal.pone.0111207.g001

an Analysis of Molecular Variance (AMOVA, [91]) in GENALEX to compare the population clusters identified by the STRUCTURE analysis. Genetic variances were partitioned at two levels, viz. among all the STRUCTURE identified population groups (K clusters) and among subpopulations within each group.

Detection of Migrants

We used three Bayesian approaches implemented in STRUCTURE 2.3.3 [48], GENECLASS 2.0 [49] and BAYESASS 1.3 [68], for identification of migrant and admixed individuals. STRUCTURE was used to calculate the posterior probability of whether individuals are residents of their sampled population or migrants from other areas by incorporating the previously identified population cluster information with a *a priori* designation of the migration rate (MIGPRIOR = 0.05). All other parameters and run times followed previous population clustering runs (as detailed above in the preceding methods section on analyzing population genetic structure). We detected no biases in a *a priori* assignment of the migration rate as the selection of particular MIGPRIOR values (0.001 to 0.1) did not substantially influence

the STRUCTURE output, therefore only results for MIGPRIOR = 0.05 are presented here.

Next, we used the likelihood-based estimator L_i/L_{max} in combination with the resampling algorithm of Paetkau *et al.* [94], implemented in the 'detect migrants' function in GENECLASS to exclusively identify first generation migrants, i.e. individuals assigned to a different population other than the sampled population. The Paetkau *et al.* [94] routine was selected on basis of its superior simulation scheme which closely mimics natural processes and results in accurate type I error rates. L_i/L_{max} is the ratio of L_i , the likelihood of a given individual being assigned to its sampled population to L_{max} , the greatest likelihood among all sampled populations [94]. We employed the Bayesian criterion of Rannala and Mountain [95] in combination with the re-sampling algorithm of Paetkau *et al.* [94] using a simulated set of 10,000 area-specific genotypes, to determine migrant thresholds (type I error α levels of 0.01 and 0.05) of L_i/L_{max} . We considered a minimum log likelihood L_i/L_{max} ratio of 2.0, which corresponds to a 100 times probability of being cross-assigned, as the threshold level for determining putative migrant status of an individual [7].

Table 1. Area-wise estimates showing population extents, occupied habitats, sampling effort and number of tiger individuals identified.

Population	Naive Occupancy (km ²)	Critical Core Area (km ²)	Tiger Reserve Size (km ²)	total scats/cyt b PCR amplified/ tiger scats/STR genotypes	other samples - blood (b), tissue (t)	all samples/all tiger STR genotypes/ individuals	estimated population size (SE range) *	% population sampled			
								male	female	unknown sex	
Melghat (M)	2,376	1,501	2,769	66/47/44/35	0	66/35/15	35 (30-39)	43	6	8	1
Satpura (S)	1,554	1,339	2,133	46/21/17/17	1 (t)	47/18/11	43 (42-46)	26	3	6	2
Pench (P)	2,174	669	1,921	137/94/86/82	3 (b)	140/85/51	65 (53-78)	78	25	24	2
Kanha Pench corridor (KPC)	1,013	NA	NA	26/24/5/5	0	26/5/5	NA	NA	2	2	1
Kanha (K)	1,850	917	2,052	159/67/65/56	12 (b)	171/68/50	60 (45-75)	83	22	27	1
Achanakmar (A)	904	626	914	23/16/5/5	0	23/5/4	12 (11-13)	33	2	2	0
Tadoba (T)	3,519	626	1,728	32/20/17/17	0	32/17/11	69 (66-74)	16	5	3	3
Bandhavgarh (B)	1,700	717	1,537	98/41/36/33	1 (b)	99/34/22	59 (47-71)	37	9	13	0
Total	15,090	6395	13,054	587/330/275/250	17	604/267/169	343	49	74	85	10

* in Jhala et al. [31], NA - not available. doi:10.1371/journal.pone.0111207.t001

Third, the non-equilibrium Bayesian assignment test of BAYESASS was used to trace each individual's immigrant ancestry within the last two to three generations. Unlike STRUCTURE and GENECLASS analyses which require loci to follow Hardy-Weinberg and linkage equilibrium, BAYESASS is robust to violations from Hardy-Weinberg equilibrium as it measures contemporary gene flow within the last few generations based only on multilocus allele sharing among individuals [68]. To ensure convergence, a total run length of eight million MCMC iterations was performed, of which the first two million runs were the burn-in phase and the remaining six million runs comprised the data collection phase with the MCMC chain being sampled every 2,000 steps. Individual assignments and immigrant ancestries were calculated at a migration rate prior of 0.05, and keeping all other settings at default. Varying the prior rate (0.01 to 0.15) did not affect the results.

Lastly, to corroborate the results of the above assignment based migrant decisions, a likelihood based parentage analysis was carried out in CERVUS 3.0 [82,96] to identify likely parent-offspring relationships between putative migrants and an individual in the cross-assigned source population based on log of the odds (LOD) scores. The LOD score that is the natural logarithm of the overall likelihood ratio for each candidate parent is calculated by multiplying together the likelihood ratios at each locus. A positive LOD score means that the candidate parent is likely to be the true parent, whereas a negative value means that the candidate parent is less likely to be the true parent. We estimated LOD scores for strict (95%) and relaxed (80%) confidence limits as 7.0 and 4.9 respectively, which were calculated from a simulated set of 10,000 offspring and 300 candidate parent genotypes, assuming 25% of candidate parents were sampled, 93% of loci were typed with typing error of 0.01 to 0.10.

Designation of migrant status to an individual was contingent upon - (i) significant assignment of first generation migrant status in GENECLASS ($P < 0.01$, $Lh/Lmax \geq 2.0$); (ii) observance of > 50% migrant or cross-assignment probability in STRUCTURE and BAYESASS; (iii) high assignment probability to first generation immigrant ancestry state ($gen1 > 50\%$) in both STRUCTURE and BAYESASS; and (iv) high membership ($Q > 0.8$) to a single non-home cluster in the STRUCTURE analysis without prior population information. Further, in most cases of putative migrants, the successful parentage assignment corroborated the migrant status of the individual tiger. We considered a conservative approach by identifying individuals as putative migrants only if all three programs suggested evidence of immigrant ancestry.

Estimation of Contemporary and Historical Migration Rates

In order to study gene flow across different timescales, we used the programs BAYESASS 1.3 [68] and MIGRATE 3.3.2 [97,98] to compare migration rates over contemporary and historical timescales, respectively. Although the two programs use different approaches to derive estimates of gene flow, both programs generate parameters from which a comparative estimate of the proportion of genetic migrants in the population per generation (m) can be inferred. In BAYESASS, a Bayesian approach incorporating an MCMC sampling scheme is used to estimate migration rates between pairs of populations over the last few (approximately <5) generations back. With an estimated generation time of four to five years in tigers [99], this period corresponds to a timescale of nearly 20-25 years ago. MIGRATE on the other hand, uses the coalescent to estimate the relative mutation-scaled effective population size, theta, θ_{Ne} ($4N_e\mu$; where

N_e is the effective population size and μ is the mutation rate) and asymmetric mutation-scaled immigration rate M (m/μ). The mutation-scaled immigration rate M , which is the immigration rate m divided by the mutation rate μ , is a measure of the importance of immigration events over mutation in contributing to variation in the population [97]. The relative effective population size, theta, is the number of individuals representing an idealized (Wright-Fisher) population that will result in the same amount of genetic drift as in the actual population. The number of migrants per generation, $4N_e m$, is the product of theta and M . MIGRATE assumes mutation-migration-drift equilibrium with values of M and theta constant over time and parameter estimates in MIGRATE date back nearly $4N_e$ generations into the past (approximately thousands of years ago). Hence, these migration rates provide estimates of gene flow that post and pre-date the estimated time (approximately 600 years ago) when humans began to significantly alter the habitats in which these tigers currently live.

For both the BAYESASS and MIGRATE runs, we used the STRUCTURE defined population clusters to estimate pairwise migration rates. BAYESASS runs were performed as described in the preceding methods section on detecting migrants. A total of 8×10^6 MCMC iterations were carried out, by discarding the first 2×10^6 steps as burn-in and sampling at every 2,000 iteration intervals of the remaining 6×10^6 MCMC chain. Runs were carried out with a migration rate prior of 0.05 while other parameters were kept at default settings. The average result from three independent BAYESASS runs is presented. Estimates of historical gene flow and effective population size were carried out in MIGRATE by using the Bayesian approach and the Brownian motion model as an approximation for the step-wise microsatellite mutation model. Following initial trial runs, the Bayesian search criteria for the MCMC sampler was set at 10 replicates of one long chain of 50,000 steps with every 100 steps of the chain being recorded, producing a total of 5×10^7 visited parameter values. The initial 10^7 steps of the MCMC run were discarded as burn-in, and the remaining 4×10^7 runs were sampled. To increase efficiency of the sampler, we used four chain-heating temperatures of 1, 1.5, 3 and 10,000, which allows a more efficient exploration of the genealogy space. We used parameter estimates from the initial run to calculate starting values of theta, for use as new parameters during subsequent runs. Parameter estimates from the final run were similar to the results of the initial runs. All MIGRATE runs were carried out on the Biportal cluster computing facility at the University of Oslo, Norway (<https://www.biportal.uio.no/>; accessed 12 May 2013).

Detection of Genetic Bottleneck

To detect past occurrences of genetic bottleneck in the sampled populations, we evaluated three summary statistics - (i) Wilcoxon's sign rank test and (ii) mode-shift test, implemented in the program BOTTLENECK 1.2.02 [100], and (iii) M ratio test [101] implemented in ARLEQUIN 3.1 [102]. We were not interested in quantifying population expansion/decline or dating the time of and therefore avoided using other considerably lengthy Bayesian procedures [103,104]. Wilcoxon's test detects bottlenecks based on the probability of heterozygosity excess over that expected at mutation-drift equilibrium in a population. It is most effective at detecting historic bottlenecks occurring over approximately 2–4 N_e generations in the past. The mode-shift test is more suited for detecting bottlenecks within the last few dozen generations [105,106]. This test is based on the premise that a stable population at mutation-drift equilibrium will have a large proportion of alleles at low frequency and a smaller proportion

at intermediate frequencies and few at high frequencies. The resulting allele proportions yield an L-shaped distribution. In bottlenecked populations the mode is shifted because of the rapid loss of alleles present at low frequency. We ran 10,000 simulations using the program BOTTLENECK in 5 populations (excluding KPC, ATR and TATR) under both the stepwise mutation model (SMM) and the two-phase mutation model (TPM) with 95% single step mutations and 5% multi-step mutations and a variance of 12 as recommended by Piry *et al.* [100]. P -values from the Wilcoxon's test were used to examine bottlenecks at each timescale and were assessed at the alpha 0.05 level. The M ratio ($M = k/r+1$) was calculated from the mean ratio of the number of alleles (k) and the allele size range (r). Assuming loci follow a generalized stepwise mutation model, the loss of rare alleles would diminish the value of k at a faster rate than r thereby a drop in the M ratio below a threshold of 0.68 would be suggestive of populations that experienced a recent bottleneck [101].

Field Data Collection for Occupancy Analysis

(A) Tiger Sign Surveys. The entire study area was divided into 10×10 km grids. Each grid that contained potential tiger habitat (all types of forest cover) was surveyed by replicate search paths for tiger sign. The number of surveys per grid ranged from 3 to 35, and was proportional to the amount of tiger habitat within each grid. Areas under agriculture, industry, and human habitation that were known to be non-habitat for tigers were not surveyed in an occupancy framework. Each survey consisted of a 5 km search for tiger signs with approximately one survey for every five km² of habitat. Surveys were not random, but instead conducted along features that were likely to have tiger sign (e.g. dirt roads, dry water courses, and animal trails) so as to maximize detections [22]. Surveys were conducted by the local guard and a local assistant who had intimate knowledge of the forest and were trained to observe and record tiger sign in pre-designed datasheets. All encounters of tiger pugmark track sets and scats were recorded. These were distinguished from those of other carnivores based on criteria described by Jhala *et al.* [107] and Karanth and Nichols [108]. A total of 79,000 km of search effort was invested in 15,800 replicate surveys between December 2009–February 2010 (cold and dry season) across the entire study landscape to adhere with the assumption of occupancy closure [70] and have minimal influence of weather (rainfall) on sign detections and distribution. A total of 1,851 grids were sampled.

(B) Prey Assessment. Within each forest beat, one or two permanent line transects of two to four km in length were delineated. Each transect was walked on two or three subsequent mornings (06:30 to 08:30 hrs) by two observers to record encounter rates of wild ungulates and domestic livestock. Data on number of each species seen and the length of transect were recorded to compute encounter rates of each species. In disturbed forests (outside of protected areas) wild ungulate densities were low, animals were shy, and difficult to record using line transects. Therefore, at every 400 m along the line transect we also sampled a plot of 20×2 m to record ungulate dung. Dung was visually distinguished to species [107] and dung density for each species, wild ungulates as a group, and domestic livestock was computed separately. Encounter rates of ungulates and dung density were used as indices of ungulate abundance. The number of transects within each 100 km² grid ranged from 1 to 24, and were proportional to the quantum of tiger habitat within that grid. The total effort invested in transect surveys was 71,468 km of walking on 26,688 occasions.

(C) Human Disturbance. At every 400 m along transects established for ungulate assessment a plot of 15 m radius was

sampled to assess indices of human impact. Presence of (a) human/livestock trails within the plot, and (b) sighting of humans and livestock from the plot were recorded [107]. The number of plots within a 100 km² grid ranged from 5 to 120. The total number of plots sampled across the landscape was 51,073.

Remotely Sensed Variables

Remotely sensed data that depict landscape characteristics and human impacts were obtained from various sources and extracted at the 10×10 km grid resolution. Forest cover was obtained from the Forest Survey of India [109] that is based on IRS 1D LISS III satellite with 4 multispectral band data at 23.5 m resolution. Normalized Differential Vegetation Index (NDVI) information were derived from 1 km² Advanced Very High Resolution Radiometer (AVHRR) data, acquired from the National Aeronautics and Space Administration's (NASA) Television Infrared Observation Satellite (TIROS) (<http://science.nasa.gov/missions/tiros/>; accessed 23 Dec 2010). Road and drainage information were obtained from Digital Chart of the World (<http://statisk.umb.no/ikf/gis/dcw/>; accessed 20 Dec 2010). Protected area shape files were obtained from the wildlife database at the Wildlife Institute of India, National Tiger Conservation Authority and State Forest Departments of India. The Shuttle Radar Topography Mission has produced the most complete, high-resolution digital elevation model of the earth [110]. Within each 1 km² grid, this information was used for computing average elevation and the coefficient of variation of elevation used as a measure of terrain ruggedness. Night light data was obtained from the United States Air Force Defense Meteorological Satellite Program (DMSP) and National Oceanic and Atmospheric Administration's (NOAA) Operational Linescan System (OLS) (<http://www.ngdc.noaa.gov/dmsp/sensors/ols.html>; accessed 18 Dec 2010). Density of roads (length of paved road per km²), and Euclidean distances to roads, protected areas and night lights were computed in ArcGIS 9.3 (www.esri.com) software.

Occupancy Modeling

Though sampling was done at the level of the forest beat (an administrative unit of about 15 km²) so as to ensure an even distribution of sampling effort across the landscape, analysis was done at the scale of 1,851 grids, each of size 10×10 km. This grid size was chosen since it was larger than the average home range size of a tiger [111,112] and the size was relevant for subsequent administrative and managerial inputs. Sign surveys of 5 km independent spatial replicates within each grid [113] were modeled to address the issue of imperfect detections of tiger sign using the program PRESENCE v6.3 [114]. Detection of tiger signs was likely to depend on the abundance of tigers within a grid [115]. We first modeled the detection process by (i) keeping detection (\bar{P}) constant across surveys, (ii) \bar{P} varying across surveys and (iii) \bar{P} as a function of tiger abundance in that grid, wherein we used average encounter rate of tiger sign as an index that surrogated tiger abundance [31,115]. The model that best explained the detection process based on Akaike Information Criteria (AIC) was then used in all subsequent models of tiger occupancy [70].

Tiger site occupancy was *a priori* expected to be positively influenced by (a) prey abundance, and (b) amount and quality of tiger habitat, and negatively influenced by (c) human disturbance [22,115,116]. We tested these hypotheses by modeling variables representing these factors as covariates using the logit link function in PRESENCE [70,114]. We initially generated data on 23 site covariates that represented landscape and habitat features (forest

area, core forest area, forest patch size, NDVI, elevation, ruggedness, drainage density, rainfall, distance to protected area), prey availability (chital, sambar, wild pig and gaur encounter rates on line transect walks, and wild ungulate dung density), human disturbance (distance to night lights, distance to roads, humans and livestock encountered on transect walks, human/livestock trails within sampled plots, and livestock dung density) that could potentially explain tiger occupancy. These covariates were examined with exploratory data analyses for their interrelationships and relationship to tiger presence (by scatter plots, box plots, and correlation analysis) and based on this a subset of 16 variables was selected for inclusion as site covariates for occupancy modeling (see Table S1 for univariate coefficients). Since many of the covariates had high correlation coefficients between them, their contribution to explaining tiger occupancy would be redundant. To account for this collinearity and to reduce the dimensionality of the covariate matrix we extracted Principal Components (PCs) from 16 variables [117]. The varimax rotated PCs were further used as independent variables in a logit link function to model tiger occupancy in the program PRESENCE ([70], available for download from <http://www.proteus.co.nz/>). Model selection was done using AIC, and model fit was assessed by comparing the actual detection histories with simulations generated from 50,000 parametric bootstrap runs of the target model in PRESENCE. The over dispersion parameter \hat{C} close to one suggests that the model provides an adequate description of the data, values of \hat{C} greater than one suggests more variation in the data than expected by the model, and values less than one suggest less variation in the data. The standard errors of model estimates were adjusted by the square root of \hat{C} as recommended by MacKenzie *et al.* [70]. Models were built using PCs that represented prey abundance, human disturbance and habitat quality; these were evaluated against the null model and the full model by their delta AIC values. A total of six models were evaluated for modeling tiger occupancy and coefficient estimates for all models with delta AIC <4 were averaged based on model weights [70] to arrive at occupancy probability (Ψ) in each grid.

Tiger Population Extents and Occupied Habitats

We used two approaches to estimate population extents and area of occupied habitats; (i) a more conservative approach wherein we considered only those grids that detected tiger sign as being occupied (the naïve estimate) and (ii) model inferred occupancy that corrected for detection bias and covariates in PRESENCE. Herein, landscape scale occupancy was computed by sum of cell occupancy probability values and divided by the total number of cells. Tiger habitat (forested area) in each grid was weighted by the tiger occupancy probability of that grid and summed across all grids to arrive at occupied tiger habitat for the landscape [115]. All adjacent tiger sign detected cells were joined and were considered to be occupied by a single tiger population.

Habitat Corridor Modeling

Grid based tiger occupancy probability (Ψ) obtained from PRESENCE was used as a measure of habitat suitability for tigers [69,70]. A cost surface for tiger habitat suitability across grids was generated as $1-\Psi$. For the non-tiger habitat (human land uses) where tiger occupancy values were not available, we considered them permeable to tigers at higher costs than forested habitats, although human habitations (townships) were considered impermeable to tigers (see Methods S2 for details). These costs were used as a resistance layer for modeling habitat connectivity using LCP [63] and circuit theory [118] analyses. Based on these cost surfaces the resulting models would optimize connectivity by selecting high

quality tiger habitat and minimize gaps formed by non-tiger habitat. Least-cost pathways (LCP) were modeled using PATHMATRIX [71], and resistance pathways were modeled using CIRCUITSCAPE [72]. Core areas of tiger reserves were considered as “sources” or areas of high potential from which tiger movement across paths of least resistance were modeled across the landscape. PATHMATRIX models several potential routes in a radiating manner from the “source” to connect to another adjacent “source”. It then selects a single “least cost” pathway as the best alternative. CIRCUITSCAPE models connectivity through habitat swaths considering resistance to movement based on pixel cost and corridor width [118]. It provides one to several potential alternatives for joining sources and helps in identifying bottlenecks within the corridors. Since the Central Indian landscape is highly fragmented and human dominated with clearly defined and limited forested habitat, we could overlay LCP on high resolution Google Earth images and align them to match geographic features within occupancy grids, to delineate realistic corridors. These least cost corridors buffered by 1.5 km (LCC) were considered the minimal essential corridors joining two tiger reserves.

Genetic Structure, Migrants and Corridor Cost

The genetic structure between populations is a consequence of the amount of genetic drift to which each local population has been subjected, due to its local effective size, and/or due to its degree of demographic, geographic and ecological isolation [119]. Since all the Central Indian tigers likely belonged to a large, mostly contiguous population till a few hundred years ago [23], pairwise genetic distances between populations should reflect levels of differentiation and barriers to gene flow, i.e., the cost of movement between these populations. The proportion of migrants between population pairs would reflect gene flow in current or recent times while F_{ST} values would indicate genetic differences over historical, more long-term time scales. We therefore expected to have more migrants detected between geographically closer populations that had lower movement costs between them. This exploratory analysis would corroborate the short-term mechanisms (migration events) that result in long-term (F_{ST}) genetic differences between populations due to tiger movement across the landscape.

Pairwise F_{ST} , R_{ST} and Phi_{PT} genetic distance estimates, obtained from AMOVA analysis in GENALEX, were linearized using the formula $F_{ST}/(1 - F_{ST})$, as given by Rousset [120]. In order to determine which spatial model best explained genetic structuring, matrices of linearized pairwise genetic distances were correlated against matrices representing geographic distances (GGD), log-transformed geographic distances (\log_{10} GGD), least-cost pathway distances (LCPD) least-cost corridor distances (LCCD), and resistance distances (RD). In addition, the effectiveness of the modeled corridors and spatial distance matrices was compared using partial correlations that allowed one model to be tested, while controlling for other competing models [55]. The biologically realistic model not only exhibited the highest significant, positive correlation, but also displayed significant positive partial correlations after controlling for each of the competing models. Mantel [121] and partial Mantel [122] tests were carried out with 10,000 randomizations in the program zt [123] to evaluate the significance of the correlations.

As patterns of isolation-by-distance (IBD) are known to bias tests of hierarchical structuring and vice-versa, we used the population clusters as a covariate in a partial Mantel test, to model the partial correlations between pairwise genetic distances and spatial distances, while controlling the effect of population clusters (following Meirmans [124]). Partial correlations between matrices

representing pairwise genetic distances and spatial distance matrices were calculated with a third matrix describing whether population comparisons were made between (1) or within (0) the STRUCTURE identified clusters. A non-significant or negative partial correlation of genetic with geographic distance, after controlling for population clusters, would rule out patterns of underlying IBD in the observed genetic structure.

Results

Identified Individuals and Descriptive Statistics

Out of 587 scat samples, 330 scats were successfully PCR amplified using the felid specific mitochondrial DNA cytochrome *b* (mtDNA *cyt b*) primers, of which 275 were identified as tiger scat based on *Bam*HI restriction enzyme digestion profile of the PCR products (Table 1 and Figure S1). From the 275 tiger scats, only 250 samples yielded microsatellite genotype data at a minimum of seven loci to be considered for *Identity* analysis in CERVUS. We identified 169 individuals with 81 recaptures from a total of 267 microsatellite loci genotypes (250 scats, 16 blood and 1 tissue). The total number of individuals identified here constitutes roughly 49% of the estimated total tiger population in the entire sampled area (Table 1). Sex identification yielded 74 males and 85 females, with the sex ratio being nearly symmetric in most localities, except in the lower sampled areas. On average, individual multilocus genotypes were 93.2% complete. We included 97% (164 out of 169) of samples, those that had complete or near complete genotypes with a maximum of two missing loci, for further analyses. Two Tadoba individuals with three missing loci (73% complete) and three individuals from the Kanha Pench corridor with four missing loci (64% complete) were also retained since sample size from these areas was small and the genotypes represented unique tigers. The panel of eleven microsatellite loci that was used for individual discrimination had very low cumulative sibling probability of identity (*PI-sib*) of 1.5×10^{-4} (Table S1), indicating very high power to discriminate individuals. Even in the samples with the least amount of genotype information (four missing loci), the cumulative *PI-sib* value (1.6×10^{-3}) of the samples was sufficiently low to determine unique individuals.

No significant evidence of linkage disequilibrium (LD) among all pair-wise loci combinations was observed, when all sampling locations were pooled ($p > 0.05$ at 1,000 permutations). Except for deviation at three loci, Fca441, Pati09 and Pati18 ($p < 0.001$), all other loci were in Hardy-Weinberg equilibrium (HWE) in the pooled population after adjusting the critical *P*-value using the Bonferroni correction procedure (Table S1). Loci not in HWE or with null allele frequencies $> 5\%$ appear to be random with respect to population (Table S2). Pati09 showed significant deviation from HWE across three populations, while Pati01 and Fca441 showed significant deviation from HWE in two populations. 6Hdz700, F53 and Fca304 each deviated from HWE in one population. Such departures from HWE could indicate the possibility of genetic structuring among populations and likely presence of related individuals in the data. The deviation from HWE in few populations could also be explained by the presence of null alleles in the data. While MICROCHECKER tests did not show any evidence of scoring errors due to stuttering or small allele dominance in the dataset, five loci (Pati01, Pati15, Pati18, Fca304 and F53) with high null allele frequencies $> 9\%$ were detected (Tables S1 and S2). Three loci deviating from HWE were likely due to the presence of null alleles in the data - Fca304 in Bandhavgarh, and Pati01 and F53 in the Melghat-Satpura-Tadoba cluster, as they showed significant deviation from HWE only with observed allele frequencies and not with null allele

corrected frequencies (not shown). Although Pat15 and Pat18 also contained null alleles at high frequencies (>9%) in Kanha, they did not deviate from HWE in any population. Since these patterns were random with respect to population (e.g., no departures from HWE in Kanha, and null allele frequency < 5% in Pench), it was more likely that these deviations could be due to the presence of population structuring in the data. Hence we retained all eleven loci in subsequent analyses.

Most tigers genotyped in this study showed high heterozygosity (Figure S2). The minimum number of heterozygotes observed across loci for an individual tiger's multilocus genotype was two and three heterozygous loci, for one and two tigers respectively. The most polymorphic individuals ($n = 5$) were heterozygous at all eleven loci. Individuals that were completely homozygous at all eleven loci, were not observed. Nearly 90% of the tigers (i.e. 152 out of 169 individuals) had heterozygous genotypes at five to nine loci, and 12 tigers were heterozygous at ten to eleven loci. Genetic diversity estimates showed a mean number of alleles per locus to be 9.1 ± 2.2 with heterozygosity He to be $75.4\% \pm 3.9$ and Ho to be $70.1\% \pm 5.9$ in the pooled population (Table 2). A summary of population-wise genetic variation, revealed significantly higher allelic diversity and heterozygosity levels in the larger populations of Pench and Kanha compared to all other localities (Table 2 and Table S2). The number of population diagnostic private alleles was high in Pench ($n = 8$) and Kanha ($n = 6$), while individual frequency for a private allele was highest in Bandhavgarh compared to all other localities (Table S3). Estimated population size was positively and linearly correlated to genetic diversity statistics (Number of alleles, $\rho = 0.857$, $p = 0.011$; polymorphism information content, $\rho = 0.738$, $p = 0.0458$; Shannon's index of diversity, $r = 0.714$, $p = 0.058$). Partial correlations between estimated population size and the allele diversity indices, after controlling for the effect of sample size, were positive and highly significant (Number of alleles, $r = 0.82$, $p = 0.012$; polymorphism information content, $r = 0.659$, $p = 0.054$; Shannon's index of diversity, $r = 0.714$, $p = 0.036$). Heterozygosity values were not correlated with population size (Ho : $\rho = -0.262$, $p = 0.428$; He : $\rho = 0.357$, $p = 0.389$). Correlation of estimated population size with actual sampled size was highly significant ($r = 0.964$, $p = 0.001$), meaning that our samples were in proportion to the size of the population.

Population Genetic Structure

According to the results of the Principal Coordinates Analysis (PCoA) based on Phi_{PT} genetic distance estimator, individuals in the area were clustered into roughly four groups with varying degrees of population partitioning (Figure 2A). The three coordinate axes accounted for 60% of the variation in the dataset. Tigers were observed to cluster in four major groups. Tigers from Kanha, Pench and Melghat formed three distinct clusters that partially overlapped each other, while Bandhavgarh tigers formed a discrete cluster with minimal overlap. Tigers from Satpura, Tadoba, and Achanakmar were scattered within the clusters formed by Kanha-Pench-Melghat.

Calculation of delta K from the output of the STRUCTURE runs using prior population information ($locprior = 1$), produced the largest modal value of the statistic at $K = 4$, suggesting pronounced population subdivision at $K = 4$ (Figure S3). On the other hand, the log-likelihood $L(K)$ value reached an inflection point at $K = 4$ before gradually plateauing at $K = 6$ to 7 and finally leveling off at $K = 8$ (Figure S3). The variance in $L(K)$ increased at higher values of K , as reported previously with other studies [92,125]. The disparity in population structuring patterns between delta K and log-likelihood values occasionally occurs in cases

Table 2. Summary statistics of mean genetic variation and bottleneck tests across sampled populations.

Population	Observed heterozygosity (St. Dev.)	Expected heterozygosity (St. Dev.)	Number of alleles (St. Dev.)	Allelic size range (St. Dev.)	M ratio (St. Dev.)	Wilcoxon's heterozygosity excess test	Mode-shift test
M	0.654 (0.234)	0.674 (0.110)	4.7 (0.6)	17.5 (4.3)	0.75 (0.21)	ns	L-shaped
S	0.673 (0.230)	0.639 (0.146)	4.2 (0.9)	16.7 (4.6)	0.70 (0.23)	ns	L-shaped
T	0.705 (0.195)	0.704 (0.094)	4.9 (1.5)	16.5 (5.9)	0.80 (0.15)	ns	L-shaped
M-S-T	0.691 (0.141)	0.774 (0.036)	7.6 (1.6)	24.9 (7.6)	0.86 (0.16)	ns	L-shaped
P	0.750 (0.070)	0.734 (0.056)	7.6 (1.5)	26.8 (11.5)	0.83 (0.18)	ns	L-shaped
K	0.685 (0.061)	0.674 (0.106)	7.2 (1.9)	22.5 (5.2)	0.86 (0.13)	ns	L-shaped
K-A	0.683 (0.085)	0.713 (0.051)	7.9 (1.6)	26.5 (10.6)	0.86 (0.20)	ns	L-shaped
B	0.641 (0.216)	0.607 (0.148)	4.5 (1.0)	18.6 (6.2)	0.66 (0.20)	ns	L-shaped
All	0.701 (0.059)	0.754 (0.039)	9.1 (2.2)	28.8 (10.5)	0.90 (0.14)	ns	L-shaped

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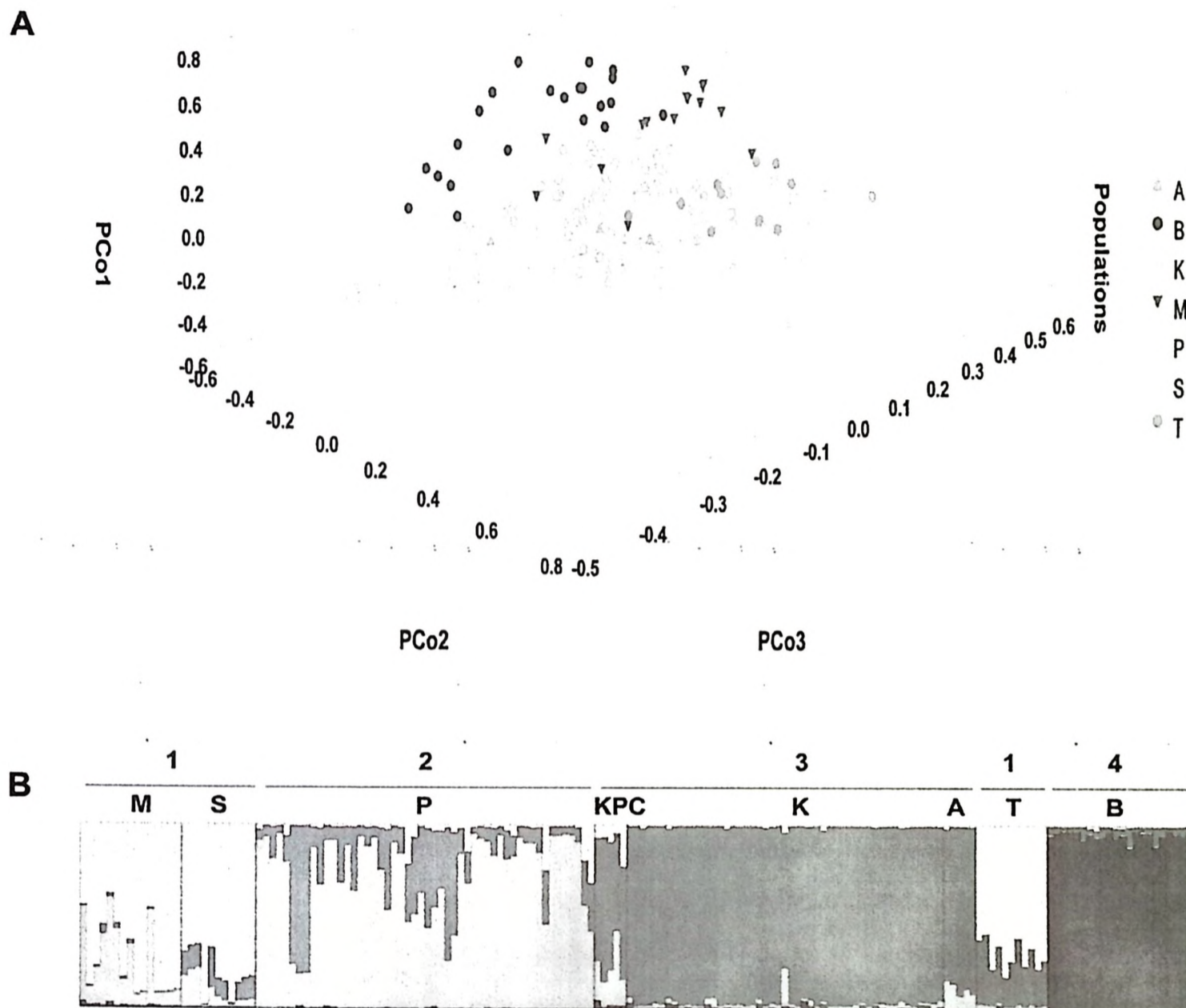


Figure 2. Results of individual clustering analyses. (A) Three dimensional plot showing partitioning between different populations as obtained from PCo analysis based on Phi_{PT} co-dominant genetic distance among individuals. (B) Summary barplot of STRUC-TURE run at $K=4$ showing population assignments for each individual. Four distinct population clusters are observed. Sampled populations are Melghat (M), Satpura (S), Pench (P), Kanha-Pench corridor (KPC), Kanha (K), Achanakmar (A), Tadoba (T) and Bandhavgarh (B). doi:10.1371/journal.pone.0111207.g002

where the F_{ST} values are significant [126]. Examination of individual Q summary barplots (Figure S3) yielded identical clustering patterns at all runs between assumed $K=2$ to 4 (carried out both with and without prior sampling location information), and distinct population saturation, indicative of population subdivision was evident at $K=4$ in conformance with the delta K approach. Based on the above, the four cluster solution ($K=4$) best describes the levels of genetic subdivision in our sample of the Central Indian tiger population (Figure 2B).

The four population clusters identified by STRUC-TURE were similar to the clusters observed using PCoA plots, and in consonance with geographic configuration as well (Figure 1). Melghat, Satpura and Tadoba represented populations with patchy connectivity and formed a unique cluster in the western and southern limits of the landscape, with few individuals being cross-assigned to the Pench and Kanha clusters. To the east of Melghat and Satpura, Pench formed a unique cluster. A few individuals in Pench had cross-assignments with Kanha suggesting gene flow between these two population clusters substantiated by a functional habitat corridor between Pench and Kanha. The next

cluster in the eastern part of the landscape was represented by tiger populations in Kanha and Achanakmar. Individuals from the forested corridor between Pench and Kanha were also assigned to this cluster, but most had mixed assignments to both populations indicating that this was not a distinct but rather an admixed population. The last cluster was represented by Bandhavgarh, in the north-eastern part of the landscape, which formed a distinct isolated population where all individuals were assigned to the sampled locality.

Partitioning of genetic variation in the AMOVA test indicated low but significant differentiation ($p<0.01$) between the STRUC-TURE identified clusters (Table S4). The major portion of genetic variance was found within populations (88%) with 7% among the population clusters and 5% among populations within clusters. Exact tests showed significant genetic variance on all three levels ($p<0.01$). Both F_{ST} and Phi_{PT} values showed highly significant structuring ($p\leq 0.001$), and had relatively similar trends in magnitude with low sampling variance. In contrast, R_{ST} estimates showed no variation between groups, and had unreliably high sampling variances and mean square error estimates. The results

of pair-wise F_{ST} and R_{ST} calculations indicated significant ($p < 0.05$) and varied (F_{ST} 0.049 to 0.241; R_{ST} 0.000 to 0.330) genetic structuring between all sampled populations in Central India (Table S5). Within cluster F_{ST} estimates were mostly lower, ranging from moderately low (0.048 to 0.062) to high (0.079 to 0.102), compared to pairwise estimates between different clusters (0.127 to 0.217).

Migrants

(A) STRUCTURE results. Eight putative migrants were identified in STRUCTURE (Table 3). Of these, four individuals (D954, D955, D958, D1399) were identified with >80% migrant and cross-assignment probability to a single non-home cluster in the STRUCTURE analysis, carried out without prior population information. The remaining four samples represented individuals (D1843, D1892, D1297, D2058) that had weaker migrant probability ($P > 0.5$ to < 0.7) and showed variable Q (0.289 to 0.758), and with the majority of samples having cluster memberships to more than one non-home locality.

(B) GENECLASS results. GENECLASS also identified eight individuals (Table 3) as putative migrants ($P < 0.01$), with high log likelihood of cross-assignment ($L_{ij}/L_{max} > 2.0$). Lowering the likelihood threshold ($L_{ij}/L_{max} < 2.0$) yielded further six putative migrants ($P < 0.05$).

(C) BAYESASS results. A total of fifteen individuals with likely immigrant or admixed ancestry were detected in the BAYESASS analysis (Table 3). Of the fifteen total migrants, eleven individuals had high migrant cross-assignment probabilities ($P > 0.8$), and four individuals had intermediate migrant assignments ($P = 0.509$ to 0.617). In general, the posterior probabilities of migrant assignment were higher in BAYESASS compared to the STRUCTURE analysis. Additionally, BAYESASS identified six other individuals (D1075, D1381, D1383, D1393, D1400, D1987) as potential migrants ($P = 0.509$ to 0.926) that were not assigned as migrants by either STRUCTURE or GENECLASS.

(D) CERVUS results. Identification of offspring-candidate parent pairs in CERVUS yielded parentage relationships in thirteen out of seventeen putative migrants (Table 3). No evidence of likely parentage (or sibling) relationships in the offspring population was observed. The cross-assigned population in ten of the thirteen individuals matched the parentage assignment in CERVUS, which serves to further corroborate the results of the migrant assignments. Only three mismatches (D1075, D1393 and D1987) were observed between the parent populations identified by CERVUS and the population assignments depicted by the migrant analysis, but this could be due to low information in the data as opposed to incorrect migrant assignment. Except for negative LOD value in two pairs (D955–D1182, LOD = -0.36 ; D1400–D1168, LOD = -2.15), LOD scores were positive in the remaining eleven putative parent-offspring pairs. The relationship between a potential migrant sampled in Pench (D958) with a candidate parent from Kanha (D1205) was identified with >80% confidence in assignment (LOD = 5.32). LOD scores in remaining offspring-parent pairs were below the 80% confidence limit (< 4.9).

The detection of migrants by the above methods yielded a total of seventeen individuals with putative immigrant ancestry (Table 3 and Figure 3). Identical migrant assignment across all three programs was observed in seven individuals (D954, D955, D958, D1297, D1399, D1843, D1892), while there was equivocal assignment in the remaining ten individuals. Sex identification revealed 12 out of 75 males (16%) and 5 out of 84 females (6%) as individuals with immigrant ancestry in the entire area. Figure 3 shows the posterior distributions of individuals assigned to nonimmigrant (gen0), first (gen1) or second generation immigrant

(gen2) ancestry states in GENECLASS, STRUCTURE and BAYESASS. All GENECLASS migrants with $L_{ij}/L_{max} > 2.0$ were classified as 100% first generation migrants. Two individuals (D955, D958) with >90% gen1 assignment and three individuals (D954, D1399, D1843) with relatively high gen1 assignment probability (0.5 to 0.7) were considered as migrants. Five individuals (D525, D1892, D2058, D1297 and D1987) showed moderate levels of migrant assignment and immigrant ancestry patterns are indicative of admixed status. The assignment status of seven more individuals (D1075, D1381, D1383, D1393, D1400, D1140 and D2154) was equivocal. While STRUCTURE could not assign them as migrants, they were identified as potential second generation migrants or admixed individuals in BAYESASS.

Contemporary and Historical Migration Rates

The mean posterior distributions of pairwise immigration rates depicting contemporary gene flow estimates in BAYESASS are shown in Tables 4 and 5. Most populations have low migrant proportions with the exception of migration from Pench to Melghat ($m = 0.09$) and Kanha to Pench ($m = 0.07$) where the rates were more than 5% (Table 4). Gene flow between Melghat and Pench was likely asymmetric and there appears to be a source-sink relationship because the expected proportion of migrants into the Pench population from Melghat is much smaller ($m = 0.015$). Asymmetric migration was also visible between the Pench and Kanha population clusters, as the proportion of migrants from Pench to Kanha was negligible ($m = 0.006$). The Bandhavgarh population was devoid of migrants as suggested by the lack of gene flow between other populations ($m < 0.01$). As in the locality-wise analysis, similar asymmetry and rates of migration were obtained between the various STRUCTURE defined population clusters (Table 5).

Results from the MIGRATE analysis showed low estimates of relative effective population size (theta, θ) and historical mutation scaled immigration rate (M) suggesting very low overall migrant proportions in the area over the long-term (Table 6). Theta estimates were low to moderate and ranged from 0.57 (Bandhavgarh), 0.77 (Kanha-Achanakmar, and Melghat-Satpura-Tadoba) to 1.5 (Pench). Estimates of M ranged from a high of 6.17 (Pench to Bandhavgarh) to a low of 0.9 (Bandhavgarh to Melghat-Satpura-Tadoba), revealing limited to no migration among populations in the landscape (Table 6). Of the twelve pairwise population comparisons, ten pairs showed asymmetric migration patterns, with the higher value of M representing immigration from the population with the larger theta value (Kanha and Pench clusters), to the population with the smaller theta value (Melghat-Satpura-Tadoba and Bandhavgarh clusters). The number of migrants per generation ranged from almost zero (Bandhavgarh to Melghat-Satpura-Tadoba cluster) to nine (Pench to Bandhavgarh). The Pench and Kanha clusters represented the largest source populations for immigrants in the area. Though marginally higher migration from Pench to Kanha was visible compared to migration in the other direction, both population clusters had overall symmetric gene flow.

Genetic Bottleneck

Except for Bandhavgarh, which had a low M ratio of 0.66, all other populations showed M values above the critical threshold of 0.68 (Table 2). Wilcoxon's sign rank test of heterozygosity excess were not significant ($p > 0.05$) regardless of the mutation models used and all localities tested showed normal L-shaped allele distributions in the mode-shift test, indicative of stable non-bottlenecked populations (Table 2). Only, the Pench and Kanha

Table 3. Summary of migrant assignments based on STRUCTURE, GENECLASS (migrants based on $\alpha_{0.01}$ and $\alpha_{0.05}$ type I error levels) and BAYESASS analyses.

tiger ID	sex	sampled locality	GENECLASS assigned population	GENECLASS L_h/L_{max}	STRUCTURE Q assignment clusters (MST/P/KA/B; no prior population information, K=4)	STRUCTURE migrant probability (gen1, gen2)	BAYESASS assigned population	BAYESASS migrant probability (gen1, gen2)	CERVUS assigned parent/population/pair LOD score	Final migrant status
D955	♂	PTR	KTR	3.234**	0.035/0.009/0.889/0.067	0.996 (0.978, 0.018)	KTR	0.999 (0.990, 0.009)	D1182/KTR/0.360	Migrant
D958	♀	PTR	KTR	2.959**	0.033/0.016/0.936/0.015	0.982 (0.964, 0.018)	KTR	0.997 (0.987, 0.010)	D1205/KTR/5.320	Migrant
D954	♂	PTR	KTR	3.883**	0.009/0.019/0.963/0.009	0.863 (0.774, 0.089)	KTR	0.962 (0.825, 0.137)	D402/KTR/0.760	Migrant
D1399	♂	PTR	KTR	3.222**	0.087/0.022/0.885/0.007	0.868 (0.552, 0.316)	KTR	0.998 (0.702, 0.296)	NE	Migrant
D1843	♂	MTR	PTR	2.343**	0.275/0.527/0.186/0.013	0.590 (0.502, 0.088)	PTR	0.986 (0.842, 0.144)	D1381/PTR/4.210	Migrant
D1297	♀	KPC	PTR	6.444**	0.075/0.683/0.215/0.026	0.610 (0.130, 0.480)	PTR	0.559 (0.124, 0.436)	D1043/PTR/2.490	Admixed
D1987†	♂	STR	PTR	2.407**	0.481/0.325/0.180/0.014	0.311 (0.005, 0.306)	PTR	0.550 (0.006, 0.544)	D2057/MTR/0.300	Admixed
D525	♂	TATR	KTR	2.562**	0.664/0.023/0.300/0.013	0.170 (0.031, 0.139)	KTR	0.617 (0.086, 0.531)	NE	Admixed
D2154	♀	TATR	PTR	<2.0*	0.460/0.158/0.358/0.024	0.007 (0.001, 0.006)	TATR	0.188 (0.056, 0.132)	NE	Admixed
D1892	♂	MTR	PTR	<2.0*	0.658/0.289/0.042/0.011	0.584 (0.113, 0.471)	PTR	0.996 (0.011, 0.985)	D578/PTR/0.070	Admixed
D2058	♀	MTR	MTR	0	0.147/0.758/0.019/0.076	0.508 (0.173, 0.335)	PTR	0.895 (0.036, 0.859)	NE	Admixed
D1140	♀	KTR	PTR	<2.0*	0.070/0.556/0.344/0.030	0.124 (0.016, 0.108)	PTR	0.241 (0.035, 0.206)	D1043/PTR/3.540	Admixed
D1075	♂	PTR	KTR	<2.0*	0.065/0.237/0.663/0.034	0.096 (0.012, 0.084)	KTR	0.509 (0.161, 0.348)	D1926/STR/2.473	Admixed
D1381	♂	PTR	KTR	<2.0*	0.213/0.466/0.316/0.004	0.190 (0.000, 0.190)	KTR	0.832 (0.012, 0.820)	D1185/KTR/0.351	Admixed
D1383	♂	PTR	PTR	0	0.068/0.510/0.420/0.003	0.159 (0.001, 0.158)	KTR	0.926 (0.009, 0.917)	D1114/KTR/4.471	Admixed
D1393	♂	PTR	KTR	<2.0*	0.089/0.083/0.807/0.021	0.188 (0.013, 0.175)	KTR	0.872 (0.264, 0.608)	D578/PTR/1.066	Admixed
D1400	♂	PTR	PTR	0	0.146/0.110/0.738/0.006	0.229 (0.015, 0.214)	KTR	0.829 (0.201, 0.628)	D1168/KTR/2.155	Admixed

Q assignments depict individual membership to each of the four STRUCTURE identified population clusters of Melghat-Satpura-Tadoba (MST), Pench (P), Kanha-Achanakmar (KA), and Bandhavgarh (B). Migrant probability refers to the P value of each individual to its cross-assigned population. The assignment likelihood of each migrant to a likely candidate parent and its source population is shown by CERVUS log (LOD) scores. Italicized individuals depict potential migrants identified unanimously by all three programs. Localities depicted include Melghat (MTR), Satpura (STR), Pench (PTR), Kanha-Pench corridor (KPC), Kanha (KTR) and Tadoba (TATR).

†Tigers reported dead during the study period, M-Male, F-Female, NE- not established.

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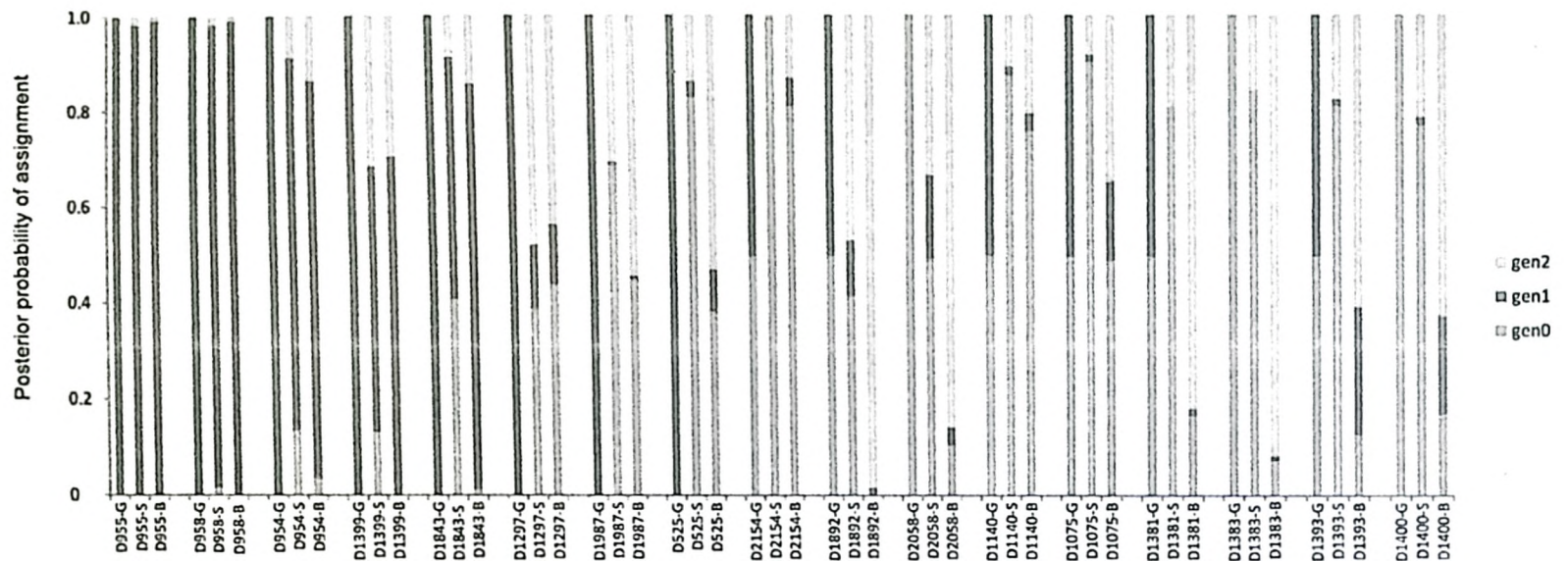


Figure 3. Individual ancestry states of putative migrants. Posterior distributions of individual assignment to nonimmigrant (gen0), and first (gen1) and second generation immigrant (gen2) ancestry states. Suffixes after individual names indicate assignment probabilities as obtained in GENECLASS (G), STRUCTURE (S) and BAYESASS (B). doi:10.1371/journal.pone.0111207.g003

populations showed significant ($p < 0.05$) evidence of heterozygosity deficiency (Table S6), which could suggest recent events of expansion in these two populations.

Tiger Occupancy, Habitat, Prey and Human Disturbance

Ten Principal Components (PCs) had Eigen values greater than one and together explained 86.6% of the variability of the original variables (Table 7). The factor loadings of the components permitted unambiguous ecological interpretation of PCs (Table 7). The detection probability of tiger sign was 21.98% (SE 0.04). Detection of tigers was best explained by index of tiger abundance. The closest competing model for detection differed by a Δ AIC value of 1207 (Table 8). Tiger occupancy was best explained by a model that included PC1 to PC9 and all the covariates conformed to the *a priori* predictions of their influence on tiger occupancy. The best model differed from the full model by Δ AIC of 0.45 and from the null model by Δ AIC of 1682. Tiger occupancy in a grid was best explained by (a) PC1 that represented availability of large

undisturbed good canopy forests, (b) PC2 and PC4 that represented grids that had low human and livestock disturbances, (c) PC3, PC6 and PC9 that represented high ungulate prey especially in the form of chital, sambar, wild pig and gaur, (d) PC5 representing lower elevation, (e) PC7 representing grids within or in the proximity of legally protected areas and (f) PC8 that gave greater loadings for grids with higher rainfall (Tables 7 and 8). The sign of the coefficients of the best model for each PC was the same when models were run using original variables in a univariate model (Table S7). The goodness-of-fit test for observed data against 50,000 model based bootstrap samples failed to show lack of model fit (χ^2 P value = 0.11), \hat{C} statistic was estimated at 1.4 and standard errors shown in Table 9 are corrected for overdispersion by a factor of 1.18. Out of the 185,100 km² area of the sampled grids, 76,913 km² was forested or potential tiger habitat. The naive estimate of grid occupancy was 17.5% while the model-averaged estimate of occupancy was 20.87% giving a 3.4% increment over the naive estimate. The naive estimate of tiger

Table 4. Locality-wise contemporary migration rates, *m*, estimated using BAYESASS, showing means (\pm standard deviation) of the posterior distributions along with the 95% confidence intervals in parentheses.

	M	S	P	K	T	B
M	0.856\pm0.042 (0.773, 0.937)	0.014 \pm 0.015 (0.000, 0.054)	0.092 \pm 0.038 (0.026, 0.173)	0.015 \pm 0.016 (0.000, 0.057)	0.011 \pm 0.013 (0.000, 0.046)	0.012 \pm 0.014 (0.000, 0.051)
S	0.014 \pm 0.017 (0.000, 0.059)	0.899\pm0.045 (0.805, 0.975)	0.037 \pm 0.031 (0.000, 0.115)	0.026 \pm 0.026 (0.000, 0.099)	0.012 \pm 0.015 (0.000, 0.049)	0.012 \pm 0.015 (0.000, 0.054)
P	0.004 \pm 0.006 (0.000, 0.020)	0.025 \pm 0.014 (0.003, 0.059)	0.897\pm0.029 (0.838, 0.952)	0.065\pm0.025 (0.022, 0.120)	0.005 \pm 0.006 (0.000, 0.024)	0.003 \pm 0.004 (0.000, 0.016)
K	0.008 \pm 0.007 (0.000, 0.026)	0.003 \pm 0.004 (0.000, 0.014)	0.005 \pm 0.007 (0.000, 0.024)	0.976\pm0.015 (0.940, 0.996)	0.007 \pm 0.008 (0.000, 0.030)	0.002 \pm 0.004 (0.000, 0.014)
T	0.025 \pm 0.032 (0.000, 0.114)	0.012 \pm 0.015 (0.000, 0.054)	0.015 \pm 0.021 (0.000, 0.068)	0.021 \pm 0.029 (0.000, 0.102)	0.917\pm0.068 (0.756, 0.998)	0.010 \pm 0.014 (0.000, 0.048)
B	0.003 \pm 0.006 (0.000, 0.017)	0.003 \pm 0.006 (0.000, 0.020)	0.003 \pm 0.006 (0.000, 0.020)	0.003 \pm 0.006 (0.000, 0.019)	0.003 \pm 0.006 (0.000, 0.019)	0.986\pm0.014 (0.952, 0.999)

The populations into which individuals are migrating are listed in the rows, while the sources of the migrants are listed in the columns. Values along the diagonal are proportions of individuals derived from the source populations each generation. Migration rates ≥ 0.05 are in bold. Individuals from Achanakmar ($n = 4$) and the Kanha-Pench corridor ($n = 5$) were excluded due to low sample sizes, and only included in the cluster based test (provided in Table 5). doi:10.1371/journal.pone.0111207.t004

Table 5. Cluster-wise contemporary migration rates, m , showing means (\pm standard deviation) of the posterior distributions along with the 95% confidence intervals in parentheses.

	MST	P	K	B
MST	0.915\pm0.027 (0.860, 0.962)	0.064\pm0.025 (0.020, 0.117)	0.015 \pm 0.016 (0.000, 0.058)	0.006 \pm 0.007 (0.000, 0.026)
P	0.015 \pm 0.016 (0.000, 0.054)	0.905\pm0.029 (0.846, 0.958)	0.076\pm0.026 (0.029, 0.129)	0.004 \pm 0.005 (0.000, 0.019)
K	0.009 \pm 0.009 (0.000, 0.033)	0.006 \pm 0.008 (0.000, 0.029)	0.981\pm0.014 (0.950, 0.999)	0.003 \pm 0.004 (0.000, 0.017)
B	0.005 \pm 0.007 (0.000, 0.028)	0.005 \pm 0.007 (0.000, 0.027)	0.005 \pm 0.008 (0.000, 0.028)	0.986\pm0.014 (0.950, 0.999)

The population clusters into which individuals are migrating are listed in the rows, while the sources of the migrants are listed in the columns. Values along the diagonal are proportions of individuals derived from the source populations each generation. Migration rates ≥ 0.05 are in bold.
doi:10.1371/journal.pone.0111207.t005

occupied habitat was 19,845 km² while the model inferred occupancy of forests was 21,290 km² giving an increment of 1.8% in occupancy estimate. The habitat variables of forest area, forest core area, rainfall, NDVI, and terrain ruggedness had significantly higher values in tiger occupied grids compared to unoccupied cells. All wild tiger prey indices were higher, while livestock abundance indices were lower in tiger occupied grids. Relevant human impact indices had significantly lower values in tiger occupied grids (Table 9 and Figure S4).

Tiger Population Extents and Occupied Habitats

Tiger populations within the landscape were primarily located in and around tiger reserves (Figure 1). The Pench-Kanha-Achanakmar tiger population was located in the largest patch of contiguous forest comprising 16,063 km² with intermittent tiger presence recorded throughout this patch even outside the legal reserve boundaries. The Satpura-Melghat forest patch was 12,720 km², while the forest patches that contained Tadoba and Bandhavgarh Tiger reserves were smaller 2,088 km² and 1,902 km² respectively and connected to larger adjacent patches by fragmented forests (Figures 1 and 4). Melghat Tiger Reserve had the largest critical core area that is legally mandated to be made free of human habitation (Table 1). The total protected area in the landscape under the tiger reserve system was 13,054 km² with 6,395 km² as core area. Tiger population extent was largest for the Tadoba population at 3,519 km², while the smallest area occupied (904 km²) was recorded in Achanakmar (Table 1).

Corridor models – maps and corridor cost values between source pairs

The least-cost corridor plot joining tiger reserves (Figure 1) shows that the longest corridor was between Bandhavgarh and Melghat; and the shortest corridor was between Kanha and Achanakmar (Table S8). The maximum number of barriers in the form of crossings of national highways was five for the corridor connecting Bandhavgarh to Melghat. CIRCUITSCAPE results detected bottlenecks in connectivity in corridors connecting Kanha with Pench, Tadoba with Kanha and Tadoba with Melghat (Figure 4). Alternative habitat connectivity besides the least cost corridor was detected by CIRCUITSCAPE to exist between Bandhavgarh and Melghat along the sparse ridge forests on the southern banks of the Narmada river as well as between Tadoba and Melghat with patchy connectivity observed through Bor wildlife sanctuary. Habitat connectivity between Achanakmar and Bandhavgarh was diffused with no clearly defined flow pathways being observed (Figure 4).

Genetic structure, migrants and corridor costs

Mantel's r correlations between pairwise genetic distances and spatial distance metrics were positive, and showed a similar trend across all three genetic distance estimators (Table S9). The highest correlations were observed for IBR and LCC distances with genetic distance while geographical distances showed the lowest correlations with genetic distance. Linearized R_{ST} had weak non-significant correlations with spatial distances, compared to F_{ST} and Phi_{PT} estimates. A significant linear relationship was observed between population pairwise $F_{ST}/(1-F_{ST})$ genetic distances vs.

Table 6. Means of posterior distributions of mutation scaled immigration rate, M , along with the 95% confidence limits (before comma) and mean number of migrants per generation (after comma) estimated from Bayesian runs in MIGRATE.

	MST	P	KA	B
MST	0.77 [0–1.93]	4.43 [0–7.2], 6.6	1.83 [0–3.87], 1.4	0.9 [0–2.67], 0.5
P	1.43 [0–3.53], 1.1	1.5 [0.533–3.0]	1.83 [0–4.4], 1.4	2.83 [0–5.4], 1.6
KA	2.97 [0–6.13], 2.3	2.17 [0–5.4], 3.3	0.77 [0–2.0]	2.43 [0–4.8], 1.4
B	3.9 [0–19.4], 3	6.17 [0–25], 9.3	4.03 [0–21.8], 3.1	0.57 [0–1.53]

Population clusters listed in rows depict the populations into which individuals migrate, while the source populations of individuals are shown in the columns. The values along the diagonal are estimates of the relative effective population size, θ .
doi:10.1371/journal.pone.0111207.t006

Table 7. Principal component (PC) loadings of covariates relevant for modeling tiger occupancy. Eigen values of the components, the percent variation of the original data explained by the PC, their ecological interpretation and *a priori* effect on tiger occupancy.

Covariates	PC1 (Forest)	PC2 (Human-Livestock)	PC3 (Chital, Sambar, Dung)	PC4 (Livestock Dung)	PC5 (Elevation)	PC6 (Gaur-Sambar)	PC7 (Legal Protection)	PC8 (Rainfall)	PC9 (Wild Pig)	PC10 (Distance to Urbanization)
Elevation (m)	-0.109	0.035	0.019	-0.032	0.962	-0.021	0.004	-0.059	0.042	0.116
Rainfall (mm)	-0.276	-0.033	0.009	0.005	-0.079	-0.048	-0.027	0.871	0.098	0.180
Mean NDVI	-0.795	0.017	0.037	-0.010	0.035	0.102	-0.002	0.195	0.037	-0.017
Forest Area of Grid	-0.796	0.041	-0.116	0.063	0.113	-0.067	-0.095	0.131	0.060	0.288
Core Forest Area in a Grid	-0.820	0.027	-0.059	0.053	-0.008	-0.191	-0.120	-0.034	-0.015	0.069
Chital Encounters per km	0.032	0.031	-0.645	0.126	0.106	0.081	-0.037	0.167	-0.506	-0.075
Gaur Encounters per km	-0.100	0.058	-0.144	0.023	0.019	-0.950	-0.065	0.039	-0.033	0.023
Sambar Encounters per km	-0.072	0.062	-0.776	0.087	0.065	-0.268	-0.125	0.117	-0.086	-0.105
Wild Pig Encounters per km	0.053	-0.007	-0.153	-0.052	-0.068	-0.055	-0.050	-0.127	-0.929	-0.009
Wild Ungulate Dung Density	-0.084	-0.008	-0.782	-0.230	-0.201	-0.001	-0.014	-0.333	-0.019	0.118
Livestock Dung Density	0.075	-0.078	-0.009	-0.976	0.032	0.026	0.003	-0.011	-0.022	-0.051
Livestock seen on transect walk	0.040	-0.960	0.033	-0.044	-0.030	0.013	0.047	0.017	-0.009	-0.012
Human and Livestock Trails	0.023	-0.921	0.014	-0.028	0.012	0.042	-0.004	-0.013	0.018	-0.035
People seen on transect walk	0.014	-0.963	0.022	-0.026	-0.030	0.018	0.038	0.021	-0.005	-0.017
Distance of Grid to a Protected Area	0.165	-0.068	0.119	-0.004	0.005	0.071	0.968	-0.024	0.058	-0.055
Distance of Grid to Night Lights	-0.237	0.056	0.053	0.054	0.126	-0.021	-0.056	0.160	0.023	0.913
Eigen Value	2.143	2.723	1.712	1.045	1.026	1.047	0.991	1.016	1.149	1.006
% Variance Explained	13.39	17.02	10.7	6.53	6.41	6.55	6.19	6.35	7.18	6.29
Cumulative Variance Explained	13.39	30.41	41.11	47.64	54.06	60.6	66.8	73.15	80.33	86.62
Ecological Attribute	Large Undisturbed Canopied Forests	People and Cattle	Wild Ungulate Prey	Livestock	Elevation	Large Wild Ungulates	Distance to Protected Area	Rainfall	Wild Pig	Distance to Night Light
<i>A Priori</i> Influence of PC on Tiger Occupancy	Negative	Positive	Negative	Positive	Negative	Negative	Negative	Positive	Negative	Positive

doi:10.1371/journal.pone.0111207.t007

Table 8. Model selection results for estimating tiger occupancy within the Central Indian Landscape incorporating imperfect detections and covariates of landscape characteristics, prey abundance, and human disturbance represented by 10 Principal Components.

Models for detection	AIC	delta AIC	AIC weight	Model likelihood	no. par.	-2 log likelihood
psi(,),p(TigSign)	7261.85	0	1	1	3	7255.85
psi(,),p(Survey Specific)	8469.56	1207.71	0	0	36	8397.56
psi(,), p(.)	8514.35	1252.50	0	0	2	8510.35
Models for Occupancy using best model for Detection						
psi(PC1+PC2+PC3+PC4+PC5+PC6+PC7+PC8+PC9),p(TigSign)	6831.99	0	0.556	1	12	6807.99
psi(PC1+PC2+PC3+PC4+PC5+PC6+PC7+PC8+PC9+PC10),p(TigSign)	6832.44	0.45	0.444	0.7985	13	6806.44
psi(PC1+PC2+PC3+PC4+PC5+PC6+PC7+PC8),p(TigSign)	6852.66	20.67	0	0	11	6830.66
psi(PC1+PC2+PC3+PC4+PC5+PC7+PC8),p(Tig. Sign)	6863.40	31.41	0	0	10	6843.40
psi(PC1+PC2+PC3+PC5+PC7+PC8),p(Tig. Sign)	6985.28	153.29	0	0	9	6967.28
psi(PC1+PC2+PC3),p(Tig. Sign)	7034.80	202.81	0	0	6	70228.00

Details of the 10 Principal Components are provided in Table 6. Goodness of fit χ^2 P value = 0.11, \hat{C} = 1.4, for best model. TigSign – Tiger sign (pugmark, scat); Survey Specific – Survey specific detection. doi:10.1371/journal.pone.0111207.t008

resistance ($r = 0.549$, $p = 0.019$) and least-cost corridor distances ($r = 0.533$, $p = 0.009$). In comparison to Euclidean geographic distance correlations, this corresponded to a 29.5% and 25.7% increase in model fit for the circuit theory based IBR and the LCC models respectively. The proportion of migrants was higher between population pairs that had lower corridor costs (Figure 5). Linearized Phi_{PT} estimates also produced significant positive correlation with both least-cost corridor ($r = 0.416$, $p = 0.035$) and resistance distances ($r = 0.462$, $p = 0.023$). This meant a 46.2% and 31.6% increase over log-transformed Euclidean distance correlations for the circuit theory and corridor models respectively.

Correlations in partial Mantel tests showed a significant, positive relationship between genetic and resistance distances, after controlling for all competing spatial distance metrics (linearized F_{ST} : $r > 0.48$, $p < 0.02$; linearized Phi_{PT} : $r > 0.39$, $p < 0.05$). In contrast, after controlling the effect of resistance distance, significant positive correlation was only observed between

linearized F_{ST} vs. geographic and least-cost corridor distances, while partial correlations between all other spatial and genetic distance metrics were either non-significant or negative. Although significant positive correlation was observed between F_{ST} and geographic distances in the standard Mantel tests, genetic and geographic distances were uncorrelated in the partial Mantel tests, after controlling the effect of population clusters, thus affirming that isolation-by-distance (IBD) pattern was absent in the data. Only resistance (IBR) and LCC distances retained a significant, positive partial correlation with genetic distances, when controlled for the effect of population clusters (linearized F_{ST} : $r > 0.4$, $p < 0.03$; linearized Phi_{PT} : $r > 0.4$, $p < 0.04$).

Discussion

Genetic diversity and population structure

The present study is illustrative of the general strengths and challenges in using non-invasive genetic samples to assess spatial

Table 9. Coefficient estimates for the best model selected for estimating tiger occupancy in the Central Indian Landscape.

Occupancy Covariates	Coefficient β Estimate	SE corrected for \hat{C}	Exponent (β)	Sign of variable loading on PC
Constant a1	-1.932	0.134	0.145	NA
PC1 (Forested Habitat)	-0.838	0.1	0.433	Negative
PC2 (Anthropogenic Disturbance)	0.452	0.151	1.571	Negative
PC3 (Chital, Sambar Encounters & Wild Ungulate Dung)	-0.909	0.142	0.403	Negative
PC4 (Cattle Dung)	0.258	0.137	1.294	Negative
PC5 (Elevation)	-0.436	0.107	0.647	Positive
PC7 (Distance to Protected Area)	-1.109	0.111	0.330	Positive
PC8 (Rainfall)	0.343	0.131	1.410	Positive
PC6 (Gaur Encounters)	-0.325	0.105	0.723	Negative
PC9 (Wild Pig Encounters)	-0.391	0.109	0.676	Negative
Detection Covariates				
Constant b1	-1.072	0.075	0.342	NA
Average Encounter Rate of Tiger Sign	0.840	0.058	2.317	NA

doi:10.1371/journal.pone.0111207.t009

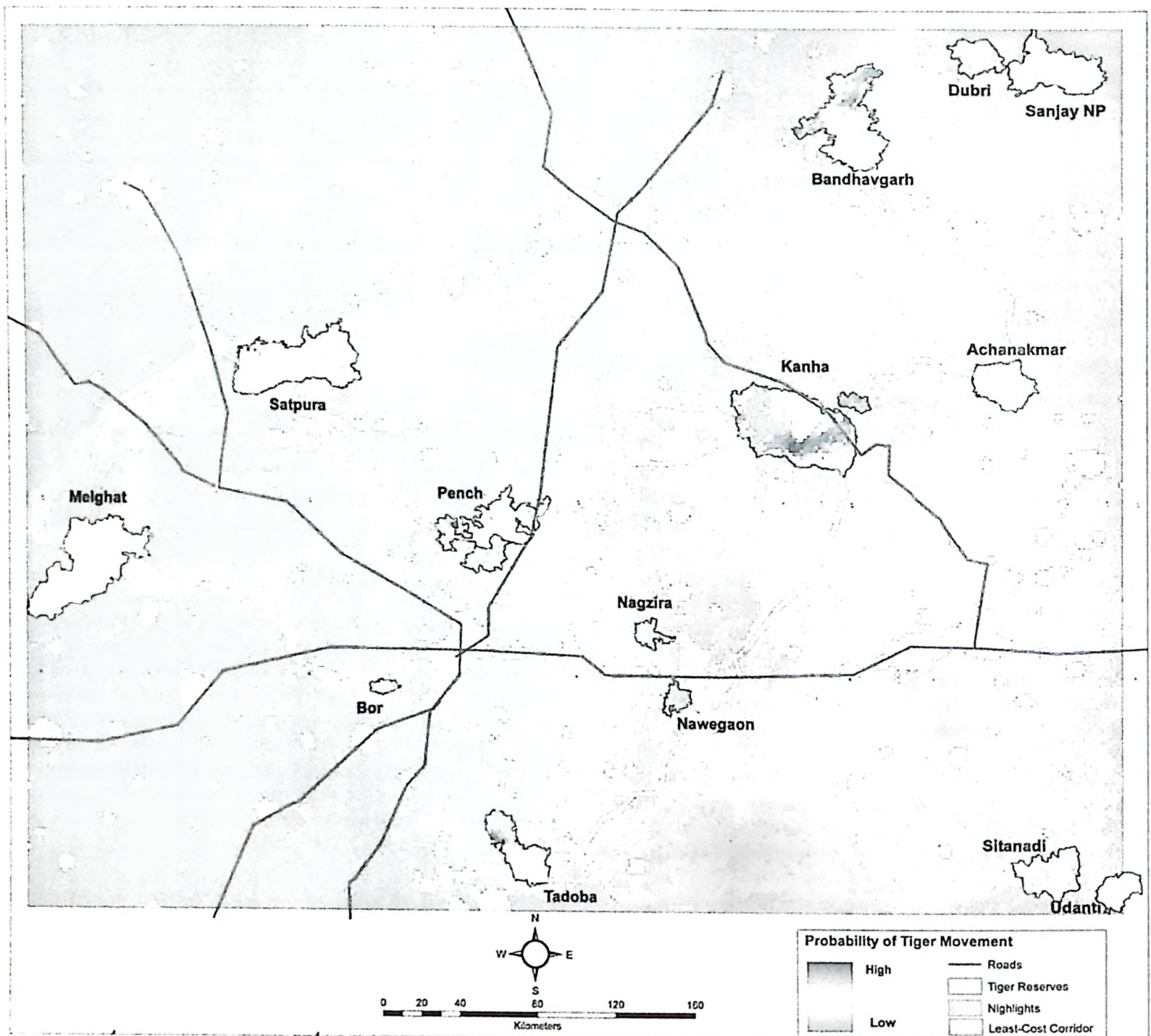


Figure 4. CIRCUITSCAPE model of cumulative current flow used to estimate landscape permeability to tiger movement. Tiger movement modeled as current flow within the Central Indian Landscape using tiger occupancy probability and drainage systems as conductance layers and human settlements as high resistance barriers in CIRCUITSCAPE. Light colors indicate potential habitat corridors. Note the prominent bottlenecks observed in the Kanha-Pench, Kanha-Tadoba, and Tadoba-Melghat habitat corridors.
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distribution patterns in an endangered and cryptic species living in fragmented habitats. Although maternally inherited mitochondrial DNA could elucidate patterns of female gene flow, the sequencing of mitochondrial genes was not attempted as the primary objective of the study was to assess the functionality of corridors through the detection of first and second generation migrants. Hence, highly polymorphic, bi-parentally inherited, co-dominant and selectively neutral nuclear loci such as microsatellites were most suited for this purpose. Microsatellite marker amplification success was low from scats, reflecting the often poor quality of samples, typical of tropical environments [127]. Even though standardized methods of sample preservation and DNA extraction were used for the study, finding fresh scats (which may have improved results) was rare despite repeated surveys, due to the low tiger density of many

sampled areas, the remoteness of the terrain, and further compounded by the heat and humidity of the region which enhanced degradation of scats. Despite these constraints a relatively sizeable sampling was achieved with the total number of identified individuals ($n = 169$) representing about 49% of the estimated population [31] in the entire landscape (Table 1). The gender proportions observed in our data are similar to the estimates obtained from camera-trap studies in the area [31]. The relatively large sample size in relation to the estimated population enhances the significance of our results.

Most individuals genotyped in this study, possessed heterozygous genotypes at >50% of typed loci, and there was no discernible differences in heterozygosity between migrant and resident individuals (Figure S2). However, unlike resident individ-

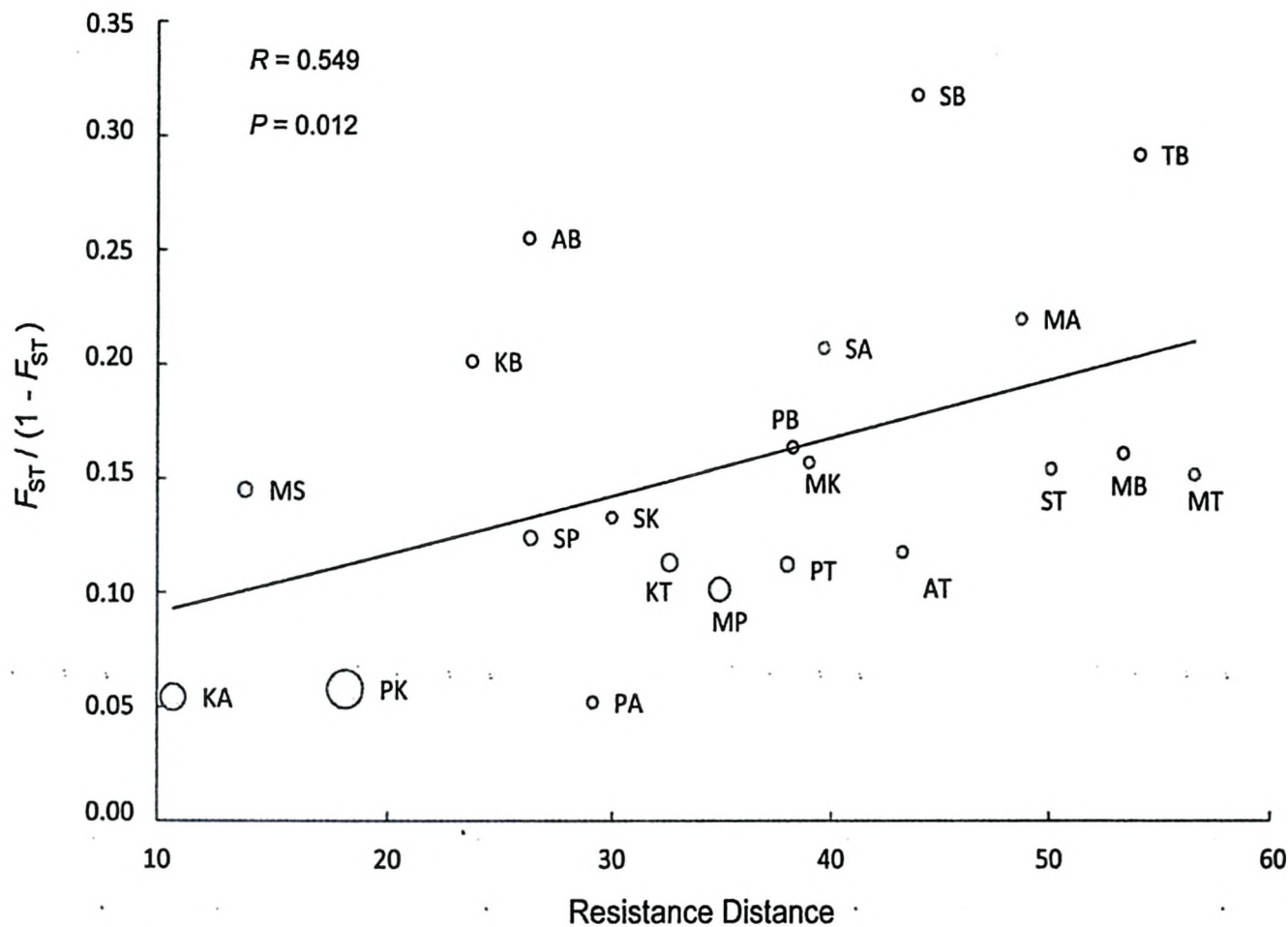


Figure 5. Regression of population pair-wise linearized F_{ST} values with corridor cost. The size of each circle is representative of the proportion of migrants shared between each population pair. Depicted corridors are Kanha-Bandhavgarh (KB), Kanha-Achanakmar (KA), Pench-Kanha (PK), Melghat-Kanha (MK), Satpura-Kanha (SK), Satpura-Pench (SP), Melghat-Pench (MP), Melghat-Satpura (MS), Kanha-Tadoba (KT), Pench-Achanakmar (PA), Melghat-Achanakmar (MA), Achanakmar-Bandhavgarh (AB), Pench-Bandhavgarh (PB), Satpura-Bandhavgarh (SB) and Melghat-Bandhavgarh (MB).

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uals, we found no migrants with fewer than five heterozygous loci, or completely heterozygous across all eleven loci. Eleven of the seventeen identified migrant individuals were slightly skewed towards a higher heterozygosity distribution, being heterozygous at eight to ten loci, while the rest of the migrants were polymorphic at five to seven loci. This could be due to the contribution by second generation migrant individuals which constituted the bulk of migrant pool. These individuals are more likely to possess a higher number of heterozygous loci than resident tigers, since they are admixed with parental genotypes from different allelic distributions.

The allelic diversity (9.1 ± 2.2) and heterozygosity ($H_o = 0.701 \pm 0.059$, $H_e = 0.754 \pm 0.039$) observed in our study is typical of genetic diversity prevalent among tigers in the Indian subcontinent [23,128,129]. Related studies, using different microsatellite markers than the ones used here, have observed levels of average expected heterozygosity (H_e) and mean number of alleles (A) to be lower in other subspecies, viz. *P. t. altaica* ($H_e = 0.26 \pm 0.11$, $k = 2.6 \pm 0.84$ [130]), *P. t. sumatrae* ($H_e = 0.493 \pm 0.039$, $A = 3.60 \pm 1.48$ [129]), *P. t. jacksoni* ($H_e = 0.571 \pm 0.027$, $A = 3.90 \pm 1.18$ [129]) and *P. t. corbetti* ($H_e = 0.670 \pm 0.027$, $A = 6.03 \pm 1.81$ [129]). Interestingly, allele diversity and heterozygosity in the Indian tiger was comparable to other felid species [129], such as the jaguar (*P. onca*, $H_e = 0.792 \pm 0.0137$, $A = 8.67 \pm 1.72$ [131]), Asian leopard (*P. pardus*, $H_e = 0.790 \pm 0.0174$, $A = 10.71 \pm 2.31$ [129]), African lion (*P. leo*, $H_e = 0.610 \pm 0.0348$, $A = 5.0 \pm 1.75$ [129]), South American puma (*Puma concolor*, $H_e = 0.774 \pm 0.0247$, $A = 7.0 \pm 1.76$ [129]), and cheetah (*Acinonyx jubatus*, $H_e = 0.708 \pm 0.130$, $A = 6.1 \pm 1.8$

[132]). Although not directly comparable with the present study because of the different markers used, a recent study in the Satpura-Maikal landscape in Central India [64] based on seven microsatellite loci, detected similar levels of heterozygosity ($H_o = 0.65 \pm 0.09$, $H_e = 0.80 \pm 0.05$), and allelic diversity ($A = 7.76 \pm 1.96$), and very low genetic subdivision (mean $F_{ST} = 0.013 \pm 0.006$). Another study in the southern parts of the Central Indian landscape, focused primarily in peripheral habitats just outside the scope of this study area [66] also observed high mean heterozygosity ($H_o = 0.54$, $H_e = 0.81$), and allelic diversity ($A = 11.71$) levels at fourteen microsatellite loci. A range-wide study [23] conducted with five microsatellite loci showed that Indian tigers have higher heterozygosity ($H_o = 0.70 \pm 0.16$) and allelic diversity ($A = 12.4 \pm 3.6$) compared to all other tiger subspecies ($H_o = 0.53 \pm 0.07$, $A = 7.2 \pm 1.2$). The study also reported low and non-significant genetic structuring of the Central Indian tigers with the Northern ($F_{ST} = 0.027$, $p = 0.063$) and Southern Indian populations ($F_{ST} = 0.019$, $p = 0.054$). This could be attributed to a historically large effective population size and inter-population connectivity in the region of Central and Peninsular India, explaining why, despite centuries of immense trophy hunting and continued habitat fragmentation, extant tiger populations in the region currently retain close to 60% of the global genetic variation in the species [23].

By using a combination of classical population differentiation and individual clustering approaches, we were able to detect patterns of population sub-structuring in the region. Results from both the PCoA and STRUCTURE analyses suggest the presence of four genetic clusters in the area. The clustered localities occur in

close proximity to each other and the overall pattern of genetic structuring observed in the landscape is concordant with existing habitat connectivity and indicative of the role that habitat fragmentation plays in shaping the distribution of allele frequencies across populations. Significant genetic structuring was also detected in the population pairwise F_{ST} and R_{ST} statistics, which may have biased parameter estimations in the STRUCTURE runs carried out without prior population information (locprior = 0) resulting in higher hierarchical levels of population subdivision at $K=8$. In contrast, the runs carried out with population information (locprior = 1, $K=4$) did not detect unnecessary genetic structuring, and ignored the prior sampling location information if the ancestry of individuals was uncorrelated [126]. The cluster solution of $K=4$ appeared optimal for the following reasons. In cases where STRUCTURE detects multiple clustering options with similar probabilities, typically the lowest K value which captures much of the biological complexity in the sample is considered to be the most conservative [126]. Additionally, the presence of related individuals in our sample and the model of correlated allele frequencies used for analysis can lead to overestimation of the true K value [126]. Variation across the four STRUCTURE-defined population clusters was weak, but significant, in the AMOVA test, as the major portion of genetic variance was attributed to within population variation. Though the AMOVA results and F_{ST} statistics indicated significant pairwise structuring across all populations in the area, the pattern shared certain similarities to the population clusters identified by STRUCTURE and the ordination results in PCoA. F_{ST} values were generally lower for localities within the same cluster compared to pairwise estimates between different clusters. We therefore treated the genetic distance estimators including F_{ST} and its analogues as relative measures of population differentiation. The estimation of these parameters requires prior identification of populations and unless the population units are clearly known, such *a priori* designation may not reflect realistic biological patterns as they would only be representing *ad hoc* division of populations [133]. Importantly, the assumptions of demographic and genetic equilibrium along with long time scales under which F_{ST} and its analogues are based may not be suited for estimating genetic differences between populations that have undergone fragmentation or demographic fluctuation events only recently. On the other hand, the results of the model based STRUCTURE clustering approach, which partitioned individuals into relatively distinct clusters based on iterative assignments, made much more sense of the biological realities of the area as the structuring observed here is likely an artifact of recent population fragmentation.

Additionally, the differences observed between F_{ST} and R_{ST} values can provide valuable insights into the balance between genetic drift and mutation events in the studied populations [134]. In this study, pairwise genetic differences between tiger populations in the landscape showed higher F_{ST} values compared to R_{ST} values. The F_{ST} statistic is based on allelic identity and accounts for gene flow between different populations as the basic premise under which it estimates pairwise genetic differences [134]. In contrast, R_{ST} relies on allele size and single stepwise mutations are the primary contributors of genetic variation for this statistic [134]. R_{ST} estimations produced non-significant results across many pairwise comparisons, and had higher sampling variances compared to F_{ST} . This suggests that populations in the area were not isolated long enough for mutations to have caused the genetic differences between populations and the primary cause of genetic structuring in the area is due to recent genetic drift. Some measure of this drift is evident from the number of private alleles found in

each population, especially Bandhavgarh, which has the highest individual allele frequency compared to all other localities (Table S3).

Although the STRUCTURE and PCoA results suggest subdivision at four clusters for the Central Indian tiger population, the significant F_{ST} structuring observed between all populations could also be indicative of ongoing fine-scale genetic differentiation in the area. Existing patterns of population structuring are a result of past fragmentation effects and fragmentation is not a static process. Gene flow in the area is currently meager and likely to become even lower, due to continued habitat loss and burgeoning anthropogenic activity in the area. Many localities still retain marginal inter-population connectivity, as evidenced by the presence of individuals having immigrant ancestry and further substantiated by camera trapping and radio-telemetry. However, genetic isolation of almost all populations in the foreseeable future is likely if current patterns of habitat fragmentation persist. In the case of Bandhavgarh the extent of fragmentation appears to be so great that the population may have already become genetically isolated for a longer period than the other reserves. Efforts should be made to revitalize the least cost corridor connecting Bandhavgarh with Achanakmar and subsequently to the gene pool of the main Central Indian complex by a combination of restorative ecology and legal instruments (See conservation implications below).

Migration in the Central Indian tiger population

The Central Indian landscape is a mosaic of habitats where tiger population densities [31] varying from high (Bandhavgarh 14 tigers/100 km²) to low (Achanakmar 0.1 tigers/100 km²) are juxtaposed in a matrix encompassing a range of land-use regimes from undisturbed natural forest to high density human settlements (Figure 1). Despite being one of the most fragmented TCL in India [31], some potential for gene flow across populations within the landscape exist because tigers, like most large carnivores, have the ability to disperse across great distances where habitat connectivity is present (e.g., ~150 km linear distance between two reserves in Nepal [67]). However, in the fragmented human-dominated Terai Arc landscape of Nepal, tigers were not found to disperse across expanses of agricultural land (10 to 20 km wide) though they did traverse through stretches of degraded forest [41]. So far, the only published dispersal estimates from the Central Indian landscape are from recent genetic studies that observed first generation migration and long-range dispersal across protected areas located roughly 200 km [65] and 650 km [66] apart, suggesting that tigers may be more resilient in traversing fragmented habitats than previously reported. Extensive annual camera-trapping since 2006 has recorded tigers dispersing between Pench and Kanha, a geographic distance of more than 150 km (Jhala and Qureshi unpublished data).

Identification of migrants by the methods used in our study requires that the populations being investigated have sufficient genetic separation and low levels of migration. We found in our study that the power to detect migrant individuals varied across localities in the region. There was no power to detect migration between localities in the same cluster (such as Kanha-Achanakmar). In these situations it was difficult to tease apart actual migration events from similar allelic patterns that arose from shared population histories and low genetic separation. On the other hand, migrant identification between localities in different population clusters produced robust assignments because of distinct genetic differences. Migrant detection was highest between localities that had discernible genetic separation and had relatively intact habitat corridors with confirmed tiger presence, such as

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between Kanha and Pench populations where four migrants and seven likely admixed individuals were detected. Other studies by Joshi *et al.* [66] and Sharma *et al.* [65], respectively, detected one and two first generation migrants between Pench and Kanha. The intervening forest patch between Kanha and Pench not only served as a movement corridor but also had some resident tigers as evidenced from camera trap data [135]. A noninvasive genetics study by Sharma *et al.* [64] detected seventeen individuals from this corridor. At the extreme end in Bandhavgarh, no migrants were detected even though distinct genetic structuring of Bandhavgarh from other population clusters provided sufficient power to distinguish migrants. Between the Melghat and Pench populations where three individuals with migrant ancestry were obtained, there was limited but adequate power to detect migrants as genetic separation was distinct but at a lower level than Bandhavgarh. One individual sampled in Satpura was cross-assigned to Pench. The corridor between Pench and Satpura has fragmented forest connectivity and tigers were reported from this area within the last ten years [42]. Two individuals with admixed ancestry were also detected between Kanha and Tadoba, though one of these had mixed assignments with Pench as well suggesting gene flow in the last few generations. Two individuals with admixed ancestry were also detected between Kanha and Tadoba. Areas of degraded forest and low density tiger occupancy such as Nagzira and Nawegaon Wildlife Sanctuaries located strategically between Tadoba and Kanha, and Bor located between Tadoba, Pench and Melghat may serve to provide stepping stone [136] type corridor connectivity (Figure 1). These areas have resident tigers, and it seems likely that the populations are sustained by sporadic dispersing individuals from larger source populations. Joshi *et al.* [66] observed that Tadoba, Nagzira and Melghat form a genetic cluster, and based on asymmetric migration patterns in their study it appears that the tiger population in Nagzira acts as a sink population for the high density source population in Tadoba.

Based on our strict criteria of defining migrants, we designated four individuals, three males (D954, D955 and D1399) and one female (D958) that had high cross-assignments ($Q > 0.8$) to a single non-home cluster, as first generation migrants. Further, a fourth male individual (D1853) that had high cross-assignments, albeit with marginally lower Q value (0.527) compared to the above four migrants, was also designated as a first generation migrant. The immigrant ancestry status in the remaining ten putative migrant individuals was classified as admixed based on - (i) intermediate levels of migrant probability in STRUCTURE; (ii) membership to more than one cluster in the individual Q assignments; and (iii) high probability of assignment to second and not to first generation immigrant ancestry state in STRUCTURE and BAYESASS.

Though one of the first generation migrants was a female, most individuals with immigrant ancestry were males (80%: 4 males out of 5 total migrants), confirming that dispersal is male-biased in tigers [41]. The low number of strict first generation migrants suggests that contemporary migration events are minor in proportion to the number of individuals with likely admixed ancestry. The identification of samples with admixed ancestry suggests that most migration events in this landscape have occurred within a few generations and is evidence that migrant tigers are able to reproduce in the new locality. This genetic evidence is further supported by field observations where a sub-adult male tiger photo-captured in Pench tiger reserve in 2006 was observed to be a territorial breeding male in Kanha tiger reserve in 2010 (Jhala and Qureshi unpublished data). The data and analyses show that tigers likely disperse between Kanha-Pench, Pench-

Satpura-Melghat, Kanha-Tadoba, Melghat-Tadoba and Tadoba-Pench.

Gene flow rates and past demography

Both the contemporary and historical analyses detected low estimates of migration rate between populations in the landscape. While this result is superficially similar to the findings of Joshi *et al.* [66], it is in sharp contrast to Sharma *et al.* [65] where they found both high historical and contemporary gene flow, although historical rates were much higher than contemporary rates. As observed in our study and by Joshi *et al.* [66], low levels of contemporary gene flow are expected given that the area is highly fragmented and extant populations occupy habitats that are completely surrounded by heavily modified landscapes, altered by agriculture and high density human settlements, thus making it difficult for tigers to disperse between populations. The highest estimate of contemporary migration was seen from Pench to Melghat, but there appears to be an asymmetric source-sink relationship between the two populations with very low migration from Melghat to Pench. Such a pattern is expected given that Pench has high tiger density (4 tigers/100 km²) likely serving as a source population, while the population density in Melghat is lower (2 tigers/100 km²). Asymmetric contemporary rates of gene flow were also apparent between Pench and Kanha, as migration from Kanha (6 tigers/100 km²) to Pench was much higher compared to movement in the opposite direction from Pench to Kanha. Joshi *et al.* [66] similarly detected high gene flow (>5%) between Kanha and Pench, with Kanha acting as the biggest contemporary source for immigrants. In contrast, Sharma *et al.* [65] state that only Pench is acting as a contemporary source population and contemporary gene flow from Pench to Kanha and Satpura is very high, and has remained relatively stable since historic pre-disturbance times. A comparative evaluation at historical and contemporary time scales in their study [65] showed that gene flow between the Pench-Satpura and Melghat-Satpura pairs remains similar, whereas there has been a 47-70% reduction in gene flow between Kanha-Satpura, Pench-Melghat and Kanha-Melghat. Our results showed that historical patterns of migration between the two major population clusters of Kanha and Pench were of equal, albeit low proportion in both directions, and that both Kanha and Pench acted as source populations in contemporary times as well. Although Sharma *et al.* [65] reported higher historic and contemporary gene flow rates compared to our study, both studies similarly observed that Kanha and Pench were important historic source populations and were the main drivers of gene flow in the area.

Contemporary density estimation studies using photographic capture-recapture techniques in the region [31] help explain some of the patterns observed in the gene flow analysis. During 2006, the Kanha population experienced a phase of relative expansion compared to a decline observed later in 2010. The situation was reversed in Pench where the population was relatively low during 2006-2009 compared to a later phase of expansion in 2010 [31,42]. From the genetic sampling done in Pench during both 2007 and 2010, which pre and post-dated this period of population expansion in the locality, a range of individuals representing likely migrant or admixed ancestry to Kanha was obtained. All first generation migrants from Kanha to Pench were detected during 2007 only, when the population in Kanha was in expansion phase. In 2010, seven individuals showing admixed ancestry from Kanha were obtained in Pench. Dispersal and subsequent breeding by immigrants from Kanha to Pench during periods of population expansion in the former appears to explain

the patterns of immigrant ancestry detected in the Pench population.

As parameter estimates of migration rate and theta in MIGRATE average across at least $4Ne$ past generations, [137] or several thousands of years ago in absolute time, the low long-term gene flow estimates observed in this study could suggest that populations may have been subject to historical fragmentation and genetic drift. Although ancient population fragmentation is perceived to have occurred in response to the forest clearing activity of agro-pastoralist Neolithic people during the mid-Holocene about 5,000–3,000 years ago [138], the effect is difficult to evaluate as early farmers likely did not clear forests at a scale comparable to recent centuries [139]. However, it is conceivable that the shift from hunter-gatherer to agro-pastoralist lifestyle and successful colonization of new areas would have negatively impacted large mammal populations including tigers and prey species through hunting (and reduction of prey base), as seen during human colonization events in other parts of the world [140,141]. Evidence from an exhaustive range-wide study of tigers has detected a massive decline of about 98% in the number of tigers over the last 200 years in peninsular India [23]. The wanton slaughter of tigers and other wildlife can be glimpsed from historical hunting records of the area, where upwards of 1,000 tigers and 2,000 leopards from this region were killed within just a few decades [25]. The population decline continues apace today, as omnipresent fragmentation and rampant poaching of tigers, other carnivores and prey species have reduced tiger populations such as at Achanakmar to only a few individuals [31], and resulted in their local extirpation in adjacent reserves of Sariska [5] and Panna [29].

Alternatively, the low estimates of historic migration rate raise concerns whether these results are artifacts of sampling or population related. MIGRATE parameter estimations assume coalescent-based models of constant population sizes and mutation-migration-drift equilibrium. Departures from the equilibrium model such as recent and sudden declines in population sizes can negatively bias the posterior parameter distributions of theta and hence migration rate estimations [137]. However, this study and a recent work by Sharma *et al.* [64] did not find significant evidence of past demographic contraction. In our study, only the population of Bandhavgarh had below par M ratios (<0.68) suggestive of bottleneck, but the evidence was equivocal since no significant heterozygosity excess or a mode-shift in allele frequencies was detected. Though bottlenecks were not observed in this study, the analyses may be undermined in a few populations because of low sample sizes (<20 individuals), as tests such as the mode-shift in allele frequencies is known to be affected by sample size variances [106]. Also, a demographic decline may not necessarily result in a bottleneck as several factors such as duration of decline, pre-bottleneck diversity, and gene flow between populations can affect the probability of detecting a bottleneck [101,106,142,143]. Furthermore, the significant heterozygosity deficit (symptomatic of recent population expansion) observed in the Pench and Kanha populations could mask signatures of population bottleneck as the addition of new individuals could increase the number of rare alleles which can bias allelic and heterozygosity distributions [106]. Demographic expansion in Pench and Kanha is likely, given the recent history of tiger population recovery in the area in the 1970s–1980s [28,144], or about six to eight generations ago (considering a five year generation time in tigers [99]). This period is well within the window of detection for genetic bottleneck tests of heterozygosity deficiency/excess which assess short term demographic changes only, maximum up to ten generations before present [143]. We could not account for other genetic

effects or demographic events which could affect the heterozygosity distributions in these two populations, although our analysis did detect some amount of higher hierarchical STRUCTURE clustering patterns which could be indicative of lineage or extended family structure, since the data definitely contained related individuals. However, even if kin-based segregation did produce a signature of heterozygosity deficit, the specific nature of the effect is difficult to evaluate without in-depth parentage and relatedness analyses, and backed by field investigations, which was beyond the scope of this study. Based on both the theta estimates and absence of bottlenecks, our results suggest that the bigger source populations in the study area have had a relatively stable population history, compared to the smaller populations, as also observed by Sharma *et al.* [65].

Our study and the recent study by Joshi *et al.* [66] had higher power to resolve hierarchical genetic structuring in the area compared to Sharma *et al.* [65] where indistinct structuring was observed. This was most likely due to the higher number of loci used in both studies compared to Sharma *et al.* [65]. Except for Tadoba where sampling was low due to logistic constraints, the small sample sizes from some other sites were due to small tiger populations. Simulation studies by Paetkau *et al.* [94] caution regarding the use of MCMC resampling methods implemented in Rannala and Mountain [95], as they tend to over-estimate migrants from a limited data set. In our case, this translates to the possibility that there may be less migration than we report in some of the smaller populations in the study system. Due to low sample sizes, individuals from Achanakmar ($n=4$) and the Kanha-Pench corridor ($n=5$) were not analyzed separately, as doing so resulted in overestimation of migration rates. Instead these localities were merged with the Kanha cluster, following the results of STRUCTURE assignments. Low sampling was also a problem in the study of Joshi *et al.* [66] as sites such as Kanha, Pench and Melghat were clearly under-sampled.

Tiger Occupancy, Habitat, Prey and Human Disturbance

Occupancy has often been used as a straightforward and economical state variable in place of abundance to monitor populations [145]. Occupancy of tigers has been estimated in the Mysore-Wayanad Landscape [115] and the Corbett-Rajaji Landscape [116] and across three major tiger landscapes of India [22]. Correcting for detection bias by replicate surveys within sampling units is especially important when detection probabilities are low, sample sizes and survey lengths are small resulting in naïve occupancy estimates that are substantially negatively biased [115]. The recent availability of powerful analytical tools and software [70,114] that permit accounting for bias caused by detections being <1 has promoted the use of correcting for such bias post data collection [115,146] compared to more rigorous designed field methods that minimize such bias in the first place. In this study we use independent spatial replicates, each of 5 km in length, with a minimum effort of one survey for every 5 km² of tiger habitat. Thus a 10×10 km² grid had anywhere between 3 to 35 replicate surveys depending on the amount of tiger habitat present within that grid. The detection probability of tiger sign was high in comparison to other studies [115] due to longer spatially independent surveys as well as higher density of surveys. Therefore, the difference between naïve and bias corrected estimates of occupancy were comparatively small (3.4%). Several assumptions that are difficult to meet underlie the use of occupancy as a state variable to monitor populations [147]. Further, tiger populations are at risk of poaching and they can be severely reduced or even extirpated from prime habitats [5,29]. Thus, model inferred occupancy from covariates of habitat, prey,

and human disturbance can provide misleading inference regarding true occupancy in the case of tigers and other species that can be severely depleted by poaching, and should therefore be interpreted with caution. However, occupancy models serve to provide a good assessment of habitat suitability at a scale relevant for conservation management [70,146]. It is in this context that we primarily use the occupancy probability in this paper so as to model habitat corridors joining tiger populations.

Detection of tiger sign was better modeled by including encounter rate of sign per km walk. Intensity of sign was found to be a reliable index of tiger abundance [22]. Detection of sign was likely to be higher with greater abundance of tigers and this was reflected in our model. Principal Components that represented distance from protected areas, prey abundance and remote canopied forests had the highest coefficients in the logit-link function that modeled tiger occupancy. All the model coefficients were in concordance with the *a priori* predictions based on our understanding of tiger ecology. Since PCs are orthogonal to each other [117] coefficients can be interpreted in terms of their sign and magnitude as the models are free from the effects of multicollinearity. The model coefficients of all site variables when used independently to model tiger occupancy as univariate models also conformed to the *a priori* predicted effects and to the coefficients obtained by the multivariate best model obtained from their PCs by PRESENCE. These results indicate that tigers are a conservation-dependent species, requiring areas having effective legal protection, good forest cover with least human impacts and high prey availability.

Corridor models, genetic structure, migrants and dispersal costs

Although both LCP and circuit theory used tiger occupancy probability as a base layer to parameterize landscape resistance surfaces, LCP defines the optimal minimal route that is required to connect two tiger reserves [53], while the resistance layers obtained from circuit theory analysis provides an understanding of all habitat connectivity currently available between tiger reserves [118]. Circuit theory is especially important to identify bottlenecks in corridors where current is constrained to flow through a narrow channel due to high resistance of the neighboring matrix. Such bottlenecks are highlighted in Figure 4 and exist in almost all corridors connecting tiger reserves. A corridor is as good as its weakest link and if the high resistance habitat matrix surrounding these bottlenecks increase in their extent they could choke the corridor, thus forming a barrier to tiger dispersal.

In our study, the ecological distances that were generated using information from habitat heterogeneity and landscape resistance surfaces (LCCD and RD), correlated significantly with pairwise genetic distances, which validated the effectiveness of the modeled linkages in representing realistic biological scenarios. In particular, IBR models depicted well the ecological costs of movement as they accounted for multiple pathways, irregular patch effects, landscape heterogeneity and wider habitat swaths connecting populations [54]. Although the raw LCP model accounted for habitat heterogeneity while selecting a single pathway as the optimal minimal corridor, it did not correlate significantly with pairwise genetic distances (except F_{ST}). Instead, the LCCs which were delineated by matching and buffering the pathway results from the raw LCP model with existing ground forest cover maps of the area provided a more realistic relationship of the ecological costs with observed genetic differences. In contrast, Euclidean distances (GGD and \log_{10} GGD) did not correlate significantly with genetic distances, due to the null model assumptions of spatial homoge-

neity where habitats are arrayed in an infinite lattice [124], and hence do not conform to the ground realities of fragmentation in the Central Indian landscape. The apparent IBD pattern observed due to the significant correlation of F_{ST} (but not Phi_{IT} or R_{ST}) with geographic distance is an artifact of metapopulation structure and discrete population clusters present in the area. This observation was affirmed by non-significant partial correlations between genetic vs. geographic distances (but not LCCD and RD) using the STRUCTURE identified population clusters as a control. Apart from fragmentation induced spatial heterogeneity, genetic structure is also a result of population history.

The results of our study imply that population subdivision and genetic structure across most localities in the area was strongly associated with habitat features that offer resistance to dispersal at different intensities such as agricultural land, roads, railway lines, high density human settlements and urban infrastructure and not only by geographic distance between populations. Mantel tests showed significant positive correlation of genetic differentiation with least-cost corridors and landscape resistance surfaces associated in traversing corridors, further confirming this observation. The tiger habitats in the region are patchy with some populations still having connectivity, while being reduced or conspicuously absent in others. The best patches of contiguous forested habitat are present in the corridor between Pench and Kanha, which extends eastward to Achanakmar. Likewise, the Satpura and Melghat populations are also connected through swathes of degraded forests, which are interspersed with agricultural land and medium density human settlements. Connectivity between Pench and Satpura is fragile as parts of the linkage are disrupted by mining activities, and broken up in places by agriculture, habitations, major highways and railway lines. The population in Tadoba is linked with Kanha in a stepping stone connectivity through patchily distributed forests. Even though the intervening matrix between Tadoba, Pench and Melghat is heavily human dominated, the populations are tenuously linked by degraded forest patches and tiger occupied habitats such as Bor Wildlife Sanctuary. Bandhavgarh has linkages with forest habitat and tiger reserves further east [31], but seems isolated from tiger populations in the study area by human settlements and agricultural land. Corridors identified herein need to be given legal status, and mitigated with appropriate green infrastructure [148] for development projects within corridor habitats so as to ensure continued gene flow between populations.

Conservation implications

It is indeed surprising that in spite of being highly fragmented [31], the tiger habitats in Central India still exist as a metapopulation with gene flow occurring between most population clusters in contemporary times. Similar conclusions were also reached in other studies [65,66], which observed indistinct genetic structuring and low migration amongst populations, although the genetic differences were not substantial to permit unambiguous identification of migrants. These findings suggest that tigers are able to disperse through suboptimal habitat fragments, than was earlier believed [41,149]. The results of our study underscore the importance of conserving and maintaining corridor connectivity for the continued persistence of tiger populations in the landscape. We found seventeen individuals or about 10% of the sampled tigers with migrant ancestry. As revealed from this study, the sizes of genetic population clusters are clearly beyond the boundaries of protected areas, and have to be managed in a metapopulation framework stressing the need for a landscape conservation policy in place of the current conservation policy focused on protected areas. The functionality of corridors as shown in this study has

important implications for the persistence of small populations such as Achanakmar, Satpura and Melghat by the rescue effect of emigrants from the large source populations in the landscape. Apart from poaching, the ecological isolation from other source populations, due to the absence of corridors was one of the prominent causes that led to the local extinction of tigers from the nearby protected areas of Panna and Sariska [5,29]. Now both of these areas have been repopulated through translocation of tigers from nearby reserves. A range of anthropogenic pressures are fragmenting important habitat corridors such as the ones linking Satpura with Pench, Pench with Kanha, Kanha with Tadoba, and Tadoba with Melghat. Dispersing tigers often have to negotiate passage through suboptimal prey-poor habitats and spend extended periods of time in proximity to human habitations, which greatly reduces survival and successful gene flow. The limited migration occurring in the landscape is probably due to tigers avoiding areas of human activity and high mortality due to commercial poaching or retributive killing in response to predation on livestock and humans. The eventual loss of genetic connectivity between populations in the near future, as observed currently in Bandhavgarh, is likely for most populations in the area if present trends of fragmentation continue unabated. In such situations, last resort alternative strategies such as translocation may be considered, as it could easily enrich genetic diversity by moving tigers across each of the four distinct genetic population clusters, to mimic natural patterns of gene flow. However, maintaining and restoring habitat corridors is the preferred conservation strategy to maintain genetic exchange between tiger populations, since corridors would serve the same function for other biota as well, exemplifying the role of the tiger as a flagship species.

Conservation efforts in such a fragmented and dynamic human-dominated landscape presents enormous challenges, but should be attempted in all areas where substantial habitat is still present. Our study gives renewed hope to tiger conservation efforts within the Central Indian Landscape and similar habitats with small fragmented tiger populations. We show that minimal habitat connectivity permits gene flow between populations, which is essential to maintain metapopulation connectivity. Our findings suggest that tigers could negotiate passage through stepping stone dispersal [136] as observed between Kanha-Tadoba, and Pench-Melghat. The most functional corridor was observed between Kanha and Pench, which has evidence of prey and offers the possibility of resident tigers in some of its larger forest patches [31,135]. However, infrastructural development in the form of adding lanes to national highways and widening of railway lines, threaten to form permanent barriers even within this corridor unless proper safeguards and mitigation measures [44] are built into these development projects. Tiger range countries like India are heavily investing in infrastructure development and mining to meet the needs of a growing economy [148]. Identification of minimal habitat corridors is vital for conservation efforts of tigers and other wide-ranging fauna like elephants (*Elephas maximus*), gaurs (*Bos gaurus*), leopards (*Panthera pardus*), and dholes (*Cuon alpinus*). They need to be offered legal protection with smart green infrastructure [148] being the norm of development policies within these corridor habitats. The extinction (nearly two decades ago) of gaur in Bandhavgarh, preceding their recent reintroduction with individuals from Kanha [150], is symptomatic of habitat fragmentation events that have impaired movement with other source populations in the landscape. We demonstrate here an integrated approach to generate reliable information to document metapopulation structure of tigers and the required habitat connectivity [17] to maintain it in Central India. Legal mecha-

nisms to safeguard these minimal corridors could potentially be the eco-sensitive category under the Environment Protection Act (1986) legislation. Currently tigers and other mega-fauna exist as a metapopulation and do exchange genetic material through functional corridors [65,66,128,151]. Such opportunities are likely to be lost rapidly in the wake of new wave of development unless legal sanctity, active restoration and mitigation of development projects become the norm. Conservation policy needs to shift the focus from protected area centered preservation to landscape scale conservation where development policies incorporate a conservation ethic.

Supporting Information

Figure S1 PCR-RFLP identification of tiger scats. (A) MtDNA *cyt b* alignment with GenBank and reference sequences showing polymorphism at the particular *Bam*HI restriction enzyme between tiger and leopard. (B) Enzyme digested bands of the 187 bp PCR product, targeting this region, showing different profiles in tiger and leopard for species identification.

(TIF)

Figure S2 Frequency of heterozygous genotypes observed at each individual multilocus genotype in all tiger individuals ($n = 169$) in this study.

(TIF)

Figure S3 Results of STRUCTURE analysis. (A). Difference in delta K and mean $\text{LnP}(K)$ for an estimated number of K populations, in models run with ($\text{locprior} = 1$) and without ($\text{locprior} = 0$) prior sampling location information. (B). Summary barplots depicting prior and non-prior STRUCTURE runs (assumed $K = 2$ to 8), of sampled populations in central India showing cluster affiliations according to individual Q values. Cluster saturation at $K = 4$, indicative of four population clusters, is observed in runs carried out both with and without *a priori* location information. At $K > 4$, increased sub-structuring is detected, but there is no concordance in clustering between the prior and non-prior runs.

(TIF)

Figure S4 Differences in tiger present ($n = 311$) and tiger absent ($n = 1540$), 10×10 km grids shown as violin plots in the Central Indian Landscape. All variables are normalized by z transformation to make the scales comparable.

(PDF)

Table S1 Information on the 11 microsatellite loci used in this study. Allele diversity statistics, observed (H_o) and expected (H_e) heterozygosity, Hardy-Weinberg equilibrium (HWE) tests, null allele frequencies and sibling probability of identity ($PI-sib$) values obtained across 169 tiger individuals. Null allele frequencies > 0.05 are italicized.

(DOCX)

Table S2 Summary of population cluster-wise genetic diversity statistics at each locus. Depicted are number of alleles (k), number of individuals typed (N), observed (H_o) and expected (H_e) heterozygosity, Hardy-Weinberg equilibrium (HWE) test significance and null allele frequencies ($Null$). The Achanakmar ($n = 4$) and Kanha-Pench corridor ($n = 5$) individuals are included in the Kanha cluster.

(DOCX)

Table S3 List of diagnostic alleles present in the sampled populations.

(DOCX)

Table S4 AMOVA results.
(DOCX)

Table S5 Population pair-wise F_{ST} (below diagonal) and R_{ST} (above diagonal) estimates.
(DOCX)

Table S6 Bottleneck test results for loci under different mutation models. P values <0.05 are depicted in italics.
(DOCX)

Table S7 Variable attributes used as site covariates in modeling tiger occupancy.
(DOCX)

Table S8 Habitat corridors, major roads, corridor cost between tiger reserves.
(DOCX)

Table S9 Results of standard and partial Mantel tests for the correlation between pairwise genetic and spatial distance metrics. The correlation coefficient (r) and probability (p) are shown using three different genetic distance estimators. Significant values ($p < 0.05$) are indicated by an asterisk (*).
(DOCX)

Table S10 Details of *cyt b* PCR amplification in reference samples using felid-specific (187 bp) and universal primers (309 bp). + indicates all samples which amplified. NA – not amplified.
(DOCX)

Table S11 Information on the pilot test carried out on scats ($n = 65$) for species identification of tiger samples by PCR and *Bam*HI restriction enzyme digestion.
(DOCX)

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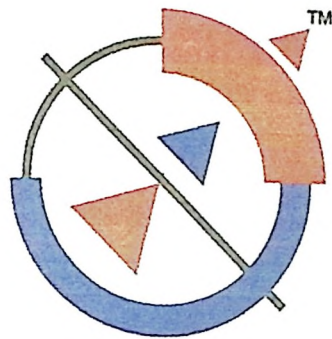


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1. Introduction

Landscape ecologists believe that “the composition and spatial form of a landscape mosaic affect ecological systems in ways that would be different if the mosaic composition or arrangement were different” (Wiens 1995). With the technological advancements of the 1980s, the emergence of remotely sensed satellite data and geographical information systems (GIS) along with spatial statistical methods facilitated the observation by ecologists of spatial patterns at local to landscape levels over time. Landscape ecology essentially deals with the causes and consequences of spatial heterogeneity and its effect on ecological process across time and space (Forman 1983; Urban and Keitt et al. 2001; Turner et al. 2001).

1.1. Consequences of spatial heterogeneity

The main consequence of increasing spatial heterogeneity is landscape modification and fragmentation, which might adversely affect biodiversity in its entirety (Haila 2002; Fazey et al. 2005; Fischer & Lindenmayer 2007). Fragmentation can lead to loss (or change) of species habitats or breaking up of species habitats into smaller fragments, thus making them vulnerable to various adverse effects (Franklin et al. 2002; Schmiegelow & Mönkönnen 2002; Kettunen et al. 2007). A species habitat is a subset of the physical environmental factors that are required for the survival and reproduction of a species (Block & Brennan 1993), and its quality defines its ability to provide conditions appropriate for an individual and for the persistence of the entire population (Hall et al. 1997). “Habitat fragmentation is a conversion of a continuous stand of habitat into smaller habitat patches” (Wilcove et al. 1986; Kozakiewicz 1993; Murcia 1995; Meffe & Carroll 1997; Forman 1997; Fazey et al. 2005). The major consequences of habitat fragmentation are increasing external influences

(such as invasion or predation), altered microclimates (associated with evapotranspiration, winds and hydrological cycles) and increased isolation from other areas with similar habitats (Saunders et al. 1991, 1993). These effects lead to net habitat loss as they break large areas into smaller patches and hence reduce the carrying capacity of the habitat and increase the extent of the edges (Sih et al. 2000). These changes in turn make the smaller patches open to predation, and the result is geographic isolation or the formation of 'islands' of the habitat within a matrix of urban and other land uses. The segregation of such islands results in isolation of populations, increasing the risk of inbreeding, which could lead to population extinctions (Farig 1997; Fahrig & Merriam 1985). The major factors threatening the persistence of the populations of these isolated patches can be demographic, environmental and genetic stochasticity as well as catastrophes (Burkey 1995; Caughley 1994). The chance of long-term persistence of an isolated population is smaller as such populations are more sensitive to stochastic events and the probability of recolonisation is low because of the fragmentation.

The long-term survival of these populations depends on their connectedness with other populations, which facilitates metapopulation dynamics (Hanski 1989, 1998). Well connected habitat patches facilitate species movement by allowing a flow of genetic material and dispersal of seeds, increasing food and water availability and adaptation to the local climate and habitat pressures and maintaining the metapopulation dynamics (Levins 1969). Levins (1969) stated that "a metapopulation is a population of populations inhabiting the discrete habitat patches with a balance between births and deaths'. According to Hanski (1998), a metapopulation is a population of populations existing in different patches in a landscape and its dynamics cover all the spatial dynamics related with it with some or no exchange of individuals and genetic material (Howe et al. 1991; Fahrig & Merriam 1994). A stable metapopulation dynamics is less susceptible to extinction as it has the ability to

withstand stochasticities affecting the local population dynamics, such as demographic and environmental fluctuations. The persistence of a metapopulation will depend on the balance between extinction–colonisation events in the patch network of the landscape (Levins 1969). Therefore, in fragmented landscapes, conservation efforts should be pinned on the metapopulation framework, not only to safeguard the long-term existence of the populations of these landscapes but also to ensure successful conservation management strategies.

Developing landscape connectivity through corridors provides a potential means of minimising the negative effects of fragmentation (Rosenberg et al. 1997). Landscape connectivity is ‘the degree to which the landscape facilitates or impedes movement among resource patches’ (Taylor et al. 1993, 2006; With et al. 1997; Tischendorf & Fahrig 2000a, 2000b). Corridors provide viable routes for species to get connected with suitable habitat patches far away, facilitate exchanges of individuals and gene flow and provide alternative habitats in the event of a stochastic event (Meffe & Carroll 1997; Magura et al. 2001; Noss 1987, 1993), thus improving the overall viability of a population in a fragmented landscape. The success of landscape connectivity in managing biodiversity and the survival of fragmented populations depend on how well linkages/corridors are designed for a species and on an objective-centred approach. A well-designed corridor can be a successful conservation tool that confers benefits to animals in a real landscape without hindering developmental requirements (Beier & Noss 1998). Increasing dispersal probabilities increases chances of recolonisation, and also individuals from a well populated patch may restore a population in another patch (Brown & Kodric-Brown 1977; Hess & Fischer 2001). The conceptual approach in designing a corridor is based on selecting the population sources that need to be connected in the landscape and on selecting the target species (Beier et al. 2009) and a set of efficient tools for attaining the objective. A corridor should be designed to be useful for multiple species rather than focusing on one species likely to serve as an

umbrella for all the native species and ecological processes (Beier 2008). In the present work, I selected the tiger (*Panthera tigris*), leopard (*Panthera pardus*), sloth bear (*Melursus ursinus*), wild dog (*Cuon alpinus*), chital (*Axis axis*), sambar (*Rusa unicolor*) and gaur (*Bos gaurus*), which represent different taxa, to identify the optimal ecological connectivity in the central Indian landscape. Details of the ecological preferences and requirements of these species are provided in Chapter II.

1.2. Causes of spatial heterogeneity

Landscape fragmentation and modification are the most detrimental reasons behind the decline of any wild species. They fragment natural habitats, causing a deterioration of the quality of the habitats, or cause a complete loss of natural habitat patches, thereby contributing to the overall loss of global biodiversity (Brittingham & Temple 1983; Yahner 1988; Foley et al. 2005). A landscape is a mosaic of spatially scattered natural and human-made land cover patches interacting with each other in various dimensions (Forman & Godron 1986). Thus, it is crucial to understand the factors underlying landscape patterns and their implications for the ecological processes (Forman & Godron 1986; Turner 1987, 1989; Wiens et al. 1993). The landscape can be looked at in terms of its (1) geographic or structural heterogeneity (patches, matrix and the pathways connecting the the patches) and (2) functional components or heterogeneity (ecological interactions of species with the landscape pattern and the responses) (Li & Reynolds 1995; Gustafson 1998; Muhlner et al. 2010). The spatial and temporal aspects of a landscape critically depend on the species or the ecological process under investigation and are characterised by the spatial and temporal resolution. Scale plays an important role in studying the patterns and processes as each level is characterised by a variety of processes, each of which has its own scale in space and time (Turner at al. 2001). Hence, an inference is closely associated with a particular scale and to

the extent of the study area (Allen & Starr 1982; Delcourt et al. 1983; O'Neill et al. 1986; Allen & Hoekstra 1992).

The present-day landscape pattern is a result of the long-term effects of a variety of drivers. A driver is any natural or human-induced factor that directly or indirectly causes a change in an ecosystem. Drivers can be classified into two categories, natural and human-induced, which are further classified as direct or proximate and indirect or underlying. A direct driver explicitly influences the landscape structure and pattern and is identifiable to differing degrees of accuracy. Floods, earthquakes and fires are few of the natural direct drivers that shape landforms, while agriculture expansion, urbanisation and infrastructure development are some of the major direct human-induced drivers of landscape change. An indirect driver operates more diffusely, often altering one or more direct drivers, and its influence is established by understanding its effect on direct drivers (Nelson et al. 2006). The major indirect human-induced driving forces of change are demographic, economic, socio-political, scientific and technological, cultural and religious (Nelson et al. 2006). The climate is the most dynamic natural indirect factor behind land cover changes operating at large time scales. Thus, to elucidate the relationship between the landscape structure and the drivers, landscape quantification is required (Turner 2005).

Quantification of the landscape pattern and structure is essential for assessing the causes and dynamics of pattern change as all ecological processes are linked (Gustafson 1998). Landscape patterns are formed as a result of abiotic conditions, biotic interactions, human pressure and the dynamics of disturbances and succession (Romme & Knight 1982; Turner 1987, 1989; Fagan & Calabrese 2006). There are several reliable materials and methods available for analysing the pattern and structure of a landscape including spatial data and statistical information. Aerial photographs, satellite imagery, published data and census and field observations are some of the data sources that can be used for quantification of spatial

heterogeneity (Dunn et al. 1991). Quantification is normally done on the basis of the characteristics of the data types and the extent of the study area, like measuring density and nearest neighbourhood for point data, composition analysis includes patch area, number of patches, inter-patch distances and their spatial arrangement, trend, autocorrelation for numerical maps. The landscape history may thus dictate not only how populations will respond to future landscape change, but also affect our ability to detect how such changes will affect viable source populations and extinction risks. The understanding of what causes landscape patterns and pattern changes with time is often translated into models to project future landscape scenarios (Baker 1989) that explore the fate of the landscape structure and connectivity and provide a base for prioritising conservation investments spatially.

1.3 Remote sensing and GIS

Remote sensing is a science of obtaining information about an object without being in direct contact with it. It extracts this information from the electromagnetic radiation reflected by objects when they are exposed to solar energy or by capturing naturally emitted energy. It has been demonstrated that remote sensing, along with GIS, is a powerful tool in different aspects of biodiversity research, management and conservation. A GIS provides a strong platform for capturing, storing, manipulating, analysing and managing spatial data at different scales. With the integration of different ecological and statistical techniques such as habitat suitability mapping, circuit theory and least cost path analysis, GIS have made it easy to streamline the process of corridor modelling and designing. The availability of high-resolution satellite data, such as data from the Advanced Very-High-Resolution Radiometer (AVHRR) (1 km), Moderate Resolution Imaging Spectroradiometer (MODIS) (250 m) and Landsat (30 m) has facilitated the investigation of habitat quality parameters and monitoring of spatio-temporal trends of land cover and ecological processes over different spatial scales.

Therefore, linking remote sensing capabilities and ecological knowledge allows a better understanding of the mechanisms that shape changes in biodiversity patterns and helps plan strategic environmental and conservation applications (Roy & Tomar 2000).

1.3. Study area

The region of central India comprising five states *viz.* Madhya Pradesh, Maharashtra, Chhattisgarh, Odisha and Jharkhand has been taken up as study area. The regional landscape is hemmed with *Aravali* range in north-west, *Satpuras* in south, *Chota Nagpur plateau* in northeast and Odisha hills in south-east. Many peaks of *Vindhya*s, *Sahyadris* and *Maikal* ranging from 200-1000 metres adorn the political states of Madhya Pradesh, Maharashtra, Chhattisgarh, Odisha and Jharkhand. Dominant with monsoon climate, rivers like *Narmada*, *Godavari*, *Tapti* and *Chambal* have flourished a biological landscape, which principally forms a zone of deciduous forest (*Champions & Seth 1968*). The study area is represented in Figure 1-1

This landscape biogeographically comes under peninsular region of India with elements from north-east, north (the Himalayan) and north-west (Mediterranean and Ethiopian) (*Mani 1984*). The study area is the richest among tiger population matrix in India with 18 Tiger Reserves and several other protected areas. With 4.1% (*Qureshi et al. 2006*) of forest cover Sal, *Anogeissus*, *Acacia*, *Syzigium*, Teak and miscellaneous vegetation is found dominantly. River *Narmada* is considered as the boundary between Sal vegetation of North and Teak vegetation of south (*Forsyth 1919*). Most of the wildlife species found throughout the zone are Cheetal (*Axis axis*), Sambar (*Cervus unicolor*), Nilgai, Chowsingha (*Tetraceros quadricornis*). However, some species are more frequent than others, while a few species are restricted to moister areas, e.g. Barking Deer (*Muntiacus muntjak*) and Gaur (*Bos gaurus*) whereas Blackbuck (*Antelope cervicapra*) and Chinkara (*Gazella gazella*) to drier open areas.

Anthropogenic disturbance are consistently getting prominent in the periphery of many tiger Parks that includes livestock grazing, firewood collection, logging, wood cutting, encroachment in park boundary etc. All these threat prevails around the complete landscape thus, making the issue of tiger conservation a prime importance in central Indian landscape. The region is the most threatened habitat for tigers and other selected species in India because of such anthropogenic disturbances (*Jhala et al. 2011*). The landscape has several metapopulation existing today for tigers and *gaur* which should be maintained for the long term existence of these species. Thus, landscape connectivity becomes essential element for their persistence.

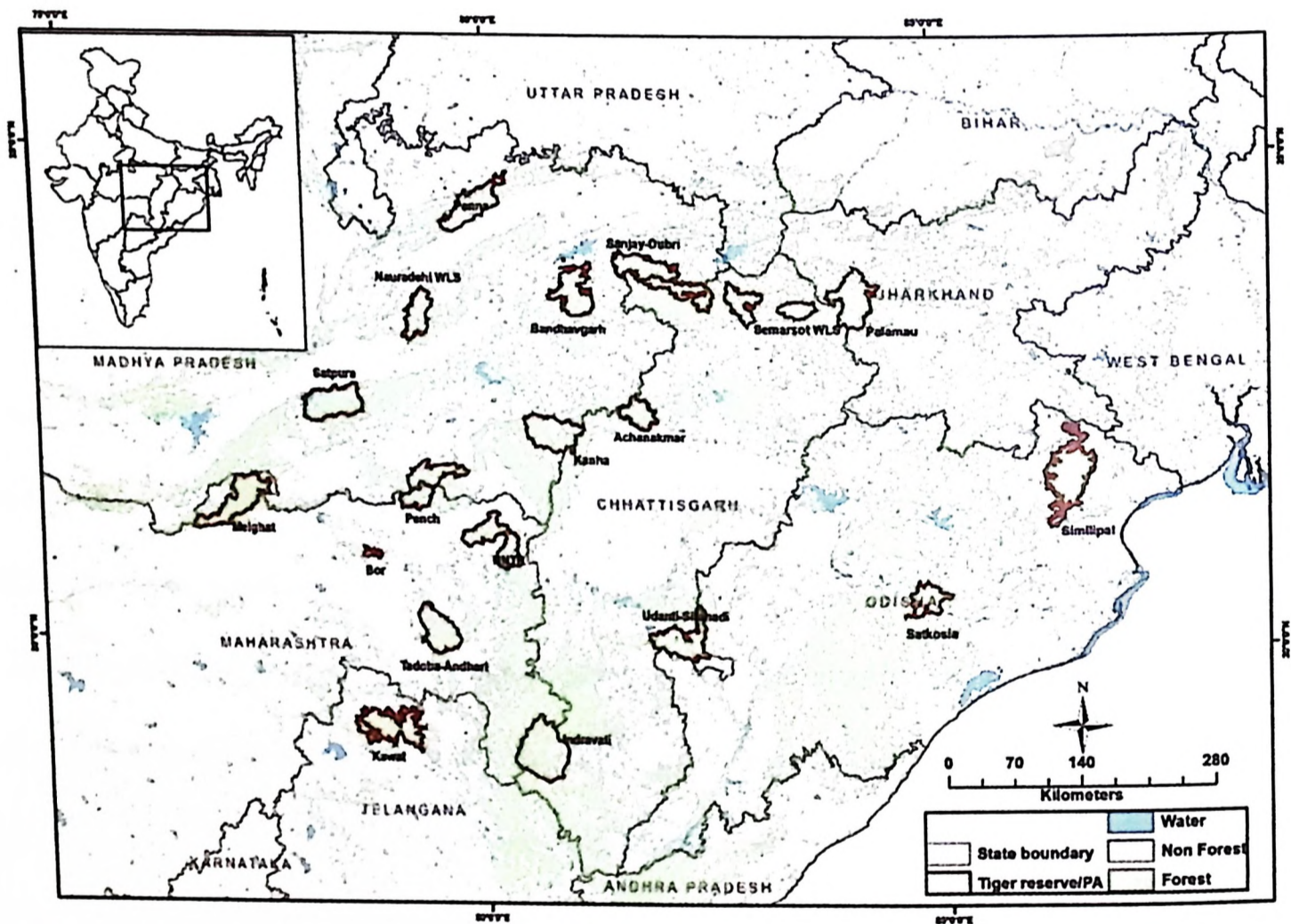


Figure 1-1 Map showing extent of study area with tiger reserve/protected area in Central Indian Landscape

1.4. Thesis outline

In chapter-II, I explored the occupancy probability for carnivores in 100 km² grids and at 25 km² for herbivore to surrogate, their habitat suitability. These models were further used to model corridors between protected areas using Circuit theory and least cost pathway analysis (LCP).

In chapter-III, I estimated the changes in land use land cover in and around the identified corridors using the time series and change detection technique. These areas were further investigated to identify trends of change and the macro drivers of change associated with these spatial patterns.

1.4.1. Objectives

The research work was carried out with three objectives:

1. Mapping Ecological connectivity between source populations of representative species of central Indian Landscape.
2. Assessment of spatio-temporal land use /land cover changes using time series & predictive change modelling in and around corridor habitats of the central Indian Landscape.
3. To evaluate the macro drivers of change across major linkages and attempt to model their persistence.

2. Identification of Potential Connectivity/Corridors

2.1. Introduction

Landscape connectivity is defined as the degree to which the landscape facilitates or impedes animal movements between resource-habitat patches (Taylor et al. 1993, 2006). The connectivity depends on the spatial arrangement of different land cover patches in a fragmented landscape and the effects of this arrangement on the abilities of species to move (Bennett 1998, 2003; Luque et al. 2012). Landscape connectivity is based on two concepts: (1) The structural concept—Physically connected landscape structures provide potential pathways for the dispersal of animals or connect distributed resource patches within the landscape. (2) The functional concept—The degree to which a landscape actually impedes the movements of organisms and other ecological processes. Functional connectivity provides both a landscape perspective and the response of species to that modified landscape with time and space (Tischendorf & Fahrig 2000b). Through functional connectivity, we can determine the extent to which ecological processes are affected by habitat alteration, and therefore this provides us the most realistic platform for planning long-term conservation goals. It is a difficult and data intensive exercise to identify functional connectivity as it requires long-term information on animal movements and a model to explain the land class chosen by the animal to move within a landscape. The term ‘connectivity’ also refers to the ability of an animal to disperse in a landscape and to the biophysical nature of the routes linking resource patches (Dunning et al. 1992). However, delineation of structural connectivity can provide a baseline model for planning initial conservation strategies and an overview of the opportunities left in a rapidly changing human-dominated landscape. In addition, a landscape with high structural connectivity has potentially better overall landscape connectivity through alternative paths and linkages (Bennett 1998, 2003). In

central India, where only few forest patches are left as a result of changes taking place at fast pace identifying structural connectivity could be the first step underpinning conservation interventions/strategies.

The potential of a landscape's connectivity to meet the balance of an ecosystem and species survival depends on the selection of viable linkages/corridors based on the species and an objective-centred approach. Corridors, also referred to as wildlife corridors or habitat corridors, are strips of landscape elements connecting two or more isolated habitat patches and enhancing the landscape connectivity by facilitating animal movements among these patches (Soulé & Gilpin 1991; Saunders & Hobbs 1991). Well-thought and robustly designed studies strongly support the effectiveness of corridors as a conservation tool and their benefits for organisms in real landscapes (Beier et al. 1998).

In the current situation of rapid development with inevitable spatial changes, the spatial modifications are affecting the landscape in many ways. Habitat fragmentation is one of the most threatening effects, adversely affects the wildlife populations and their survival. Habitat fragmentation is the conversion of a continuous habitat into fragmented patches, thereby exposing it to external influences (like invasion or predation); altering the microclimate and increasing isolation from other habitat patches. The geographically distant habitat patches restricts animal movements, making the animals vulnerable to inbreeding depression and demographic, environmental or genetic stochasticity, which could lead to extinction of the population (Burkey 1995). Therefore, to avoid these effects, it is crucial that these patches remain connected with each other. In this context, corridors play a vital role in linking these habitats and strengthening the overall landscape connectivity. A connected landscape provides a better outlook for the landscape structure (Taylor et al. 1993). It is crucial for the long-term survival of wildlife populations (Fahrig & Merriam 1985, 1994; Fahrig & Paloheimo 1988; Fahrig 2003) and maintains the dynamics of the

metapopulation (Levins 1970). With increased dispersal probabilities, the chances of recolonisation increase, the source–sink dynamics is maintained, and individuals from well-established populations may rescue the other populations from getting extinct (Brown & Kodric-Brown 1977).

Corridor design requires careful planning so that the connectivity of the landscape is enhanced. The important factors that should be considered when designing a corridor are the selection of the target species, the scale and efficient tools to map the linkages (Beier et al. 2009). Selection of a focal or target species is crucial as it frames the modelling perspective around the ecological needs and usage of the landscape by the particular species. The species selected for corridor design should be an apt representative of a landscape, with its ecological needs overlapping with those of other species living in that landscape. Conservation of that species should result in the preservation of other species as well (Fleishman et al. 2001; Roberge & Angelstam 2004). Seven species (three carnivores, three herbivore species and one omnivore) were selected as representative of the central Indian landscape, keeping in mind a multispecies approach as such an approach accounts for the habitat and dispersal needs of most of the other species present in the landscape (Hilty & Merenlender 2000b; Roberge & Angelstam 2004). The tiger (*Panthera tigris*), leopard (*Panthera pardus*), wild dog (*Cuon alpinus*) and sloth bear (*Melursus ursinus*) are the four top carnivores, at the top of the food chain, and they indicate balance in the ecosystem. Therefore, the aforementioned species were selected as representative species for designing the wildlife linkages in the central Indian landscape. The other three species—herbivore species—chosen were the chital (*Axis axis*), sambar (*Rusa unicolor*) and gaur (*Bos gaurus*). If the dispersal needs of these three herbivores are accounted in the design, then the other herbivores are likely to be considered. The mapping of corridors was done by co-relating

the habitat suitability of the species and the feasibility of landscape structures for the movements of these species in the landscape (Taylor et al. 1993, 2006).

2.1.1. Habitat suitability mapping and occupancy models

A habitat suitability map best describes the relation between the spatial extent of the distribution of a species and the environmental factors that limit the distribution (Guisan & Thuiller 2005; Soberon & Peterson 2005; Thuiller & Münkemüller 2010) and the habitat structure (Jokimäki & Huhta 1996; Saab 1999; Cody 1981). Such maps are produced by relating the present species distribution with the current environmental conditions and identifying the major factors suitable for the distribution of an animal (Peterson 2003b; Thuiller et al. 2005). The environmental variables selected for habitat suitability mapping depend on the influence of these variables on the species distribution. They may be factors limiting the distribution of the species, disturbances and availability of resources (Thuiller & Münkemüller 2010). Environmental variables and topographic conditions (terrain, forest cover), human presence and prey abundance were the covariates selected for habitat suitability mapping of the focal species. There are a variety of statistical and machine-learning models available for mapping habitat suitability using a variety of algorithms. Statistical modeling provides a mathematical basis for finding out the parameters that are suitable for the target species, their roles and the strength of their association (Guisan 2002). Statistical modeling is an efficient means of describing the functional relationship among variables (Rohef 1982; Box 1966). Another set of machine learning tools is available that can be used to make predictions and makes use of more complex relationships among the variables with or without assuming fixed hypotheses (Garzon 2006). The occupancy modelling technique is one of the robust methods used to understand distribution patterns and the functional use of the habitat of the landscape. Occupancy is defined as the proportion of area, patches or sample units that is occupied (Donovan & Hines 2007).

Occupancy modeling, like other species distribution models, infers the pattern of species occurrences in a given area. This modeling method provide more reliable estimates as it accounts for imperfect detectability. ‘Detectability’ refers to the reality that, even in locations that are surveyed by investigators, it is very common for animals and even entire species to be missed and go undetected (Mackenzie et al. 2005a). The model is designed to use species detection, represented as ‘1’, and non-detection, represented as ‘0’, data to estimate the occupancy probability, which is further interpreted as the proportion of the area occupied by the species of interest (Mackenzie et al. 2006). The model solves the problem of ‘false-absences’, which arises when a species is present but is somehow missed by the observer during a survey. The reliability of wildlife surveys depends on the site characteristics, on the weather conditions and largely on the observer’s skill. Surveys often face a challenge of imperfect detection (Mackenzie et al. 2003; Kéry & Schmidt 2008). If imperfect detection were not accounted for in the model, the output would always be an underestimate of the site occupancy, bias estimated relationship with covariates resulting in misinterpretation (Gimenez et al. 2008). Occupancy models addresses this problem and produce unbiased estimates of the occupancy and associated parameters.

2.1.2. Landscape connectivity modelling and corridor mapping

Assessment of a landscape’s connectivity combines the physical structure of the landscape and an organism’s response to that structure. The landscape structure and composition is a measure of the distribution of resource patches in a landscape (Dunning et al. 1992; Merriam 1984, 1991; Baudry & Merriam 1988). Along with a habitat suitability map, these give a weighted base map (Schumacher 1996) that can be used to model the ecological connectivity in the landscape (Bier et al. 2008) and to evaluate the contributions of multiple dispersal pathways in different habitat patches at the regional level.

I modelled the ecological niches of the selected species in an occupancy framework and obtained a probability map considering the ecological requirements of the focal species. The probability values obtained from the occupancy models were used as the bases to investigate the permeability of the central Indian landscape using algorithms from circuit theory in CIRCUITSCAPE. Least-cost path analysis was performed to select the optimal routes out of all the possible linkages in the landscape.

2.1.3. Threats and conservation issues

2.1.3.1. Tiger (*Panthera tigris*)

Conservation status: Endangered

The tiger (*Panthera tigris*), being at the top of the food chain, indicates the balance in the ecosystem. Hence, it has been selected as the umbrella species for wildlife linkage designing and conservation. The tiger plays an important role as the top predator, regulating and maintaining the forest ecosystem (Terborgh 1991; Sunquist et al. 1999). Being a large-sized cat, it prefers solitary life except for the time when a mother is with her offspring. Large, undisturbed forests, abundant prey, sufficient water resources and seclusion away from human disturbance are the basic requirements of tigers (Seidensticker & McDougal 1993; Miquelle et al. 1999). The chital, sambar and gaur are its preferred prey, and sometimes tigers feed on barasingha, nilgai, wild boar, chinkara and langur (Seidensticker 1976;1997;1999; McDougal 1977; Johnsingh 1983; Stoen & Wegge 1996; Biswas & Sankar 2002). The average home range of the tigers has an extent of 65–80 km² (Schaller 1967).

2.1.3.2. Leopard (*Panthera pardus*)

Conservation Status: Near Threatened

The leopard is also a member of the family Felidae (cat family) and is a top predator. The leopard is a wide-ranging species and have exceptionally good adaptable natures because of their ability to live in areas that are unknot used by other felids (Nowell & Jackson 1996).

Leopards are found in almost all kinds of natural habitat and can survive in close proximity to humans (Harihar et al. 2011; Athreya et al. 2013). They are highly elusive by nature, have a solitary lifestyle, spend most of the time on trees and can even climb up trees when they are carrying a kill. The chital, sambar and langur are the species that constitute most of their diet. Leopards can feed on a greater variety of prey compared with other members of the cat family, including other deer species, nilgai, wild boar, hare and cattle (Seidensticker 1976; Karanth & Sunquist 1995). Their habitat requirements include forest cover, ample prey and water availability. The home range of a leopard may have an extent between 30 km² and 45 km² (Bailey 1993; Odden et al. 2014).

2.1.3.3. Sloth Bear (*Melursus ursinus*)

Conservation status: Vulnerable

The sloth bear is widely distributed in the Indian subcontinent, and central India harbours the largest population. It is omnivorous in nature. Sloth bears are found in a wide variety of habitats, from grasslands to moist evergreen forest. They are termite hunters, They feed on plant matter such as mahua flowers, *amaltas* pods, *tendu* fruits, honey and fruits such as such as those of *Ziziphus mauritiana*, *Ficus benghalensis* and *Aegle marmelos* (Bargali et al. 2003; Dhamorikar et al. 2017). Rough rocky terrain and naturally formed caves are their preferred habitat. Their presence is not limited to protected areas; they are found even in unprotected forests (Joshi et al. 1995; Puri et al. 2015). The mean home range size of a sloth bear is between 9 km² and 14 km² (Laurie & Seidensticker 1977). Sloth bears live in groups, and usually five to seven individuals form associations (Laurie & Seidensticker 1977; Prater 1971; Baskaran 1990; Joshi 1996). They generally avoid human presence, but they are aggressive if an encounter happens.

2.1.3.4. Wild dog (*Cuon alpinus*)

Conservation Status: Endangered

The wild dog (dhole) is one of the top predators. It is a social canid, and it is found in peninsular India and in parts of northeastern India. The dhole is a highly social animal and has communal hunting habits (Pocock 1936; Johnsingh 1982; Fox 1971; 1984). Packs have more females than males. Wild dogs prefer medium-sized prey such as chital and hare. Rarely do they take wild boar. Their distribution depends on the availability of food, water and forest cover. Their home range is around 85 km² (Kamler & Srivastha et al. 2015).

2.1.3.5. Gaur (*Bos gaurus*)

Conservation Status: Endangered

The gaur is a large-sized animal that prefers evergreen, semi-evergreen and deciduous forests. It is adaptable to different habitat types, but water sources must be present in them (Sankar et al. 2001; 2013).

The gaur is one of the largest wild ungulates found in the forests of the central Indian highlands. The species is listed in Schedule I of the Indian Wildlife Protection Act, 1972. It is also included in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and is categorised as Vulnerable by the International Union for Conservation of Nature and Natural Resources (IUCN). The gaur is extinct in Sri Lanka and Cambodia and faces the risk of extinction in Bangladesh. The reason for the decline in the range and population is habitat destruction and poaching. The central Indian highlands provide the largest of gaur habitats in the Indian subcontinent. There are a number of gaur populations scattered in the landscape. These are isolated from each other due to habitat fragmentation. Degradation and loss of habitat are the major factors threatening the survival of this animal, along with hunting and foot and mouth disease, transmitted through livestock grazing (Areendran 2007; Duckworth et al. 2008). Increasing

developmental activities, forest clearing and agriculture expansion are some of the causes of habitat fragmentation. The gaur usually avoids using areas close to places with high human densities, and incidences of negative interactions with humans are increasing due to increasing human activities in the habitat of the gaur. Because the gaur is a forest-dwelling species, continuous forest connectivity is the basic requirement for its existence (Choudhary 2002). Therefore, to ensure its long-term survival, it is important to monitor and maintain forest structural connectivity in the landscape.

2.1.3.6. Chital (*Axis axis*)

Conservation Status: Least Concern

The chital, also known as the spotted deer, is the third largest deer present in peninsular India. The chital is a social animal and is typically found in herds of around 10–30 individuals. Chital are mostly found grazing in scrubland and grassland habitats. In summer, they are found in woodlands. They are very dependent on water and therefore prefer to stay in close proximity to water sources (Duckworth et al 2015).

At present, the chital is found not only in protected areas but also outside protected areas in good numbers (Jhala et al. 2010, 2014). There is a wide distribution in Madhya Pradesh, Maharashtra and Chhattisgarh. In Jharkhand and Odisha the species is confined to protected areas. Because the chital provides an important prey base for large carnivores, it is important to maintain its population for the balance of the forest ecosystem (Karanth & Sunquist 1995; Biswas & Sankar 2002). The animal is doing well inside the protected areas, but the populations outside the protected areas are facing threats due to habitat destruction, poaching for meat and livestock-borne diseases. It is crucial to safeguard the habitat of the species outside protected areas, especially in corridor forest patches, so that ample numbers flourish in these areas, encouraging large carnivores to disperse.

2.1.3.7. Sambar (*Rusa unicolor*)

Conservation Status: Vulnerable

The sambar is the largest deer species. It is widely distributed throughout the central Indian landscape, from Madhya Pradesh to northern Telangana (Jhala et al. 2010, 2014). Its presence has been recorded in protected areas as well as in forest corridors, with the exception of Odisha where most of the sambar are found only in protected areas. Sambar are one of the preferred prey of large carnivores, and their numbers need to be adequate for viable populations of large carnivores to be maintained in the forests. Sambar are also present in the forest patches linking the protected areas, which indicates that carnivores may be using these corridors for dispersal. Hunting for meat and antlers is the foremost factor causing a decline in the sambar population, and another major contributing factor is habitat loss. Forest fragmentation due to deforestation, agriculture expansion, rapidly spreading mines and infrastructure development is making the sambar population patchy and is posing a severe threat to the existence of sambar (N. Prakash, pers. comm. 2014). As the animal is shy in nature, it gets severely affected by the presence of humans. Thus, human activities adversely influence the presence of sambar.

2.2. Materials and Methods

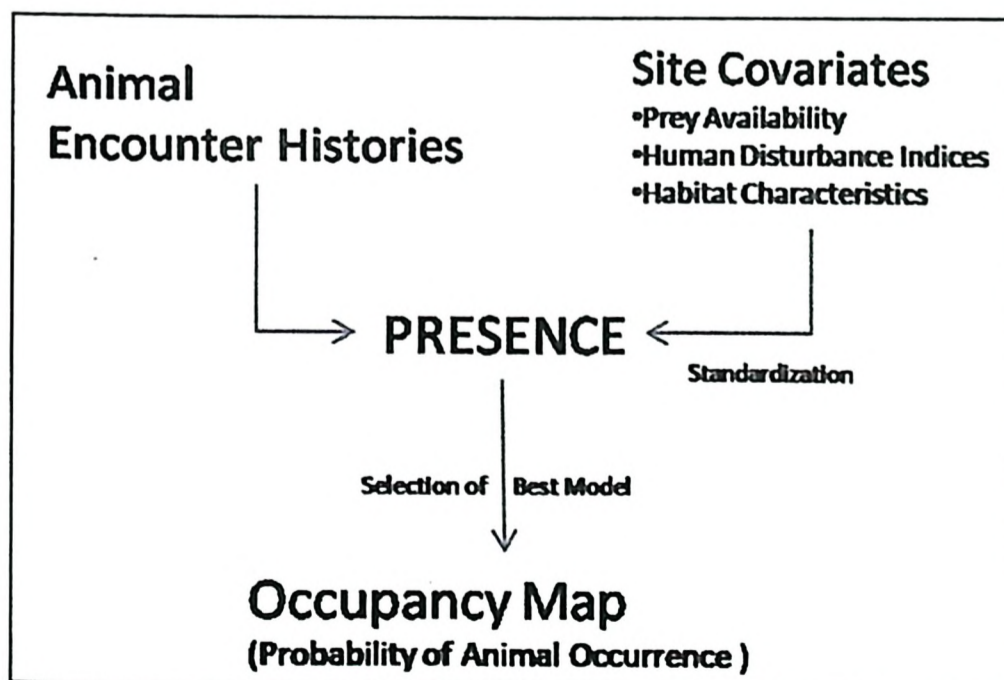


Figure 2-1: Schematic representation of workflow

2.2.1. Field data collection and processing

2.2.1.1. Collection of carnivore and herbivore signs

In most of the states in central India, the beat is the basic unit for management purposes and sets the basis for data collection. A beat in a forest usually covers an area of around 15–20 km² and has natural boundaries. To obtain representative samples, and following the administrative hierarchy followed by most forests in India, the beat was chosen as the basic sampling unit. Data were collected through a sign survey and a transect walk for carnivore signs, herbivore signs and human disturbance.

A walk of 5 km was used in the carnivore sign survey. Evidence of carnivore presence (foot marks, scats, scent marks, rake marks and direct sightings of the animals) was collected. A survey sheet detailing the parameters to be noted during the sign walk was used (Annexure 1).

A straight transect of length 2 km was walked early in the morning to determine the ungulate abundance, and the number of ungulates, distance of sighting, angle, type of habitat and activity were recorded. When returning along the same path, ungulate faecal matter was collected for pellet counts, and signs of human disturbance activities were noted. Wood cutting, lopping, grass cutting and human trails indicate the probable presence of humans in a forest.

2.2.1.2. GIS processing of the data

After the collection of data on carnivores, herbivores and human presence in the field, the data were brought to the GIS platform for further analysis. Although care was taken during the collection of data in the field, the data were still prone to noise, possibly because of writing, spelling or sometimes GPS calibration errors. To avoid geographical errors in the data, every GPS point was plotted in the GIS, and corrections were made wherever required.

After the data were cleaned, the information attached to each GPS point was extracted using a 100 km² fishnet for the carnivores. This size of the fishnet was selected on the basis of the home range of the top carnivore, which varied from 80 km² to 200 km² (from females to males). The average size is 100 km², and it presents a good representation of the data (Jhala et al. 2008).

For herbivores a grid size of 25 km² was selected to extract information from the data collected through transect walks. The choice of grid size was based on the fact that the usage of space of herbivores is less than that of carnivores. Thus extracting information relating to ungulates at a 100 km² grid size was found to be inappropriate for representing their spatial and resource usage.

2.2.2. Remote sensing data and processing

Along with the field data, remote sensing data were used. Remote sensing provides useful information about a geographical area in terms of the habitat quality, weather and terrain (Turner et al. 2001; Joseph 2003; Lillesand 1987, 2007; Richards 2006).

The remote sensing data (Table 2-1) provided primary information about an area. Further, this was used to extract information on other ecological aspects. The derived information generated from the datasets was primarily Euclidean distances. The Euclidean distance is the distance of a raster cell from a source location or from a set of sources and categorises the nearness or farness of the cell from the source. The source can be a water body, a road, a forest, etc. The theory of island biogeography demonstrates the role that distance plays in ecological processes and preferences and provides the basis for choosing Euclidean distance to account for external human pressures (MacArthur & Wilson 1967; Etherington 2016). Therefore, the Euclidean distances from core areas (within protected areas) and from night-time lights were calculated. Details are provided in the following sections

Table 2-1 Details of remotely sensed data used for analyzing habitat covariates and patterns in the landscape

	Dataset	Sensors	Spatial Resolution	Radiometric Resolution
1	Forest Cover Forest Survey of India (2011)	IRS 1D LISS III	23.5 m	4 Multispectral bands
2	Normalized Difference Vegetation Index (NDVI)	Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m	3 Multispectral bands
3	Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM)	90 m	2 bands
4	Night-time visible lights (1992,2012 & 2015)	US Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) VIIRS (2016)	1000m	2 bands (NIR&JR)

2.2.2.1. Distance to night-time lights

Night-time visible lights are one of the popular sources of information used to monitor human activities and other natural phenomena (Elvidge et al. 2001, 2009). The data are useful in identifying regions of intense human activity (Elvidge et al. 1997; Croft 1973, 1978) and in extracting information about population density (Dobson et al. 2000), urban growth and its impacts on the environment (Liu et al. 2013), forest fires, etc. (Kiran et al. 2009). The data were used to generate a distance raster, providing information about the remoteness of protected areas from human-dominated areas.

2.2.2.2. Distance from core area

In the current situation, where most of the forested land has been lost, the remnant forest patches are islands in a human-dominated environment. These forest patches are sources of livelihood for the large populations dwelling on their fringes (Angelsen et al. 2011). Not only resources at forest edges are utilised—people also foray inside the forest for livestock

grazing, firewood collection and NTFP collection. An inward buffer of 3 km was drawn to extract the core forest area, which was considered least affected by human pressures.

2.2.3. Corridor mapping

The mapping of corridors connecting the source areas was done by co-relating the habitat suitability of the focal species and the degree of permeability of the landscape structure to animal movements. The methodology included modelling the species habit suitability using occupancy modelling, permeability investigations using CIRCUITSCAPE and least-cost path analysis.

2.2.3.1. Occupancy modelling to map species distribution

The central Indian landscape was divided into $10 \times 10 \text{ km}^2$ and $5 \times 5 \text{ km}^2$ grids. Grids in which species signs were detected during the field survey were considered occupied. Information on carnivores was extracted using a 100 km^2 grid, while a 25 km^2 grid was chosen for herbivores. This information on species presence or absence based on beat-level surveys was then co-related with covariates in an occupancy framework (MacKenzie et al. 2006). Occupancy modelling uses animal presence/absence surveys and covariates, yielding cell-based probabilities of occupancy. Information collected on the prey base and human disturbances and remotely sensed data about the habitat quality, forest patch size, human footprint and other urbanisation indices were used as covariates for preparing occupancy models for all the seven selected species. The probability values obtained provide an index of habitat suitability. In the present work, the probability values were used to identify the potential forest structural linkages available in the landscape.

Occupancy modelling was performed using the package PRESENCE (Hines, 2006) for all the seven species. The program uses a likelihood-based method to estimate the detection probability and probability of site occupation. Maximum likelihood estimation (MLE) is a

method of obtaining values for the parameters of a model. The values are determined by maximising the likelihood function such that the model produces data similar to the observed data (MacKenzie et al. 2006; Fiske & Chandler 2011). For the present study, single-season site occupancy models that correct for detection/non-detection were used in program PRESENCE . Covariates are also integrated in occupancy models to reduce the variances in the parameter estimates (Mackenzie et al. 2006). Information about 31 covariates was extracted in grids on the basis of the ecological requirement of the target species. The information collected on the covariates was categorised on the basis of the habitat quality, prey abundance and human disturbance factors in the region. To remove the dimensionality and collinearity in the variables, these were standardised using principal component analysis (PCA) or Z-scores.

a) Principal component analysis and Z-scoring

PCA is statistical technique used to convert a set of correlated variables into a set of few uncorrelated variables using an orthogonal transformation. The technique is useful when too many variables or too much information is available about a site and the selection of a few variables is difficult. The technique summarises all or most of the information in a few variables called principal components. These principal components are at most equal in number to the original number of variables. The transformation accounts for most of the variability in the first component, and the variability decreases with each successive component. PCA was used to reduce the dimensionality of the dataset. It is difficult to make the model converge when the number of variables is very large. Model convergence is necessary as it shows that the estimates do not change from iteration to iteration. PCA was performed using the statistical software package SPSS (SPSS Inc., released 2007).

b) Z-scoring

Z scoring is done to scale all variables in similar magnitude, a method used to standardise numerical values by establishing their relationship to the mean of a group of values. The Z-score is a numerical measurement of a value's relationship to the mean such as if a information on distance is in 1000's and other variables such encounter rate is in decimals, therefore z-scoring brings them into same magnitude by dividing them with their mean values. If a Z-score is 0, it indicates that the score is identical to the mean score. The score may also be positive or negative, with a positive value indicating that the score is above the mean and a negative score indicating that it is below the mean.

c) Model selection and fitting

The model selection was done on the basis of Akaike information criterion (AIC) values and their weights (Burnham & Anderson 2000, 2002). Model with smallest AIC values is selected for interpretation. In the case of multiple top models, models with less than two AIC difference was averaged technique to estimate the final occupancy (Mackenzie et al. 2006; Burnham & Anderson 2002). I fitted null model for occupancy and detection. Further, occupancy models was improved by using covariates and species abundance was used to improve the detection probability.

The GOF of models was evaluated using the parametric bootstrap approach developed by Mackenzie and Bailey (2004). This estimates the Pearson chi-square test statistic and \hat{c} (\hat{c}) for the observed and expected values. \hat{c} is a measure of over dispersion. If $\hat{c} > 1$, there is overdispersion. $\hat{c} < 1$ indicates underdispersion, and a lack of fit is indicated if $\hat{c} > 4$ (Mackenzie & Bailey 2004; Mazerolle 2015).

2.2.3.2. Modelling landscape connectivity and corridor mapping

CIRCUITSCAPE was used to model the dispersal pathways in the landscape considering the physical structure as well as animal movement responses. The program follows the random walk theory and electrical circuit theory. The movements of animals through the landscape are related to the flow of current in an electrical circuit, which is governed by Ohm's law (McRae et al. 2013). CIRCUITSCAPE is based on graph theory data structures, in which graphs are networks of nodes connected by edges. In the case of a circuit model, each raster cell (representing a habitat patch or source population) acts as a node, while edges reflect movement probabilities (Urban & Keitt 2001). The CIRCUITSCAPE requires landscape data to be represented as grids of raster cells. Each cell represents the quality of the habitat, barriers and movement routes of animals. To prepare a resistance map for the present analysis, I multiplied the landscape cell values with the difference of the occupancy probability and 1, i.e. $1-\Psi$. The theory is useful in predicting the habitat permeability and the probability of dispersal across the landscape.

A conductance map was prepared to model the connectivity of the central Indian landscape using CIRCUITSCAPE. A conductance map represents the preference of land cover feature by animal for movement. To prepare the conductance map, the forest cover was weighted with the occupancy probability values obtained from the occupancy models. Non-forested areas were assigned a low conductance value of 0.0005 as dispersal through agricultural areas may happen though it is not preferred, as shown by telemetry studies conducted on carnivores (Smith 1993). Telemetry studies further show that animals tend to avoid moving through urban areas. Therefore, night-time lights were assigned conductance values of 0. A nighttime map with a raster value greater than 10 was considered to have high-density urban areas for assigning a conductance value. River channels or streams also provide dispersal

routes to animals, and thus a low (0.001) value of conductance was assigned where these were present.

a) Least-cost pathways

I aimed to segregate the optimal path/corridor for focal species from the connectivity network at a larger level. Selection of the best route or the most optimal path between two core habitat patches was carried out using least-cost path (LCP) analysis (Bunn 2000). A geographic information system performs least-cost path analysis to find the optimal path based on graph theory. LCP analysis is based on a raster-based algorithm that weights the minimal cost distance between the source and target cell. Each cell is weighted on the basis of its permeability to the organism in question (Adriaensen et al. 2003). The Linkage Mapper software package was used to compute the effective distances among the samples using a least-cost path algorithm. The tool computes the cheapest route between a source and a destination location using a friction or resistance surface layer. The resistance or friction surface layer is a continuous raster in which each cell value is the relative cost of moving through that cell for a given species. The least-cost path algorithm determines the shortest weighted distance from each cell to the target location in cost units rather than geographic units. The friction layer is prepared by converting the landscape heterogeneity into cost units. The cost units of a particular landscape were decided based on the ecology of the tiger and its behaviour. CIRCTUISCAPE models prepared for all the carnivore and herbivore species were compared to prepare a final model for identifying the optimal path using least cost algorithm. The identified corridors (LCP) was then verified and edited using Google Earth and experts' ground knowledge. A buffer of village boundaries (around 6 km) was selected as an effective width allowing movement of species in the landscape.

2.3. Results and Discussion

To estimate the status and suitability of the forest habitat in central India, the occupancy of the seven focal species was estimated using the program PRESENCE. The selected covariates were first standardized using PCA to develop occupancy models for the carnivores. Z-score standardisation was used to develop occupancy models for the herbivores. The outputs of the model were used to identify the connectivity in the central Indian landscape, and optimal paths were selected using the least-cost approach

2.3.1. Tiger (*Panthera tigris*)

For modelling the tiger occupancy, 23 covariates were selected based on the behavioural and ecological requirement of tigers (Table 2-4). These site covariates provided information on habitat quality, prey abundance and human disturbance in the landscape. To reduce the dimensionality in the dataset and to examine the interrelations among these variables, factor analysis was done in SPSS. After performing the Principal component analysis (PCA or factor analysis), the variability of these covariates was summarized in seven principal components, explaining 62% variation in the data (Table 2-2 and Figure 2-2).

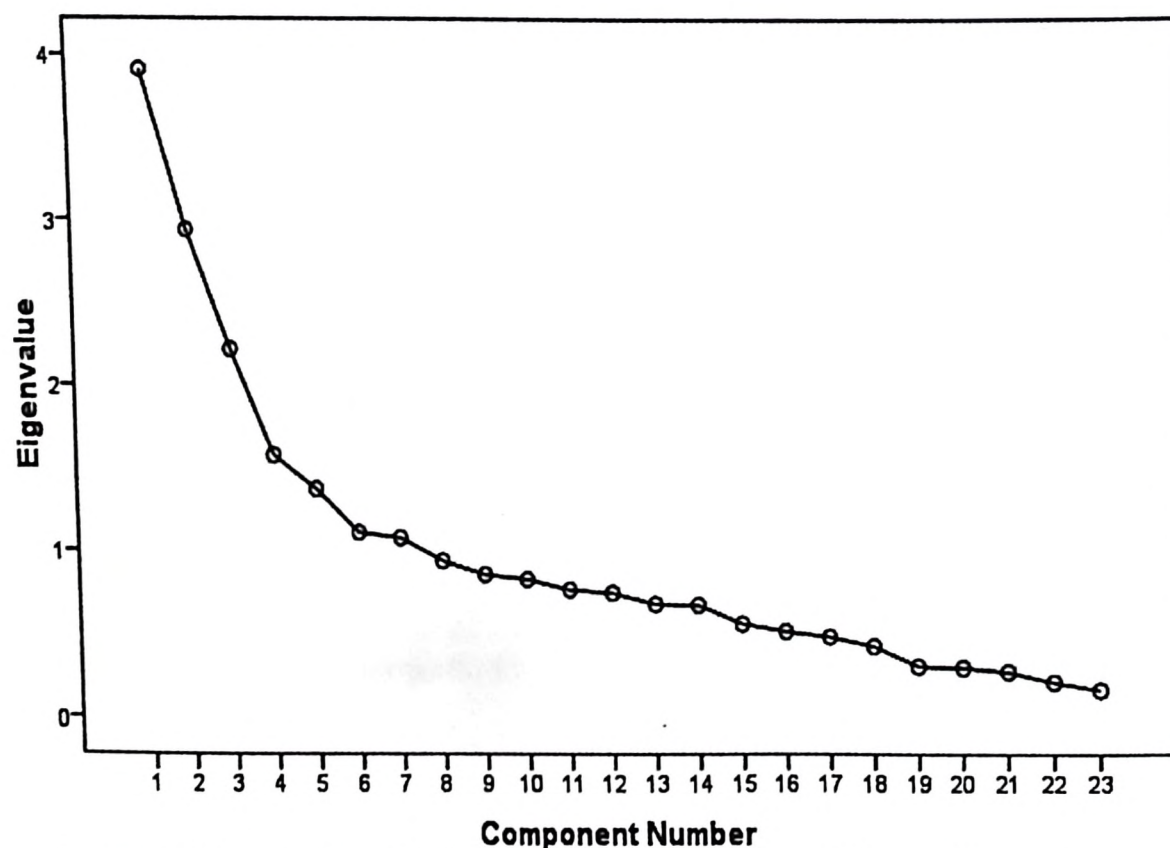


Figure 2-2 Scree plots showing the decreasing order of eigenvalues of covariates selected for modelling tiger occupancy

Table 2-2: Total variance explained by Factor analysis (PCA) performed in SPSS on covariates selected for modelling tiger occupancy.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.909	16.997	16.997	3.909	16.997	16.997	2.914	12.669	12.669
2	2.937	12.769	29.766	2.937	12.769	29.766	2.616	11.374	24.043
3	2.215	9.630	39.396	2.215	9.630	39.396	2.217	9.637	33.680
4	1.577	6.858	46.253	1.577	6.858	46.253	1.763	7.663	41.343
5	1.374	5.973	52.226	1.374	5.973	52.226	1.719	7.475	48.819
6	1.112	4.836	57.062	1.112	4.836	57.062	1.700	7.392	56.211
7	1.082	4.702	61.765	1.082	4.702	61.765	1.277	5.554	61.765
8	.943	4.099	65.864						
9	.862	3.746	69.610						
10	.833	3.623	73.232						
11	.770	3.349	76.581						
12	.752	3.268	79.850						
13	.683	2.972	82.821						
14	.677	2.945	85.767						
15	.567	2.465	88.231						
16	.521	2.267	90.499						
17	.489	2.124	92.623						
18	.430	1.869	94.491						
19	.308	1.341	95.832						
20	.300	1.306	97.138						
21	.277	1.204	98.342						
22	.215	.934	99.276						
23	.167	.724	100.000						

Table 2-3: Ecological interpretation of principal components for modelling tiger occupancy

S. No	Principal Components	Ecological Interpretation
1	PC-1	Protected forest with wild prey
2	PC-2	Protected dense evergreen forest
3	PC-3	Human disturbance
4	PC-4	Open forest Nilgai
5	PC-5	Rugged high elevation terrain
6	PC-6	Small prey
7	PC-7	Gaur

Table 2-4: Principal component loading after varimax rotation of covariates selected for modelling tiger occupancy in Central Indian landscape. The cumulative percent variation explained by seven components was 62%.

Variables	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6	PC-7
Encounter Rate of Chital	0.80						
Pellet Count of Chital	0.76						
Encounter Rate of Sambar	0.71						
Pellet Count of Sambar	0.69						
Distance from Protected Areas	-0.47	-0.36					
Encounter Rate of Wild Pig	0.45					0.41	
Mean NDVI for Post-monsoon		0.81					
Mean NDVI for Pre-monsoon		0.81		-0.32			
Distance from Core Area	0.30	0.66					
Nightlights Area		-0.47		-0.46			
Canopy Cover		0.45					
People Seen			0.87				
Livestock Seen			0.83				
Human Tail			0.80				
Encounter Rate of Nilgai				0.78			
Pellet Count of Nilgai				0.76			
Elevation					0.95		
Ruggedness		0.39			0.84		
Pellet Count of Barking Deer						0.75	
Encounter Rate of Barking Deer						0.68	
Pellet Count of Wild Pig						0.54	
Pellet Count of Gaur							0.76
Encounter Rate of Gaur							0.74

There were eight models better than the null model in explaining the tiger occupancy in the study area (Table 2-5). The model with the highest AIC value was selected as the best model.

It explained the tiger occupancy (ψ) using the variables PC1, PC2, PC3, PC4, PC5, PC6 and PC7. These principal components represented information about the prey abundance (PC1, PC6 and PC7), forest habitat quality (PC2 and PC4), terrain (PC5) and influence of human disturbance (PC3) (Table 2-6). The naïve occupancy estimated without using an occupancy framework was 6.9% in the sampled area. The naïve estimate was improved by 2% (6.9% to 8.8%, SE=0.37) when it was corrected for detection bias in the occupancy framework. The detection probability of tiger signs was improved when the tiger abundance information was used. The top model differed from delta AIC by a value of 3229. The coefficient of the best model showed that tigers prefer undisturbed dense forest cover where there is good availability of prey and that they are intolerant of human presence (Seidensticker & McDougal 1993; Miquelle et al. 1999) (Table 2-6). The results further showed that the preferred diet of tigers includes medium-sized prey such as chital, sambar and gaur (Johnsingh 1983; Stoen & Wegge 1996) and that tigers may feed on small prey, depending on the availability. The contribution of the best model was highest (close to 99%) in the model average estimates, and therefore was not used. The top model was tested for GOF using 30,000 parametric bootstraps showed fit ($\hat{c} = 0.655$, $p = 0.30$).

Table 2-5: Various models to estimate the occupancy of tigers using different environmental correlates in Central India and model selection based on AIC values.

Model	AIC	Delta AIC	AIC weight	No. of Parameter	-2log(likelihood)
Ψ (PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7), p(Tiger Sign)	12044.54	0.00	0.99	10	6012.27
Ψ (PC1 + PC2 + PC3 + PC4 + PC6 + PC7), p(Tiger Sign)	12053.85	9.30	0.01	9	6017.92
Ψ (PC1 + PC2 + PC3 + PC6 + PC7), p(Tiger Sign)	12058.22	13.68	0.00	8	6021.11
Ψ (PC1 + PC3 + PC6 + PC7), p(Tiger Sign)	12105.20	60.65	0.00	7	6045.60
Ψ (PC1 + PC3 + PC7), p(Tiger Sign)	12113.64	69.10	0.00	6	6050.82
Ψ (PC1 + PC3), p(Tiger Sign)	12150.46	105.92	0.00	5	6070.23
Ψ (PC1), p(Tiger Sign)	12254.35	209.81	0.00	4	6123.18

Ψ (.),p(Tiger Sign)	13002.10	957.55	0.00	3	6498.05
Ψ (.),p(.)	15273.84	3229.29	0.00	2	7634.92

Table 2-6: Coefficients of best models explaining tiger occupancy in Central Indian Landscape.

	Variables	Estimate	Standard Error
A1	Ψ . Constant	-2.71	0.07
A2	Ψ .PC1	1.05	0.06
A3	Ψ .PC2	0.38	0.06
A4	Ψ .PC3	-0.61	0.08
A5	Ψ .PC4	0.15	0.06
A6	Ψ .PC5	0.20	0.06
A7	Ψ .PC6	0.21	0.05
A8	Ψ .PC7	0.23	0.04
B1	p1	-1.92	0.04
B2	p1.Tiger Sign	0.42	0.01

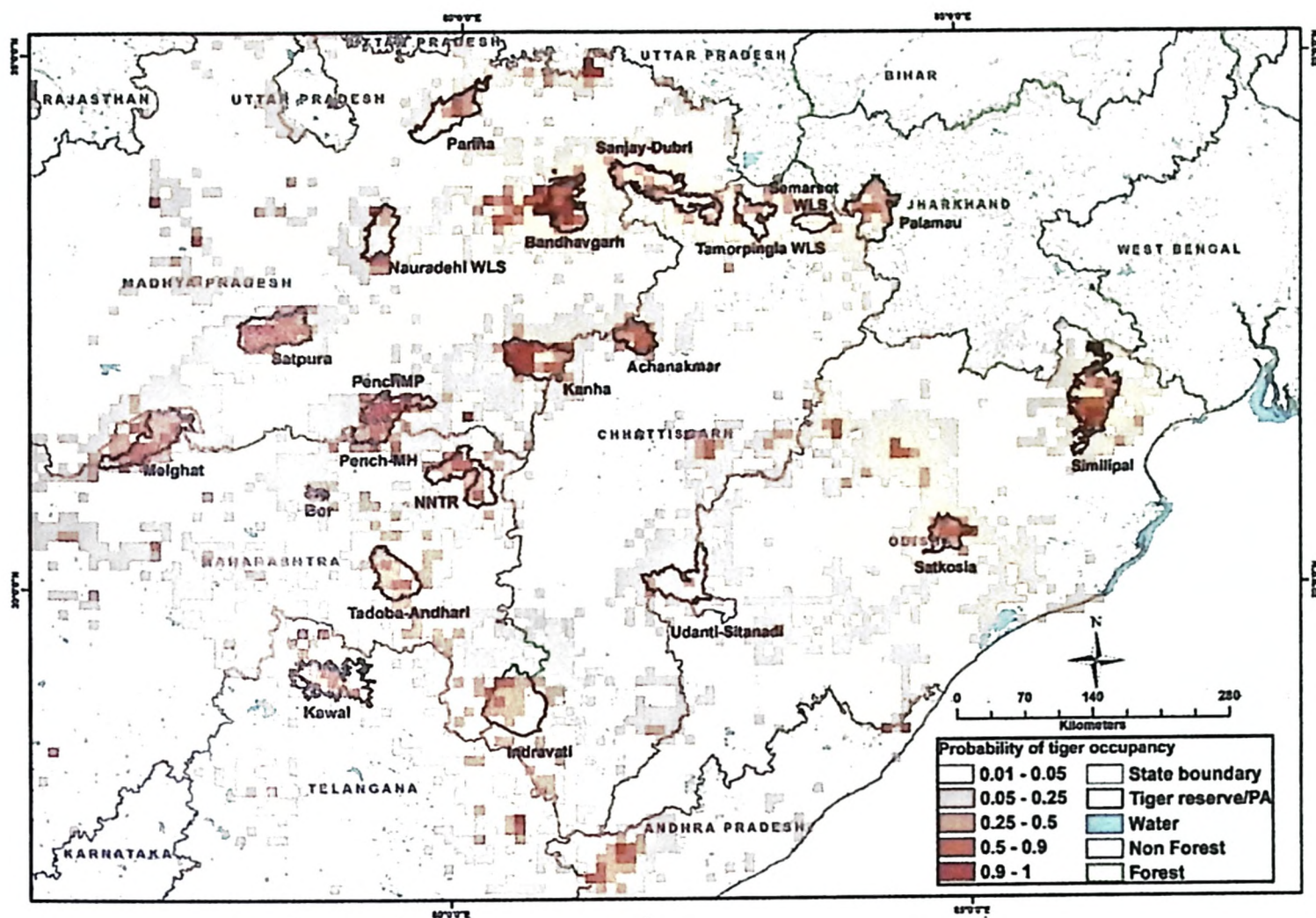


Figure 2-3 : Occupancy map of tiger modeled for 100 km² habitat patches using PRESENCE that account for detection bias and ecological covariates

2.3.1.1. Connectivity map for tiger

Results of circuit theory provided all the potential pathways for tigers between the 22 sources areas (tiger reserve/protected areas) in the study area. Based on the resistance values, Kanha tiger reserve is the most connected park with other reserves while Bor, Panna, Simlipal, Satkosia protected areas have high resistance values (Figure 2 -4).

Protected areas with high resistance values are connected through hostile matrix and need immediate attention to maintain their connectivity for tigers. Parks such as Simlipal Palamau and kawal do not have alternate routes therefore, future of tigers inhabiting in these parks highly depend on the identified corridor connection (Figure 2 -5)

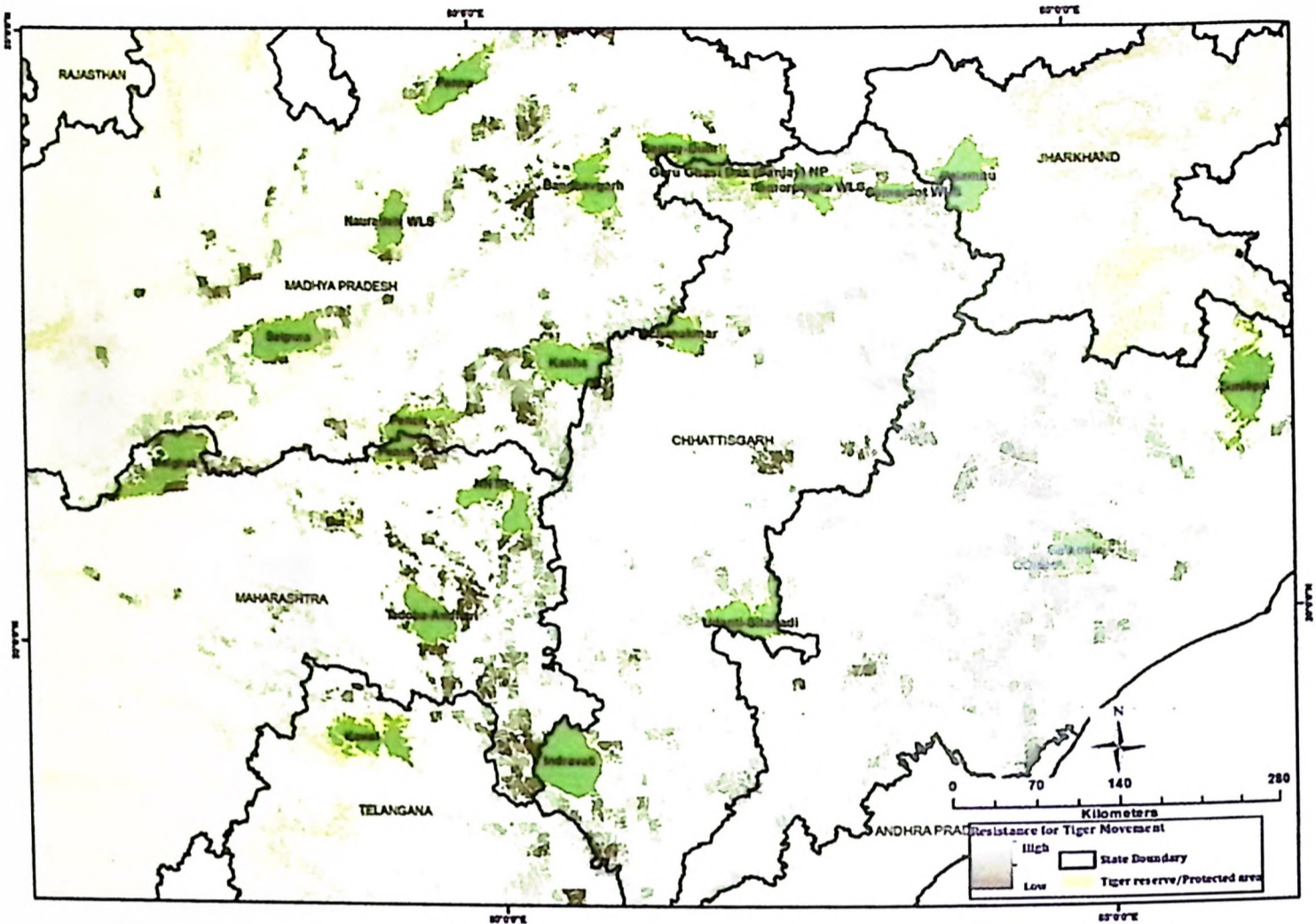


Figure 2-4 Resistance map for tiger movement in Central Indian Landscape derived by inverting the probability of Occupancy

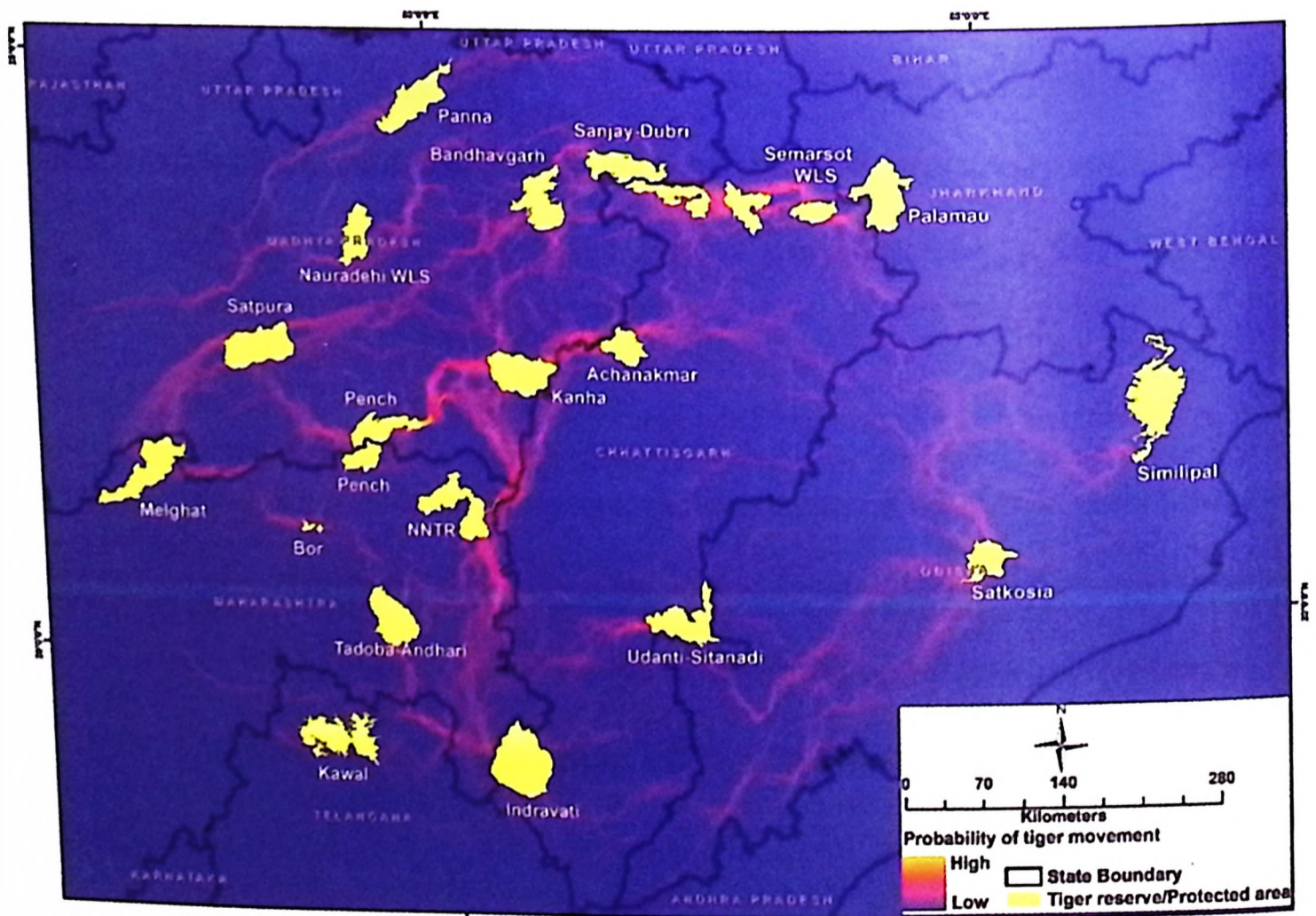


Figure 2-5 Potential habitat connectivity for tiger movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.2. Leopard (*Panthera pardus*)

For modelling leopard occupancy, 33 covariates were selected based on the behavioural and ecological requirements of the leopard. These site covariates provided information on the habitat quality, prey abundance and human disturbance in the landscape (Table 2-9). To reduce the dimensionality in the dataset and to examine the interrelations among these variables, factor analysis was carried out using SPSS. After performing the PCA (factor analysis), the variability of the covariates was summarised in nine principal components, explaining 61% of the variation in the data (*Table 2-7: Total variance explained by Factor analysis (PCA) performed in SPSS on covariates selected for modelling leopard occupancy.* Table 2-7 and Figure 2-6). The component loadings and their ecological interpretation are given in Table 2-8 and Table 2-9.

Table 2-7: Total variance explained by Factor analysis (PCA) performed in SPSS on covariates selected for modelling leopard occupancy.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.696	14.231	14.231	4.696	14.231	14.231	3.032	9.189	9.189
2	3.480	10.546	24.778	3.480	10.546	24.778	2.956	8.959	18.147
3	2.324	7.043	31.821	2.324	7.043	31.821	2.238	6.783	24.930
4	1.786	5.413	37.235	1.786	5.413	37.235	2.068	6.267	31.197
5	1.722	5.219	42.454	1.722	5.219	42.454	1.869	5.663	36.860
6	1.561	4.731	47.184	1.561	4.731	47.184	1.812	5.492	42.352
7	1.243	3.768	50.952	1.243	3.768	50.952	1.801	5.456	47.808
8	1.128	3.419	54.370	1.128	3.419	54.370	1.619	4.905	52.713
9	1.083	3.280	57.651	1.083	3.280	57.651	1.613	4.888	57.602
10	1.019	3.087	60.737	1.019	3.087	60.737	1.035	3.136	60.737
11	.994	3.011	63.748						
12	.933	2.826	66.574						
13	.887	2.689	69.263						
14	.820	2.486	71.749						
15	.799	2.422	74.172						
16	.763	2.312	76.484						
17	.729	2.208	78.691						
18	.698	2.115	80.807						
19	.632	1.915	82.722						
20	.604	1.831	84.553						
21	.582	1.764	86.317						
22	.549	1.662	87.980						
23	.513	1.555	89.534						
24	.500	1.516	91.050						
25	.460	1.393	92.443						
26	.455	1.379	93.822						
27	.414	1.254	95.077						
28	.399	1.209	96.286						
29	.301	.912	97.199						
30	.295	.894	98.093						
31	.264	.800	98.893						
32	.209	.633	99.526						
33	.156	.474	100.000						

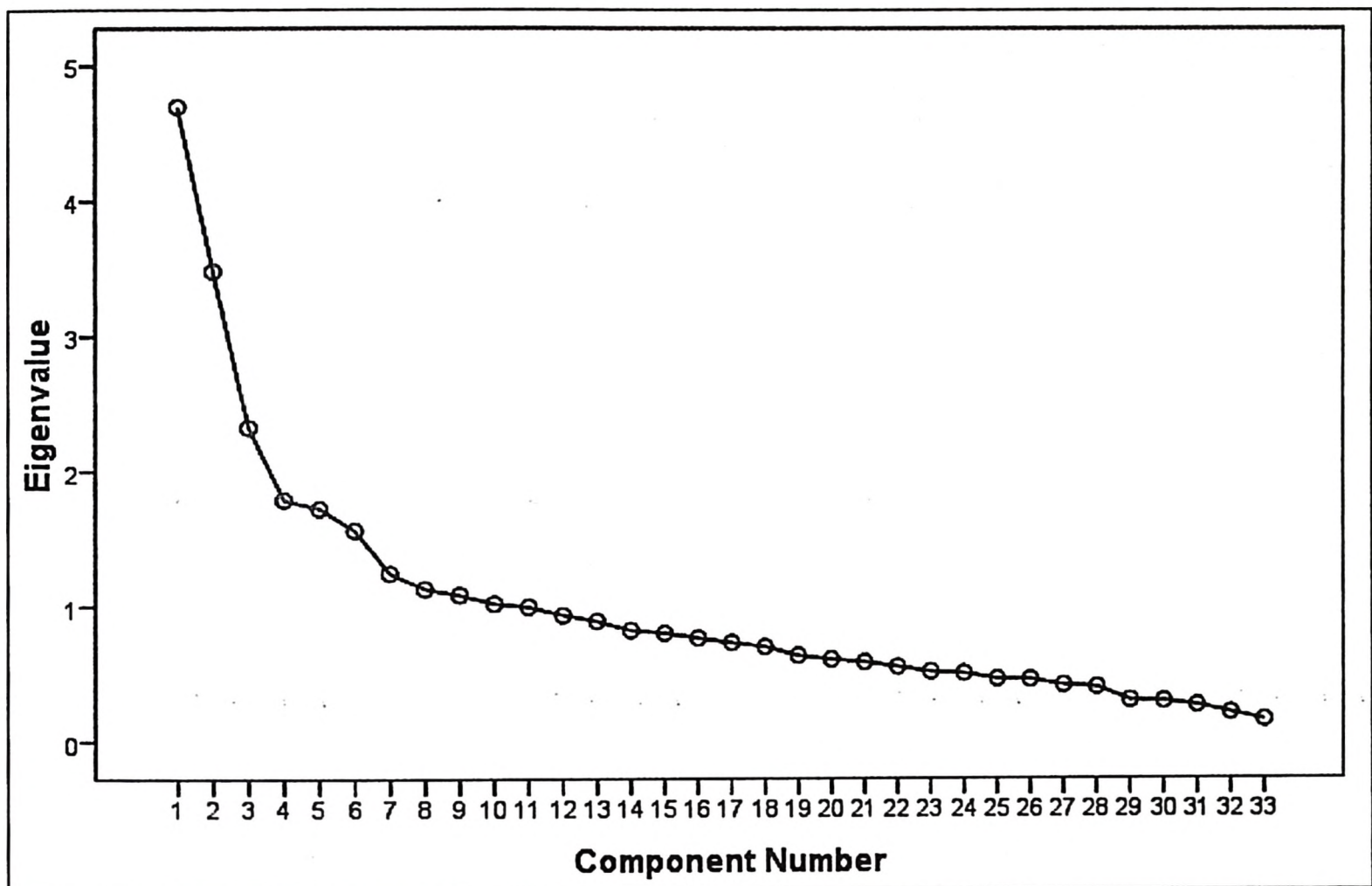


Figure 2-6 Scree plots showing the decreasing order of eigenvalues of covariates selected for modelling leopard occupancy

Table 2-8: Ecological interpretation of principal components for modelling leopard occupancy

S.No	Principal Components	Ecological Interpretation
1	PC-1	Vegetation within protected area
2	PC-2	Big prey species like chital & sambar within protected area
3	PC-3	Human Disturbance
4	PC-4	Small Prey dung
5	PC-5	Presence of nilgai
6	PC-6	Small prey Encounter rate
7	PC-7	Terrain
8	PC-8	Barking deer & langur
9	PC-9	Presence of chinkara

Table 2-9: Principal component loading after varimax rotation of covariates selected for modeling leopard occupancy in Central Indian landscape. The cumulative percent variation explained by nine components was 61%.

Variables	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6	PC-7	PC-8	PC-9
Post Monsoon NDVI	0.81								
Pre Monsoon NDVI	0.80								
Moist Tropical Deciduous forest	0.59								
Core Area	0.57								
Canopy Cover	0.51								
Dry Tropical Deciduous forest	0.47								
Area of Nightlight	-0.41	0.76							
Encounter Rate of Chital		0.75							
Pellet Count of Chital		0.74							
Pellet Count of Sambar		0.71							
Encounter Rate of Sambar		-0.53							
Distance from Protected Areas	-0.28								
People Seen			0.87						
Livestock Seen			0.84						
Human Tail			0.79						
Pellet Count of Wild Pig				0.73					
Pellet Count of Hare				0.68					
Pellet Count of Langur				0.65					
Encounter Rate of Nilgai					0.82				
Pellet Count of Nilgai					0.78				
Encounter Rate of Hare						0.73			
Encounter Rate of Peafowl						0.68			
Encounter Rate of Wild Pig						0.46			
Pellet Count of Peafowl						0.44			
Elevation							0.93		
Ruggedness							0.82		
Encounter Rate of Barking Deer								0.75	
Encounter Rate of Langur								0.56	
Pellet Count of Barking Deer								0.53	
Encounter Rate of Chinkara									0.82
Pellet Count of Chinkara									0.79

The model that best explained the leopard occupancy included eight principal components describing the prey abundance (including small prey), quality of the forest cover available within the protected areas and human disturbance (Table 2-8, Table 2-11 and Table 2-11). This model differed from the null model by a value of 6301. The naïve estimate of the leopard occupancy was improved by 6% (from 19.5% to 26.8%, SE=0.62) after correcting for detection bias in the occupancy framework. The detection probability was best explained by including the leopard abundance. The beta coefficients explain that the diet of the leopard includes chital and sambar and that the leopard can feed on small prey such as barking deer, chinkara and langur (Seidensticker 1976; Karanth & Sunquist 1995; Johnson et al. 1993). Dense vegetation and low levels of human presence are positive indicators of leopard occupancy (Kshetry et al. 2014) and the adaptability of the leopard to terrain complexity.

Table 2-10: Various models to estimate the occupancy of leopard using different environmental correlates in Central India and model selection based on AIC values.

Model	AIC	Delta AIC	No. of Parameter	2log(likelihood)
Ψ (PC1 + PC2 + PC3 + PC5 + PC6 + PC7 + PC8 + PC9), p(Leopard Sign)	25732.0	0.0	11	12855.0
Ψ (PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9), p(Leopard Sign)	25732.9	0.9	12	12854.5
Ψ (PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8), p(Leopard Sign)	25740.3	8.3	11	12859.2
Ψ (PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7), p(Leopard Sign)	25794.4	62.4	10	12887.2
Ψ (PC1 + PC2 + PC3 + PC4 + PC5 + PC6), p(Leopard Sign)	25886.0	154.0	9	12934.0
Ψ (PC1 + PC2 + PC3 + PC4 + PC5), p(Leopard Sign)	25898.5	166.5	8	12941.3
Ψ (PC1 + PC2 + PC3), p(Leopard Sign)	25902.0	170.0	6	12945.0
Ψ (PC1 + PC2 + PC3 + PC4), p(Leopard Sign)	25903.6	171.6	7	12944.8
Ψ (PC1 + PC2), p(Leopard Sign)	25981.2	249.2	5	12985.6
Ψ (PC1), p(Leopard Sign)	26386.3	654.3	4	13189.2
Ψ (.), p (.)	32033.4	6301.4	2	16014.7

Table 2-11 : Coefficients of best models explaining leopard occupancy in Central Indian Landscape.

	Variables	Estimate	Standard Error
A1	Ψ . Constant	-0.35	0.07
A2	Ψ . PC1	0.57	0.06
A3	Ψ . PC2	1.07	0.08
A4	Ψ . PC3	-0.46	0.06
A5	Ψ . PC4	0.11	0.05
A6	Ψ . PC5	0.22	0.06
A7	Ψ . PC6	0.52	0.06
A8	Ψ . PC7	0.39	0.06
A9	Ψ . PC8	0.15	0.05
B1	p1	-2.40	0.03
B2	p1. Leopard Sign	0.77	0.01

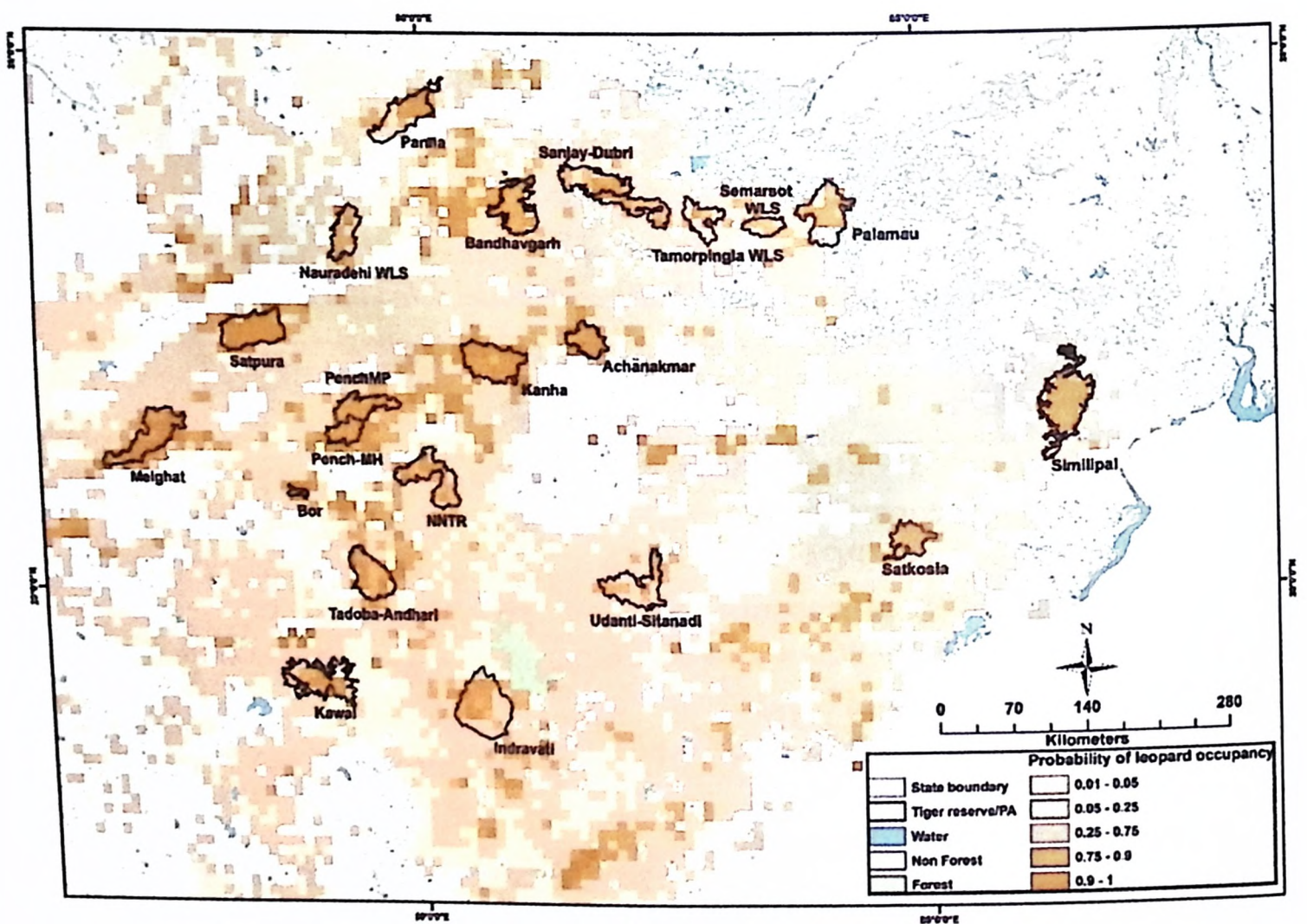


Figure 2-7: Occupancy map of leopard modeled for 100 km² habitat patches using PRESENCE that account for detection bias and ecological covariates

2.3.2.1. Connectivity map for Leopard

CIRCUITSCAPE model for leopard showed the movement probabilities along all possible dispersal paths in the landscape (Figure 2 - 9). Similar to the results received for tigers, parks having low resistance linkages in the landscape are Kanha, Pench-MP and Achanakmar and Bor, Kawal and Panna have high resistance value. High resistance values indicate less probabilities of movement for leopard.

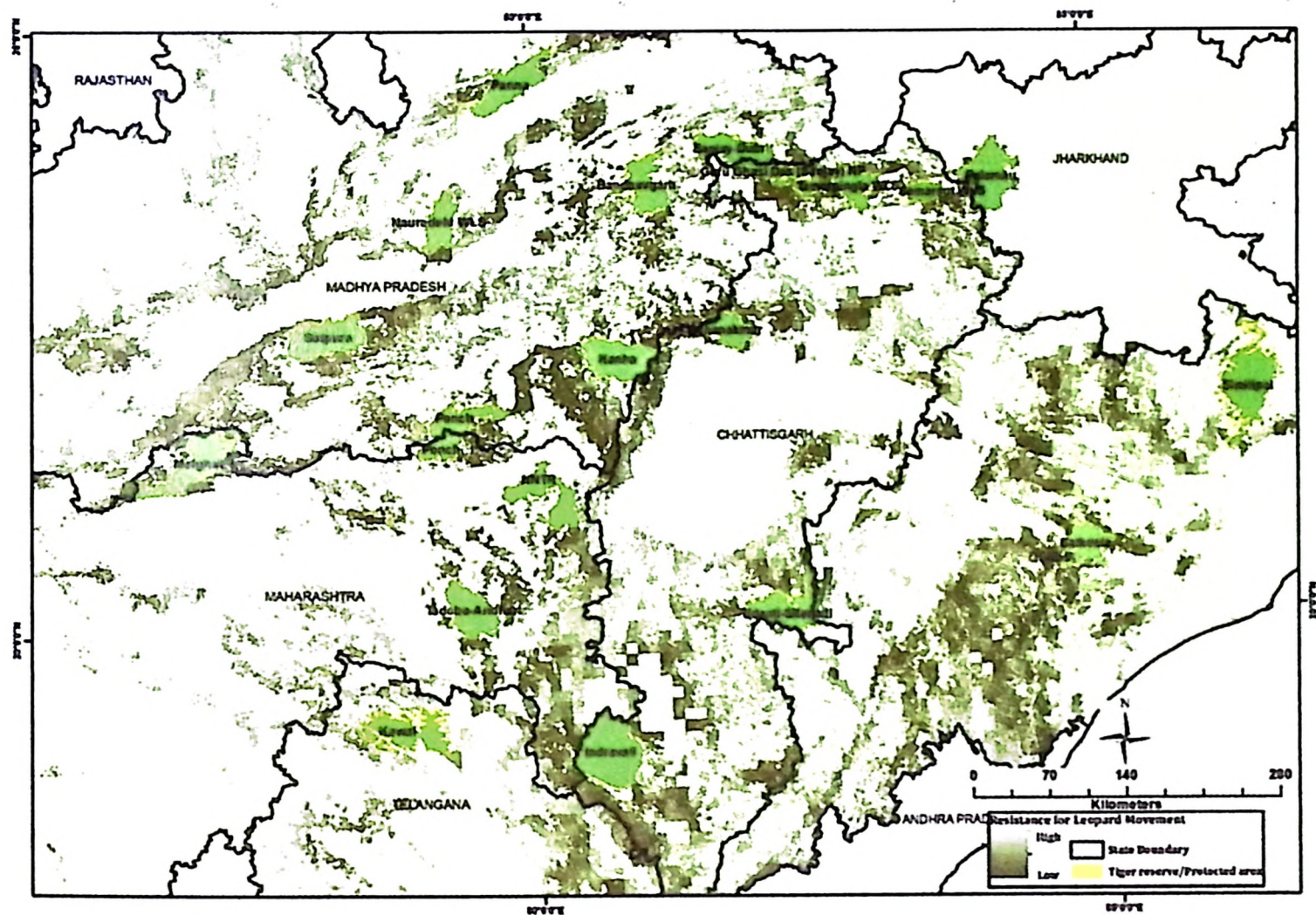


Figure 2-8 Resistance map for leopard movement in Central Indian Landscape derived by inverting the probability of Occupancy

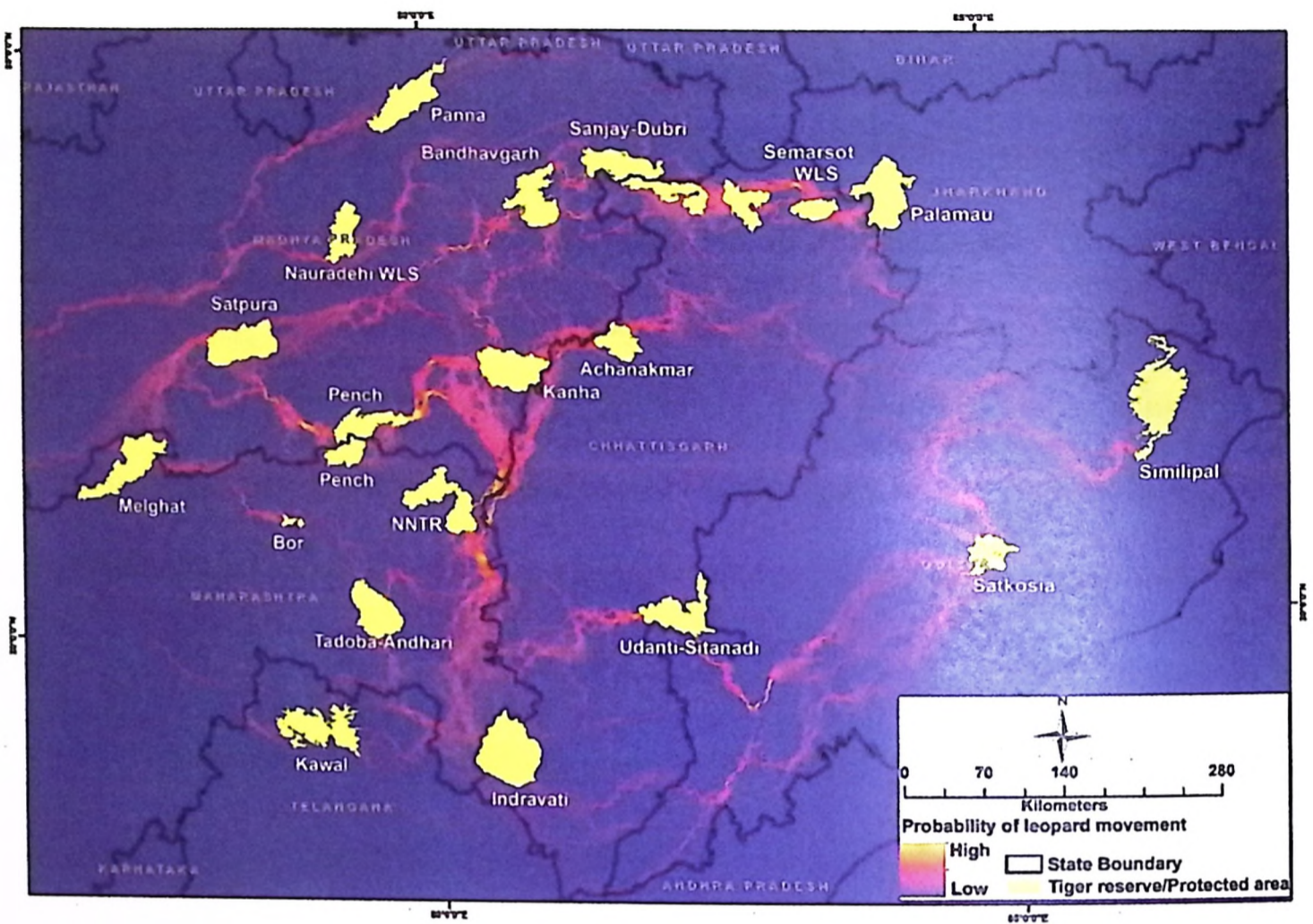


Figure 2-9 Potential habitat connectivity for leopard movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.3. Sloth Bear (*Melursus ursinus*)

The sloth bear occupancy in the central Indian landscape was modelled using 21 covariates including habitat quality, presence of other carnivores and the ecological requirements of the leopard. The redundancy in the data was reduced by using eight principal components that captured the entire variability of the data. The principal components accounted for 58% of the variability in the dataset (Table 2-12 and Figure 2-10).

Table 2-12: Total variance explained by Factor analysis (PCA) performed in SPSS on covariates selected for modelling sloth bear occupancy

Component	Total Variance Explained								
	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.314	14.407	14.407	3.314	14.407	14.407	2.320	10.088	10.088
2	1.810	7.871	22.278	1.810	7.871	22.278	1.761	7.657	17.745
3	1.662	7.227	29.505	1.662	7.227	29.505	1.759	7.647	25.391
4	1.622	7.051	36.557	1.622	7.051	36.557	1.734	7.539	32.930
5	1.496	6.504	43.061	1.496	6.504	43.061	1.733	7.533	40.464
6	1.287	5.597	48.658	1.287	5.597	48.658	1.654	7.190	47.654
7	1.250	5.434	54.092	1.250	5.434	54.092	1.436	6.245	53.898
8	1.010	4.393	58.485	1.010	4.393	58.485	1.055	4.586	58.485
9	.997	4.335	62.820						
10	.994	4.324	67.143						
11	.964	4.193	71.336						
12	.915	3.979	75.315						
13	.852	3.705	79.021						
14	.797	3.466	82.486						
15	.720	3.131	85.618						
16	.664	2.887	88.505						
17	.517	2.246	90.751						
18	.472	2.052	92.803						
19	.466	2.026	94.829						
20	.429	1.867	96.696						
21	.355	1.543	98.238						
22	.248	1.076	99.315						
23	.158	.685	100.000						

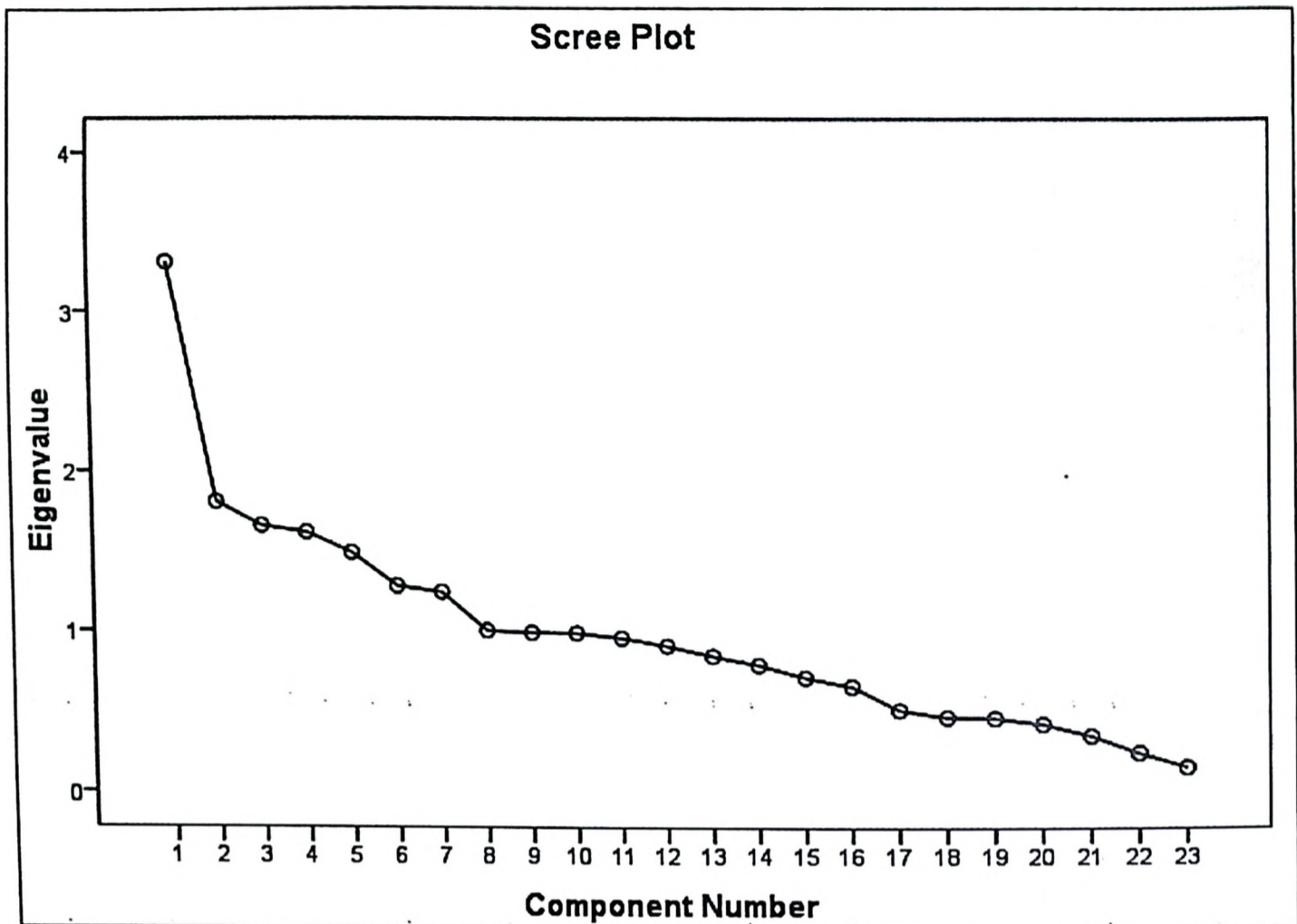


Figure 2-10: Scree plots showing the decreasing order of eigenvalues of covariates selected for modelling sloth bear occupancy

Table 2-13: Ecological interpretation of principal components for modelling sloth bear occupancy

Principal Component	Ecological Interpretation
pc1	Vegetation
pc2	Carnivore
pc3	Human disturbance
pc4	Terrain
pc5	Forest Type-I(Moist tropical)
pc6	Nightlight information
pc7	Forest Type-II(Dry Tropical forest)
pc8	Forest Type-Mixed

Table 2-14: Principal component loading after varimax rotation of covariates selected for modeling sloth bear occupancy in Central Indian landscape. The cumulative percent variation explained by 8 components was 58 %

Variables	pc1	pc2	pc3	pc4	pc5	pc6	pc7	pc8
NDVI-post monsoon	0.87							
NDVI-pre monsoon	0.86							
Canopy cover	0.59							
Core area	0.38	0.34						
Leopard encounter rate		0.83						
Tiger Encounter Rate		0.77					0.42	
Leopard Encounter Rate		0.49						
Wild dog Encounter Rate	-0.22	-0.35						
Livestock			0.79					
People Seen			0.79					
Human Trail			0.64					
Dem				0.94				
Ruggedness	0.37			0.84				
Moist sal-bearing forest and very moist, mixed deciduous					0.91			
General edaphic and seral types of moist deciduous forests					0.9			
Nightlight Area						-0.85		
Distance to Nightlights						0.77		
Sal -Tropical dry deciduous	0.28						0.74	
Dry teak-bearing forest and Very dry teak forest							0.6	-0.33
Moist teak-bearing forests &moist mixed deciduous forest								0.67
Anogeissus & Boswellia								0.34

The best model (based on the AIC value) included contributions from principal components 1, 2, 3, 4, 6 and 7 to explain the sloth bear occupancy. The components described information on distribution relating to tropical forests, the quality of the forest cover, the terrain and the level of human disturbance (Table 2-15 and Table 2-16). The naïve estimate of the occupancy was improved by 7% (from 36.3% to 43%, SE=0.64) after correcting for detection bias in the occupancy framework. The best model differed from the null model by a value of 1648. The signs of the beta coefficients (Table 2-16) showed that the sloth bear prefers tropical forest, moderate terrain and distance from human disturbance and is not affected by the presence of other carnivores (Joshi et al. 1995; Puri et al. 2015). The top model was tested for GOF using 30,000 parametric bootstraps showed fit ($\hat{c} = 0.89$, $p = 0.73$).

Table 2-15: Various models to estimate the occupancy of sloth bear using different environmental correlates in Central India and model selection based on AIC values..

Model	AIC	Delta AIC	No. of Parameter	2log(likelihood)
Ψ (pc1+pc2+pc3+pc4+pc6+pc7), p (.)	51954.43	0.00	8.00	51938.43
Ψ (pc1+pc2+pc3+pc4+pc5+pc6+pc7), p (.)	51956.41	1.98	9.00	51938.41
Ψ (pc1+pc2+pc3+pc4+pc5+pc6+pc7+pc8), p (.)	51958.41	3.98	10.00	51938.41
Ψ (pc1+pc2+pc3+pc4+pc5+pc6), p (.)	51962.50	8.07	8.00	51946.50
Ψ (pc1+pc2+pc3+pc6), p (.)	51976.89	22.46	7.00	51962.89
Ψ (pc1+pc2+pc3+pc4), p (.)	52260.62	306.19	6.00	52248.62
Ψ (pc1+pc2+pc3+pc4+pc5), p (.)	52262.61	308.18	7.00	52248.61
Ψ (pc1+pc2+pc3), p (.)	52272.68	318.25	5.00	52262.68
Ψ (pc1+pc2), p (.)	52298.54	344.11	4.00	52290.54
Ψ (.), p (.)	53603.03	1648.60	2.00	53599.03

Table 2-16: Coefficients of best models explaining sloth bear occupancy in Central Indian Landscape.

	Variables	Estimate	Standard Error
A1	Ψ . Constant	-0.30	0.03
A2	Ψ .pc1	0.95	0.04
A3	Ψ .pc2	1.38	0.08
A4	Ψ .pc3	-0.18	0.04
A5	Ψ .pc4	0.12	0.03
A7	Ψ .pc6	0.56	0.03
A8	Ψ .pc7	0.09	0.03
B1	p1	-0.64	0.01

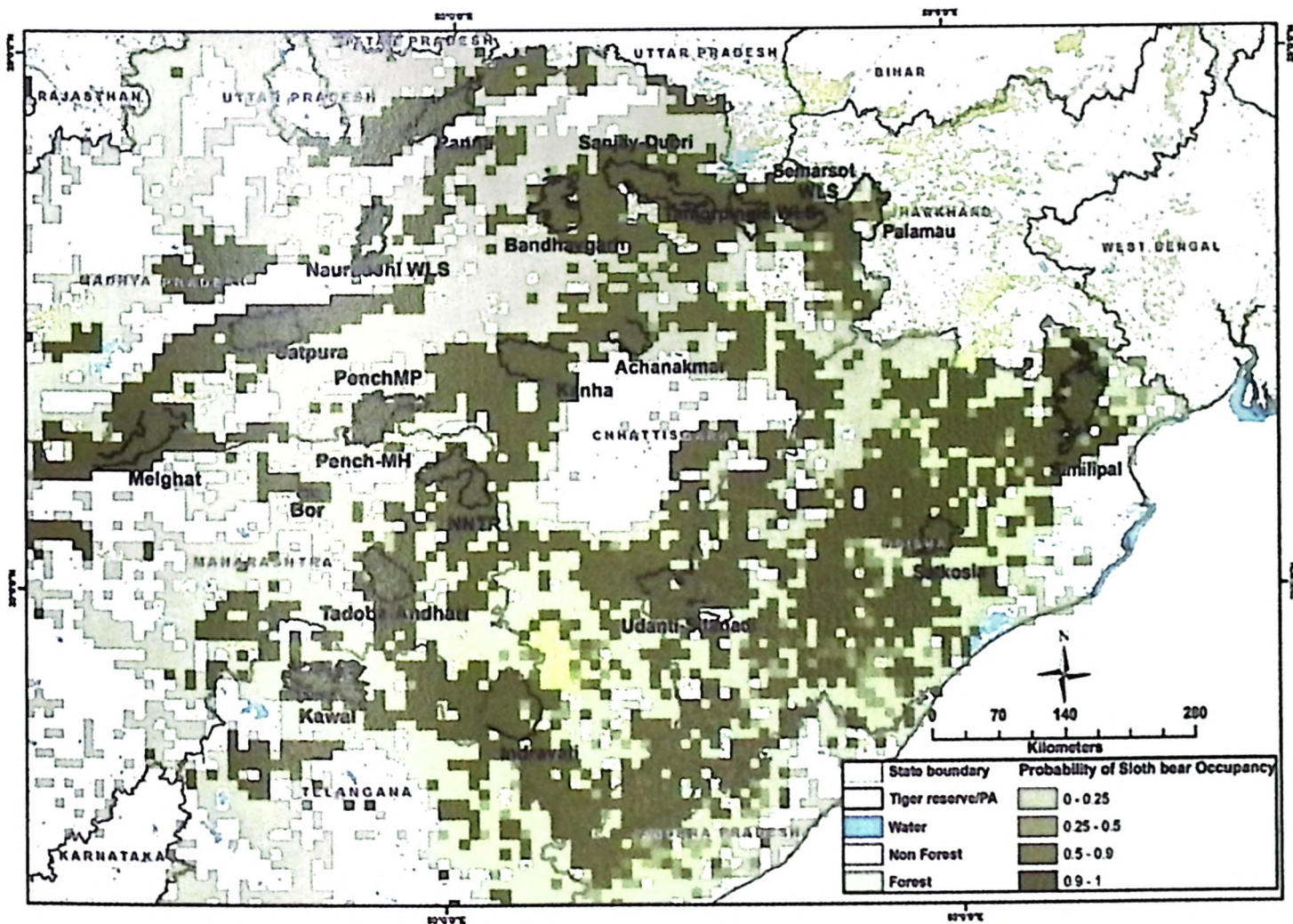


Figure 2-11 Occupancy map of sloth bear modeled for 100 km² habitat patches using PRESENCE that account for detection bias and ecological covariates

2.3.3.1. Connectivity map for Sloth bear

Circuitscape model for sloth bear reported similar results as for tigers, Kanha being the most connected park with low resistance values. Bor, Panna, Simlipal are few reserves having highest resistance values (Figure 2-12 and Figure 2-13). High resistance values

shows that connectivity is only because of few forest patches passing through the high interspersed in high human developed areas.

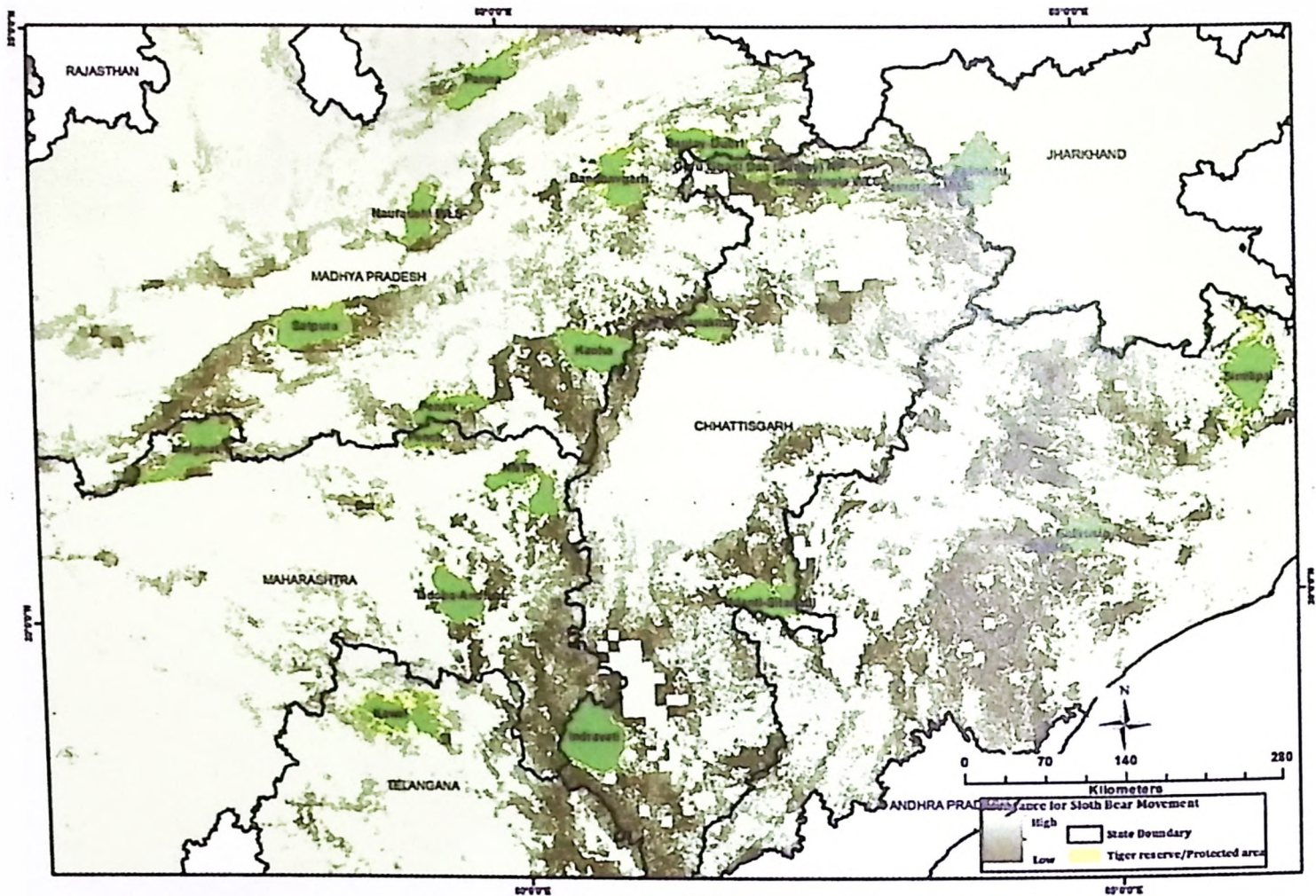


Figure 2-12 Resistance map for Sloth bear movement in Central Indian Landscape derived by inverting the probability of Occupancy

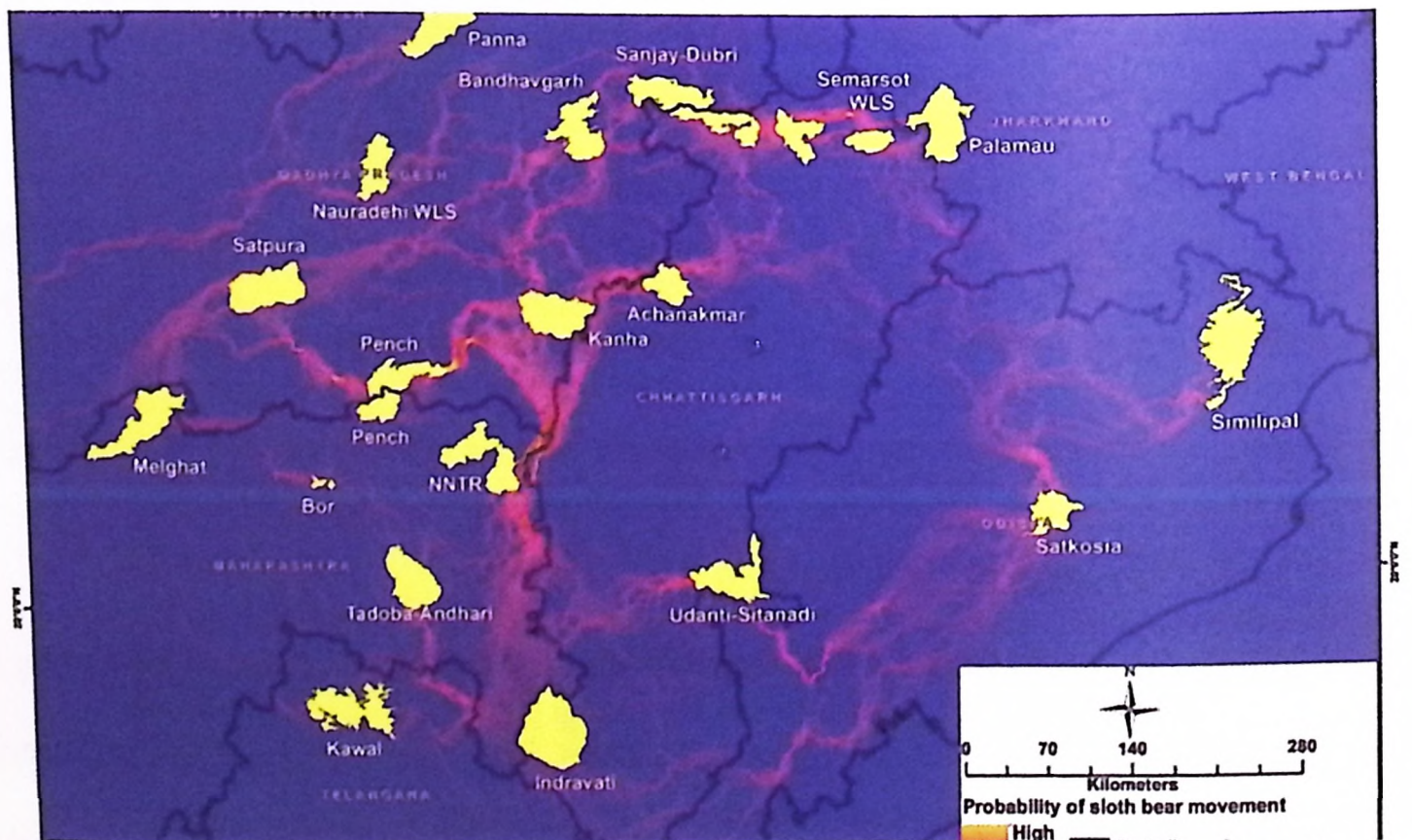


Figure 2-13 Potential habitat connectivity for sloth bear movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.4. Wild dog (*Cuon alpinus*)

For modelling the wild dog occupancy in this landscape, around 31 covariates were selected based on the ecology of the dholes and on the available literature. These site covariates includes habitat parameters and prey information. To reduce the dimensionality in the dataset and to examine the interrelations among these variables, factor analysis was done in SPSS. After performing the Principal component analysis (PCA or factor analysis), the variability of these covariates was summarized in ten principal components, explaining 62% variation in the data (Table 2-17 and Figure 2-14).

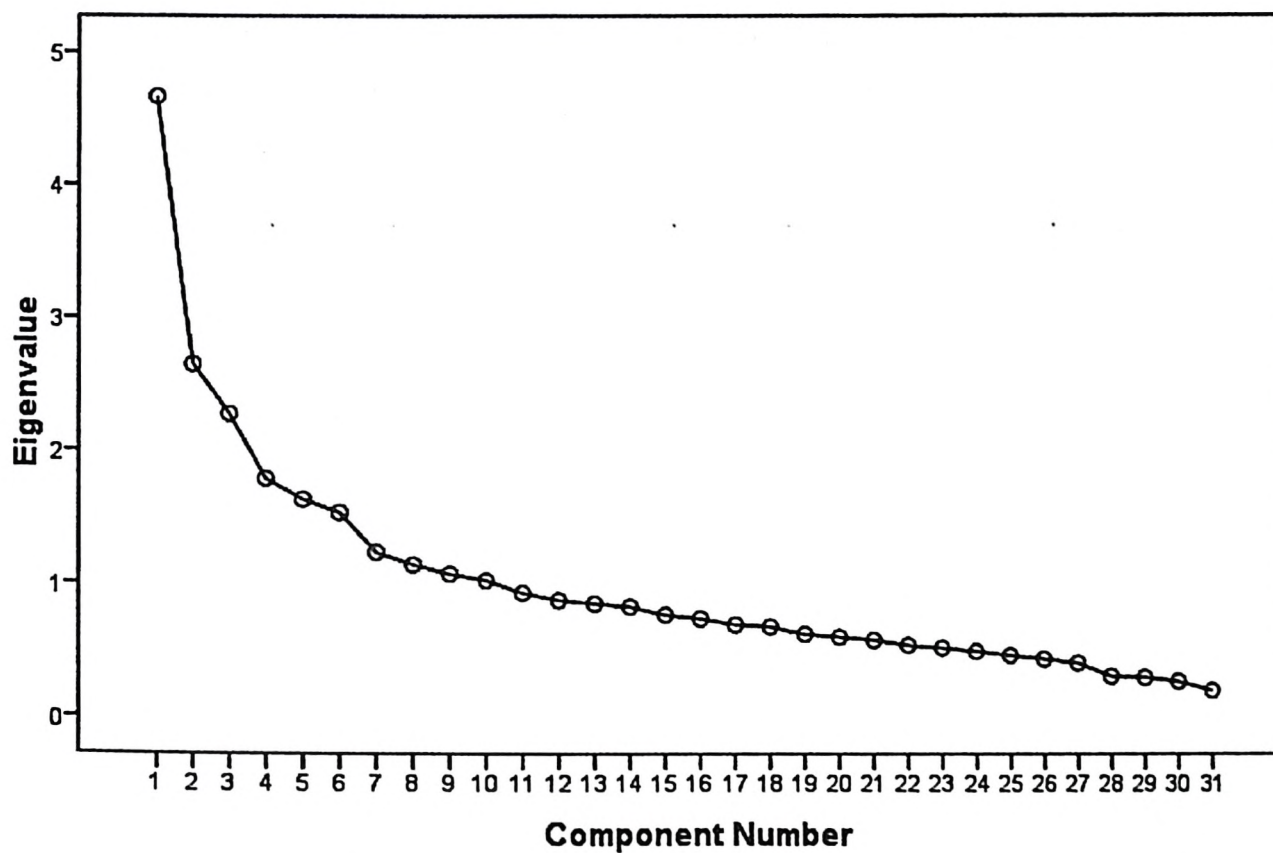


Figure 2-14: Scree plots showing the decreasing order of eigenvalues of covariates selected for modelling wild dog occupancy

Table 2-17: Total variance explained by Factor analysis (PCA) performed in SPSS on covariates selected for modelling wild dog occupancy

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.666	15.052	15.052	4.666	15.052	15.052	2.907	9.378	9.378
2	2.645	8.532	23.584	2.645	8.532	23.584	2.225	7.179	16.557
3	2.273	7.332	30.916	2.273	7.332	30.916	2.086	6.728	23.285
4	1.784	5.756	36.673	1.784	5.756	36.673	1.977	6.378	29.663
5	1.630	5.257	41.930	1.630	5.257	41.930	1.805	5.822	35.486
6	1.532	4.941	46.870	1.532	4.941	46.870	1.769	5.706	41.191
7	1.233	3.978	50.848	1.233	3.978	50.848	1.727	5.570	46.761
8	1.140	3.678	54.526	1.140	3.678	54.526	1.624	5.239	52.001
9	1.069	3.449	57.975	1.069	3.449	57.975	1.574	5.077	57.078
10	1.022	3.296	61.271	1.022	3.296	61.271	1.300	4.194	61.271
11	.928	2.993	64.264						
12	.873	2.815	67.079						
13	.848	2.736	69.815						
14	.825	2.662	72.477						
15	.764	2.466	74.942						
16	.735	2.371	77.313						
17	.691	2.228	79.542						
18	.676	2.180	81.721						
19	.619	1.996	83.717						
20	.597	1.925	85.641						
21	.574	1.851	87.493						
22	.534	1.724	89.217						
23	.513	1.656	90.873						
24	.487	1.572	92.445						
25	.458	1.476	93.922						
26	.431	1.390	95.312						
27	.401	1.293	96.605						
28	.301	.972	97.577						
29	.293	.945	98.522						
30	.263	.849	99.370						
31	.195	.630	100.000						

Table 2-18: Ecological interpretation of principal components for modelling wild dog occupancy

S.No	Principal Components	Ecological Interpretation
1	PC-1	Big prey species like chital & sambar within protected area
2	PC-2	Human Disturbance
3	PC-3	Small Prey dung
4	PC-4	Vegetation within protected area
5	PC-5	Presence of nilgai
6	PC-6	Small prey Encounter rate
7	PC-7	Terain
8	PC-8	Barking deer & langur
9	PC-9	Presence of chinkara
10	PC-10	Presence of Gaur

Table 2-19: Principal component loading after varimax rotation of covariates selected for modeling wild dog occupancy in Central Indian landscape. The cumulative percent variation explained by 10 components was 61%.

Variables	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6	PC-7	PC-8	PC-9	PC-10
Encounter Rate of Chital	0.8									
Pellet Count of Chital	0.76									
Pellet Count of Sambar	0.7									
Encounter Rate of Sambar	0.69									
Distance from Protected Areas	-0.47			-0.34						
People Seen		0.87								
Livestock Seen		0.83								
Human Tail		0.79								
Pellet Count of Wild Pig			0.74							
Pellet Count of Hare			0.68							
Pellet Count of Langur			0.66							
Area of Nightlight				-0.63						
Dry Tropical Deciduous forest				0.62						
Distance from Core Area				0.59						
Canopy Cover				0.5						
Moist Tropical Deciduous forest				0.43					-0.31	
Encounter Rate of Nilgai					0.86					
Pellet Count of Nilgai					0.81					
Encounter Rate of Hare						0.76				
Encounter Rate of Peafowl						0.64				
Encounter Rate of Wild Pig						0.46				
Pellet Count of Peafowl						0.4				
Elevation			0.39							0.92

Ruggedness	0.35	0.83	
Encounter Rate of Barking Deer		0.75	
Pellet Count of Barking Deer	0.47	0.56	
Encounter Rate of Langur		0.54	
Encounter Rate of Chinkara	0.26		0.84
Pellet Count of Chinkara			0.79
Encounter Rate of Gaur			0.74
Pellet Count of Gaur			0.72

The best model (based on the AIC value) included contributions from principal components 1, 2, 3, 4, and 6 explaining wild dog occupancy. The components described information on distribution relating to the quality of the forest cover, level of human disturbance and presence of prey (big and small sized both) (Table 2-18 and Table 2-19). The naïve estimate of the occupancy was improve from 14.0 % to 23% (SE=0.64) after correcting for detection bias in the occupancy framework. The best model differed from the null model by a value of 4534. The signs of the beta coefficients (Table 2-21) showed that the wild dogs prefer to good quality vegetation cover with sufficient prey base of chital and sambar as well as small sized prey such as hare, peafowl and wild pig etc. They avoid human presence.

Table 2-20: Various models to estimate the occupancy of wild dog using different environmental correlates in Central India and model selection based on AIC values.

Model	AIC	Δ AIC	$-2 \log(\text{likelihood})$	No. of Parameters
Ψ (PC1 + PC2 + PC3 + PC4 + PC6), p(Wild dog sign)	17546.7	0.0	8765.35	8
Ψ (PC1 + PC2 + PC3 + PC4 + PC6 + PC8), p(Wild dog sign)	17546.9	0.2	8764.45	9
Ψ (PC1 + PC2 + PC3 + PC4 + PC6 + PC7), p(Wild dog sign)	17548.66	2.0	8765.33	9
Ψ (PC1 + PC2 + PC3 + PC4 + PC6 + PC7 + PC8), p(Wild dog sign)	17548.88	2.2	8764.44	10
Ψ (PC1 + PC2 + PC3 + PC4 + PC5), p(Wild dog sign)	17620.76	74.1	8802.38	8
Ψ (PC1 + PC2 + PC3 + PC4), p(Wild dog sign)	17624.41	77.7	8805.20	7
Ψ (PC1), p(Wild dog sign)	17655.91	109.2	8823.96	4
Ψ (PC1 + PC2), p(Wild dog sign)	17656.11	109.4	8823.05	5
Ψ (PC1 + PC2 + PC3), p(Wild dog sign)	17657.51	110.8	8822.75	6
Ψ (.), p(Wild dog sign)	17846.59	299.9	8920.30	3
Ψ (.), p (.)	22080.45	4533.8	11038.22	2

Table 2-21: Coefficients of best models explaining wild dog occupancy in Central Indian Landscape.

	Variables	Estimate	Standard Error
A1	Ψ . Constant	0.59	0.14
A2	Ψ .PC1	1.95	0.21
A3	Ψ .PC2	-0.06	0.08
A4	Ψ .PC3	0.10	0.08
A5	Ψ .PC4	0.51	0.09
A6	Ψ .PC6	0.18	0.08
B1	p1	-3.24	0.04
B2	p1. Dhole Sign	0.94	0.02

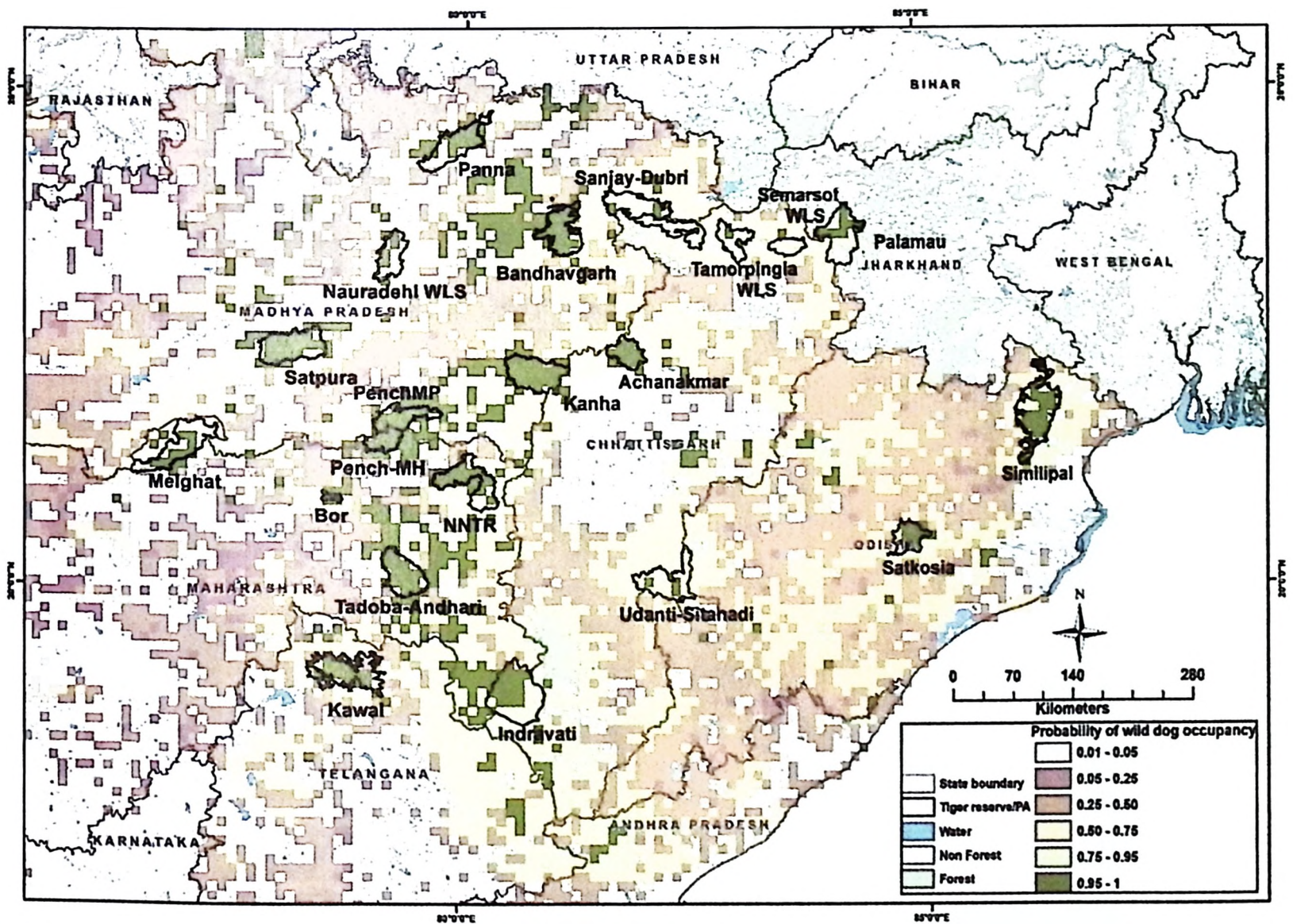


Figure 2-15: Occupancy map of wild dog modeled for 100 km² habitat patches using PRESENCE that account for detection bias and ecological covariates

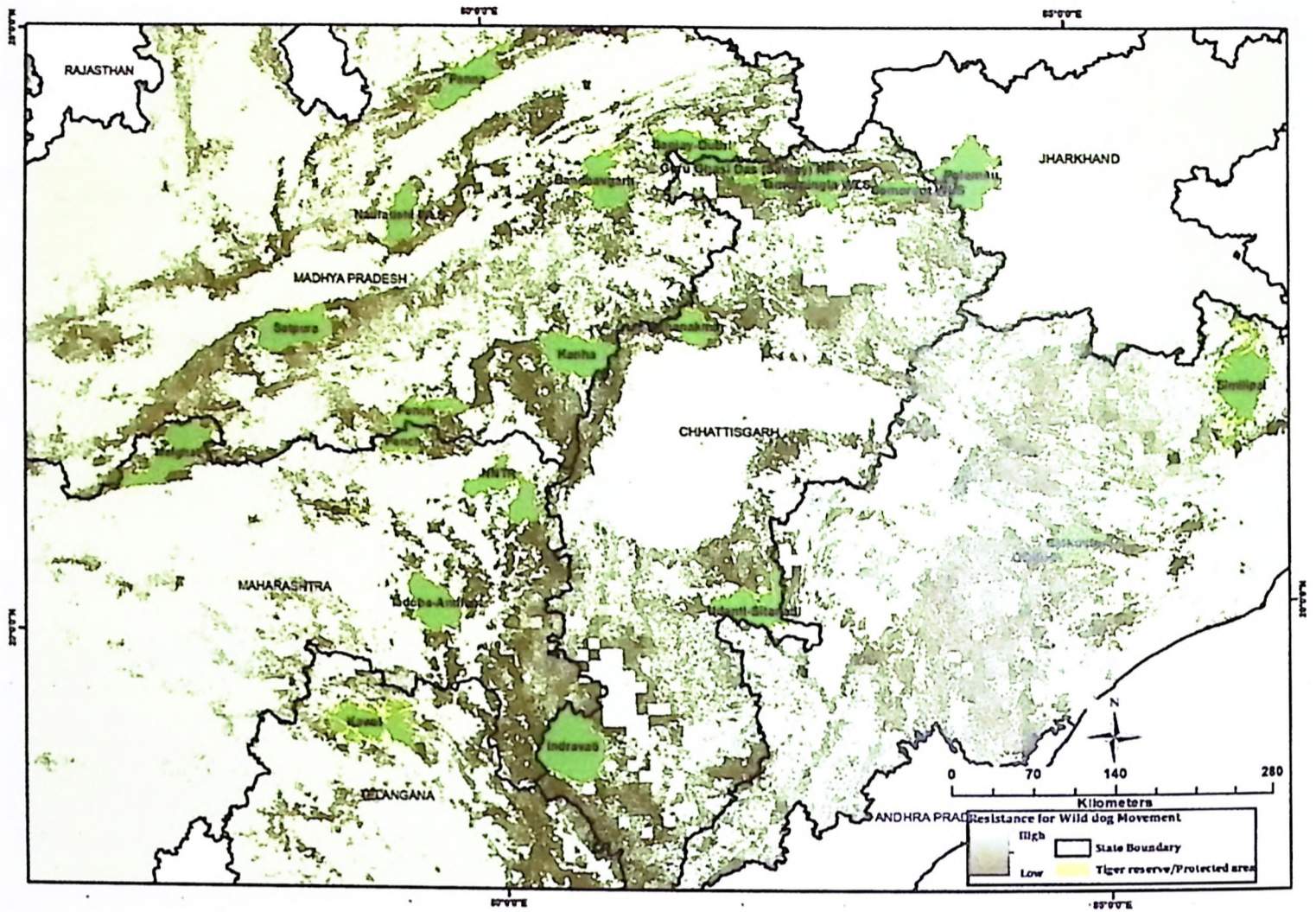


Figure 2-16 Resistance map for Wild dog movement in Central Indian Landscape derived by inverting the probability of Occupancy

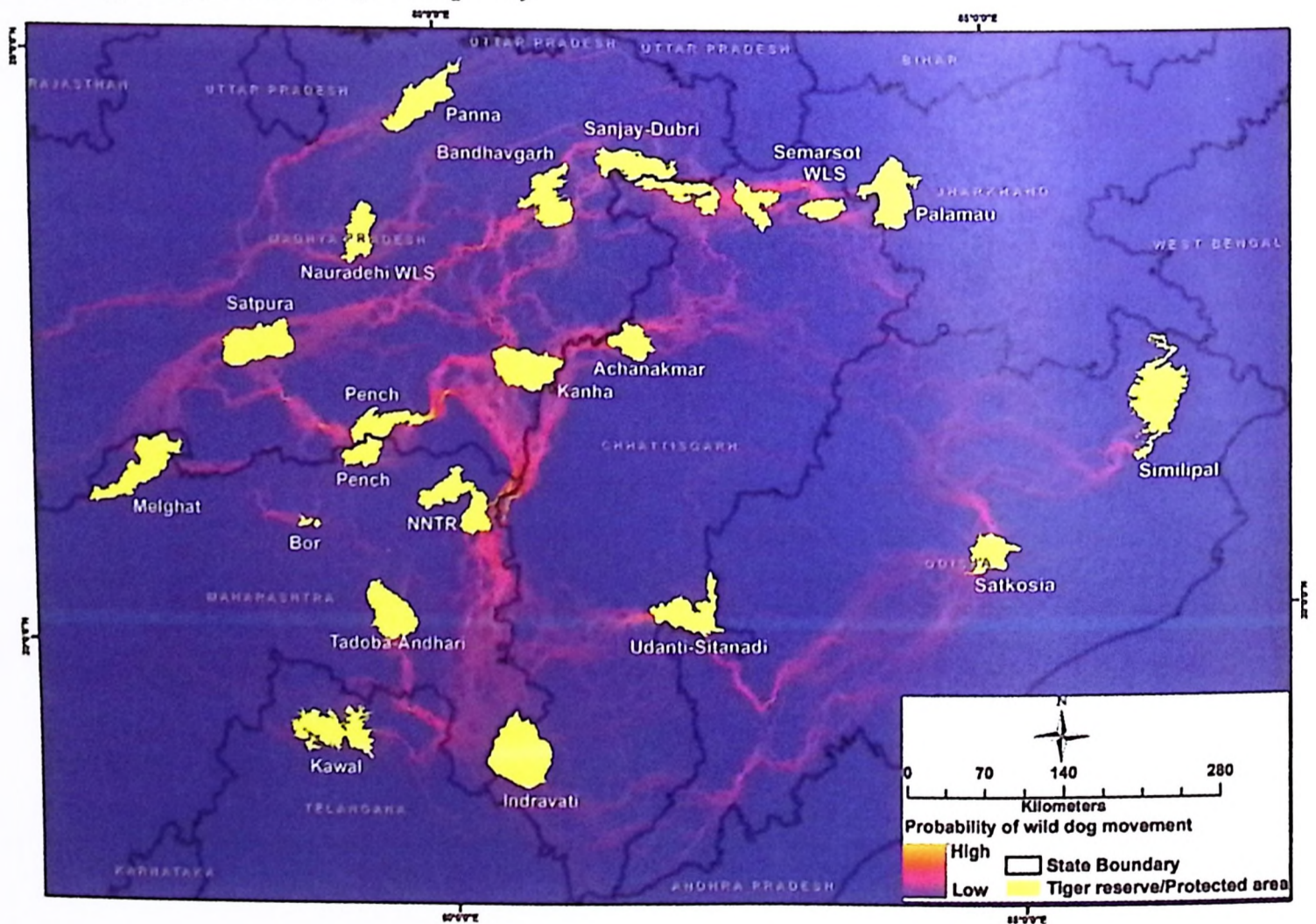


Figure 2-17 Potential habitat connectivity for wild dog movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.5. Gaur (*Bos gaurus*)

The gaur occupancy was modelled using 17 standardised covariates that describe the habitat quality and the human disturbance in the landscape (Table 2-22). The best model explaining the gaur occupancy in the landscape included five variables describing the forest quality, ruggedness of the terrain, human disturbance, protected forest and distance to water Table 2-23 and Table 2-24). The naïve occupancy estimate was improved by 1.4% (from 3.2% to 4.6%, SE=0.22) after correcting for detection bias in the model. The difference between the AIC value of the best model and that of the null model is 701.58. The sign of the beta coefficients (Table 2-24) showed that the animal prefers tropical forest, less human disturbance and complex terrain and prefers to live near water sources (Schaller 1967; Choudhury 2002).

Table 2-22: List of covariates selected for modelling occupancy for herbivores in Central Indian landscape

S. No	Covariates
1	Distance to protected area
2	Distance to water bodies
3	Aspect
4	Digital terrain model
5	Ruggedness
6	Forest cover
7	NDVI-post monsoon
8	NDVI-pre monsoon
9	Core area
10	Mean nightlight value
11	Distance to nightlights
12	Wood cutting
13	Looping
15	Grass cutting
16	People seen
17	Livestock seen

Table 2-23: Various models to estimate the occupancy of gaur using different environmental correlates in Central India and model selection based on AIC values.

Model	AIC	Delta AIC	No. of Parameter	2log(likelihood)
Ψ (Distance to pa* + Forest + Ruggedness+ People seen + Distance to water), p (.)	9453	0.00	7	4719.52
Ψ (Distance to pa* + NDVI + Ruggedness+ People seen + Distance to water), p (.)	9471	18.46	7	4728.75
Ψ (Distance to pa* + forest + Terrain + Human trail + Distance to water), p (.)	9478	24.51	7	4731.77
Ψ (Forest), p (.)	9892	439.34	3	4943.18
Ψ (People Seen), p (.)	10016	562.85	3	5004.94
Ψ (NDVI), p (.)	10032	578.75	3	5012.89
Ψ (Ruggedness), p (.)	10058	605.17	3	5026.10
Ψ (Human trail), p (.)	10063	610.06	3	5028.54
Ψ (Terrain), p (.)	10111	658.14	3	5052.59
Ψ (.), p (.)	10155	701.56	2	5075.30

*Protected Area

Table 2-24: Coefficients of best models explaining gaur occupancy in Central Indian Landscape.

Variables	Estimate	Standard Error
A1 Ψ . Constant	-4.19	0.11
A2 Ψ . Distance to protected area	-1.28	0.10
A3 Ψ . Forest cover	0.65	0.07
A4 Ψ . Ruggedness	0.29	0.05
A5 Ψ . People seen	-1.71	0.28
A6 Ψ . Distance to water bodies	-0.23	0.06
B1 p1	-1.55	0.04

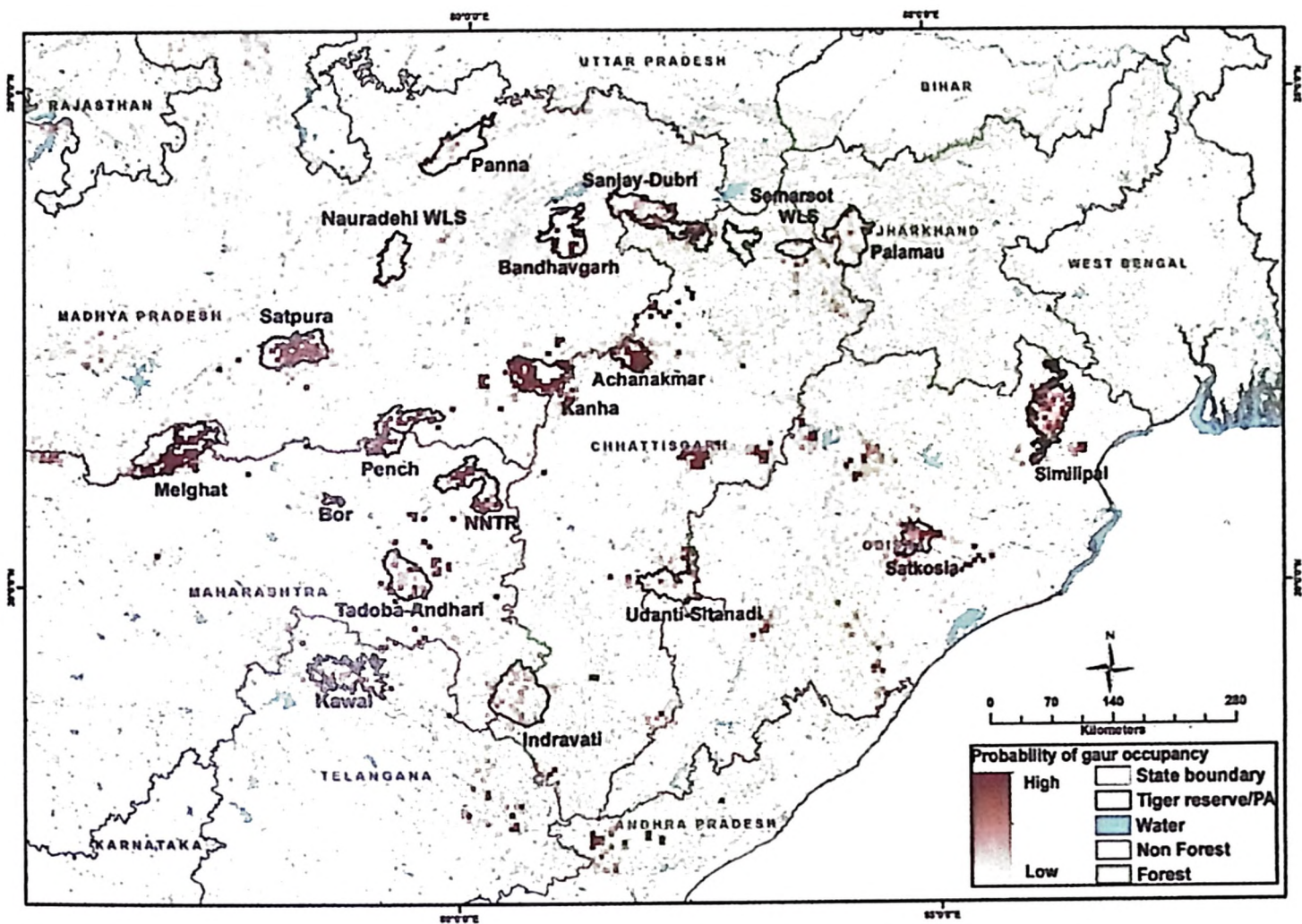


Figure 2-18 Occupancy map of gaur modeled for 25 km² habitat patches using PRESENCE that account for detection bias and ecological covariates

2.3.5.1. Connectivity map for Gaur

CIRCUITSCAPE results for gaur also showed that high resistance values in Simlipal, Satkosia and in Kawal , parks with low resistance values are Kanha, Achanakmar and Pench (MP & MH). This shows that reserve with low resistance value provide conducive matrix for gaur movement in the landscape while protected areas with high resistance value are provide less possibility of their movement.

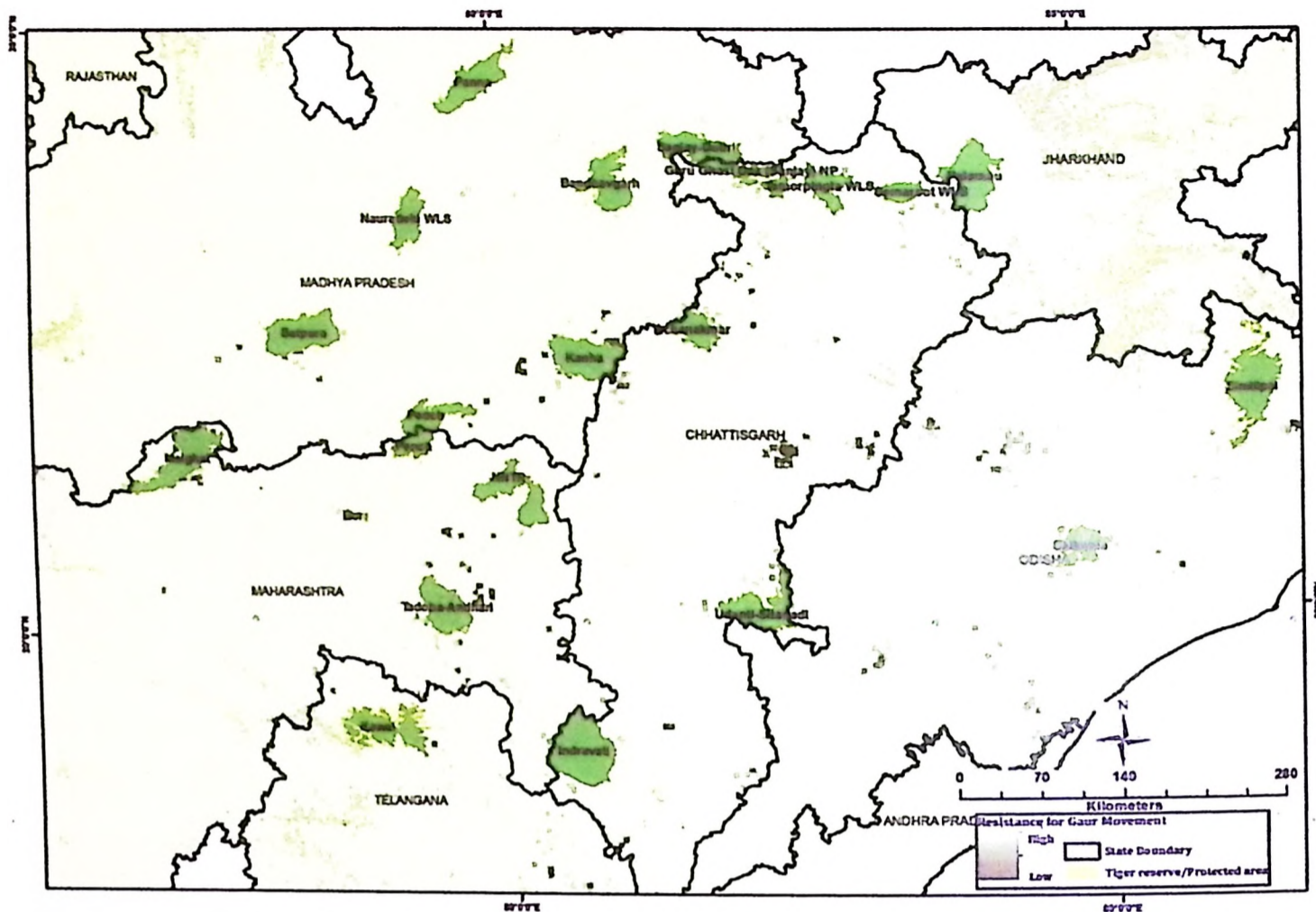


Figure 2-20 Resistance map for Gaur movement in Central India landscape derived by inverting the probability of Occupancy

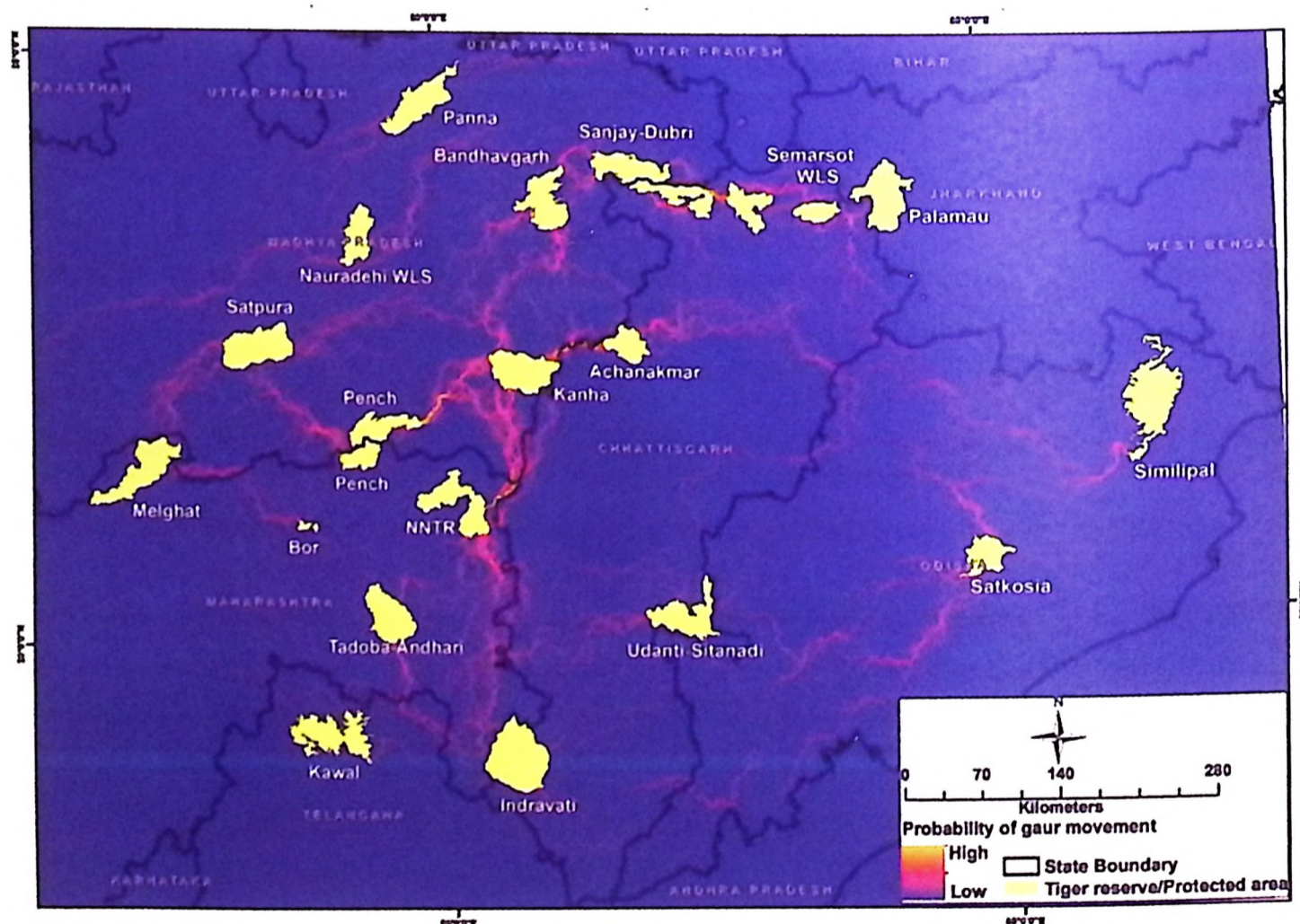


Figure 2-19 Potential habitat connectivity for gaur movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.6. Chital (Axis axis)

The chital occupancy was modelled using 17 standardized covariates describing the habitat quality and human disturbance in the landscape (Table 2-22). The best model that explained the occupancy of Chital in the landscape included five variables describing the forest quality, terrain ruggedness, human disturbance, protection status and distance to water (Table 2-25 and Table 2-26). The naïve occupancy estimate was improved by 4% (from 17.5% to 21.6%) after correcting for detection bias in the model.

Table 2-25: Various models to estimate the occupancy of chital using different environmental correlates in Central India and model selection based on AIC values.

Model	AIC	Delta AIC	No. of Parameter	2log(likelihood)
$\Psi(1+dwater+dpa+rug+ndvipost+pseen), p(.)$	42198	0	7	42184
$\Psi(1+dwater+dpa+rug+ndvipost+ht), p(.)$	42238	40	7	42224
$\Psi(1+dwater+dpa+rug+ndvipost), p(.)$	42240	42	6	42228
$\Psi(1+dwater+dpa+rug+for), p(.)$	42252	54	6	42240
$\Psi(1+dwater+dpa+rug+for+dnite), p(.)$	42253	55	7	42239
$\Psi(1+dwater+dpa+rug+moist), p(.)$	42557	359	6	42545
$\Psi(1+for), p(.)$	42692	493	3	42686
$\Psi(1+dwater+dpa+rug+rd+drytrop), p(.)$	42763	565	7	42749
$\Psi(1+dpa), p(.)$	42766	568	3	42760
$\Psi(1+moist), p(.)$	43040	842	3	43034
$\Psi(1+dnite), p(.)$	43244	1046	3	43238
$\Psi(1+rd), p(.)$	43256	1058	3	43250
$\Psi(1+ht), p(.)$	43256	1058	3	43250
$\Psi(1+rug), p(.)$	43265	1067	3	43259
$\Psi(.), p(.)$	43266	1068	2	43262

Table 2-26: Coefficients of best models explaining chital occupancy in Central Indian Landscape.

	Variables	Estimate	Standard Error
A1	Ψ . Constant	-0.11	0.03
A2	Ψ . Distance to water bodies	-0.41	0.04

A3	Ψ . Ruggedness	-0.70	0.03
A4	Ψ . Distance to protected area	0.86	0.04
A5	Ψ . NDVI	-0.36	0.06
A6	Ψ . People seen	-1.05	0.01
B1	p1		

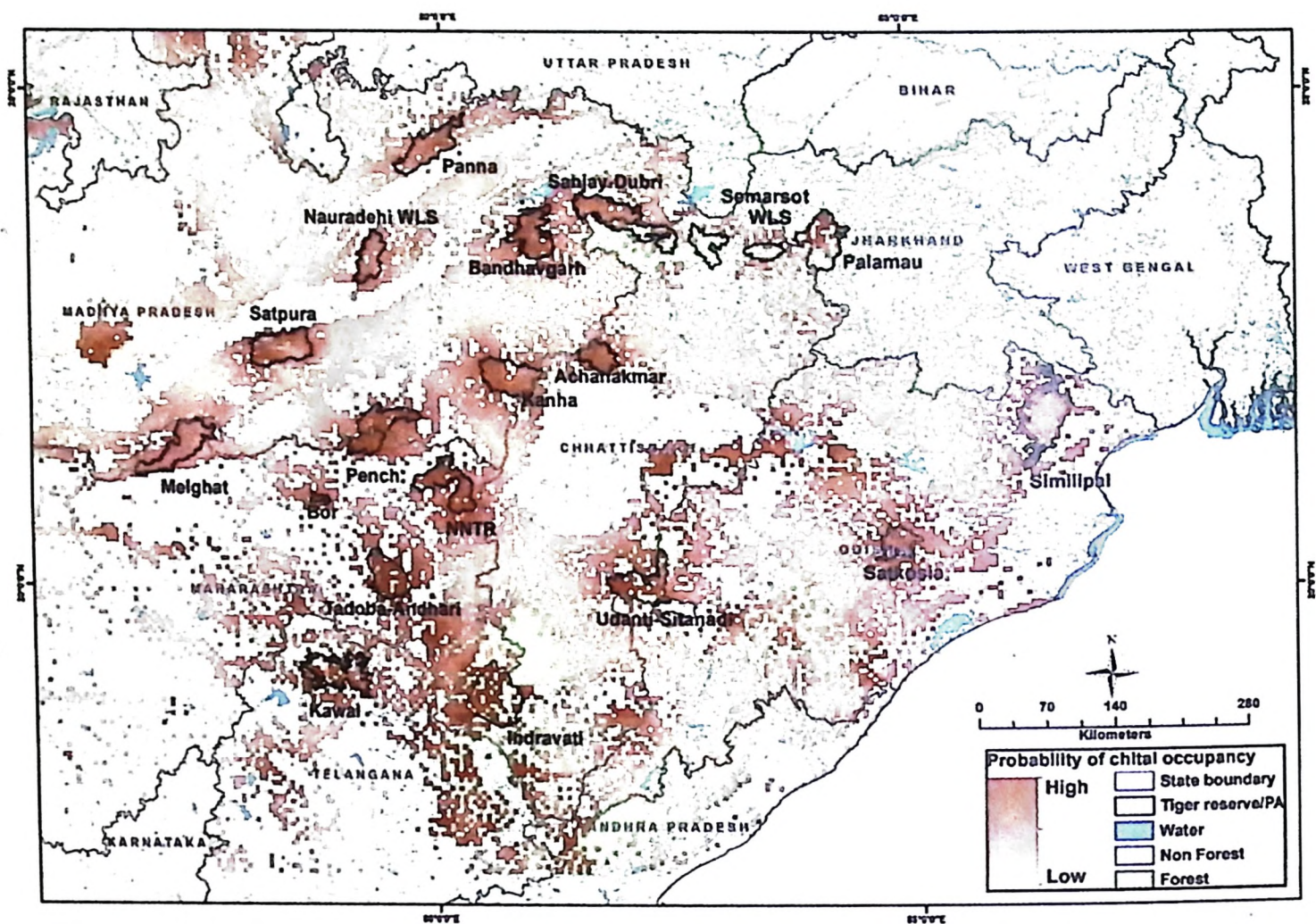


Figure 2-21 Occupancy map of chital modelled for 25km² habitat patches using PRESENCE that account for detection bias and ecological covariates

2.3.6.1. Connectivity map for Chital

The circuit theory results showed that connectivity from Kanha, Pench and Achanakmar have low resistance values providing favourable habitat for chital movement through multiple dispersal pathways in the landscape. High resistance values of Simlipal, Bor and Panna shows destructed connectivity of these protected areas from other habitat patches, thus not encouraging for chital movement.

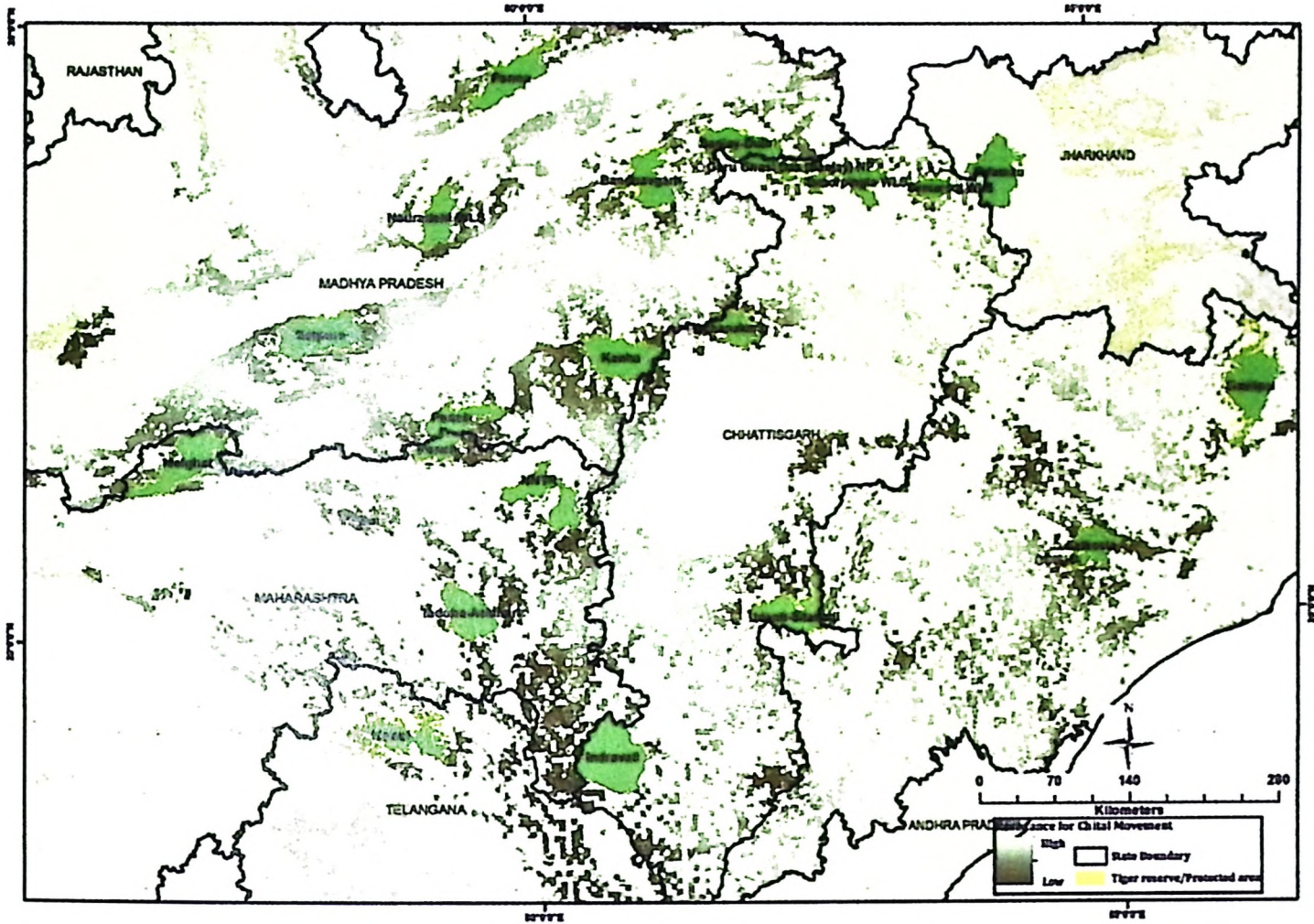


Figure 2-22 Resistance map for chital in Central Indian Landscape Landscape derived by inverting the probability of Occupancy

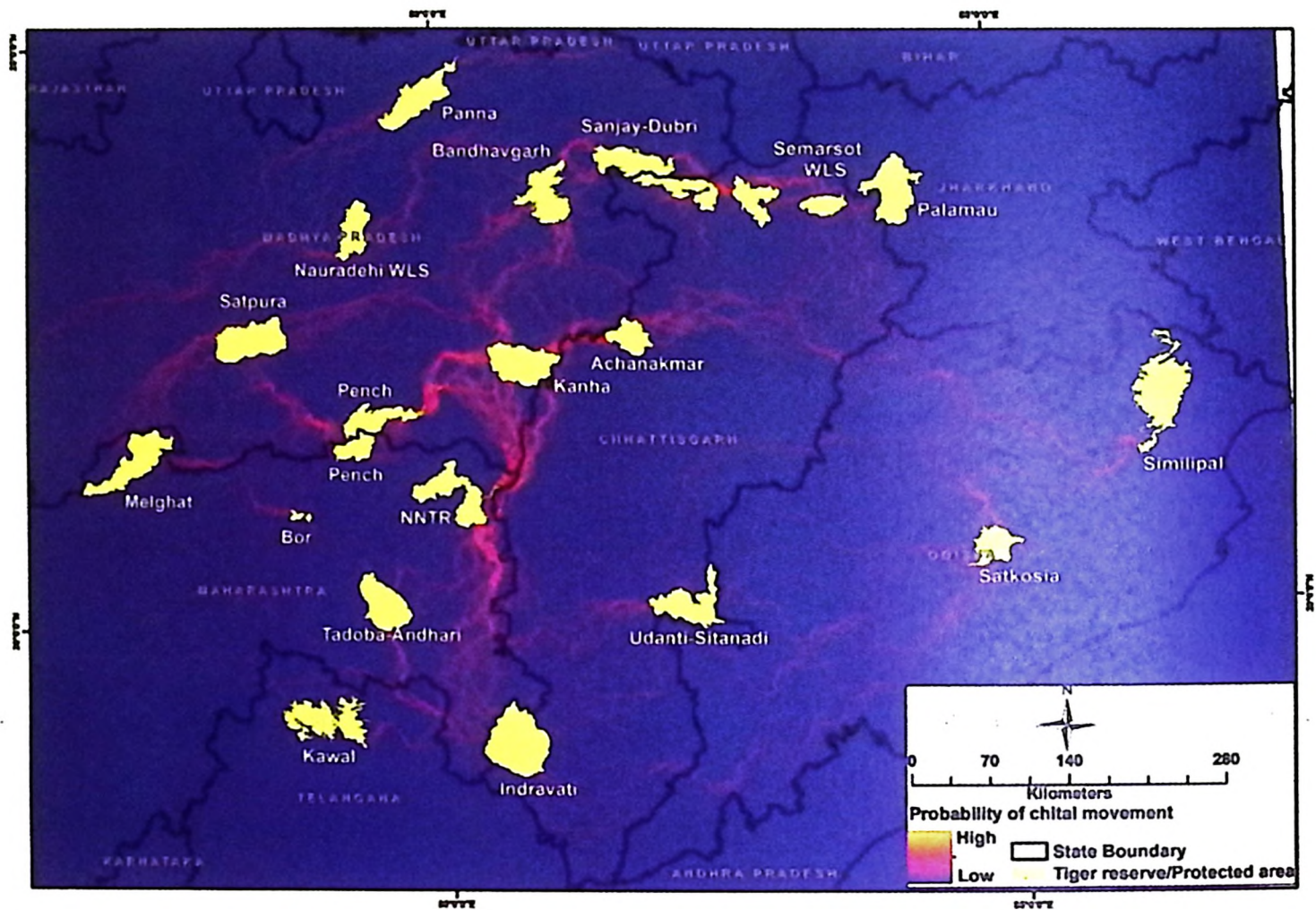


Figure 2-23: Potential habitat connectivity for chital movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.7. Sambar (*Rusa unicolor*)

The sambar occupancy models included 17 standardised covariates providing information about the habitat, presence of human disturbance and protection status in the study area (Table 2-22). The top model explaining the sambar occupancy in the landscape included information on distance from water bodies, distance from protected area, ruggedness, presence of human disturbance and forest cover in the landscape. The naïve occupancy estimate was improved by 3.7% (from 14.1 % to 17.8%) after correcting for detection bias in the model

Table 2-27: Various models to estimate the occupancy of sambar using different environmental correlates in Central India and model selection based on AIC values.

Model	AIC	Delta AIC	No. of Parameter	2log(likelihood)
Ψ (1+dpa+for+pseen+eucwater+moistt+rug), p (.)	35572	0	8	35556
Ψ (1+dpa+for+pseen+eucwater+moistt), p (.)	35580	8	7	35566
Ψ (1+dpa+for+dnite+eucwater+moistt), p (.)	35636	64	7	35622
Ψ (1+dpa+ndvip+dnite+eucwater+moistt), p (.)	35676	104	7	35662
Ψ (1+dpa+for+dnite+eucwater), p (.)	35730	159	6	35718
Ψ (1+dpa+for+dnite+eucwater+dryt), p (.)	35732	160	7	35718
Ψ (1+dpa+ndvip+dnite+eucwater), p (.)	35944	372	6	35932
Ψ (.), p (.)	36762	1190	2	36758

Table 2-28: Coefficients of best models explaining sambar occupancy in Central Indian Landscape.

	Variables	Estimate	Standard Error
A1	Ψ . Constant	-1.92	0.04
A2	Ψ . Distance to protected area	-0.51	0.03
A3	Ψ . Distance to water bodies	-0.17	0.03
A4	Ψ . Moist tropical forest	0.32	0.03
A5	Ψ . Forest cover	0.50	0.04
A6	Ψ . People seen	-0.61	0.09
A7	Ψ . Ruggedness	0.10	0.03
B1	p1	-1.08	0.02

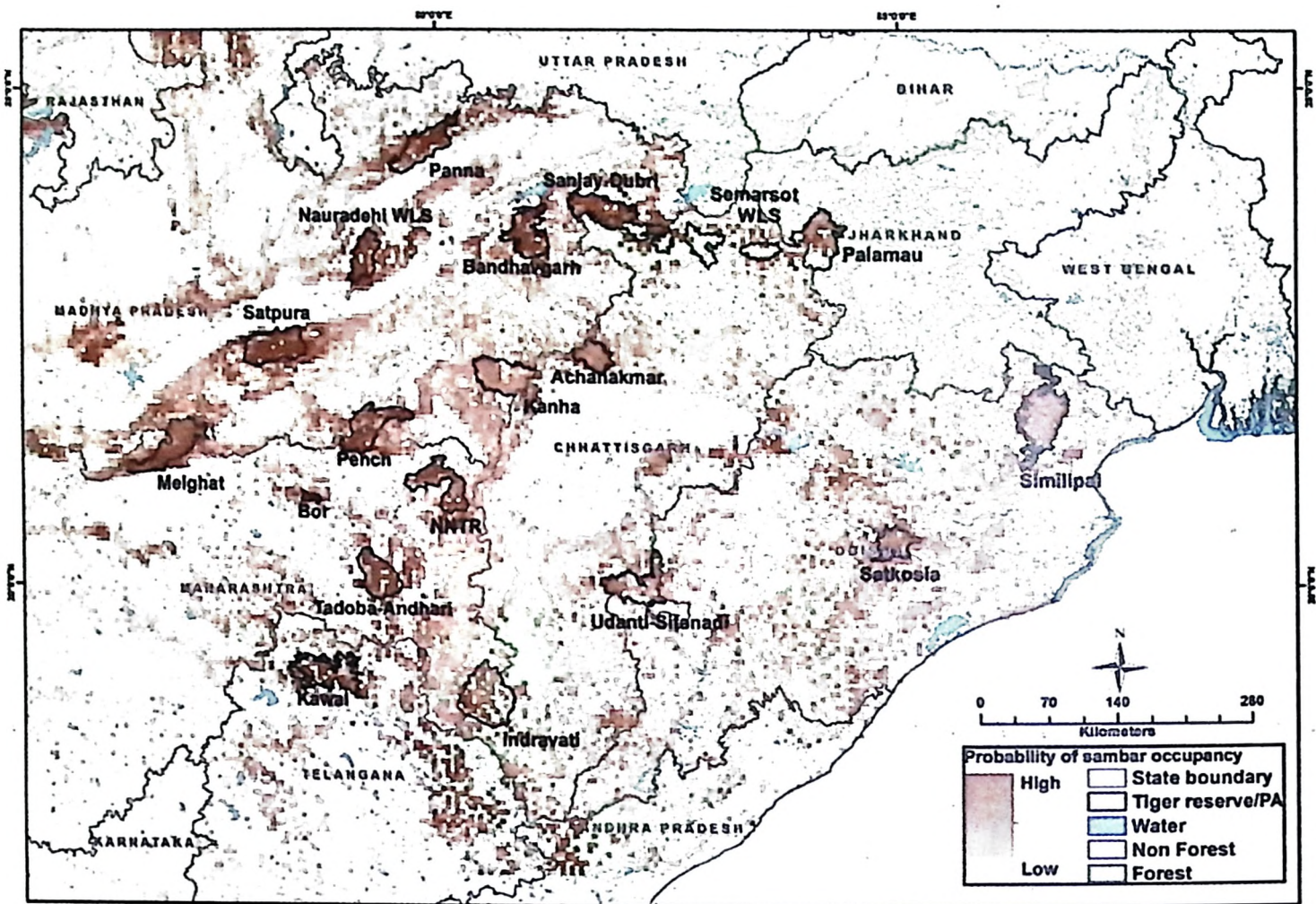


Figure 2-24: Occupancy map of sambar modeled for 25km² habitat patches using PRESENCE that account for detection bias and ecological covariates

2.3.7.1. Connectivity map for Sambar

Matrix connectivity modelled through circuit theory showed that most difficult connection for Sambar is from Simlipal, Bor and Panna having high resistance. Low resistance values of Kanha, Pech and NNTR shows less disturbance in the corridor region suitable for Sambar movement. Sambar being a shy specie is highly affected the presence of humans and usually avoid those habitats.

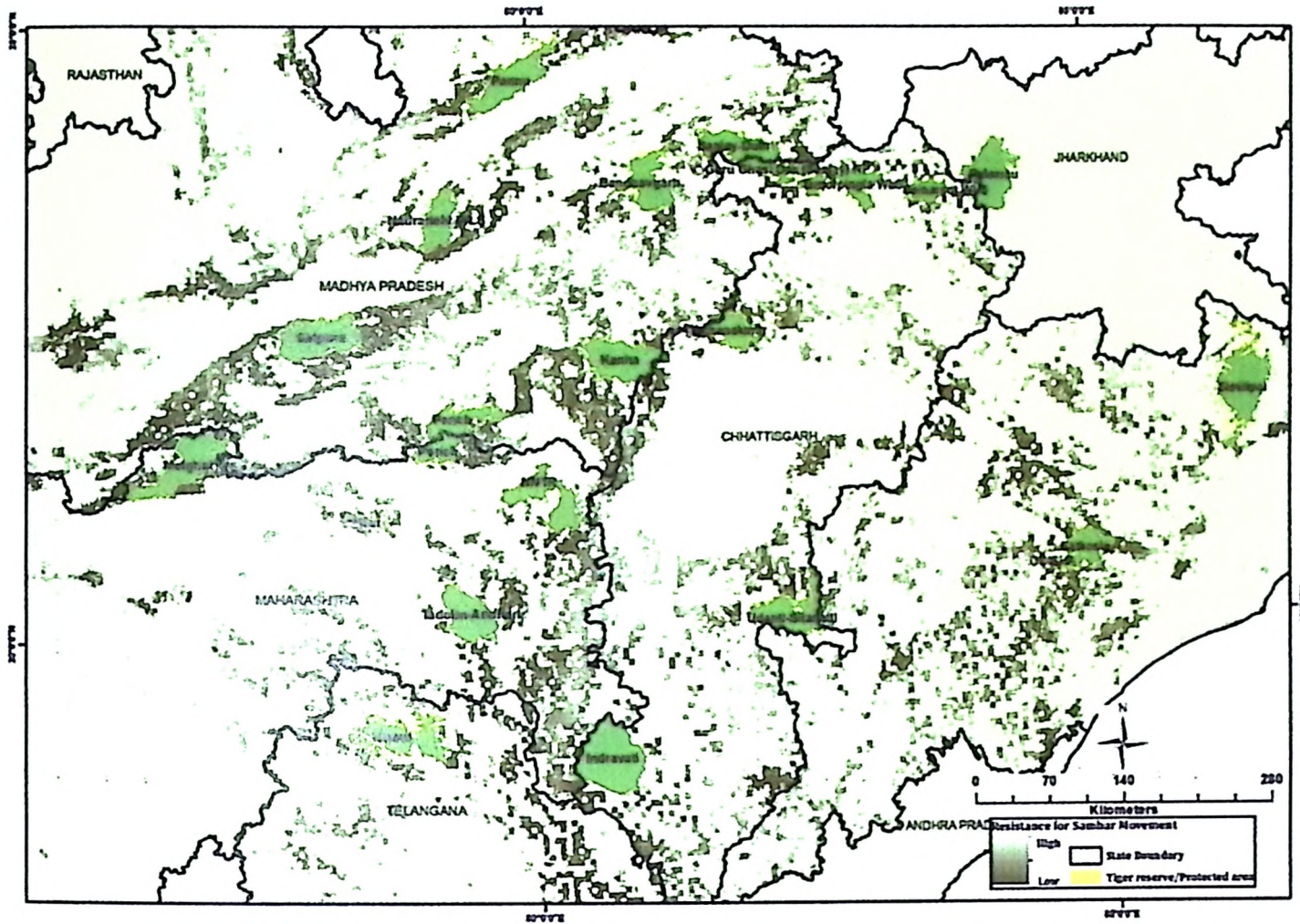


Figure 2-25 Resistance map for sambar movement in Central Indian Landscape derived by inverting the Occupancy probability

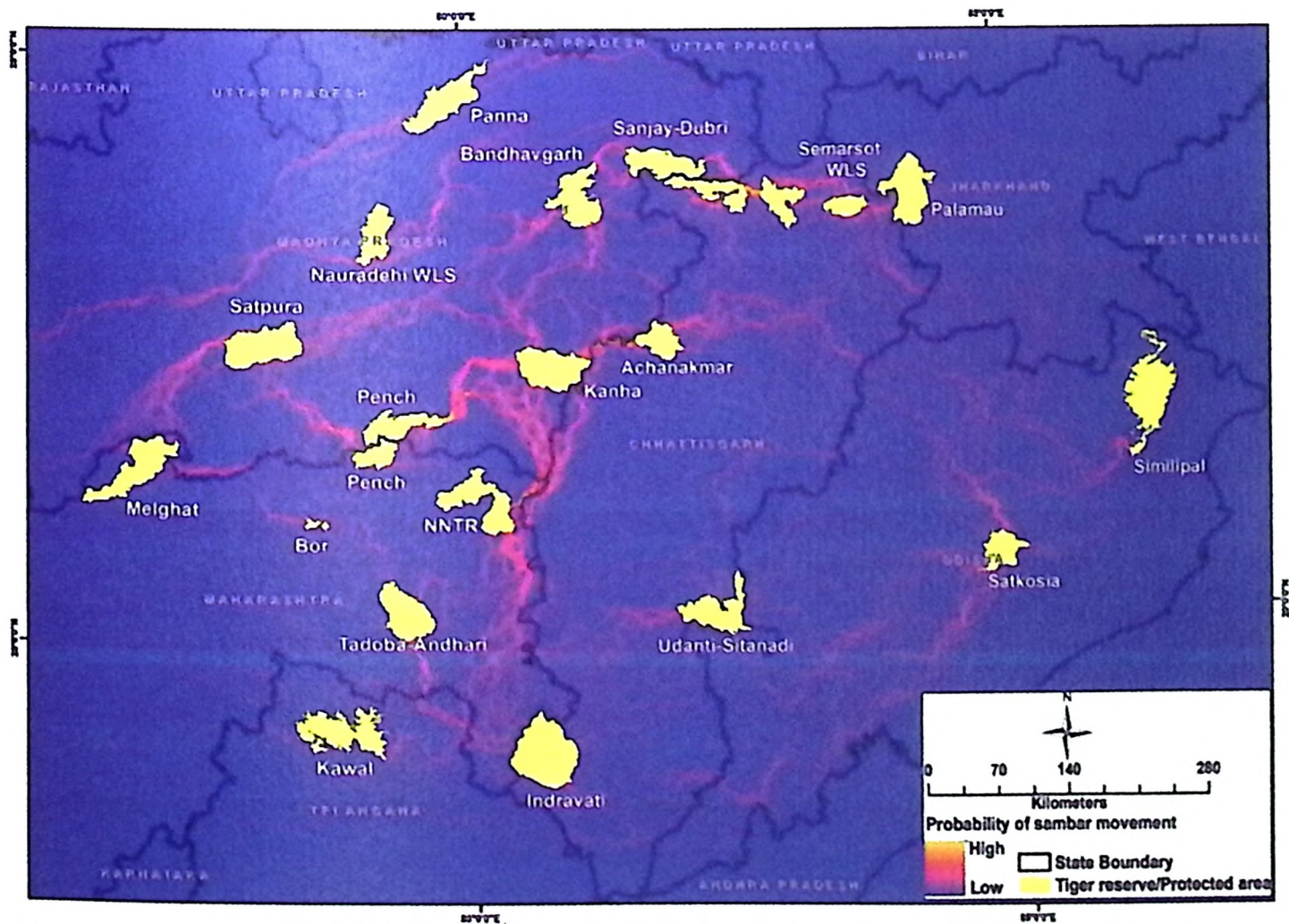


Figure 2-26 Potential habitat connectivity for sambar movement in Central Indian landscape modelled through CIRCUITSCAPE

2.3.8. Summary of modelling results

2.3.8.1. Carnivore models

The carnivore occupancy models indicated that all the three carnivores (the tiger, leopard and dhole) have similar habitat and prey base preferences, with some minor differences (Sharma et al. 2013b). The beta co-efficient values showed that dense forest, prey abundance and distance from human disturbance are the factors influencing the occupancies of tigers, leopards and dholes in the landscape (Figure 2-27). As expected, the tiger and leopard occupancies were high in areas having dense forest abundant with large and medium-sized ungulates such as sambar and chital. This kind of good habitat is available in reserves with high protection levels and low levels of human presence. Grids where the human disturbance was high were observed to have low occupancy values for tigers and leopards. Leopards exhibit greater flexibility towards terrain complexity and choice of prey. Therefore, the leopard is more adaptable towards a changing landscape. There is a significant overlap in the occupancies of the three carnivores in the area, and high correlation in their prey preferences, because of the combination of spatial and temporal partitioning. However, to ensure the long-term survival of these carnivores and their co-existence, it is essential to conserve their habitat, manage ungulate populations and maintain low levels of human disturbance as well as suitable dispersal pathways for the carnivores to move in and reproduce, thereby overcoming carrying-capacity issues (Wang 2009)

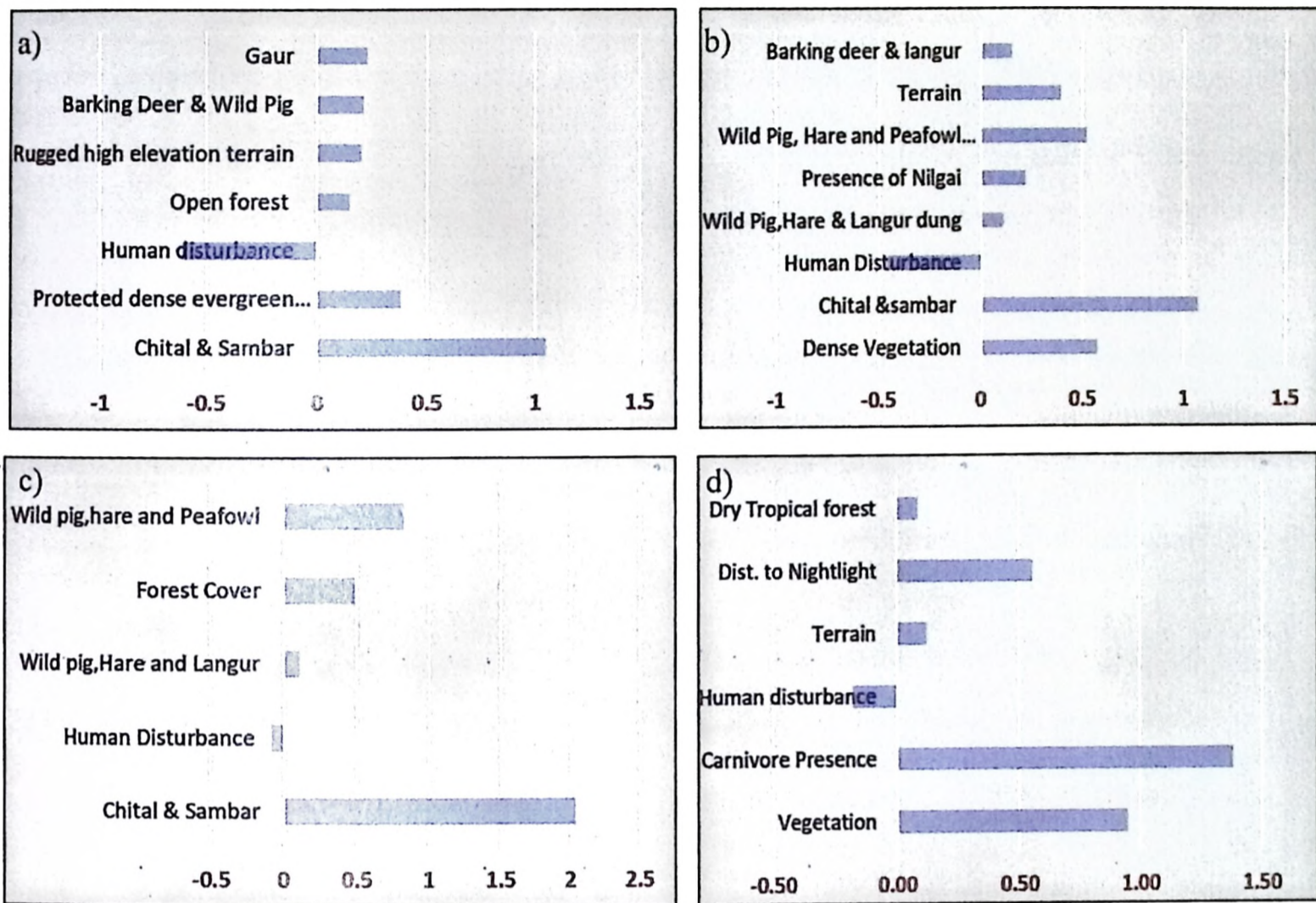


Figure 2-27 Factors and their relative importance in influencing Occupancy for a) Tiger b) Leopard c) wild dog d) Sloth bear

There was an overlap of sloth bear presence and the presence of other carnivores, indicating a preference for similar kinds of habitat and resources. However, the models have limitations in detecting sloth bear occupancy due to a lack of information about food resources. Nevertheless, the predicted bear occupancy showed that potential habitat for bears all over the landscape, showing their adaptability, opportunistic nature of feeding on available resources and living in and outside forest areas of the sloth bear.

2.3.8.2. Herbivore models

For both the chital and sambar, occupancy models showed that high NDVI values and water resources are the basic requirement for herbivores occupancy. Sambar and chital have greater extent of overlap in their habitat selection except for terrain complexity where sambar can thrive well. In contrast, the gaur showed a narrow range of preferred habitat.

High occupancy of chital and sambar in corridor areas is an encouraging sign, can make them more usable by carnivore for their migration and dispersal. In case of gaurs, occupancy was high in protected areas only and low values were observed outside protected areas. The specie is affected by the habitat disturbances in spite of their large body size. Therefore, future of these populations highly depend that forest patches of these protected areas remain connected, providing opportunity of these animals to exchange genes and for alternate resource patches. Therefore, management and monitoring of ungulates is vital in structuring and maintaining of large carnivore populations in the landscape.

2.3.8.3. Connectivity models

There was considerable overlap in the linkages of carnivores and herbivores modelled using CIRCUITSCAPE (Figure 2-28 and Figure 2-29). This may be due to the available forest structural connectivity through forest fragments. Therefore, these identified routes provide an opportunity to connect the protected area network in the landscape for a wide range of species. The chital, sambar and gaur form an important prey base for carnivores, and therefore their abundance highly influences the occurrence of carnivores. The existence of forests outside protected areas with sufficient prey availability is an encouraging factor for carnivores to disperse in the landscape. A good quality corridor with a prey base would progressively enhance the movements of carnivores and can thus help regulate the forest ecosystem outside protected areas. Therefore, passages suitable for carnivores can serve as equally suitable routes for herbivores to disperse in the landscape.

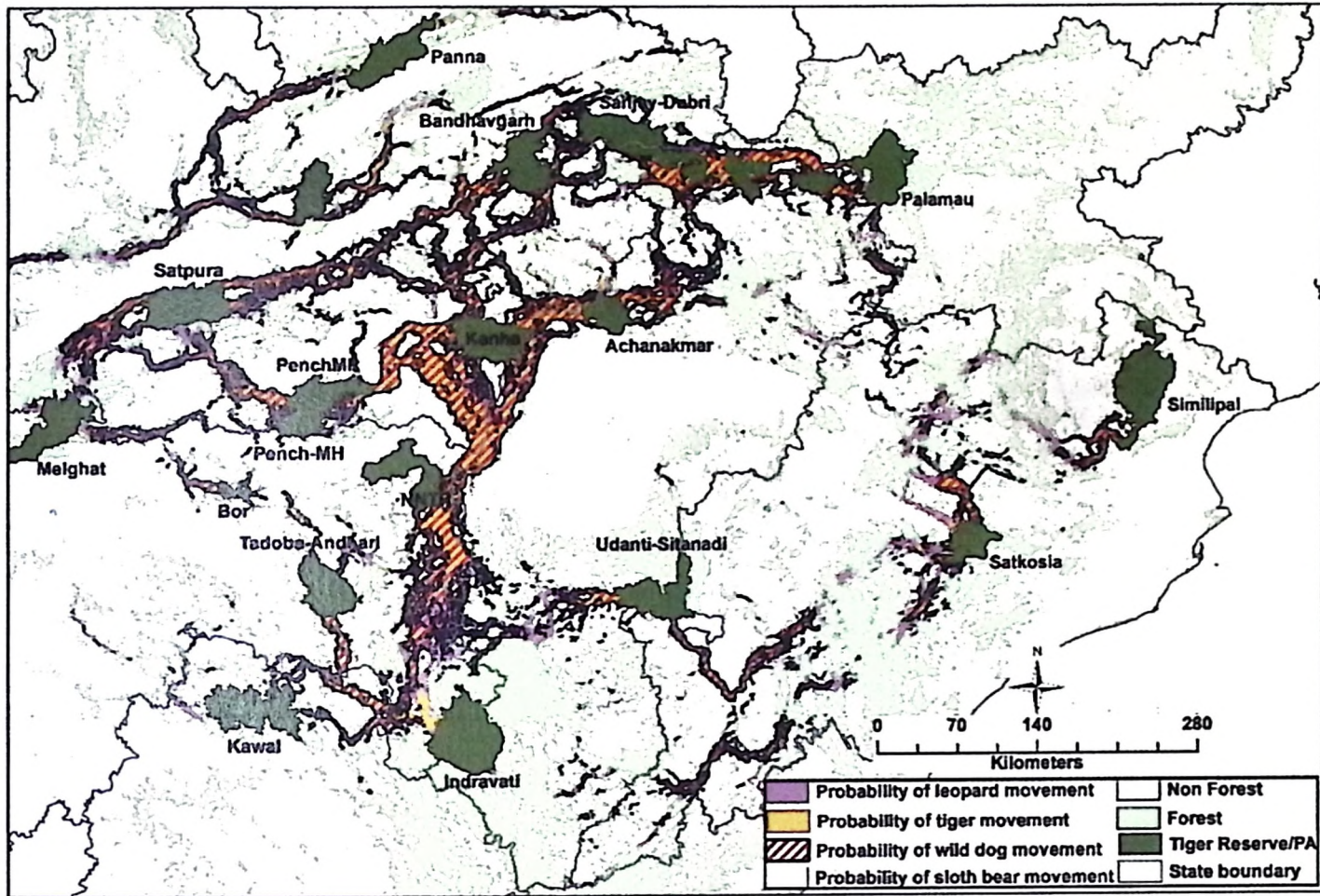


Figure 2-28 Comparison of habitat connectivity for tiger, leopard, wild dog and sloth bear in the landscape

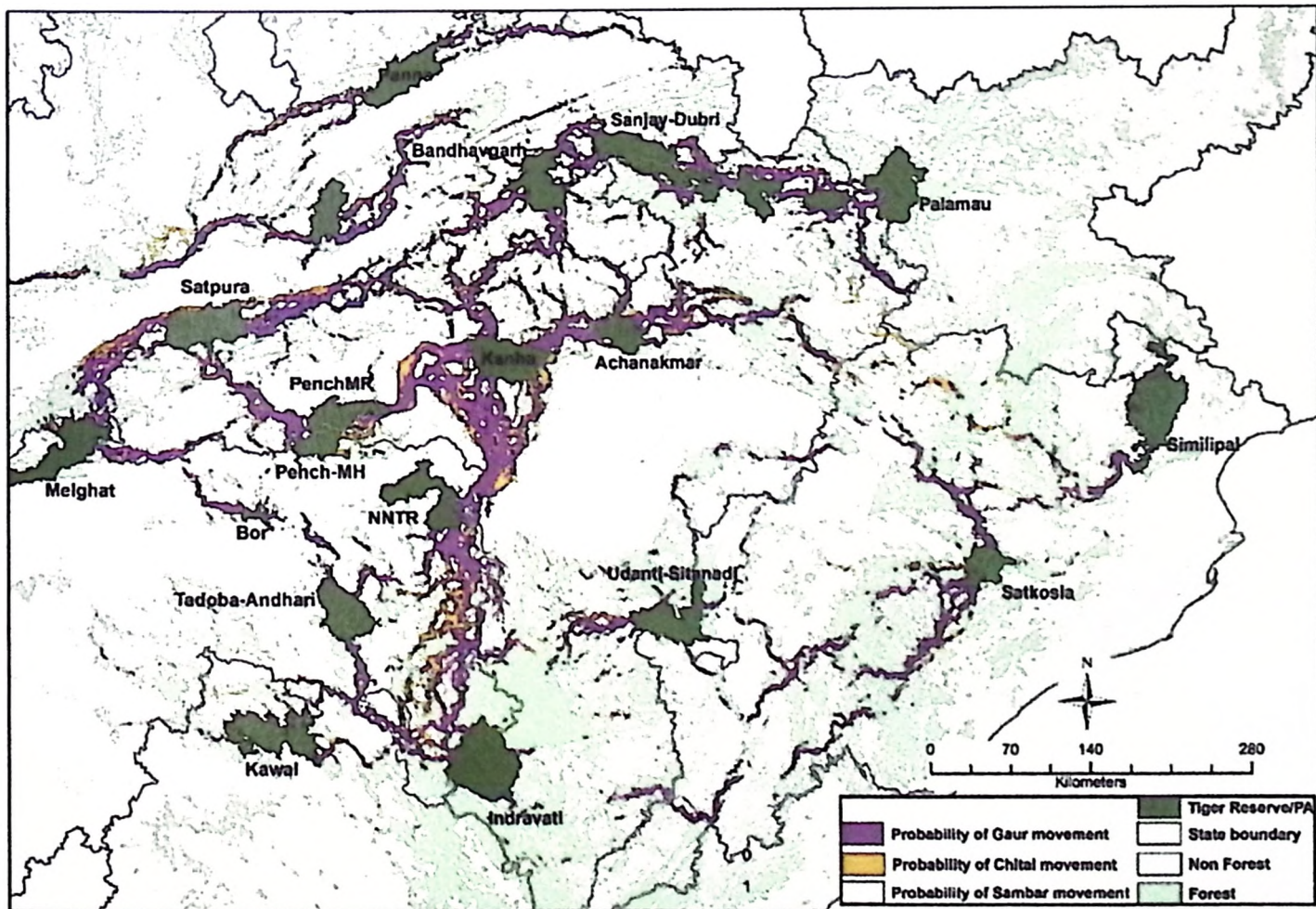


Figure 2-29 Comparison of habitat connectivity for gaur, chital and sambar in the landscape

Connectivity models also reveal that Kanha, Pench, Achanakmar, NNTR, Tadoba protected areas are well-connected parks with multiple dispersal pathways, followed by Tadoba, Melghat, Sanjay-Dubri and Bhandhavgarh. However, Simlipal, Satkosia, Kawal, Panna have disjunction connectivity due to hostile matrix and are on the verge of getting isolation.

3. Time Series Analysis and Drivers of Change

3.1. Introduction

Corridors play a critical role in the long-term persistence of wildlife populations as they facilitate the maintenance of meta-populations. Corridors passing through human-dominated landscapes help connect habitat patches that are suitable for wildlife (Gilpin & Hanski 1991; Hanski & Simberloff 1997; Hanski 1994, 1998; Cushman et al. 2013). Populations of small patches that are isolated from other source populations are at risk of becoming locally extinct due to inbreeding depression or stochastic events (Dunning et al. 1992; Lacy 2000). As a result of the connectivity provided by corridors, populations may be saved from genetic problems and stochastic events (Merriam 1991; Wilson & Lindenmayer 1996a; Brown & Kodric-Brown 1977; Gilbert et al. 1998; Gonzalez et al. 1998; Reed 2004). Connections between habitat patches provide a route for species' movements and help the recolonisation of the remnant patches, thereby improving the viability of a population (Noss 1987; Fahrig & Merriam 1985; Forman 1983; Opdam 1990).

Corridors are under anthropogenic pressures and are threatened due to an escalation of developmental activities and an increasing demand for forest resources and land (Reddy et al. 2003). Changes in the physical structure of a habitat, due to natural calamities or steady modifications resulting from human activities, have been the primary cause behind the extinction of many species in the past (Houghton 1994). Land use–land cover changes (LULC) always have an enduring impact on natural areas, and a rapid decline in the extent of these areas is a continuous process caused due by different natural and anthropogenic actions (Brown 1981; Myers 1986; Lunney 1991; Houghton 1994). Millennium Ecosystem Assessment 2003 (Turner et al. 2001; Bennett 2003) discusses how modifications in land

cover due to natural processes, stochastic events or increasing anthropogenic activities continuously alter the structure of a landscape. Anthropogenic pressures such as expansion of agricultural areas (Tigas et al. 2002), widening of linear infrastructure (Mader 1984), construction of dams, mining and urban sprawl are currently the major drivers of landscape change (McNeelay 1987; Swanson et al. 1988; Hilty et al. 2006), posing threats to the landscape connectivity that is essential for wildlife. Therefore, monitoring the dynamics of LULC patterns in these linkages and the surrounding areas and subsequently identifying the ideal connectivity and the threats to them is crucial to ensure that habitat patches in a landscape remain connected for wildlife populations to survive in the long term.

The structure of a landscape results from a broad range of drivers that directly and indirectly affect its composition and the arrangement of different features in the landscape. The present-day landscape pattern is an outcome of long-term driving factors. Sometimes it gets shaped by stochastic events. A driver is a natural or human-driven factor affecting the spatial structure of a land. Drivers of LULC change are categorised on the basis of their nature and effects as (1) natural and (2) human-induced (the latter influence the dynamics of landscape change either directly or indirectly). Natural processes such as climatic variations and topographical changes affect the development of landscape patterning, while stochastic events such as volcanic eruptions, seismic activity, floods and forest fires influence LULC changes directly. Lambin and Geist (2002), in their detailed assessment of the dynamics of LULC changes in tropical regions, have classified drivers as proximate drivers and underlying drivers. They emphasise the fact that a single variable cannot be responsible for altering the landscape; it is the combined effect of several factors that drives land cover changes. Therefore, information about both, proximate and underlying driving forces, should be analysed collectively to understand the transformation of a landscape best.

3.1.1. Landscape structure and pattern

The terms 'land use' and 'land cover' are used interchangeably in pattern studies, but their meanings are different. 'Land cover' refers to the cover on the ground, like vegetation, urban areas, bare land and water bodies, while 'land use' refers to the use of land cover, for example as wildlife habitats, agricultural areas and recreational areas. Both the terms are generally used together, referring to the combined categorisation and classification of the natural elements and usage of a landscape by humans. The forest cover, along with its extent, is the most important variable, meeting the fundamental requirement of wildlife species—a habitat (Bennett 1988, 1990a, 1990b). Thus, conservation of forest cover and monitoring changes in its extent and quality are crucial for the persistence of wildlife populations. Quantification of the landscape structure in the context of forests and observing its dynamics over time and space help identify the alterations occurring in a given area (Forman & Godron 1981, 1986; Merriam 1988; Turner 1989; Forman 1995; Hansson et al. 1995). This quantification can further aid the deciphering of the underlying causes behind any change, such as a series of disturbances and succession (Romme & Knight 1982; Risser et al. 1987; Turner 1987b, 1989), and thereby provide the baseline information needed to develop mitigation measures. Knowledge of (LULC) changes provides a basis for future projections (Baker 1989b) and can help explore the fate of landscape structure and connectivity, as well as help prioritise conservation investments on a spatial scale (Xiao et al. 2004).

3.1.2. Drivers of forest cover change

One of the prime objectives of land use research is to identify the factors and variables that affect the structure of the landscape and pattern of land use change (Lambin et al. 2003; Rindfuss et al. 2004, 2008; Lambin and Geist 2006). Extensive research indicates that humans are primarily responsible for altering the structure of natural landscapes, especially forest land cover, over space and in the known historical timeframe (Hofgaard 1999). Many

investigators argue that increasing human demands leading to conversion of forest land to croplands and dwelling areas and construction of new infrastructure (dams, roads, railway tracks, etc.) are the major and direct causes of forest cover loss (Mader 1984; Lambin et al. 2001; Lambin and Geist 2002; Long et al. 2007; Kissinger et al. 2011; Hosonuma et al. 2012; Alexander et al. 2015). Demographic changes, energy demands, policy changes, market trends and socio-political, cultural and religious demands are a few of the indirect or underlying factors causing adverse forest cover changes (Meyer & Turner 1992; Kalaba 2014 from MEA). According to some studies, demographic and economic factors are the major drivers of deforestation and must be accounted for when analysing the underlying forces of forest land cover change (Aguiar et al. 2007; Geist & Lambin 2002; DeFries et al. 2010). An increasing population in an area not only results in increasing food and energy demands but also exerts pressure on rural areas for commercial agriculture and dwelling spaces, thereby leading to the emergence of suburban areas.

3.1.3. Time series analysis and forest cover change detection analysis

Time series analysis (henceforth TSA) carried out with an array of available algorithms can be used to analyse a sequence of observations about an area and to detect patterns and trends in the data (Chandler & Scott 2011). TSA is one of the many effective methods used in differentiating patterns from random noise (if any) in data and subsequently in explaining the past and forecasting future events.

Martinez & Gilabert (2009), and others (De Jong et al. 2011; Maus et al. 2015; Julian et al. 2017), have effectively demonstrated the use of TSA in finding the changes and disturbances occurring in forest areas. Most TSA findings are represented using two components: trend and seasonality (Chandler & Scott 2011). Trend is defined as a non-repetitive linear or non-linear change, occurring gradually. Trends can be classified as monotonic or non-monotonic. A monotonic trend represents an increasing or decreasing change over time and space,

whereas a non-monotonic trend can have both increasing and decreasing patterns within a timeframe. A monotonic trend can have linear or non-linear patterns.

Seasonality in TSA represents a periodic process that repeats at regular intervals of time (Hill & Lewicki 2006). Seasonality accounts for changes in vegetation phenology due to climatic variations and is useful for forest quality studies and for agriculture studies. TSA produces a trend map, representing the positive ('greening') and negative ('browning') trends of the landscape. Positive or greening trends (Figure 3-1) represent increases in vegetation or forest cover, while negative or browning trends (Figure 3-2) indicate losses in green cover in the area.

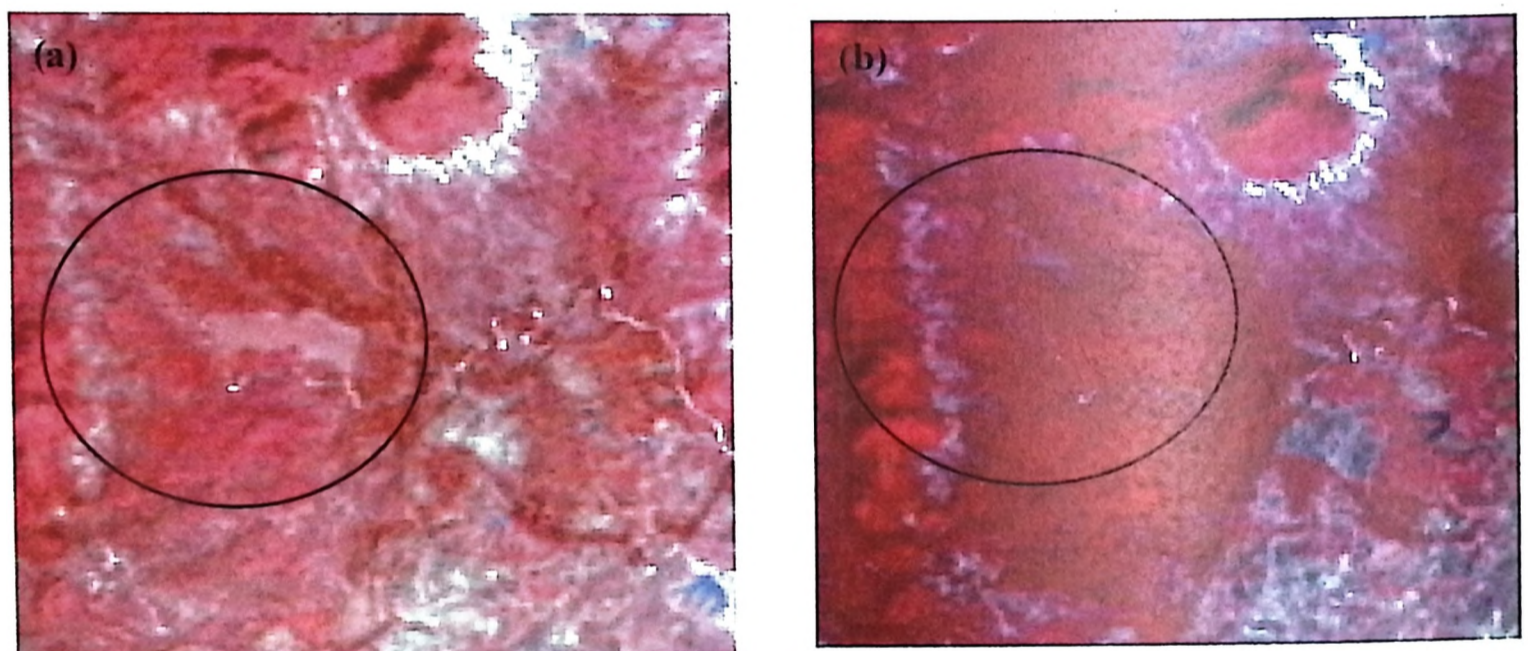


Figure 3-1: a) Landsat image of 2005, b) Landsat image of 2016. A positive greening trend is illustrated here in panel (b) as compared to panel (a), in the area highlighted in the figures. The false colour composite shows an increased intensity in panel (b). This is data from area near Kanha Tiger Reserve, Central India

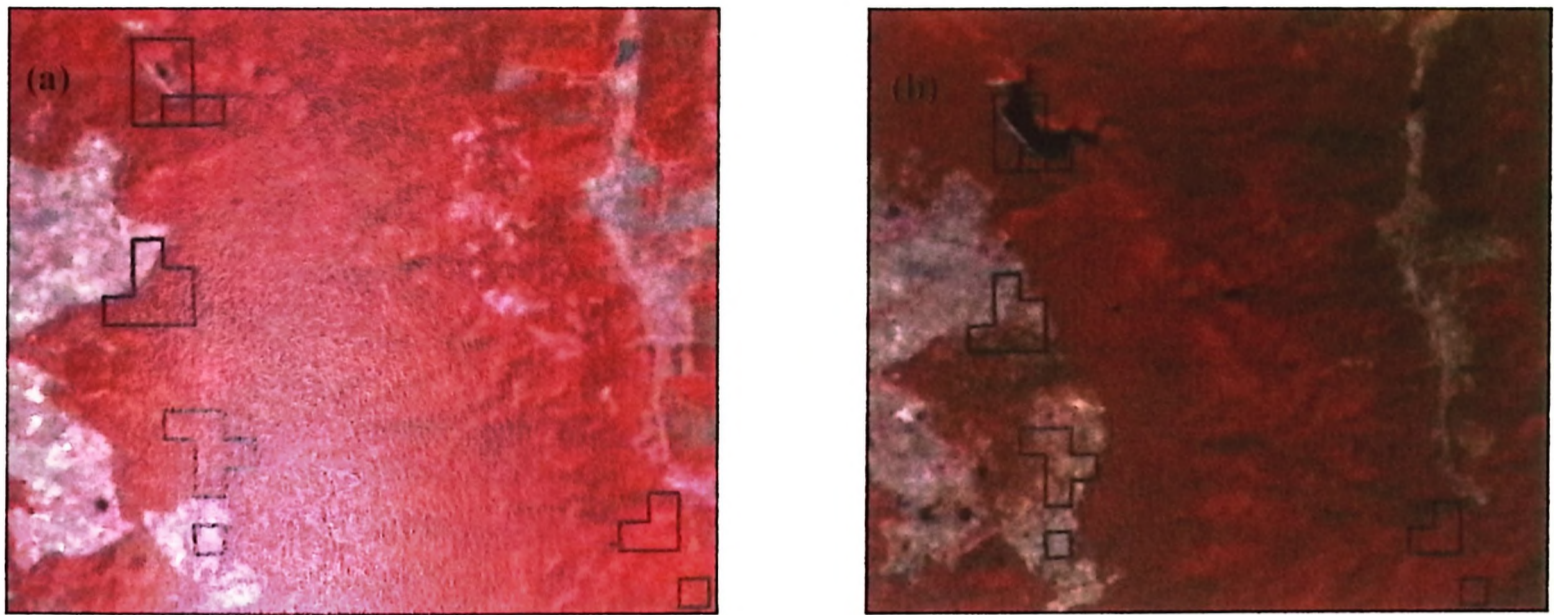


Figure 3-2: a) Landsat image of 1995, b) Landsat image of 2016. A negative or browning trend is illustrated here in panel (b) as compared to panel (a), in the area highlighted in the figures. The false colour composite shows a decreased intensity in panel (b). This is data from area near Kanha Tiger Reserve, Central India

Land cover classification and change detection analysis of corridors and adjoining areas help understand the pressure these areas are facing and are critical in planning conservation and management plans (Cihlar 2000). Remote sensing with the variety of multi temporal and resolution data, has proved to be the most efficient and minimally time-consuming tool, for determining LULC changes (Langley et al. 2001). Landsat is the longest running satellite programme. It has been acquiring images of the earth for the past 50 years. It captures a wide range of spectral signatures of earth features, such as the land, oceans and atmosphere, and their dynamics (Huang et al. 2010; Kennedy et al. 2010). It has comprehensively collected data for the largest span of time, providing multiple measurements of an area that are potentially relevant to monitoring LULC changes.

The spatio-temporal changes in the landscape around the corridors were estimated by performing a TSA. The algorithm ‘greenbrown’ was used on the MODIS-Enhanced Vegetation Index to carry out the TSA, at 250 m (Forkel et al. 2013). The present research was focused on structural changes, and thus seasonality was not accounted for. Areas

indicating changes were further investigated at an enhanced scale, and forest cover and change maps were produced using Landsat Thematic Mapper at 30 m.

3.2. Materials and Methods

3.2.1. Satellite data acquisition and pre-processing

3.2.1.1. Time series analysis

MODIS products have been freely available since 1972 and have good temporal, spectral and spatial coverage for historical time series applications (Wardlow et al. 2007). Enhanced Vegetation Index (EVI) data from MODIS (Moderate Resolution Imaging Spectroradiometer) for the last 16 years (from 2001 to 2016) were used for the present study. These data are available at 16-day intervals, i.e., two images per month, one for the first half and the other for the second half. Satellite data for the second half of the month were obtained at a resolution of 250 m. The swath width of MODIS is about 2330 km, and it collects data at three spatial resolutions: 250 m, 500 m and 1000 m. Whereas the 250-m resolution is a moderate resolution, it is potentially suitable for capturing land cover dynamics for large-area studies (Justice & Townshend 1988, 2002; Hansen et al. 2002; Wessels et al. 2004, Lunetta et al. 2006). A total of 192 images (70 GB) were downloaded.

MODIS is an instrument aboard the Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1) satellites. These two satellites view the entire earth's surface every 1–2 days and procure data in 36 spectral bands between 0.405 μm and 14.385 μm . Data were procured from the website of the United States Geological Survey (USGS) (www.earthexplorer.com). USGS works jointly with the National Aeronautics and Space Administration (NASA) to collect and provide various types of remote-sensing information for studying the different processes of the earth for the benefit of humankind. USGS is a scientific agency established in 1879 and offers data from multiple satellites through the

Earth Explorer interface. This online tool developed by USGS facilitates searching of satellite, aircraft and other remote-sensed information. It is a smart tool, and a user can search or browse areas and datasets and can obtain metadata through interactive and textual queries.

The downloaded images were embedded in the HDF (Hierarchical Data Format) file format. This format is part of a set of file formats (HDF4, HDF5) designed to store and organise a large collection of data. The format was developed at the National Centre for Supercomputing Applications. The MODIS-EVI data for the central Indian landscape were available as four or five different tiles. Data was mosaicked and converted to the Lambert conformal conic projection (LCC) system (Table 3-1). This raster data was rescaled to -1 to +1 by multiplying with a correction factor 0.0001.

Table 3-1: Details of LCC projection/coordinate system

Projected Coordinate System	
Projection:	Lambert Conformal Conic
False Easting:	2000000
False Northing:	2000000
Central Meridian:	82
Standard_Parallel_1:	12.47294444
Standard_Parallel_2:	35.17280556
Latitude_Of_Origin:	20
Linear Unit:	Meter
Geographic Coordinate System	
Datum:	D_WGS_1984
Prime Meridian:	Greenwich
Angular Unit:	Degree

The data processing was carried out in several steps, using shell and Python scripts in a

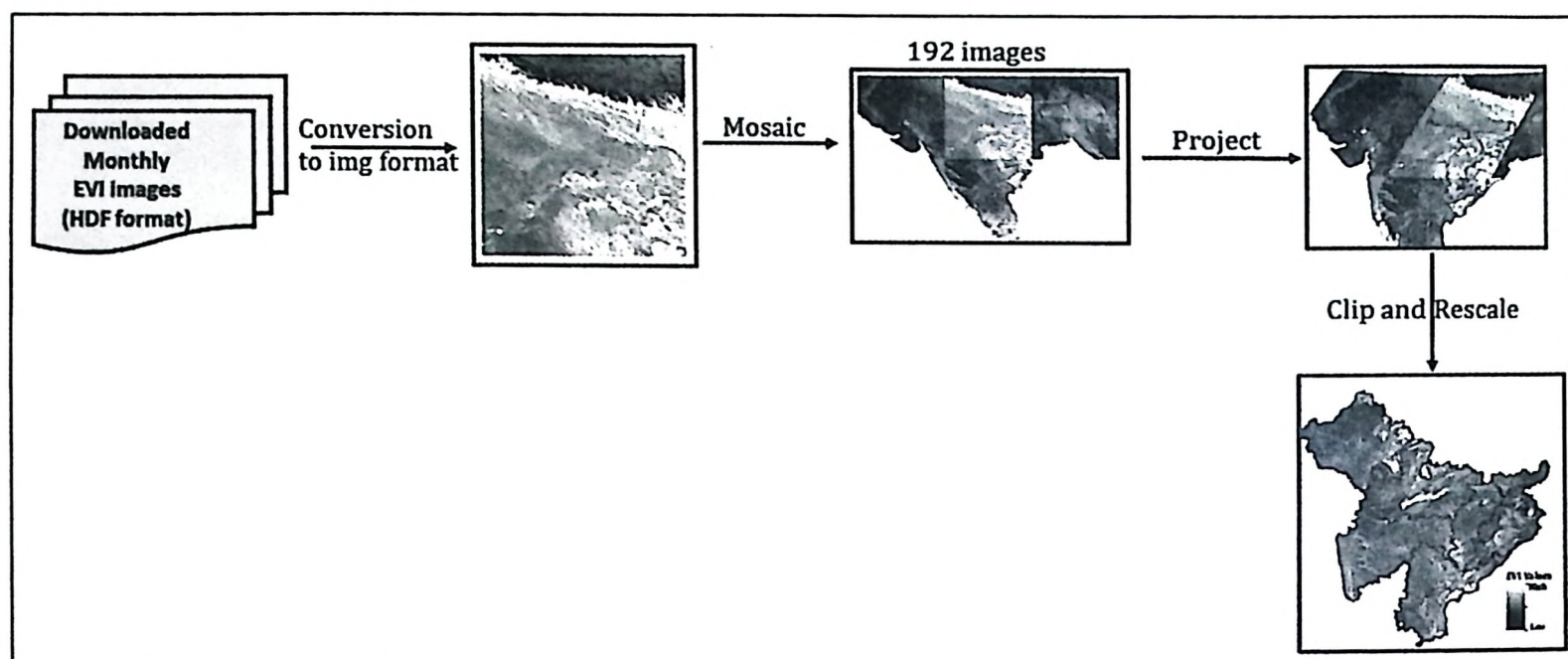


Figure 3-3: Flowchart showing processing of satellite data for time series analysis

Windows operating system. A total of 192 raster image files, occupying a space of around 70 GB, were used. Processing this massive amount of data was not convenient when commercial software packages were used. Therefore, the processing was done using Python libraries through shell scripting, which took around one-tenth the time a typical software package would have taken. A flow chart is shown in (Figure 3-3) that provides details of the steps involved in the preparation of the base data for running the TSA for the last 16 years.

EVI was used as it has a higher sensitivity for high-biomass regions and delivers a better vegetation signal by decoupling the canopy from the background and reducing the noise due to atmospheric influences (Huete et al. 1997, 2002). EVI not only minimises many of the signal noises but also does not get saturated as NDVI does. Therefore, it is a much better index for analysing the green vegetation and its trends (Matsushita et al. 2007). The equation used to compute the EVI is:

$$EVI = G \times (NIR - RED) / (NIR + C1 \times RED - C2 \times Blue + L)$$

Where NIR, Red and Blue are the corrected surface reflectance.

L is the canopy background adjustment that addresses non-linear, differential NIR and red radiant transfer through a canopy

C1, C2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band.

The coefficients adopted in the MODIS-EVI algorithm are; $L=1$, $C1 = 6$, $C2 = 7.5$, and G (gain factor) = 2.5.

3.2.1.2. Change detection analysis

Landsat satellite images were acquired for three epochs (1995, 2005 and 2016) to prepare LULC maps for central India. Using the Landsat raster images, LULC maps were produced, and these maps were examined to identify changes in the landscape. As Landsat has been observing the earth's surface since 1972, it provides consistent, and currently the most extended, information through space and time. Due to the availability of continuous data from Landsat satellites for the last 41 years, these data are a good option for characterising forest structure; its multi-temporal dynamics and changes, which are often subtle and gradual (Banskota et al. 2014). Around nine satellites were launched under this program collecting data at different timeframes. Data from Landsat Thematic Mapper (TM-5) were downloaded for the years 1995 and 2005. Data from Landsat TM-8 were procured for 2016. Details of the Landsat data used are provided in the next section.

a) Details of Landsat TM-5

The Landsat Thematic Mapper(TM) sensor was launched in July 1982 and was operational till May 2012. It had a 16-day repeat cycle, and it was referenced to the Worldwide Reference System-2. This satellite was decommissioned in January 2013. It captured information in seven spectral bands with a resolution of 30 m for bands 1 to 7(Table 3-2). Thermal infrared band 6 information was collected at 120 m, but resampling was carried out at 30 m. The approximate size of a single scene is 170 km north-south by 183 km east-west.

b) Details of Landsat TM-8

Landsat 8 satellite is on board the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) instruments, launched in February 2013. The information is collected in a 16-day repeat cycle, referenced to the Worldwide Reference System-2. The approximate size of the scene is 170 km north–south by 183 km east–west (Table 3-2). The satellite capture information is in a spectral range similar to that of Landsat 7’s ETM+ sensor, with enhanced quality. Two new spectral bands have been added in this series, compared with Landsat 7: a deep blue visible channel (band 1), designed for water resource and coastal zone investigation, and a new infrared channel (band 9), for detecting cirrus clouds. Two thermal bands (TIRS) capture data with a minimum of 100-m resolution, but they resample at 30 m. Due to the addition of the two bands and improved quality of the data (16 bits), the size of a Landsat 8 file is greater compared with a Landsat 7 file.

Table 3-2: Characteristics of Landsat 4-5 Thematic Mapper (TM) Landsat 8 Land imager (OLI) and thermal infrared

	Bands	Wavelength (micrometres)	Resolution (meters)
Landsat 4-5 Thematic Mapper (TM)	Band 1 - Blue	0.45-0.52	30
	Band 2 - Green	0.52-0.60	30
	Band 3 - Red	0.63-0.69	30
	Band 4 - Near Infrared (NIR)	0.76-0.90	30
	Band 5 - Shortwave Infrared (SWIR) 1	1.55-1.75	30
	Band 6 - Thermal	10.40-12.50	120* (30)
	Band 7 - Shortwave Infrared (SWIR) 2	2.08-2.35	30
Landsat 8 Operational Land Imager(OLI) and Thermal Infrared	Band 1 - Ultra Blue (coastal/aerosol)	0.435 - 0.451	30
	Band 2 – Blue	0.452 - 0.512	30
	Band 3 - Green	0.533 - 0.590	30
	Band 4 - Red	0.636 - 0.673	30

Sensor (TIRS)			
	Band 5 - Near Infrared (NIR)	0.851 - 0.879	30
	Band 6 - Shortwave Infrared (SWIR) 1	1.566 - 1.651	30
	Band 7 - Shortwave Infrared (SWIR) 2	2.107 - 2.294	30
	Band 8 - Panchromatic	0.503 - 0.676	15
	Band 9 - Cirrus	1.363 - 1.384	30
	Band 10 - Thermal Infrared (TIRS) 1	10.60 - 11.19	100 * (30)
	Band 11 - Thermal Infrared (TIRS) 2	11.50 - 12.51	100 * (30)

3.2.2. Detail of methods and algorithm

3.2.2.1. Time series analysis

TSA was performed to detect trends in forest cover or vegetation using the package ‘greenbrown’ package in R (Forkel 2015). The package provides different methods of carrying out trend and breakpoint analysis. The algorithm calculates the ‘greening’, which indicates the increase in green cover, and the ‘browning’, which refers to the decline in green cover in time series data. The trends in the increase and decrease of green cover are usually not linear but are rather abrupt due to specific events such as floods, fires or infrastructure development. To identify these sharp changes and hotspots, the package also detects the breakpoints in the time series caused by different effects of inter-annual variability. There can be many reasons behind these breakpoints. The following are examples:

- 1) Artefacts of a harmonised datasets from different sensors
- 2) Meteorological distortions such as clouds and snow cover
- 3) Environmental processes or ecosystem disturbances (Forkel et al. 2013)

This study used the annual aggregated time series (AAT) method to estimate the trend across the landscape. The AAT method aggregates the monthly EVI values to annual values and therefore calculates the annual mean or annual peak. Subsequently, the slope of the trend of the annual mean EVI values is estimated using the linear least-square regression method. Further, linear least-square regression is used to fit a statistical or mathematical model, after the best model fit for the data is estimated, by minimising the sum of squares between the data points and the regression line. The Mann-Kendall test is then used to test the significance of the trend in each time series computed on the annual aggregated EVI values (Mann 1945; Kendall 1975). The TSA was performed using R (<https://www.r-project.org/>).

3.2.2.2. Change detection analysis

LULC maps were prepared for the years 1995, 2005 and 2016. The maps were produced using Landsat raster images of 30-m resolution with the following classes: vegetation, human habitation or agriculture and water bodies. The methodology adopted for digital forest change detection included preparation of forest maps that were then compared for change detection (Figure 3-4). Raster-based classification was carried out using a combination of various indices, and unsupervised classification of multispectral Landsat images (Richard 1993).

Indices are mathematical combinations or transformations of spectral bands that highlight the spectral properties of different land features, making them appear distinct for better interpretation (Huete 1988; Jinru Xue and Baofeng Su 2017). The indices used for preparing the LULC maps were the following:

1. Normalised Difference Vegetation Index (NDVI)
2. Normalised Difference Building Index (NDBI)
3. Normalised Difference Water Index (NDWI).

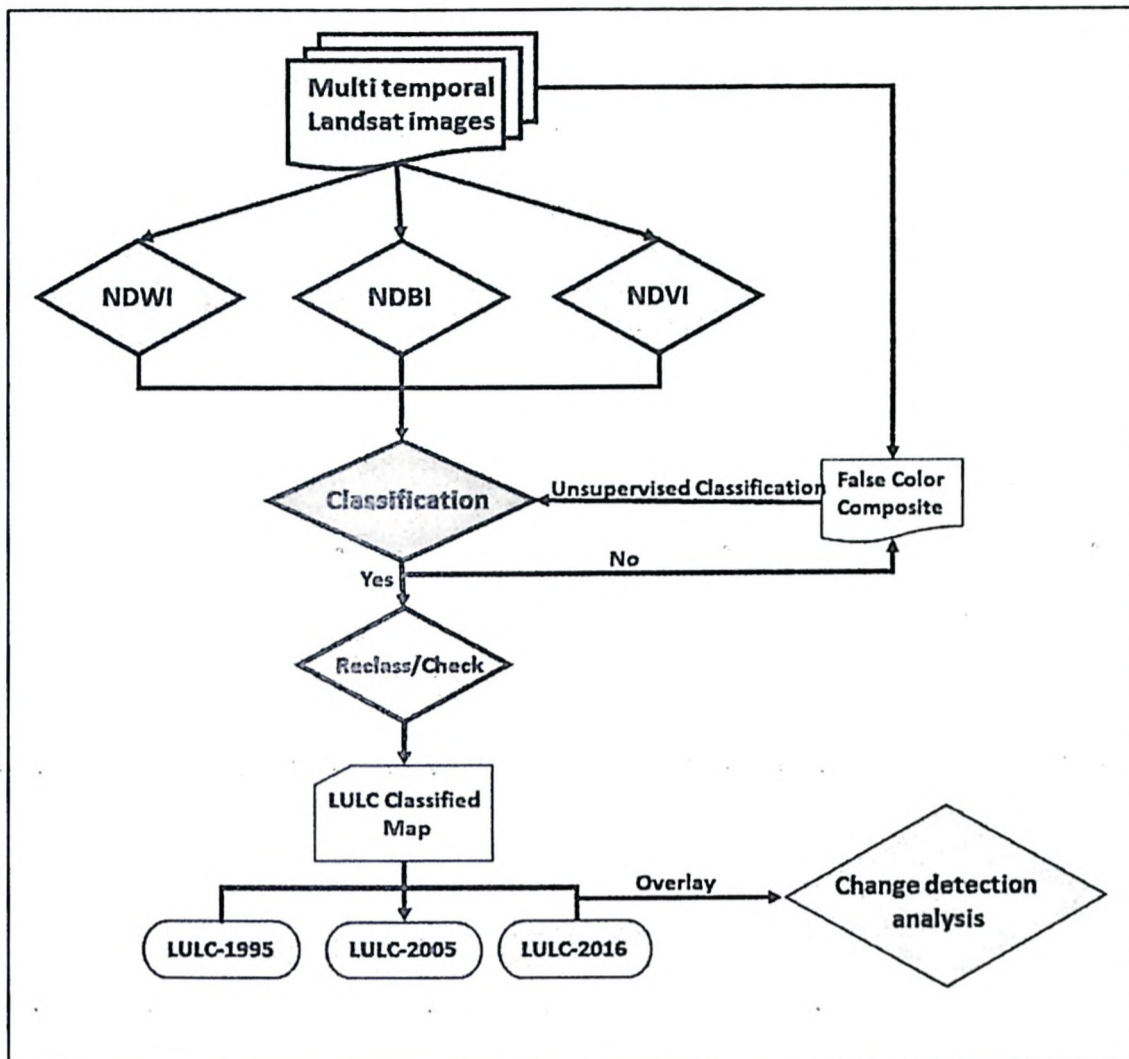


Figure 3-4: Flowchart showing methodology used in land use-land cover change analysis

a) Normalised Difference Vegetation Index

The Normalised Difference Vegetation Index (NDVI) is a well-known and widely preferred standardised index for quantifying green vegetation. The NDVI is calculated as the ratio of the infrared band to the red band. The spectral range of the red band is 0.58–0.68 μm . This part of the electromagnetic region is strongly absorbed by vegetation. The chlorophyll content of plants strongly absorbs wavelength in the red region of the electromagnetic spectrum for photosynthetic activity. On the other hand, the leaf structure reflects most of the incident radiation of the infrared band (0.72–1.1 μm) (Justice et al. 1985). Therefore, variations in the values of these two bands provide useful information about the quantity and quality of the vegetation. The NDVI value ranges from -1 to +1.

A positive value represents greenness, and negative values are mainly generated from clouds, water, and snow (Figure 3-5). Values near zero indicate the presence of rock and bare soil. Very low values of the NDVI (0.1 and below) correspond to barren areas of rock, sand or snow. Moderate values (0.2–0.3) are of shrub and grassland, while high values (0.6–0.8) indicate temperate and tropical rainforests. The formula used to calculate the NDVI is given below:

$$\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})}$$

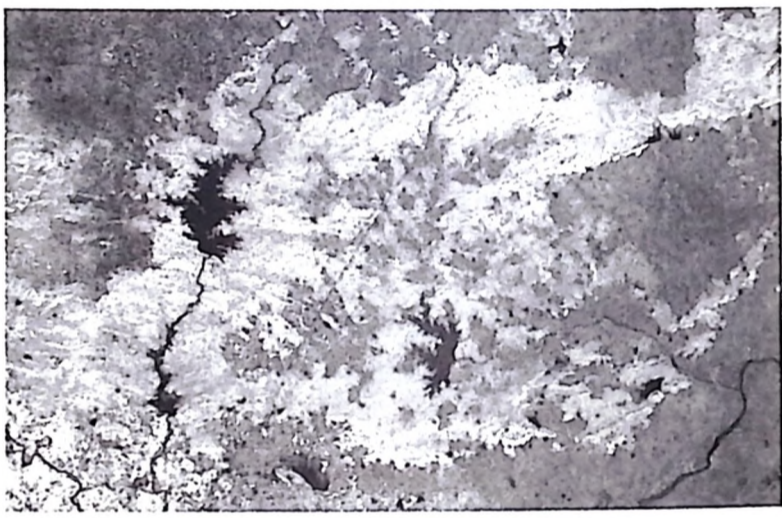
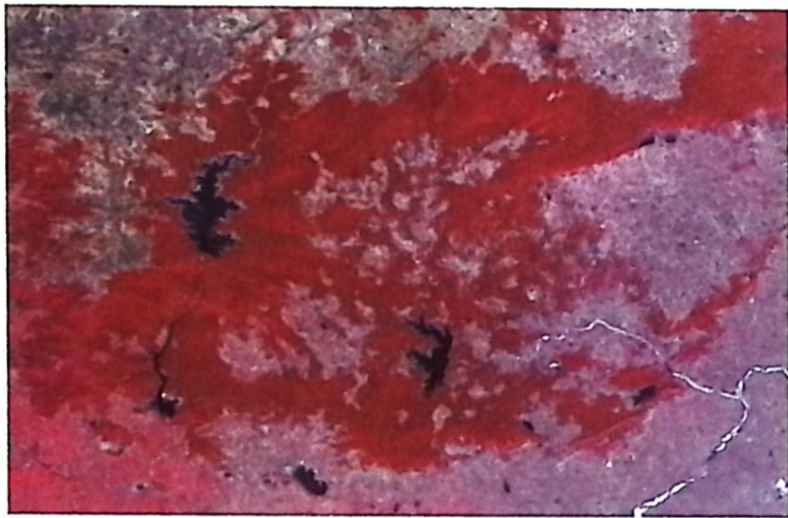


Figure 3-5: Landsat TM image for 2016: NDVI values calculated using Landsat TM NIR and red bands

b) Normalised Difference Water Index

The Normalised Difference Water Index (NDWI) is used for mapping water bodies present on the earth’s surface. The NDWI is derived from the near-infrared (NIR) and short wave infrared (SWIR) bands (Gao 1996). The index enhances the water information efficiently and provides results similar to those of the NDVI, in the range from -1 to +1, where a value from -1 to 0 indicates a bright surface with no vegetation or water content and +1 signifies that there is water (Figure 3-6). The formula used to calculate the NDWI is:

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}}$$

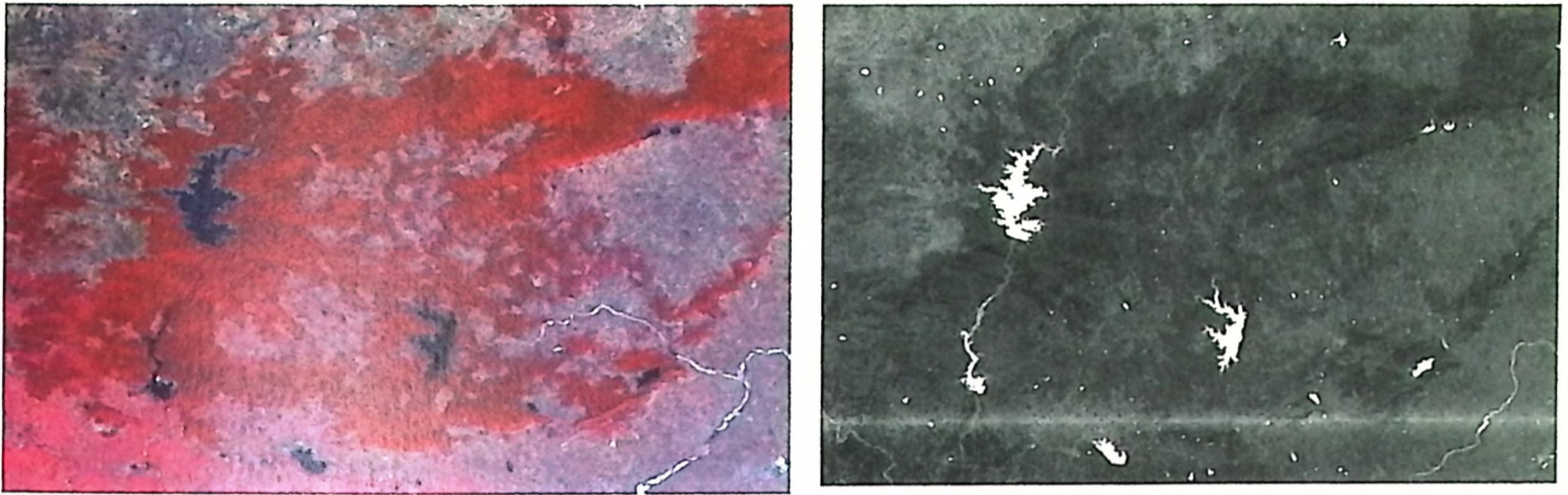


Figure 3-6: Landsat TM image for 2016: NDWI values calculated using Landsat TM NIR and green bands

c) Normalised Difference Built-up Index

The Normalised Difference Built-up Index (NDBI) is an index to enhance the spectral properties of built-up areas and other land cover (McFeeters et al. 1996; Zha et al. 2003; Mwakapuja et al. 2013). The index utilises the spectral properties of the mid-infrared (MIR) (TM-5) and near infrared (NIR) (TM-4) bands (Figure 3-7). The formula used to calculate the index is:

$$\text{NDBI} = \frac{(\text{TM5}-\text{TM4})}{(\text{TM5}+\text{TM4})}$$

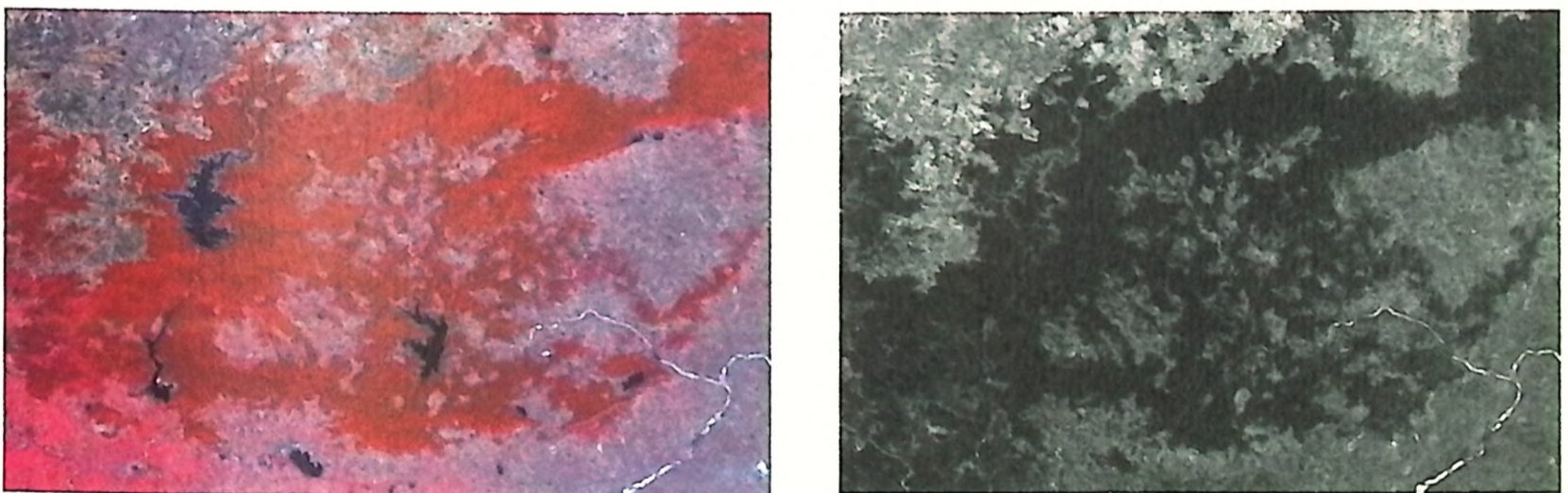


Figure 3-7: Landsat TM image for 2016: NDBI values calculated using Landsat TM TM-5 and TM-4 bands

d) Unsupervised classification

Unsupervised classification is an automated classification technique that uses raster images. Pixels are grouped into different classes on the basis of their spectral properties. In unsupervised classification, an algorithm generates a cluster of pixels that have similar spectral properties and subsequently groups the data into classes defined by the user. The user provides the number of desired classes, and the algorithm statistically creates bins of pixels with no prior knowledge of the area or classes (Richards 1993). The technique produces a map with n classes on the basis of spectral values that are then assigned thematic information by the user, such as forest, water, agriculture or settlements.

e) Mapping urban extent using nighttime visible lights

Nighttime visible lights were used to map the extent of urban areas and to investigate the urban dynamics in the region of the corridors since 1995. The global radiance-calibrated dataset had a 1-km resolution in WGS84 projection and represented the urban areas of the years 1995 and 2005. Data from the VIIRS sensor were procured to map the urban extent of the year 2016. A dataset of fine resolution was available for 2015. The data were resampled using the nearest-neighbour technique at a 1-km resolution in LCC projection to match the cell size. All the rasters of nightlights were converted to the same LCC projection/coordinate system. Details of the LCC projection system are provided in Table 3-1. The pixels of the satellite data were then classified as urban or non-urban areas. Zeros were treated as non-urban centres, and pixels with values greater than zero were classified as urban. Using this classification technique, maps were prepared for the urban patches of 1995, 2005 and 2016.

There were some mismatches and errors. For example, pixels that were found to be urbanised in a particular year were found to be non-urban the next year. The shapes of the urban centres were different over the years. To overcome these issues, a cumulative addition of the urban patches of each successive year was applied to the classified rasters. Many

studies have concluded that the conversion of land cover to urban areas is an irreversible change and that these areas will continue to grow either in extent or density (Lee et al. 1998; Hegazy & Kaloop 2015). The morphological theories of urban growth also state that an urban area will continue to develop outwards from its centre (Burgess 1923), grow forming patterns like expansion on the roadsides (Hoyt 1939) or emerge in different irregular patterns according to the demographic and economic changes happening in the area (Harris & Ullman 1945).

In this work, 1995 was considered the base year, and the subsequent years' urban pixels were added to the base year's pixels to obtain the data for the intermediate period. Figure 3-8 illustrates the approach. To estimate the urbanisation trend, the number of urban areas, total area under urban patches and inter-patch distances were calculated for every corridor region.

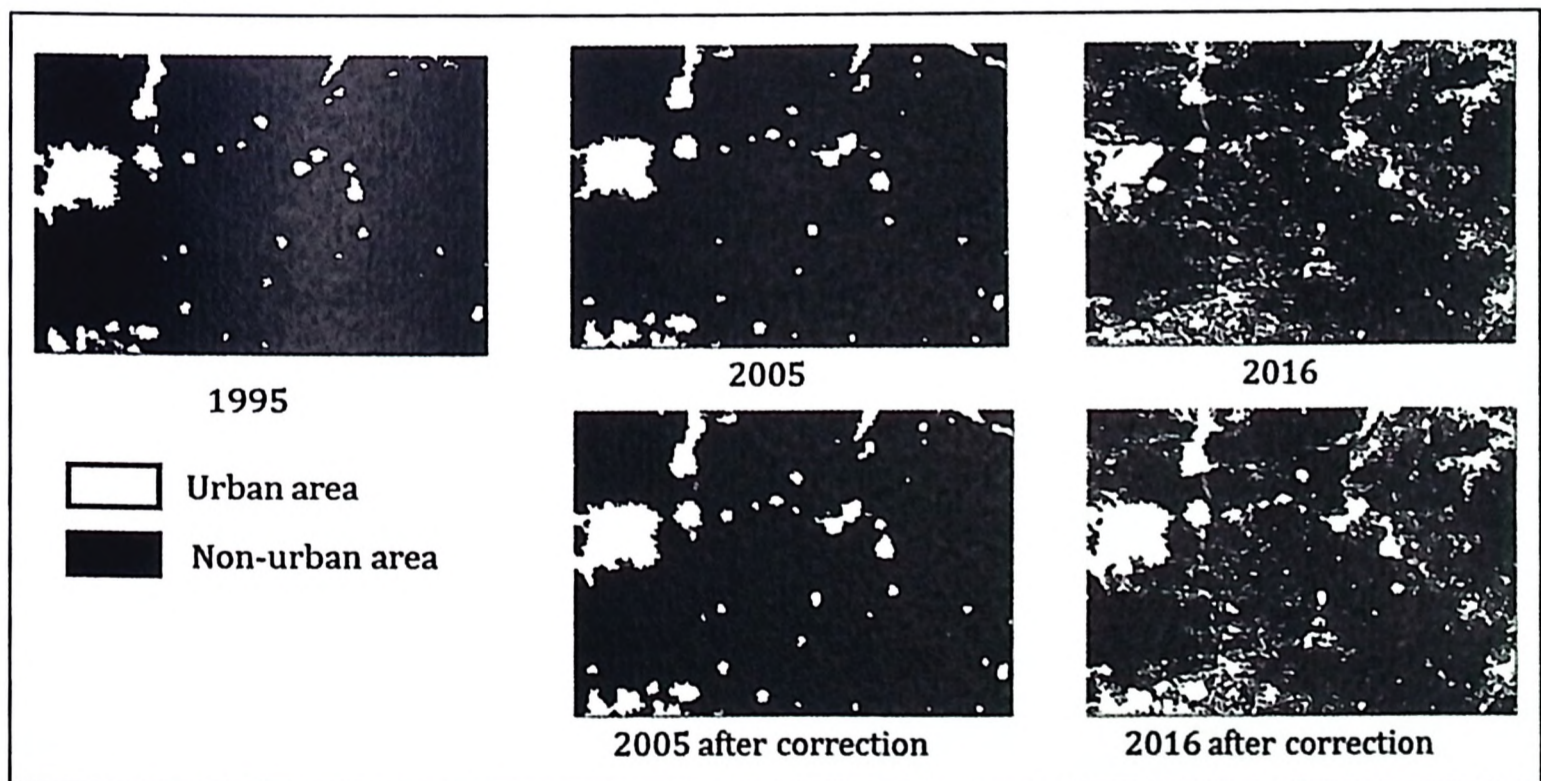


Figure 3-8: Illustration of urban areas in 1995, 2005 and 2016 using nighttime lights without correction and after using cumulative approach

f) Demography

Among the major drivers of deforestation are the growth of the population, the distribution of the population and the urbanisation in the area. These factors exert pressure on the forest cover locally as well as from certain distances (Verburg et al. 2002). Village data from census reports published by the Government of India were used to estimate the population trend in and around the corridor region. A census is conducted once every 10 years, and therefore the data of the three time periods corresponding to the forest cover maps were used listed in Table 3-3.

Table 3-3: Census report data used for each time period.

S.No	Forest cover map time period	Census report
1	1995	1991
2	2005	2001
3	2011	2011

The total population and the number of households were used to explore the trends of population growth. These trends were then related to the forest cover loss in each habitat linkage, and the urban patch expansion was classified using the nighttime lights. The percentage growth of individuals and the number of households in the villages within every corridor were calculated for each decade. The decadal growth rate of the population of a district was also considered in analysing the growing pressure on the forest cover nearby.

3.3. Results and discussion

TSA of MODIS-EVI data was performed to get the changes in the forest cover that occurred in the landscape in the last 16 years. The details are presented in Section 3.3.1. Change detection analysis helped acquire the spatial details of the forest loss in each corridor. The results also helped detect the magnitude of change, rate of change and nature of change.

3.3.1. Time series analysis

Using the algorithm 'greenbrown' on the MODIS-EVI data, a slope map presenting the trend was obtained for the entire central Indian landscape. The slope ranged from -0.034 to +0.035, with negative values representing browning (decrease) and positive values signifying a greening (increasing) trend in the landscape. Slope values from 0.011 to 0.02 represented increases in green cover, and a range of values from -0.02 to -0.017 signified a decrease in the vegetation. The p -values ranged from 1.18×10^{-12} to 1 for the entire landscape (Figure 3-9). Most of the forested areas show a neutral trend, with slope values of 0 or less than 0. Greening trends were observed mainly in agricultural areas due to the growth of weeds. There were few of these areas, and they were patchily distributed. Significant negative trends (browning) due to infrastructure development and expansion of urban areas were observed in the landscape. Areas that were transformed substantially were captured clearly at this scale, but places altered to a small spatial extent were not captured. Thus, Landsat data of 30-m resolution were used to assess changes in the corridors.

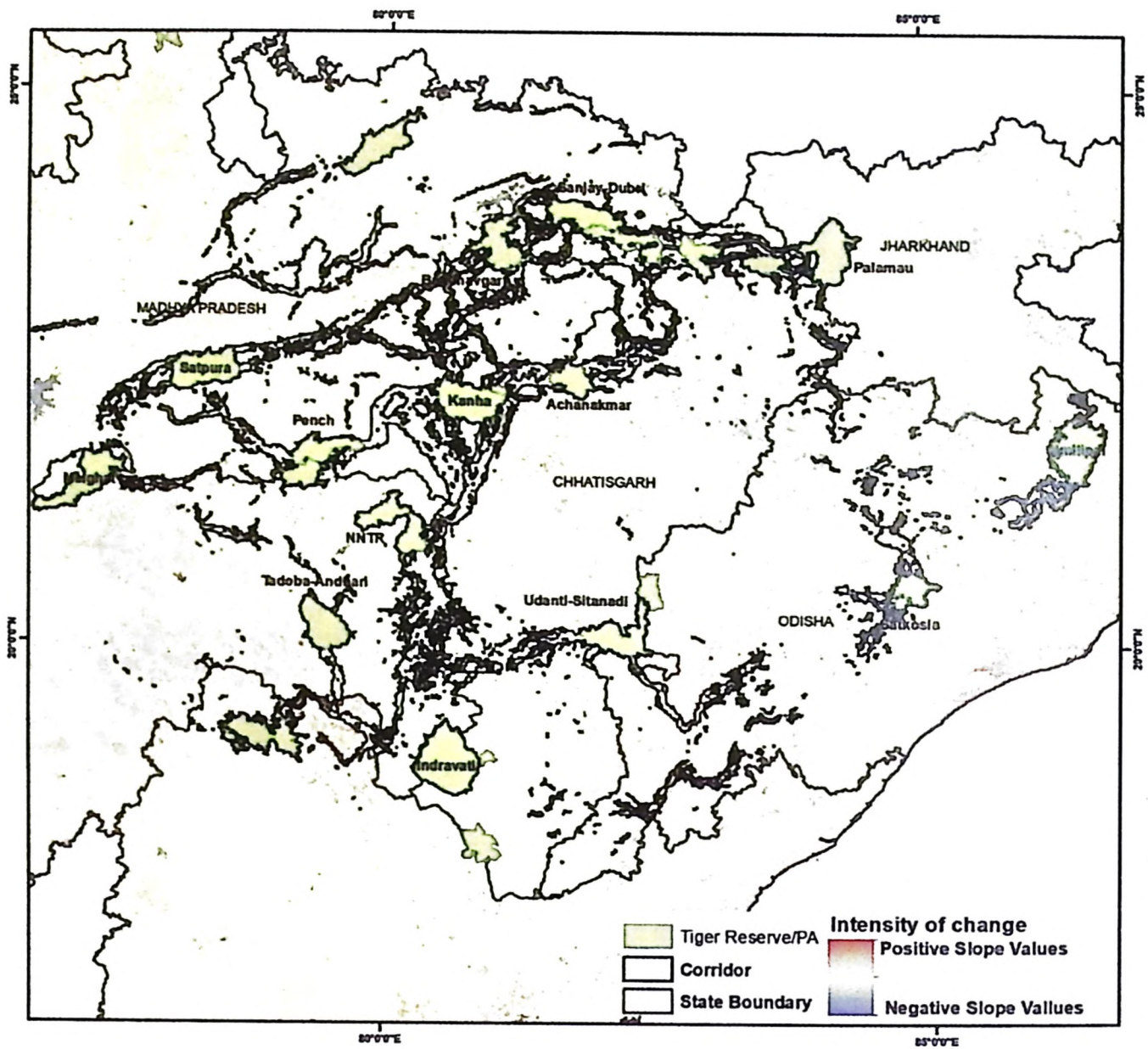


Figure 3-9: A map displaying the positive and negative trend in vegetation change for the entire central Indian landscape

3.3.2. Forest cover map and change detection analysis

Forest cover maps of 30-m resolution were produced for 1995, 2005 and 2016.

Table 3-4: Detailed profile of corridors

S.No	Name of the corridor	Connecting Tiger reserve/Protected areas	State	Extends over Districts	Forest Divisions	Length
1	Bhandhavgarh-Achanakmar	Bhadhavgarh, Achanakmar	Chhattisgarh Madhya Pradesh	Bilaspur Shahdol, Umaria	Marwahi, Bilaspur Annupur, Dindori, South Shahdol, Umaria	131 km
2	Bhandhavgarh-Sanjay-dubri-Guru ghasidas NP	Bhandhavgarh Sanjay-Dubri, Guru ghasidas NP	Chhattisgarh Madhya Pradesh	Koriya Sidhi, Shahdol, Umaria	Mahendragarh, gurughasidas North Shahdol, South Shahdol, Umaria, Sidhi	123km
3	Kanha-Achanakmar	Kanha Achanakmar Boramdeo NP & Phen WLS	Chhattisgarh Madhya Pradesh	Kabirdham (previously Karwardha) Balaghat, Dindori, Mandla	Kawardha, Boramdeo East Mandla, Dindori	89km
4	Kanha-Pench	Kanha TR & Pench TR	Madhya Pradesh	Balaghat, Mandla, Seoni	North Balaghat, South Balaghat, South Seoni, West Madla	165km
5	Simlipal-Satkosia	Simlipal TR & Satkosia TR	Odisha	Anugul, Debagarh, Jaipur Khendujhar, Mayurbhanj, Sambalpur	Anugul, Athamalik, Cuttack, Deogarh Dhenkanal, Karanjia, Keonjhar, Khonejhar, WLS, Rairakhol	235km
6	GurughasidasNP-Lawalong WLS	Guru Ghasidas NP & Palamau Tamorpingla WLS, Semarsot WLS, Lawalong WLS	Jharkhand Chhattisgarh	Palamau Surguja	Latehar Gurughasi das, Surrajpur, Balrampur, Tamorpingala	218km
7	Pench-Satpura-Melghat	Pench TR, Satpura TR & Melghat TR	Madhya Pradesh Maharashtra	Betul, Chhindwara, Hoshangabad, East Nimar, Harda Amravati	Burhanpur, East Chhindwara, Harda, Hoshangabad, Khandwa North Betul, South Betul, south Chhindwara West Betul, West Chhindwara West Melghat	443km
8	Kanha-NNTR-Tadoba-Indravati	Kanha, Navegoan-Nagzira, Tadoba, Indravati	Chhattisgarh Madhya Pradesh Maharashtra Telangana	(now Kabirdham)Kawardha, Rajnandgaon, Bijapur Balaghat Gadchiroli, Chandrapur, Gondiya Adilabad	Kawardha, Khairagarh, Rajnandgaon, Bijapur South Balaghat Allapali, Bhamragarh, Bramhpuri, Chandrapur Gadchiroli, Gondia, Sironcha, Wadsa Khazagnagar	705km

Table 3-5: Forest cover area (in km²) and change from previous year (shown in brackets)

Corridor ID	Corridor	1995	2005	2016	Overall Change	Percent loss
1	Bhandhavgarh-Achanakmar Bhandhavgarh-Sanjay	761	762(1)	681(-81)	-80	11
2	dubri-Guru ghasidas	1003	972(-31)	887(-85)	-116	12
3	Kanha-Achanakmar	700	671(-29)	640(-31)	-60	9
4	Kanha-Pench	1301	1294(-7)	1279(-15)	-22	2
5	Simlipal-Satkosia	2026	1910(-116)	1953(+43)	-73	4
6	Gurughasidas-Lawalong	1417	1395(-22)	1380(-15)	-37	3
7	Pench-Satpura-Melghat	3923	3800(-123)	3781(-19)	-142	4
8	Kanha-NNTR-Tadoba- Indravati	5448	5247(-201)	4931(-316)	-517	9

* Nawegoan-Nagzira tiger reserve

Table 3-6: Change in nighttime lights area (in km²) in each corridor

Corridor ID	Corridor	1995	2005	2016	Overall Change	Percent Growth
1	Bhandhavgarh-Achanakmar Bhandhavgarh-Sanjaydubri-Guru	62	112	292	230	371
2	ghasidas	47	95	356	309	657
3	Kanha-Achanakmar	0	1	92	92	0
4	Kanha-Pench	29	68	191	162	559
5	Simlipal-Satkosia	287	468	850	563	196
6	Gurughasidas-Lawalong	24	29	323	299	1246
7	Pench-Satpura-Melghat	472	702	864	392	83
8	Kanha-NNTR*-Tadoba-Indravati	512	889	1378	866	169

* Nawegoan-Nagzira tiger reserve

Table 3-7: Change in inter-patch distance (in km) of urban patches in each corridor

Corridor ID	Corridor	1995	2005	2016	Overall Change	Percent Reduction
1	Bhandhavgarh-Achanakmar Bhandhavgarh-Sanjaydubri-Guru	64	54	25	-39	61
2	ghasidas	199	138	29	-170	85
3	Kanha-Achanakmar	0	0	43	43	0
4	Kanha-Pench	78	92	33	-45	58
5	Simlipal-Satkosia	110	59	28	-83	75
6	Gurughasidas-Lawalong	187	187	30	-157	84
7	Pench-Satpura-Melghat	50	50	40	-11	21
8	Kanha-NNTR*-Tadoba-Indravati	78	64	34	-44	56

*Nawegoan-Nagzira tiger reserve

Table 3-8: Total population of villages in corridor

Corridor ID	Corridor	1995	2005	2016	Overall Change	Percent Growth
1	Bhandhavgarh-Achanakmar Bhandhavgarh-Sanjay dubri-Guru	29	60	70	41	142
2	ghasidas	83	115	141	58	70
3	Kanha-Achanakmar	23	25	29	7	30
4	Kanha-Pench	77	81	91	14	19
5	Simlipal-Satkosia	115	142	160	45	39
6	Gurughasidas-Lawalong	105	124	154	49	47
7	Pench-Satpura-Melghat	119	164	184	65	55
8	Kanha-NNTR-Tadoba-Indravati	205	269	296	91	44

*Population is divided by 1000

3.3.2.1. Bandhavgarh–Achanakmar

This corridor connects the important source populations of Kanha and Bandhavgarh Tiger Reserve. An extent of around 626 km² of Achanakmar is critical tiger habitat, and this area provides a vital connection between the source populations of the two tiger landscapes (Figure 3-10). This corridor passes through the states of Chhattisgarh and Madhya Pradesh, and it is 131 km long. There are 91 villages in this corridor (Table 3-4).

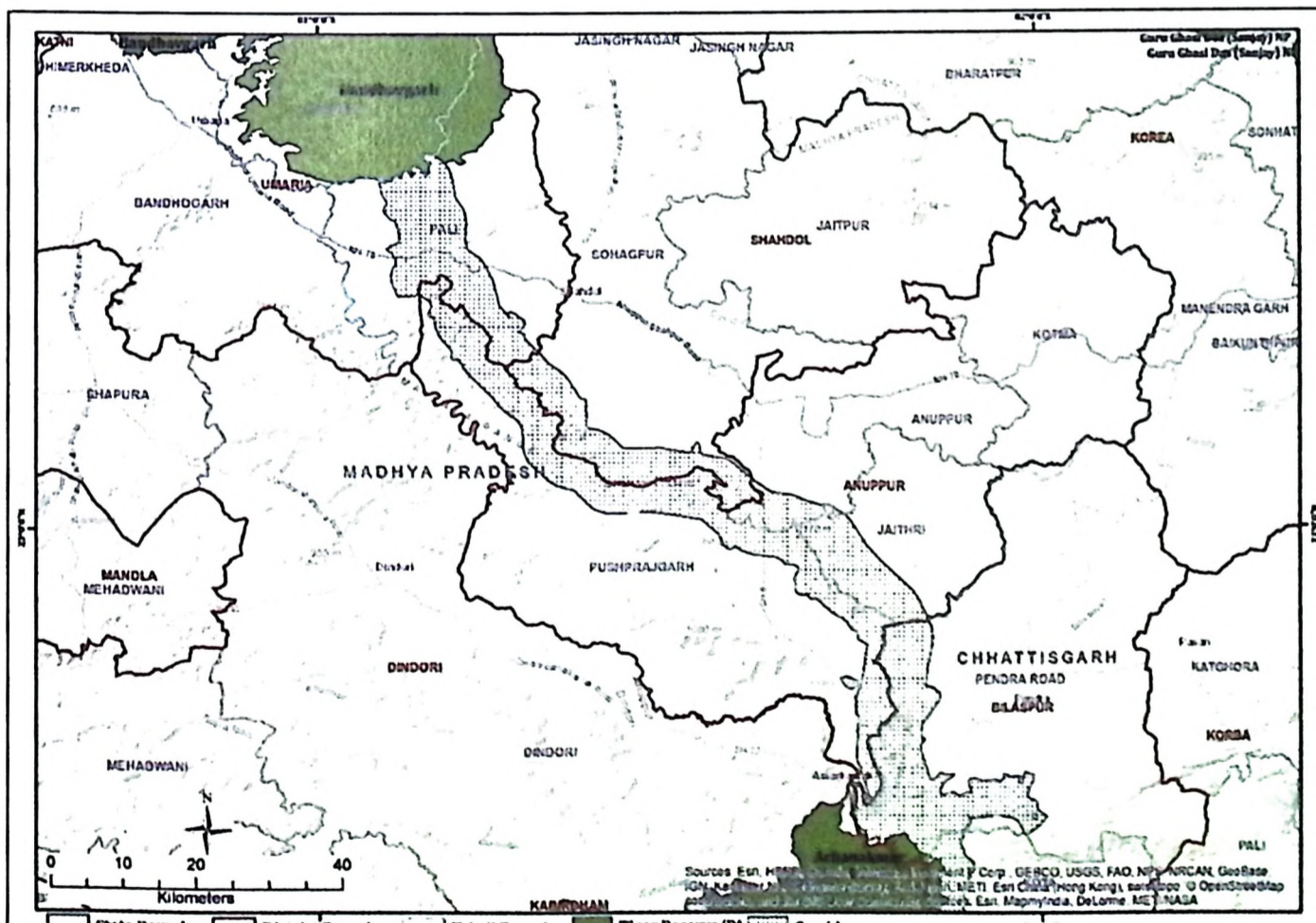


Figure 3-10: Location map of Bandhavgarh–Achanakmar corridor, central India

a) Forest cover change

The forest cover in this corridor area has declined, by around 80 km² (11%) since 1995. Around 10% of the forest area was lost during the period 2005–2016 (Table 3-5). The map reveals that the forest cover change is quite spread out all over the entire corridor, with most changes having occurred near the towns, which are undergoing urbanisation rapidly (Figure 3-11 and Figure 3-12).

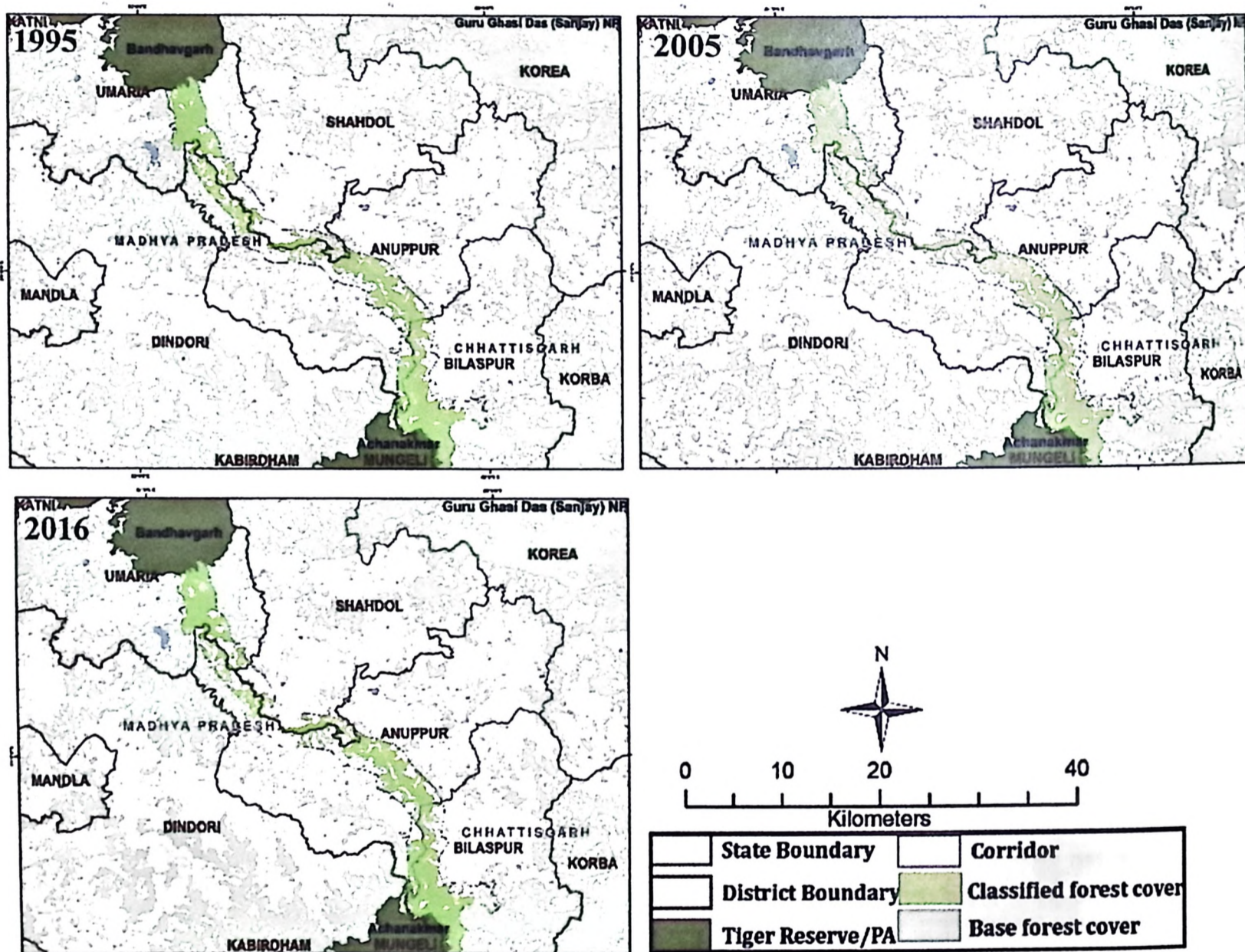


Figure 3-11: Forest cover in Bandhavgarh–Achanakmar corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

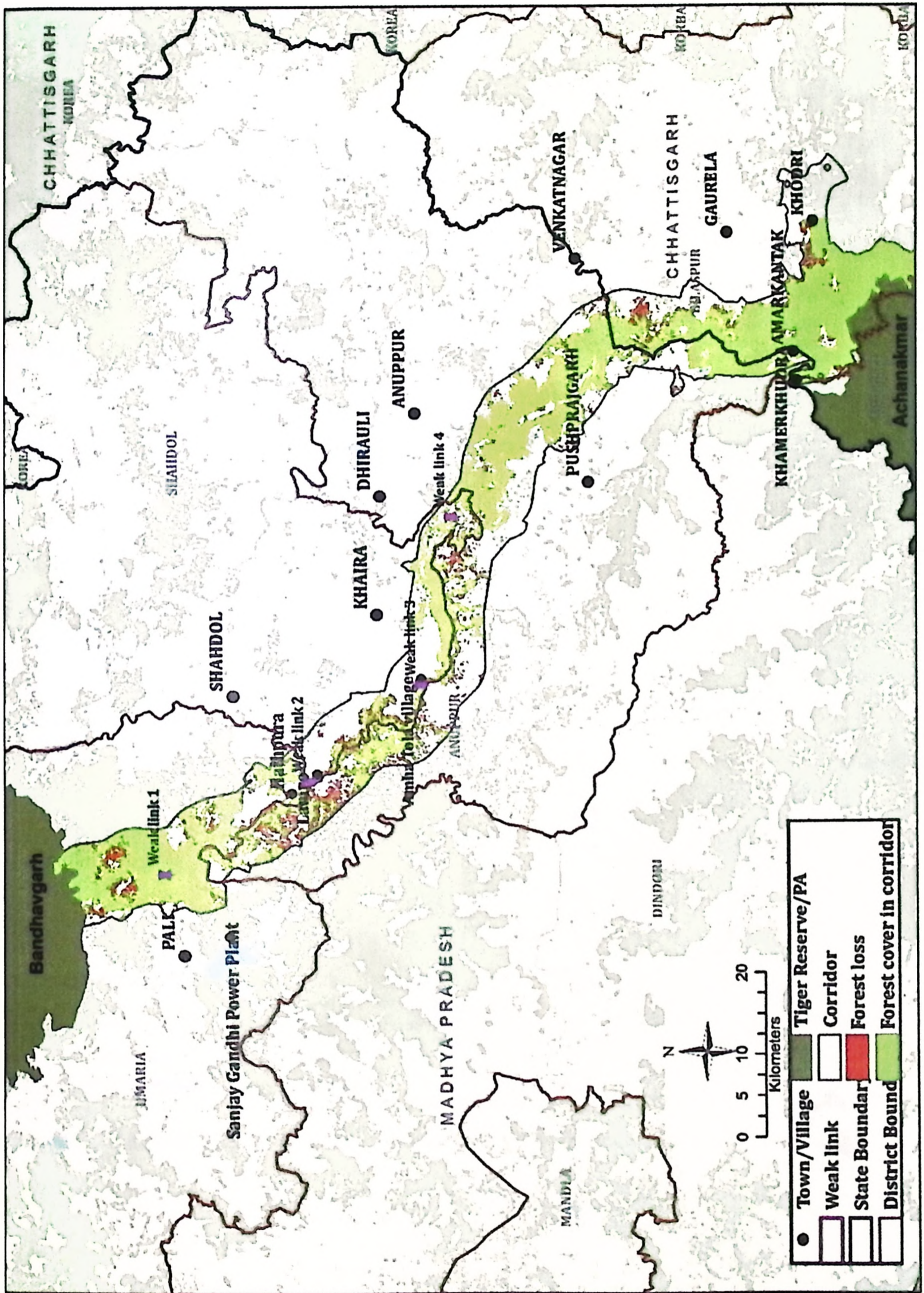


Figure 3-12: Forest cover change from 1995-2016 in Bhandhavgarh-Achanakmar corridor

b) Geographic and demographic change analysis

Nighttime lights change analysis

There has been an exponential increase in the built-up area in the last two decades, from 62 km² in 1995 to 292 km² in 2016, indicating a growth in the area of urban patches at a rate of 19% per annum (Figure 3-13). Similarly, the values obtained for the inter-patch distance for each year show a decreasing trend, from 64 km to 25 km, indicating an expansion of the urban patches in the landscape (Table 3-6 and Table 3-7).

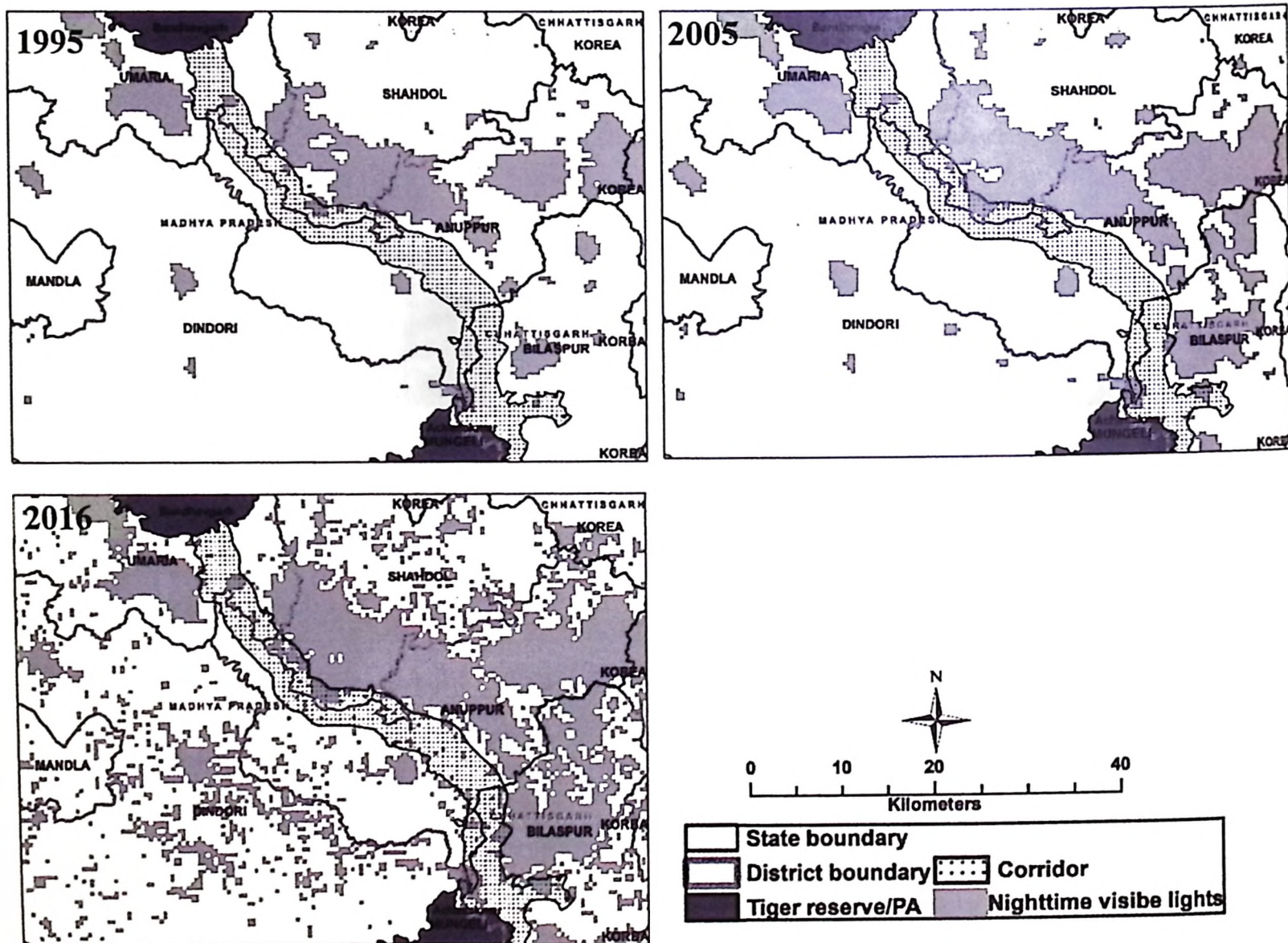


Figure 3-13: Growth in nighttime lights area during 1995–2016 in Bandhavgarh–Achanakmar corridor

Demographic changes

According to the census report, the population in the region has increased rapidly, at an annual rate of 7%, over the last 20 years, and the number of households has increased at a rate of 4% per annum since 1991 in the area (Table 3-8). The population growth, in combination with other factors, affects the adjoining forest areas adversely. A comparison of the demographic, geographic and forest change trends over the years shows a linear relationship (Figure 3-14).

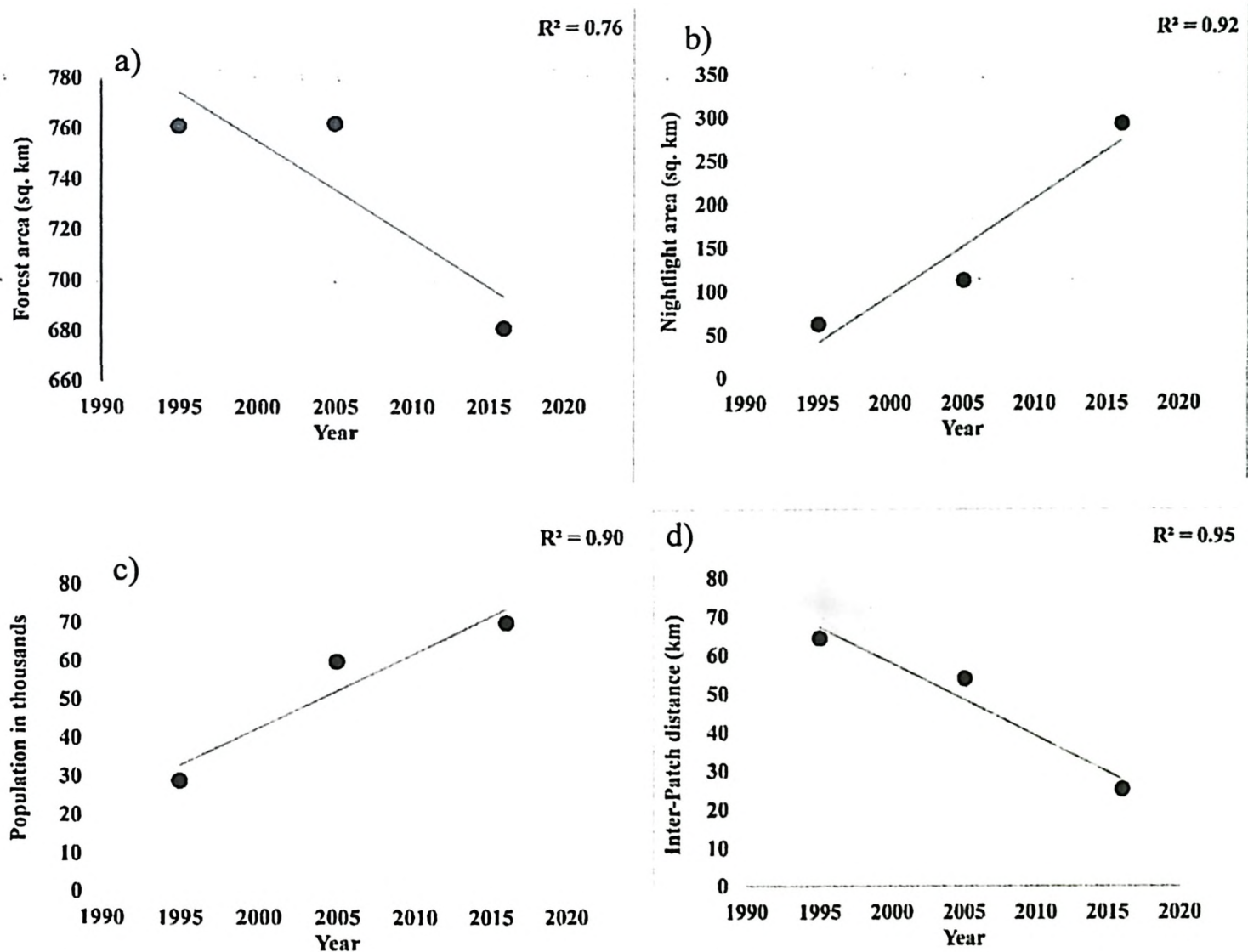


Figure 3-14: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches Bhadavgarh-Achanakmar corridor

c) Threats and weak links

The corridor between Bandhavgarh and Achanakmar is highly fragmented and passes through human-dominated areas. There are very few forest patches left to maintain this linkage. National Highway 78 and a state highway cross this corridor at various locations, disturbing it further. A total of four weak links were observed in this corridor (Table 3-9). Immediate action is required at weak links 2 and 3 to maintain the linkage. The forests of Shahdol and Ahirgwa ranges are patchy, and the width of the corridor is less than optimum in these ranges (Annexure II). The expanding coal mines areas nearby, such as Sohagpur (Fernandes and Shivlingam 2011), extension of the infrastructure of Sanjay Gandhi Power Plant after 1995 and the sprawl in cities like Amarkantak are other serious threats to this corridor and to the forest patches nearby.

Table 3-9: List of weak links in Bandhavgarh–Achanakmar corridor

S.No	Name	Nearby landmark	Latitude	Longitude	Problem
1	Weak link 1	Pali range (Umaria)	23 21 54.16 N	081 08 41.24 E	Corridor is bifurcated by NH-78
2	Weak link 2	Ahirgawa range (Annupur) near Lamro	23 12 44.53 N	081 15 23.63 E	Corridor width is less than 0.5 km
3	Weak link 3	Shahdol range (South shahdol)	23 05 26.10 N	081 22 18.17 E	Surrounded by agriculture fields Corridor width is less than 0.3 km
4	Weak link 4	Shahdol range (South shahdol)	23 03 24.72 N	081 34 27.62 E	Corridor width is less than 0.3 km

3.3.2.2. Bandhavgarh–SanjayDubri–Guru Ghasidas National Park

This corridor connects the important tiger population source population of Bandhavgarh reserve with the Sanjay Dubri and Guru Ghasidas national parks via two forest linkages (Table 3-4 and Figure 3-15). There is one connection of length 48 km through Behori Tehsil, in Shahdol District (Link 1). The other connection is 75 km long and passes through forest

patches in the districts of Shahdol and Umaria, in Madhya Pradesh, and Korea, in Chhattisgarh (Link II). The total length of these two habitat linkages is 123 km. There are 148 villages in this corridor.

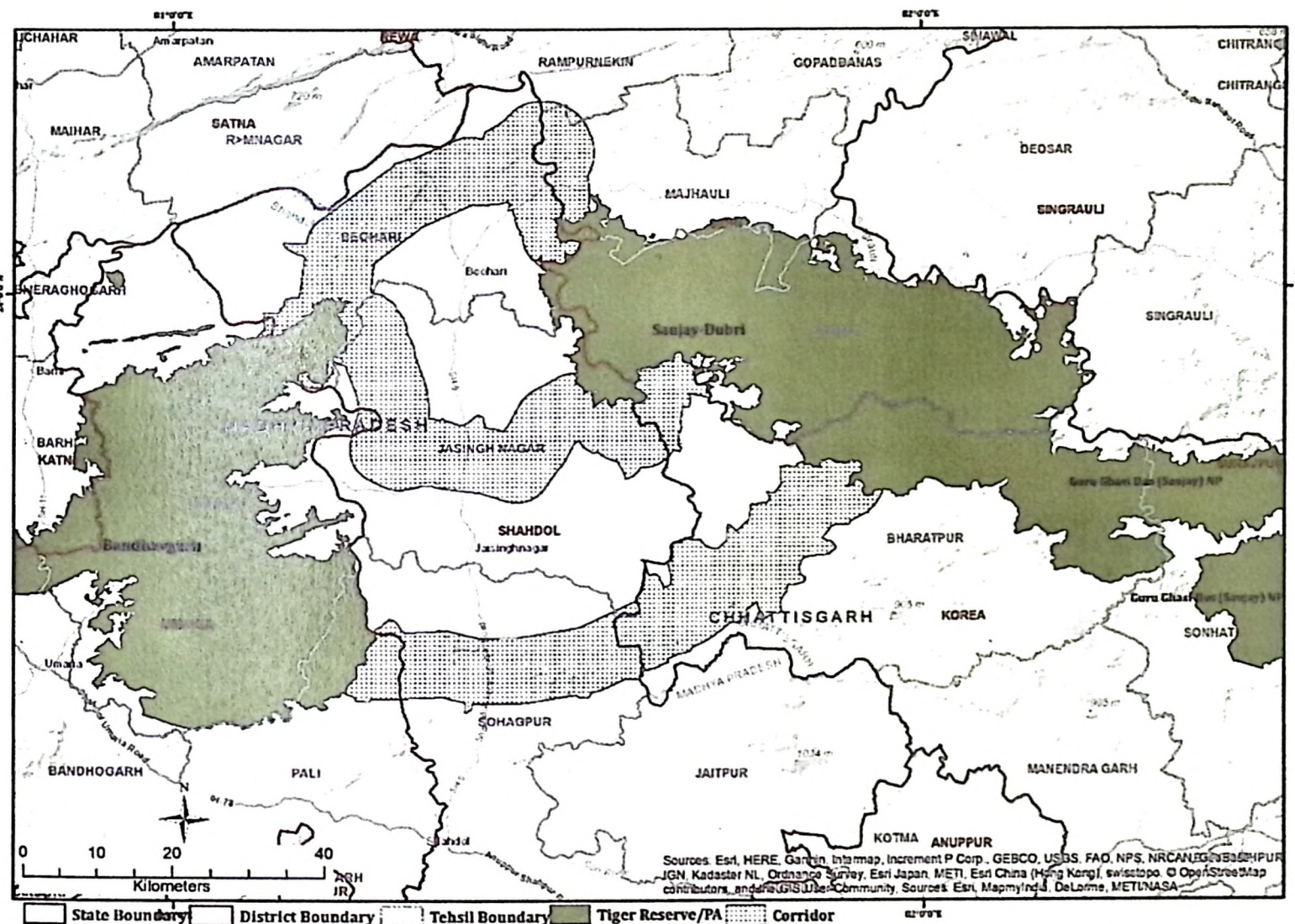


Figure 3-15: Location map of Bandhvgarh–Sanjay-Dubri corridor, central India

a) Forest cover change

This corridor lost 116 km² of forest in the last 20 years (Table 3-5). The change was significant during 2005–2016, contributing 9% of the total change. The rate of change in forest area was 0.5% per annum. The spatial pattern of change reveals that forests were

lost all along the length of the corridor and that mostly the forest edges are getting affected (Figure 3-16 and Figure 3-17).

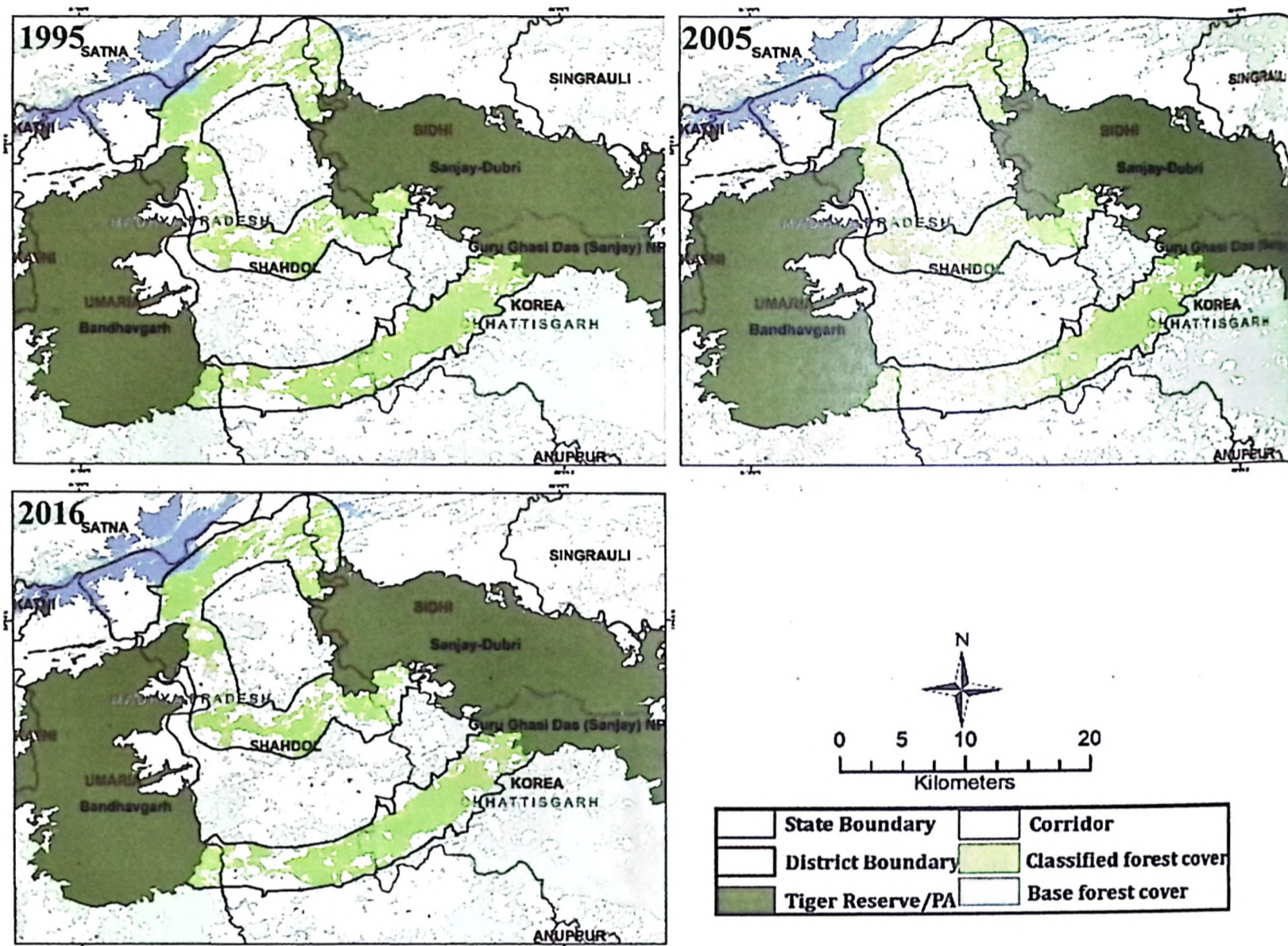


Figure 3-16: Forest cover in Bandhavgarh-Sanjay Dubri-Guru Ghasidas corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

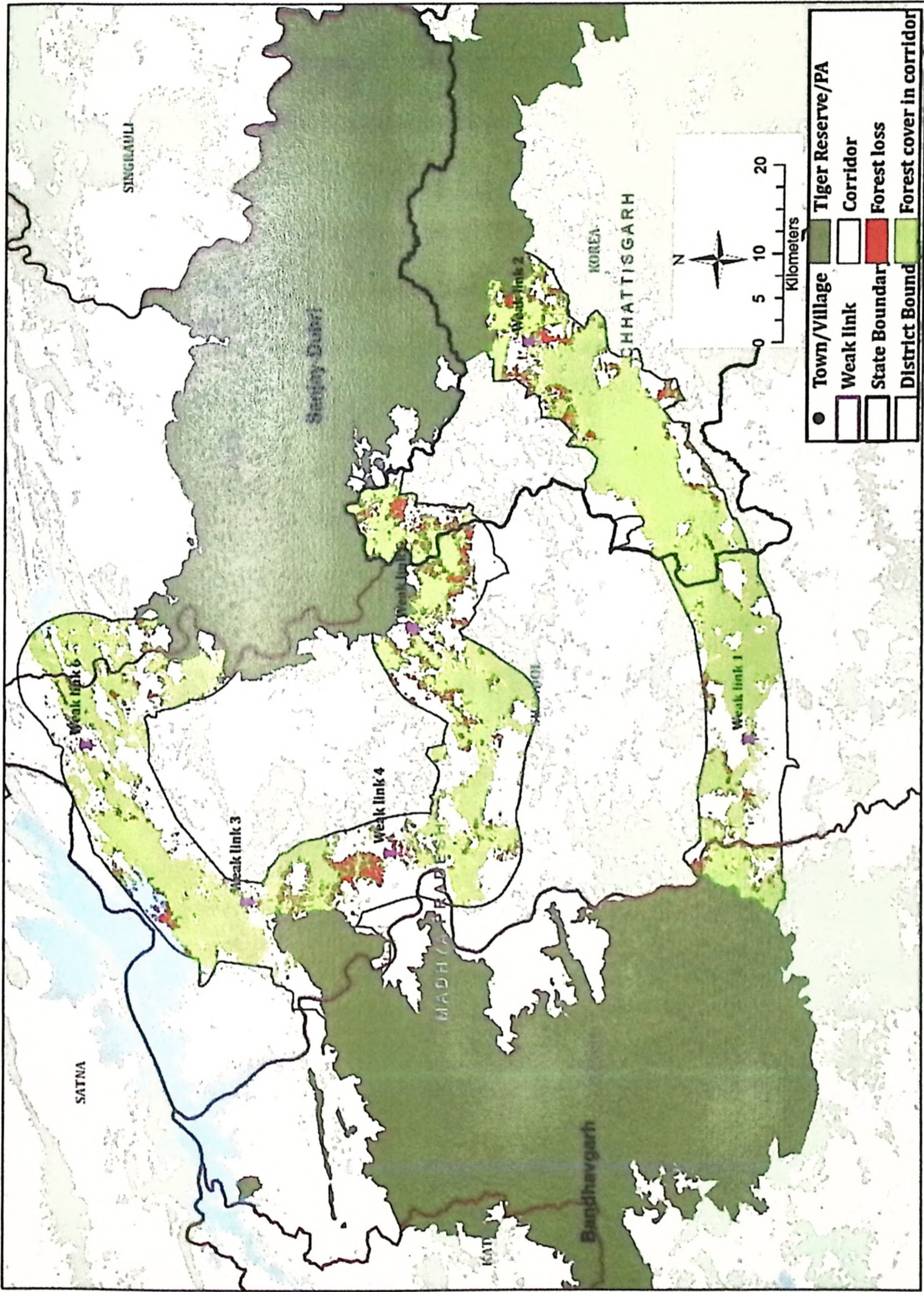


Figure 3-17: Forest cover change in Bandhavgarh-Sanjay Dubri-Guru Ghasidas during 1995-2016

b) Geographic and demographic change analysis

Nighttime lights change analysis

The nighttime lights area in the landscape has increased six-fold from 1995 to 2016, from 47 km² to 356 km² (Figure 3-18). In the decade 1995–2005, the change in area doubled, but the maximum expansion took place from 2005 to 2016, when the number of nighttime light patches increased from eight to 61 (Table 3-6 and Table 3-7). The overall development in the area occurred at a rate of 33% from 1995. The growing number of patches further reduced the inter-patch distance, which dropped from 199 km² to 29 km². The reduction in the inter-patch distance clearly indicates that the infrastructure in the area grew until the small urban patches merged into a single large urban landscape.

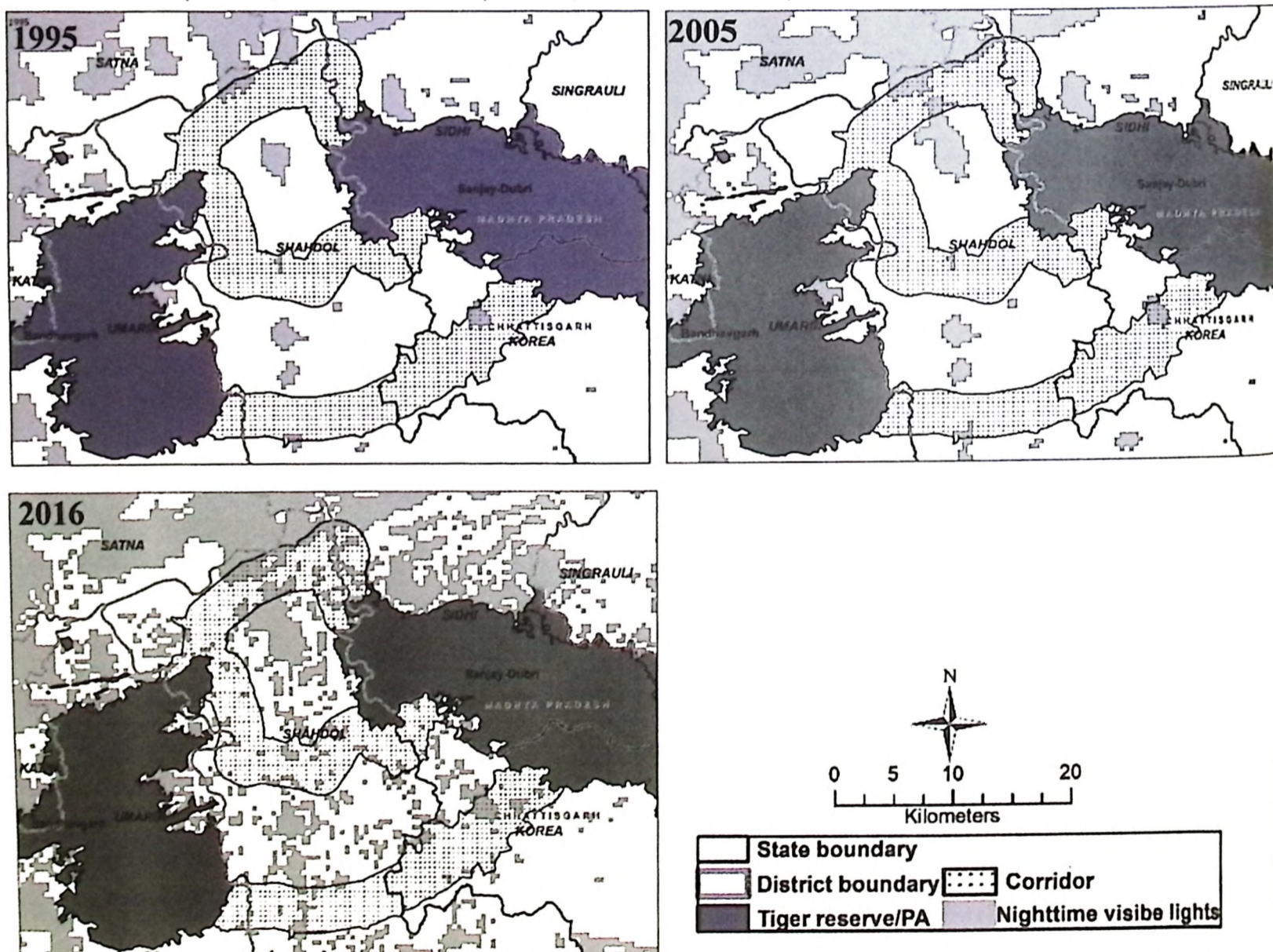


Figure 3-18: Growth in nighttime light area and forest cover change during 1995–2016 in the Bandhavgarh–Sanjay Dubri–Guru Ghasidas National Park corridor

Demographic changes

Demographic analysis of the area shows that the human population of the villages has increased at a rate of 70% in the last 20 years, representing an annual rate of growth of 3.4% (Table 3-8). The population growth is related to the reduction in the inter-patch distance and an increase in the nighttime lights (Figure 3-19). The reduction in forest cover and increase of nighttime lights have created bottlenecks in the corridor.

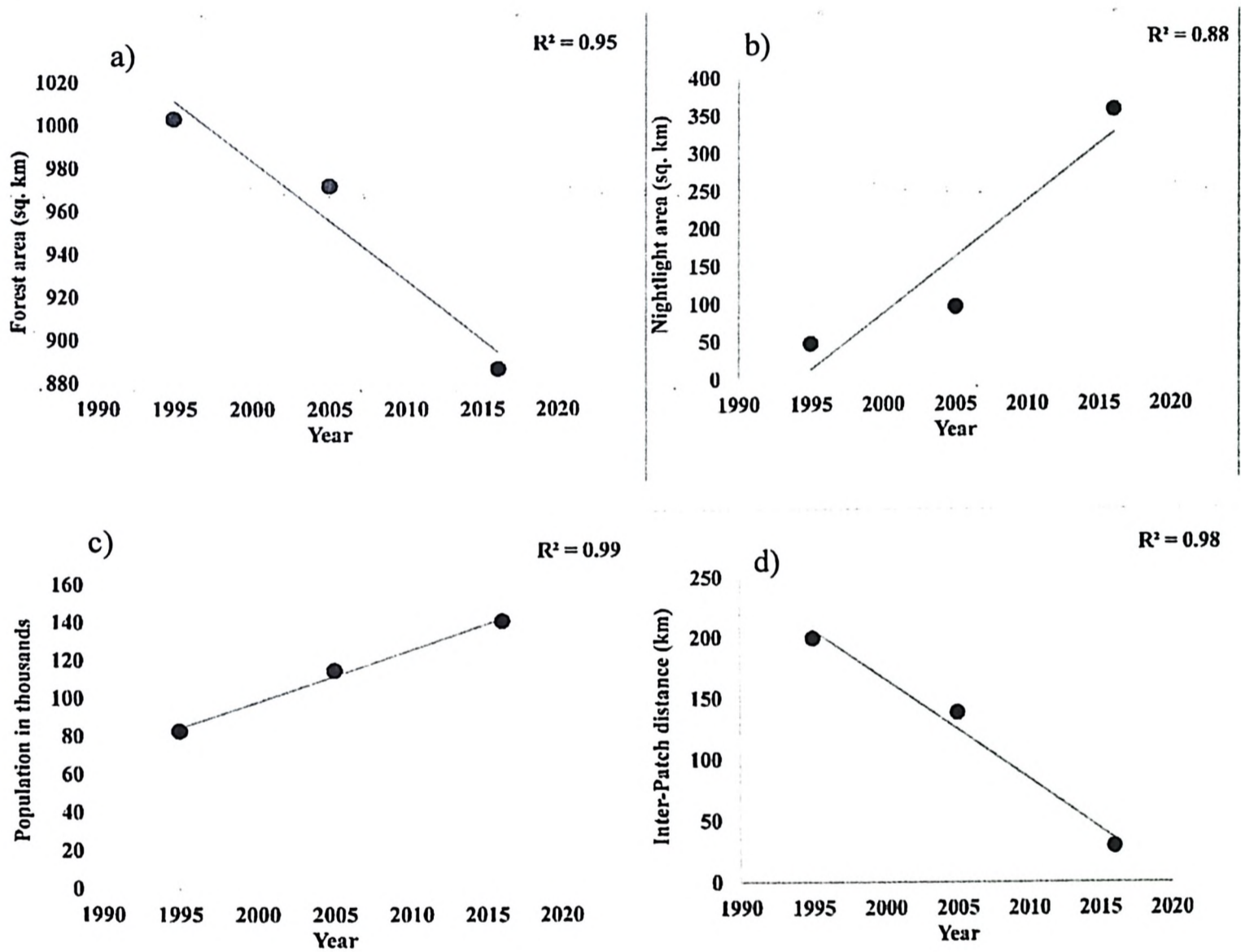


Figure 3-19: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches Bandhavgarh–Sanjay Dubri–Guru Ghasidas National Park corridor

c) Threats and weak links

The Bandhavgarh landscape holds one of the highest densities of the tiger, the leopard and deer species and is a new home of the gaur. Therefore, this corridor is crucial for populating other protected areas with these species and for maintaining the viability of the population of the landscape. However, the landscape unit is also a potential belt for mining different minerals, especially coal. Therefore, a very careful approach is required when sanctioning different developmental projects within this region. The area is rich in mineral resources including coal, iron ore and copper. Two of the major coalfields are threatening the contiguity of the forest patches in this area. These are the Shohagpur coal blocks, near Link II, in Shahdol District, and the Singrauli coal blocks, to the north of Sanjay Dubri National Park. The Shohagpur coal blocks fall within 10 km of Bandhavgarh Tiger Reserve, and they threaten its connections with Achanakmar. The Shohagpur coal blocks almost cut across Link II near the villages of Mirada, Patori and Semra. Also, a few blocks of the Singrauli coalfield are affecting the forest patches connecting Bagdara Wildlife Sanctuary, in the north, along with the Dongrital–Mahan–Chhatrasal and Amelia corridors (Fernandes and Shivlingam 2011). Recently, the government has also given a clearance for mining in the Mahan forests for coal. The movements of tigers, leopards and elephants in these connections have been reported, and sustaining these forest patches is vital for their movements. Other major threats to this corridor are the network of state highways across the forest patches and spreading agricultural activities.

A total of six weak links have been identified in this corridor (Table 3-10). Four of them are in North Shahdol Division (Figure 3-17 and Annexure-II). Immediate attention is required to strengthen weak links 3 and 4. At present, the landscape matrix is permeable, and restoration is possible through agroforestry/plantation options.

Table 3-10: List of weak links in Bandhavgarh–Sanjay Dubri–Guru Ghasidas corridor

S.No	Name	Nearby landmark	Latitude	Longitude	Problem
1	Weak link 1	Gohparu range (South shahdol) near amjhor village	23 31 09.78 N	081 24 33.06 E	Corridor is connected through degraded forest with less than 0.6 km width SH-9 crossing the forest patch
2	Weak link 2	Kuwarpur range (Mahendragarh) near badhwar village	23 44 29.89 N	081 50 54.10 E	fragmented forest and agriculture
3	Weak link 3	Beohari West range (North shahdol) near tikhwa village	24 01 03.55 N	081 14 06.87 E	Corridor width is less than optimum ~0. 0.8 km
4	Weak link 4	Godawal range (North shahdol) Near jhalra village	23 52 48.40 N	081 17 17.48 E	Linkage is almost broken, high agricultural activities
5	Weak link 5	Amjhor range (North shahdol)	23 51 26.74 N	081 32 05.06 E	Highly fragmented corridor
6	Weak link 6	Beohari East range (North shahdol)	24 10 17.09 N	081 24 22.82 E	Corridor is broken here

3.3.2.3. Kanha–Achanakmar

The corridor connects the source population of Kanha Tiger Reserve with Achanakmar, passing through the intact forest of East Mandla and Dindori forest divisions, in Madhya Pradesh, and Kawardha Division, in Chhattisgarh (Table 3-4 and Figure 3-20). The corridor also connects with Boramdeo National Park through Boramdeo Division, and it is important to maintain the meta-populations of this landscape. The Kanha–Achanakmar forest connectivity is the only crucial link that connects sub-populations of the Kanha–Pench landscape with Bandhavgarh through Achanakmar. Around 53 villages are present in the corridor habitat.

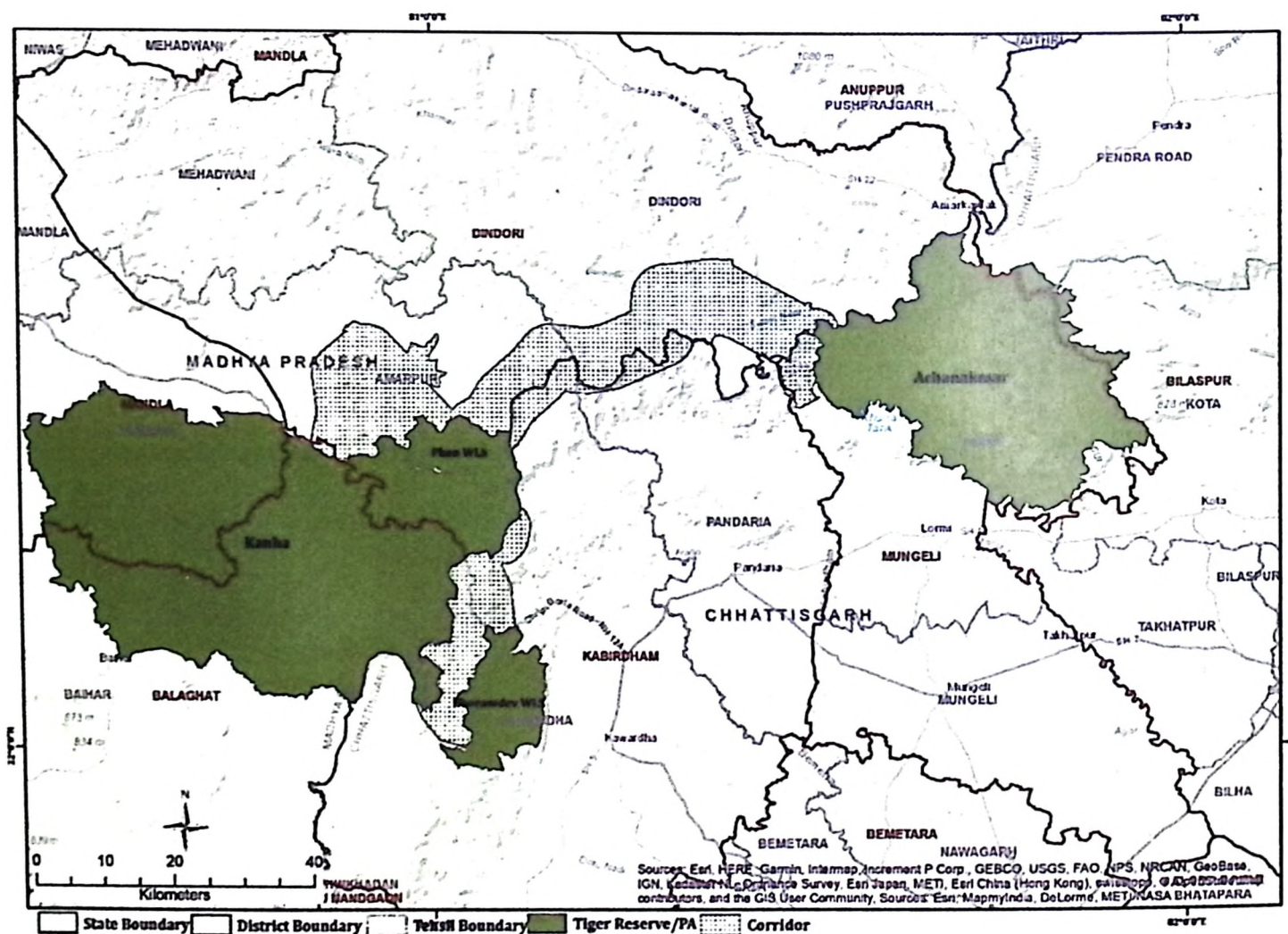


Figure 3-20: Location map of Kanha–Achanakmar corridor, central India

a) Forest cover change

A decline in the forest area since 1995 of around 60 km², at an annual rate of 0.5%, has been detected. The percent loss in forest area was almost the same in the two time periods, representing 9% of the overall loss in the green cover (Table 3-5 and Figure 3-21 and Figure 3-22).

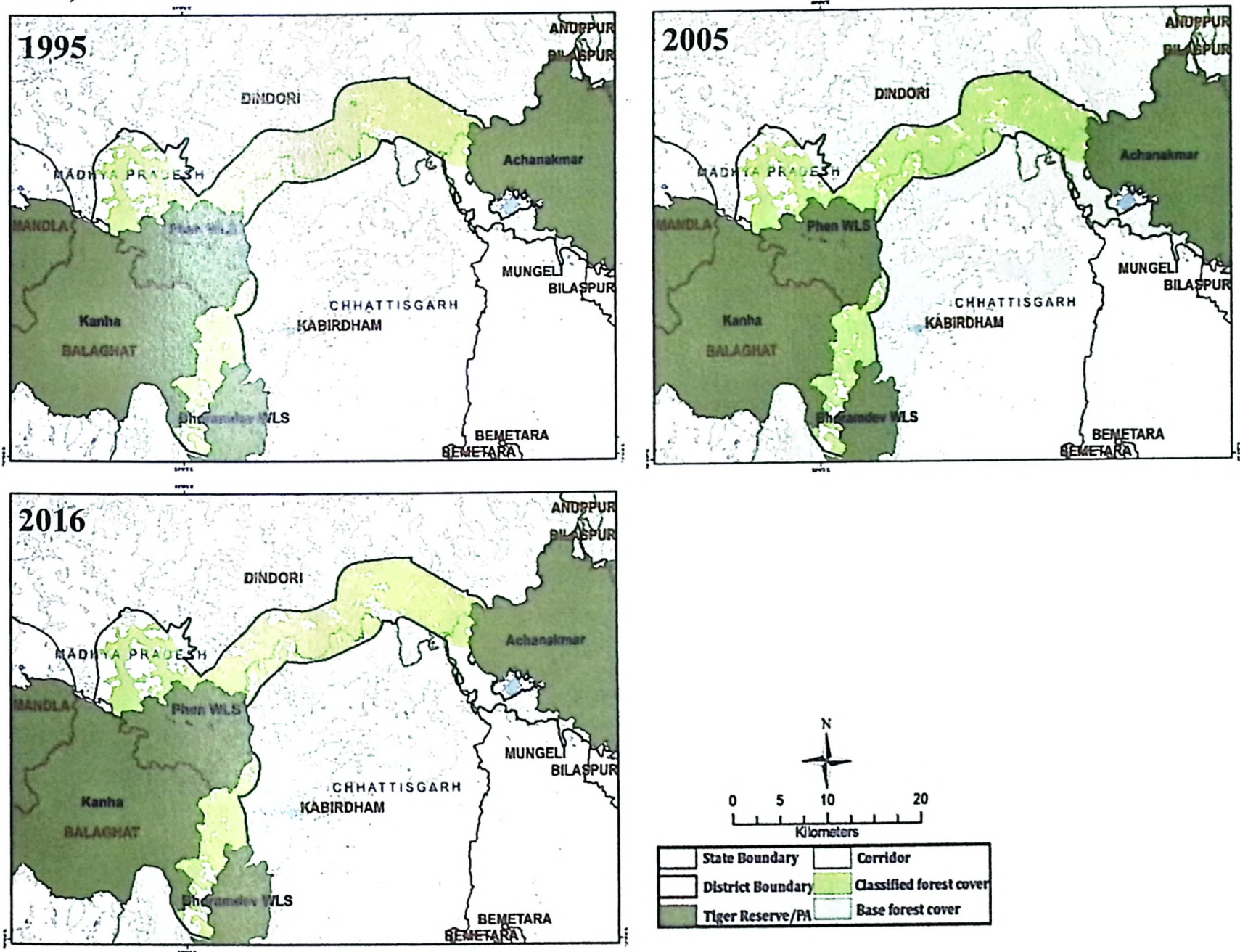


Figure 3-21: Forest cover in Kanha–Achanakmar corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

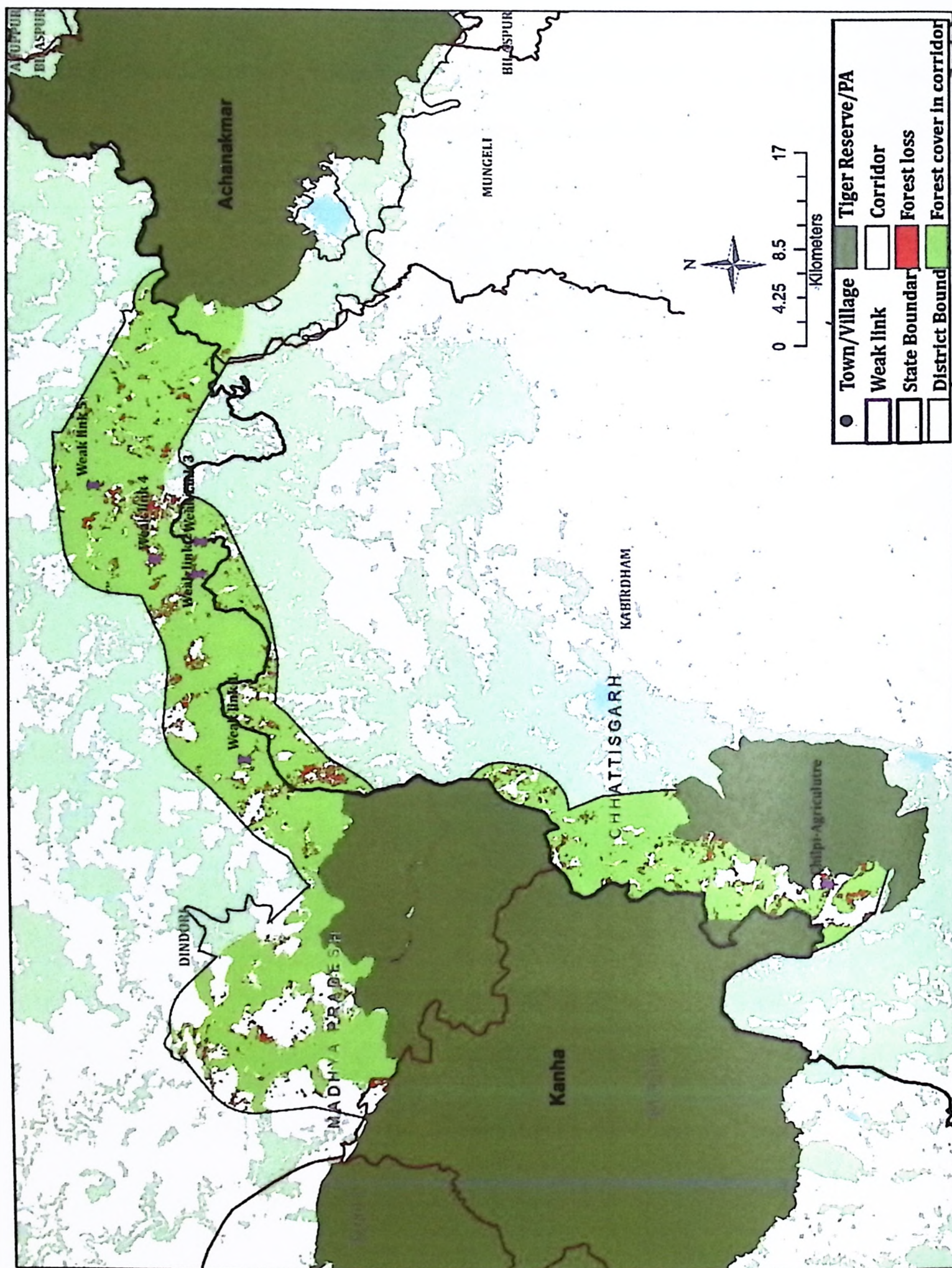


Figure 3-22: Forest cover change in Kanha-Achanakmar

b) Geographic and demographic change analysis

Nighttime lights change analysis

The corridor region was only partially developed until 2005. In 2016, nighttime lights were detected in the area (Table 3-6). The total area under nighttime lights was 92 km², with an inter-patch distance of 43 km, indicating that there were a large number of human clusters in the region (Table 3-7 and Figure 3-23).

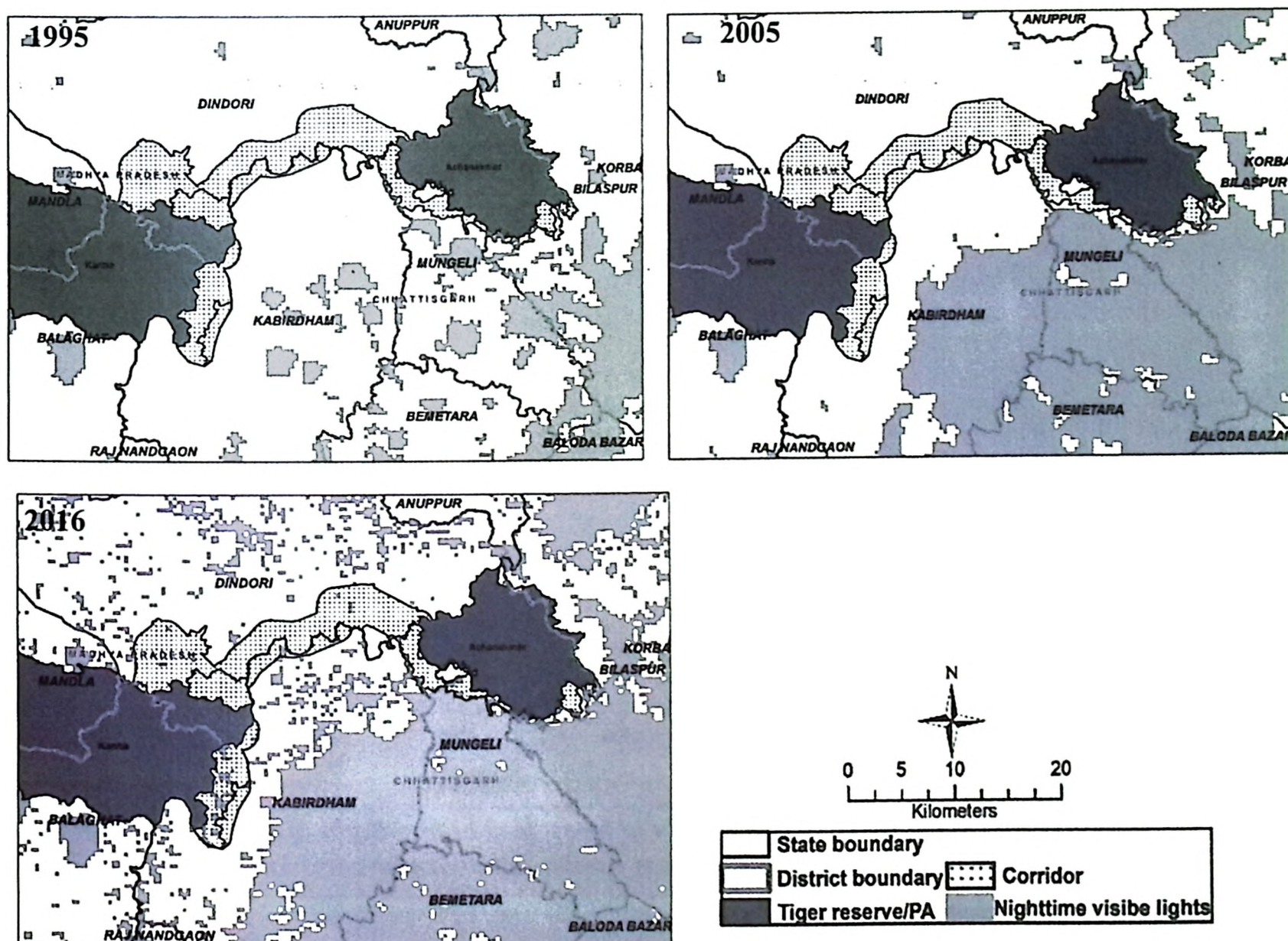


Figure 3-23: Growth in nighttime lights area during 1995–2016 in the Kanha–Achanakmar corridor

Demographic changes

An overall increase in the population of 30% was reported from this area. The growth of the population in this region has taken place at a rate of 2% per year, with highest growth being in the decade 2005–2016 (Table 3-8). A comparison of the trends in the geographic extent, urban expansion and forest loss shows a significant relationship (Figure 3-24).

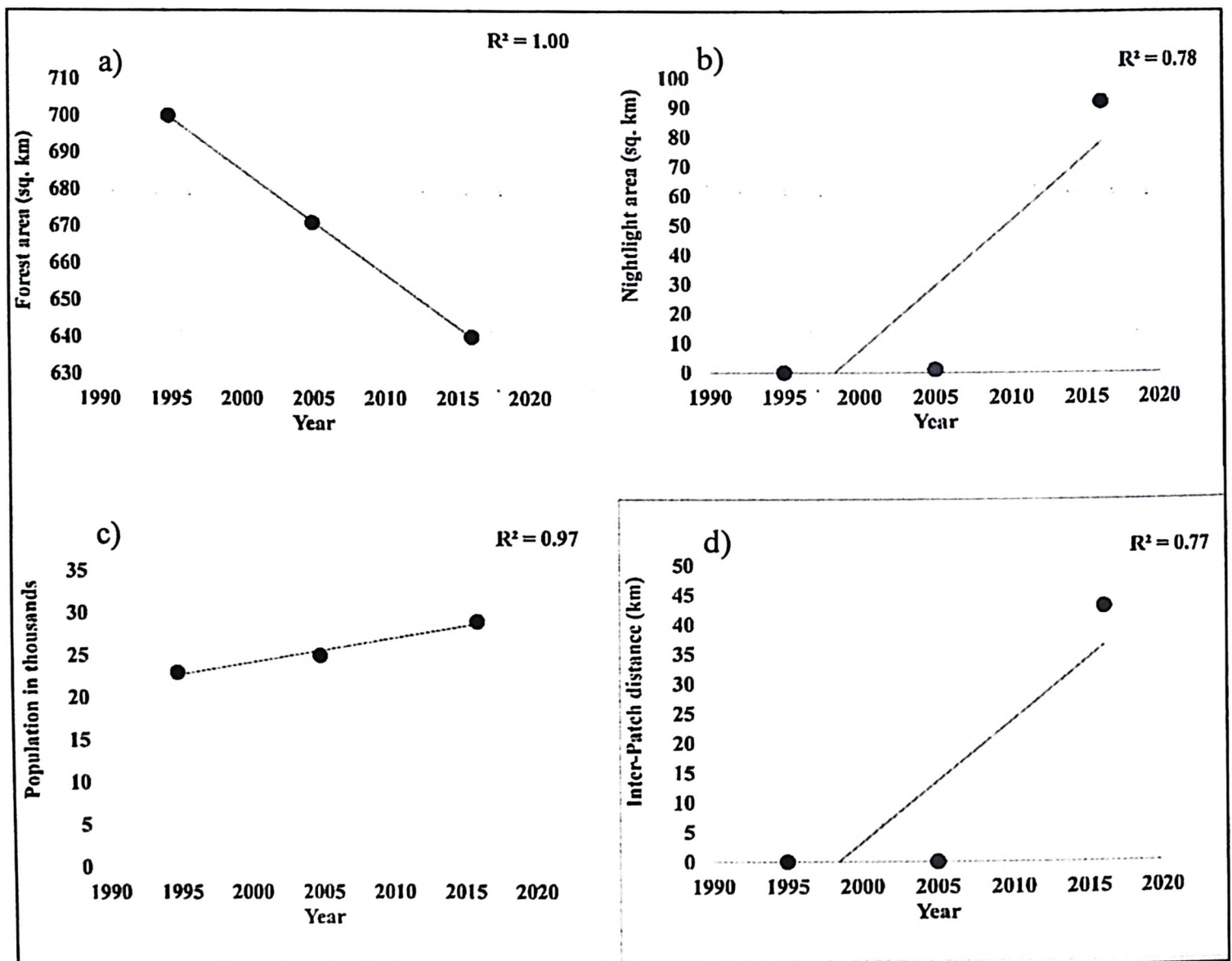


Figure 3-24: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches Kanha-Achanakmar corridor

c) Threats and weak links

The Kanha–Achanakmar and Kanha–Boramdeo corridors are significant for the dispersal and breeding of wild animals in the landscape to maintain the meta-population dynamics. The forested linkage provides a safe passage for the sub-populations of the Kanha–Pench landscape with Achanakmar. This corridor is the only route connecting the important source

population of Kanha–Pench with the Bandhavgarh–Sanjay Dubri landscape complex. Although the corridor passes through contiguous forest patches that are rich with plants and animals, there are many local communities living inside these forests. The forest resources, along with their ecosystem services, meet the basic livelihood and social requirements of these communities. Therefore, securing this corridor would need an integrative approach considering the requirements of the locals and their participation. There are a total of six locations where the corridor needs attention (Table 3-11). Links 2, 3 and 5 are crucial for maintaining the corridor connectivity in Dindori Division (Annexure II).

Table 3-11: List of weak links in Kanha–Achanakmar corridor

S.No	Name	Forest range & division	Latitude	Longitude	Problem
1	Weak link 1	Mawai range (East mandla)	22 28.20 N	081 08.10E	Fragmented landscape with agriculture and linear development Corridor width is 0.18 km, connected by narrow strip of forest
2	Weak link 2	South samnapur (Dindori) forest range Border of south samnapur	22 30.22N	081 17.49E	Forest patch is connected via strip of 0.15 km width
3	Weak link 3	(Dindori) forest range Border of Bajag range (Dindori)	22 30.10N	081 19.13E	Patchy landscape with scattered agriculture fields Connectivity is fragmented and is connected through thin strip of vegetation, width is less than 0.15 km
4	Weak link 4	near Kadawani village	22 32.18N	081 18.24E	Area is full of agriculture fields SH-9 cuts the corridor at several places Agriculture landscape, corridor is getting narrower
5	Weak link 5	Bajag range (Dindori)	22 34.95N	081 21.97E	
6	Weak link 6	Rengakhar and Chilpi range (Kawardha)	22 02.58N	081 01.83E	

3.3.2.4. Kanha–Pench corridor

This corridor connects the two most important source populations of central India, Kanha and Pench tiger reserves (Figure 3-25). The forest linkage provides a safe route for the movements of large mammals such as the tiger, leopard, sloth bear, sambar and gaur and is a refuge for other small species as well. The corridor is crucial for the dispersal and viability of the species dwelling in the two protected areas and is the most crucial forest connectivity in India. The two protected areas are connected through the two linkages, one passing through Mandal, Senoi Forest Division, and the other connected through the forests of Balaghat Division, with a total length of approximately 175 km. The corridor passes through three districts of Madhya Pradesh, namely, Mandla, Seoni and Balaghat districts, and there are around 114 villages inside the corridor (Table 3-4).

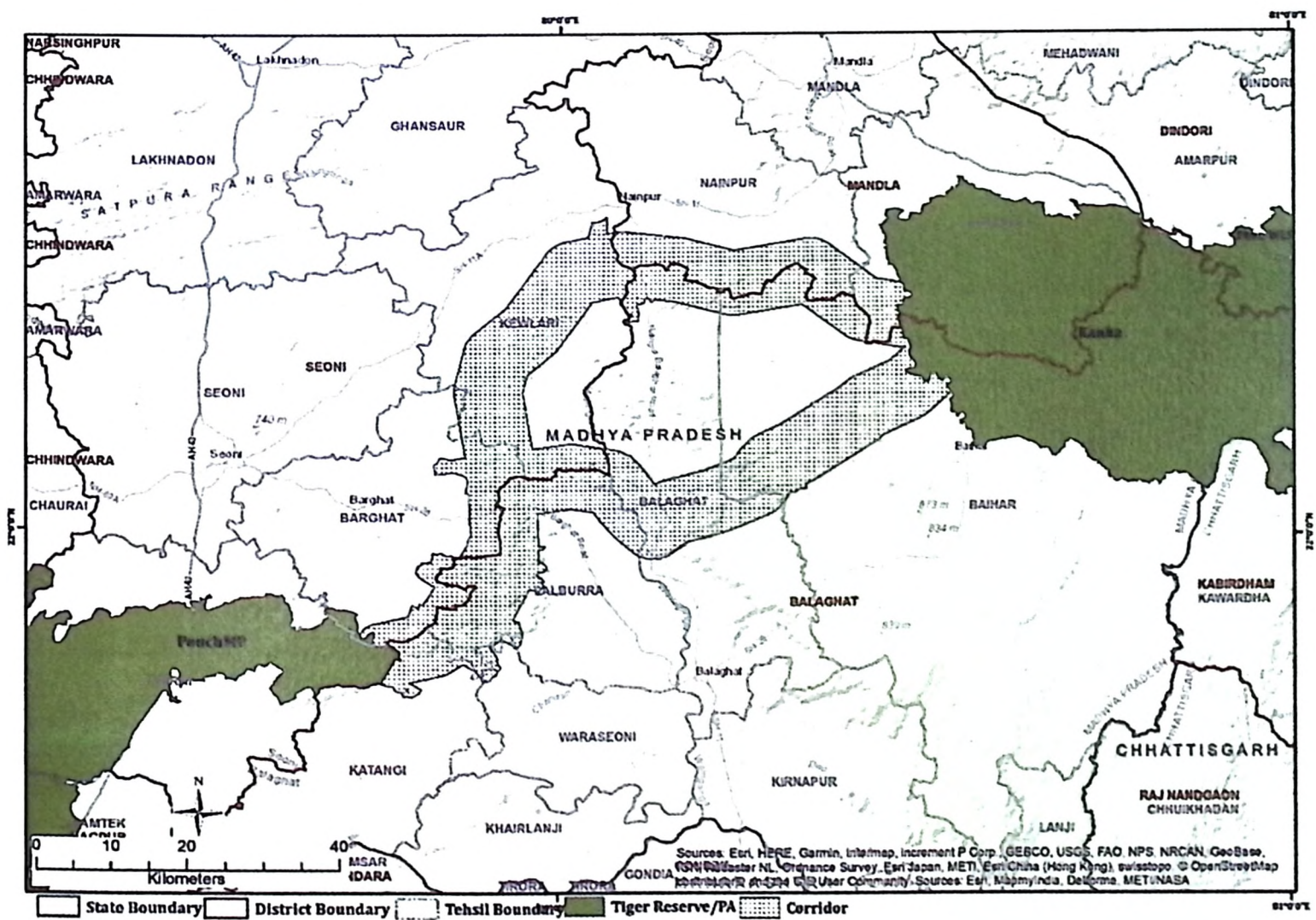


Figure 3-25: Location map of Kanha–Pench corridor, central India

a) Forest cover change detection

The forest area has been declining at a rate of 0.1% in the last two decades, with 22 km² of forest area being lost (Table 3-5 and Figure 3-26). This figure seems to be minimal, but the corridor is facing a threat of fragmentation due to increasing developmental activities, which have destroyed it at several places. New human settlements and expansion of old ones were observed on analysis of the satellite images, indicating fragmentation of forest patches.

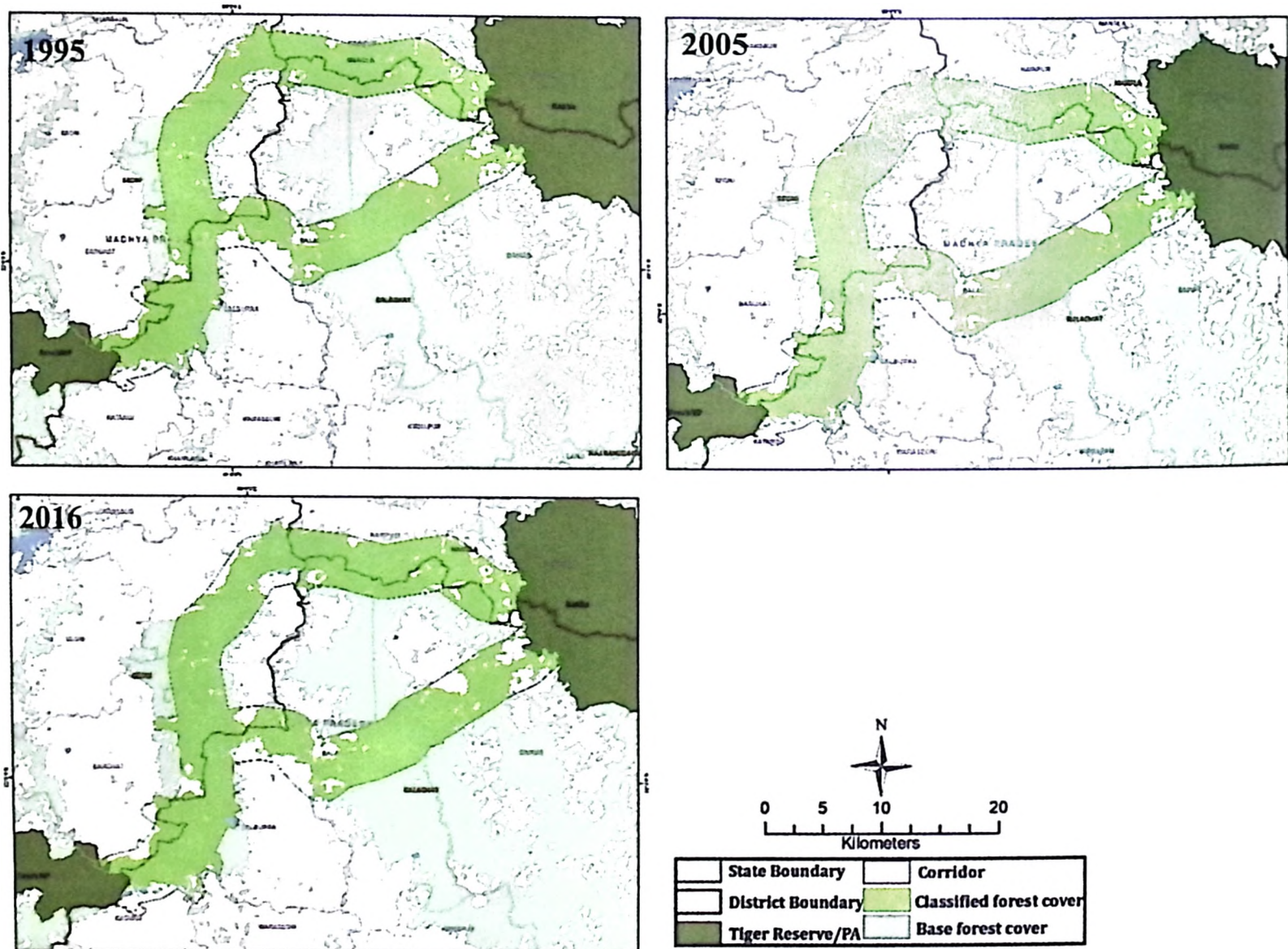


Figure 3-26: Forest cover in Kanha–Pench corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

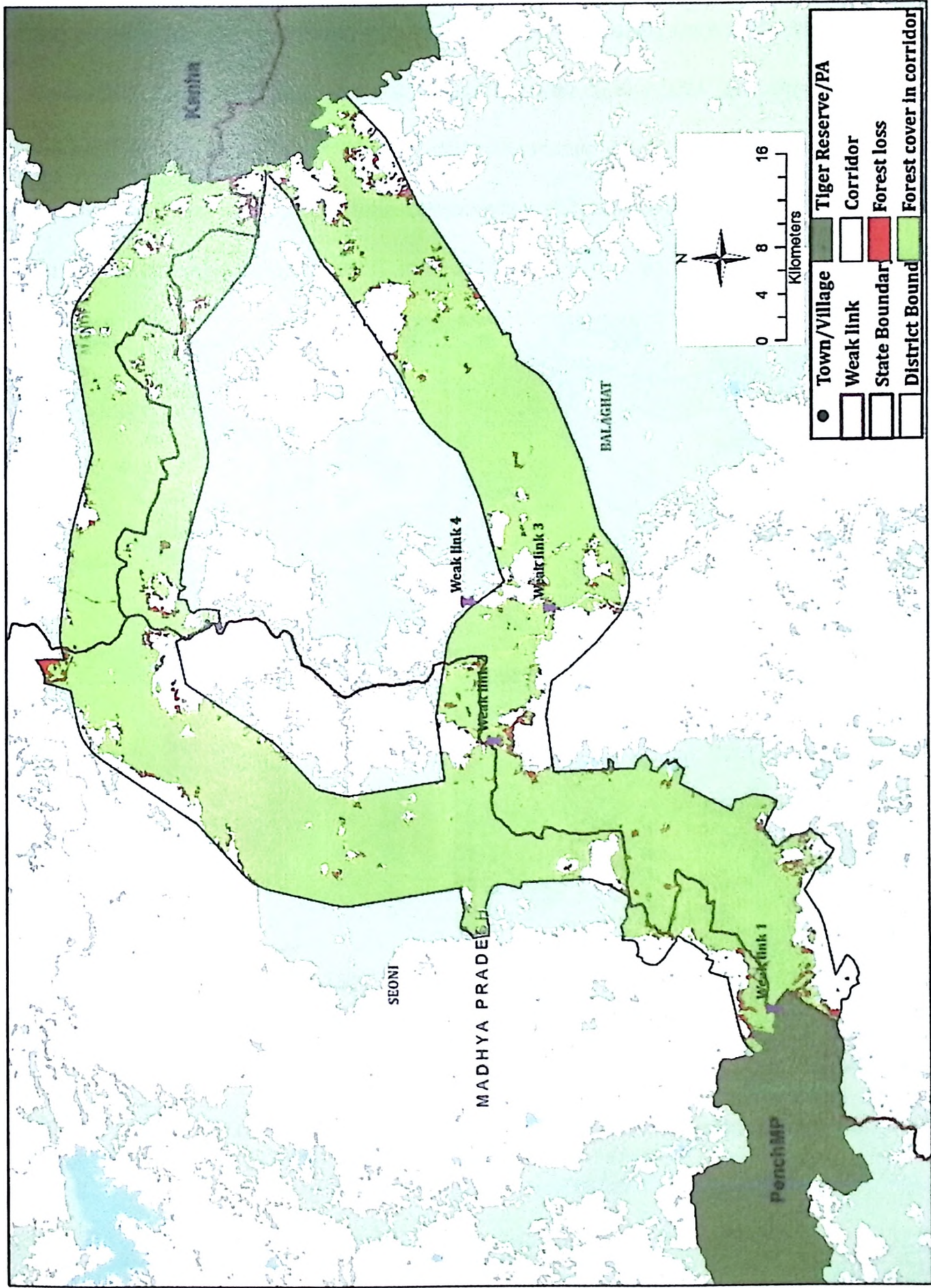


Figure 3-27: Forest cover change in Kanha-Pench corridor during 1995-2016

b) Geographic and demographic change analysis

Nighttime lights change analysis

A 28% growth in nighttime lights may be observed in the corridor area, with 17 new patches becoming visible after 1995 and 23 lit areas visible after 2005 (Table 3-6). The inter-patch distance was calculated for these patches, and it declined from 78 km in 1995 to 33 km, indicating an increase in the extent of the urban centres in the last 20 years (Table 3-7, Figure 3-28).

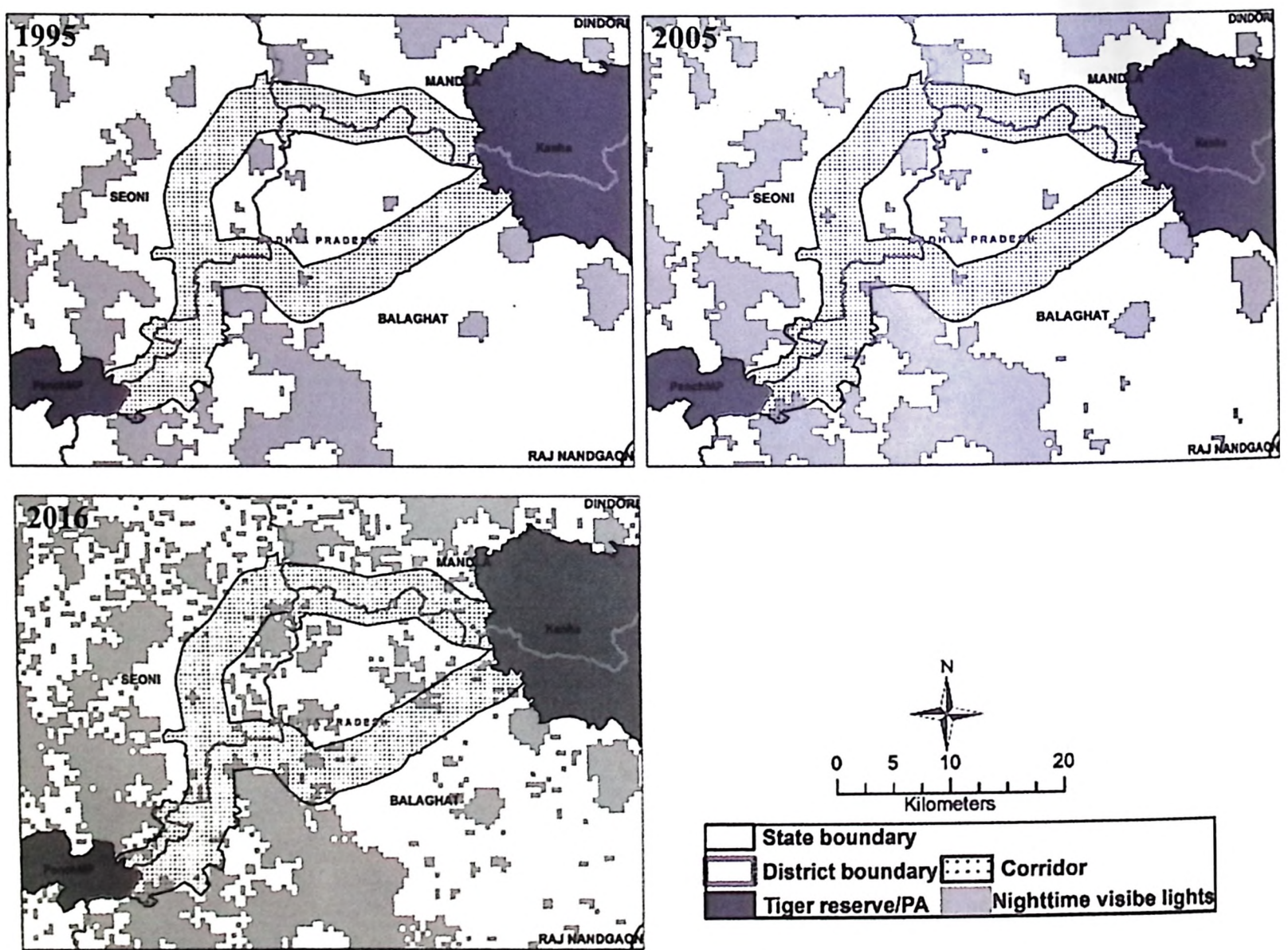


Figure 3-28: Growth in nighttime lights area during 1995–2016 in Kanha–Pench corridor

Demographic changes

Census estimates show an increase of 19% in the population of these 48 villages, at a rate of 0.9% per annum. The area has also grown in terms of households, and there were 6753 new households after 1991. The households have grown at a rate of 0.4% per annum, which shows that one new household was generated for every two persons (Table 3-8). Though the forest loss was not significant, the area has seen an expansion of the urban areas as the inter-patch distance has declined rapidly after 2005.

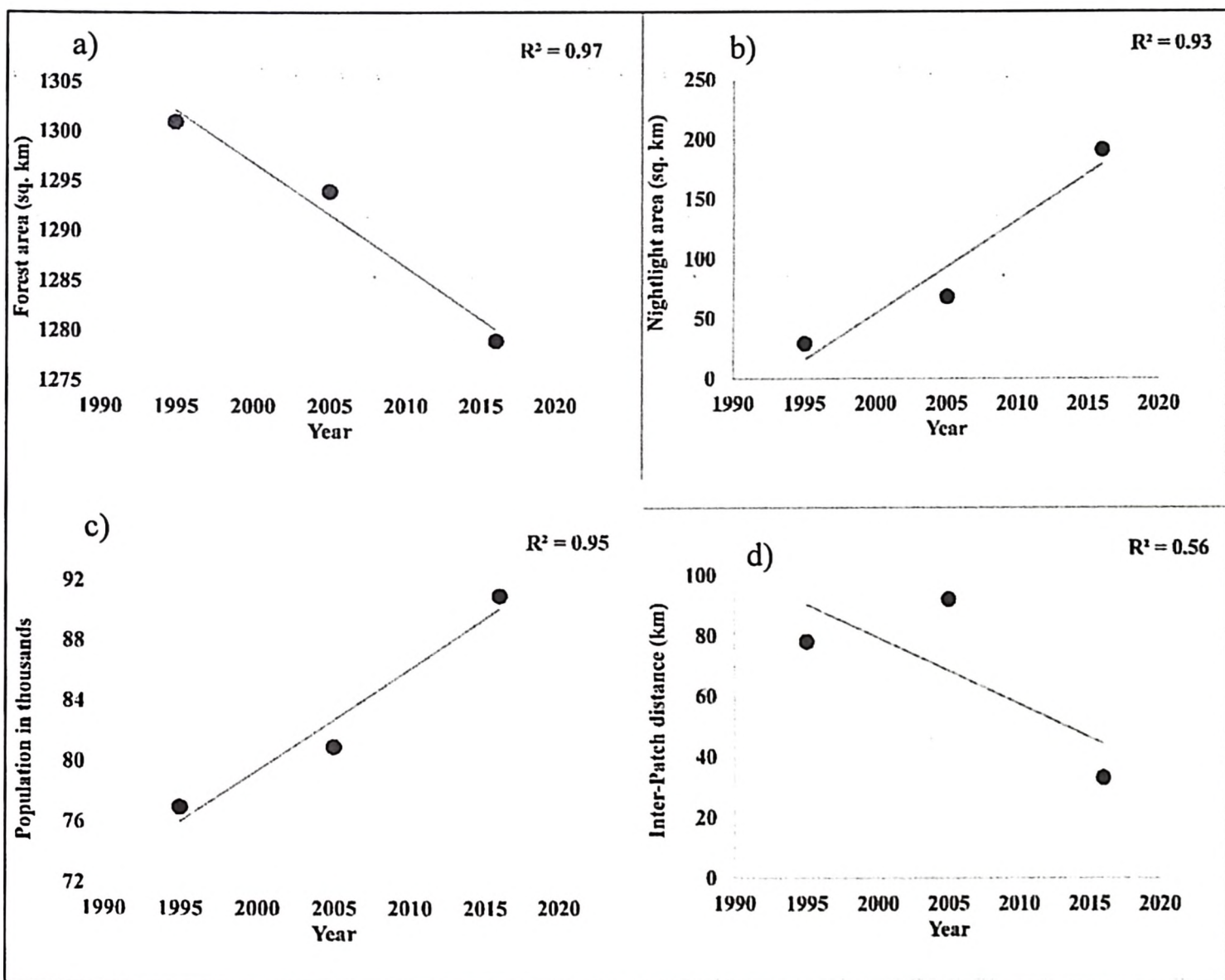


Figure 3-29: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches Kanha-Pench corridor

c) Threats and weak links

Many studies have found that tigers and other small mammals are using this corridor to disperse into the Satpura–Melghat unit and to the other adjacent protected areas. The entire corridor is under pressure because of various human activities, livestock grazing and developmental expansion. The growth in human population and tourism around the two tiger reserves has also exacerbated the cases of human–wildlife conflict, which could affect the perception of local people regarding the conservation of this connectivity (Borah et al. 2011). Therefore, if this corridor is not planned or managed properly, the dispersal of animals in the future could be hindered, turning Kanha and Pench into ecological islands.

Mining activities, construction of new roads and widening of existing roads and railway tracks are some of the major threats to this vital connectivity. The corridor is weak at four locations (Table 3-12) where the landscape is highly fragmented. Sustaining the linkage requires mitigation measures. Weak link 1 is the most vital for maintaining the connectivity of Pench with the other parts of the landscape. The corridor is weak here due to the fragmentation of the Rukhad forest patch by National Highway 7(NH 7) just after the Pench Tiger Reserve boundary. The presence of the highway has been detrimental for animals using this corridor, having caused several deaths in the past because of heavy uncontrolled traffic. The other three links are also important for maintaining an alternative corridor to Kanha from Pench. Link-II is significantly fragmented and stressed around the three weak links (2, 3 and 4) in North Balaghat Division (Annexure II). Here, four of the state highways cross the corridor, especially SH-11, which crosses Balaghat Forest Division near Mohgaon Khurd and Amoli village. The forest connectivity is further getting fragmented near Bhalewada village area by these road and railway networks. The presence of roads and railway lines in these forest patches can prove to be detrimental for the wildlife of the area in terms of increasing the number of deaths on the tracks and hindering the movements of

animals. Forest-restorative measures should be taken through agroforestry and regulations for linear infrastructure adopted for the safe passage of wild animals.

Table 3-12 List of weak links in Kanha–Pench corridor

S.No	Name	Nearby landmark	Latitude	Longitude	Problem
1	Weak link 1	Ari, near rukhad	21 51.28N	079 46.71E	Corridor is dissected by road-SH-54 Corridor width is less than 3 km , forest clearing further aiding fragmentation
2	Weak link 2	Lal Bara range (South Balaghat)	22 04.12N	079 59.88E	Highly fragmented patch, 4 linear structure including SH-11 and Railway line
3	Weak link 3	South lamta (North Balaghat)	22 01.57N	080 06.43E	Corridor is connected through a narrow forest patch of around 2km width 3 linear developments are crossing the linkage
4	Weak link 4	South lamta (North Balaghat) near Amoli	22 05.33N	080 06.74E	(SH-11 and Railway line)

3.3.2.5. Simlipal–Satkosia

Odisha has a vast, contiguous forest spread throughout the state, and wildlife species are reported to be found almost everywhere in these forests. Two tiger reserves, Simlipal and Satkosia, in the state are connected with the forest patches of Mayurbhanj, Kendujhar, Jajapur, Dhenkanal and Angul districts, creating a viable tiger corridor (Table 3-4). The corridor between the two tiger reserves is long and fragile, passing through human-dominated areas. The fragmented forest patches are connected, forming a stepping stone corridor between the two tiger reserves. The corridor is 235 km long, passing through nine forest divisions spread across six districts (Figure 3-30). Around 236 villages are present in the corridor region.

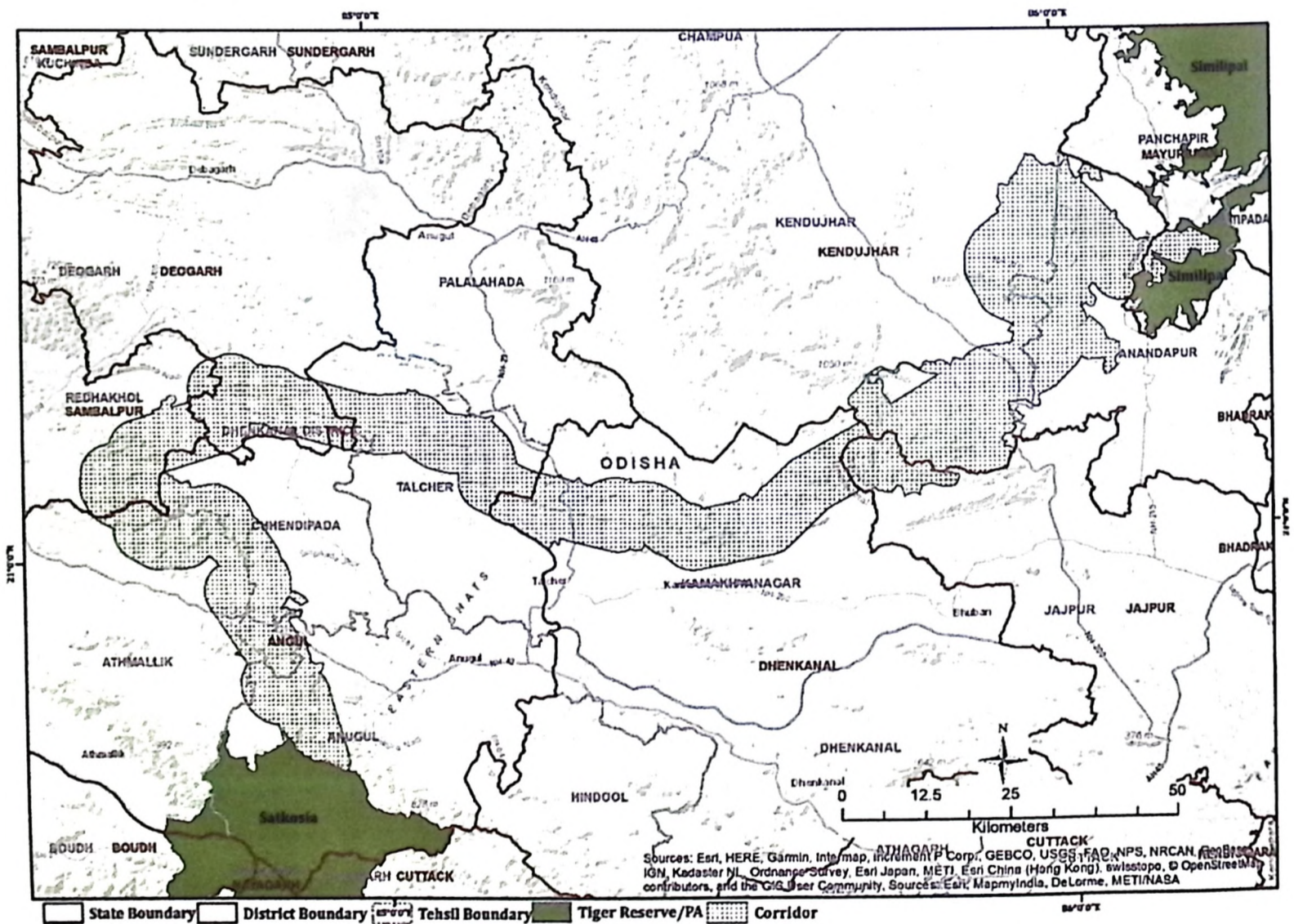


Figure 3-30: Location map of Simlipal–Satkosia corridor, central India

a) Forest cover change detection

The forest cover map of 1991 shows that the landscape was already fragmented and that there were a few forest patches that were connected through the complex terrain. During the past 20 years, 73 km² of forested area was lost (Table 3-5 and Figure 3-32). The rate of change was 0.2% per annum. The change map prepared for the decade 1995–2005 shows that the forested area was modified by development activities of the mining sector. Analysis of the changes that occurred during 2005–2016 showed a regeneration of forests in the region where mining was carried out. The regeneration was in some areas, and the quality of forest was not degraded in areas that were already forested, but a few forest patches were lost due to coal mines, such as Talcher, near Kaniha and Balanda. The forest patches of Kaniha and Talcher ranges provide stepping stone connectivity with Dhenkanal Division. Kaniha and Talcher ranges provide stepping stone connectivity with Dhenkanal Division.

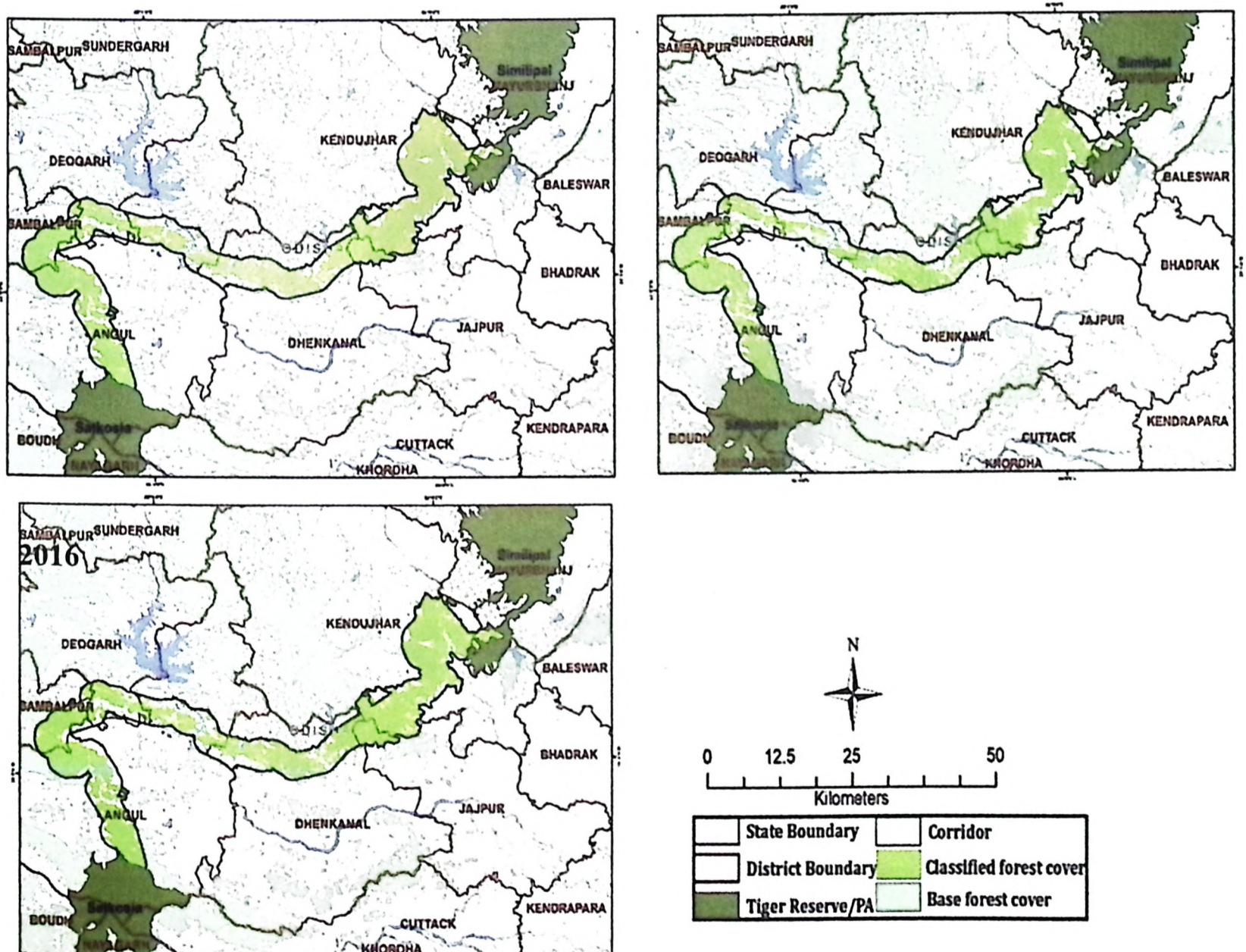


Figure 3-31: Forest cover in Simlipal-Satkosia corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

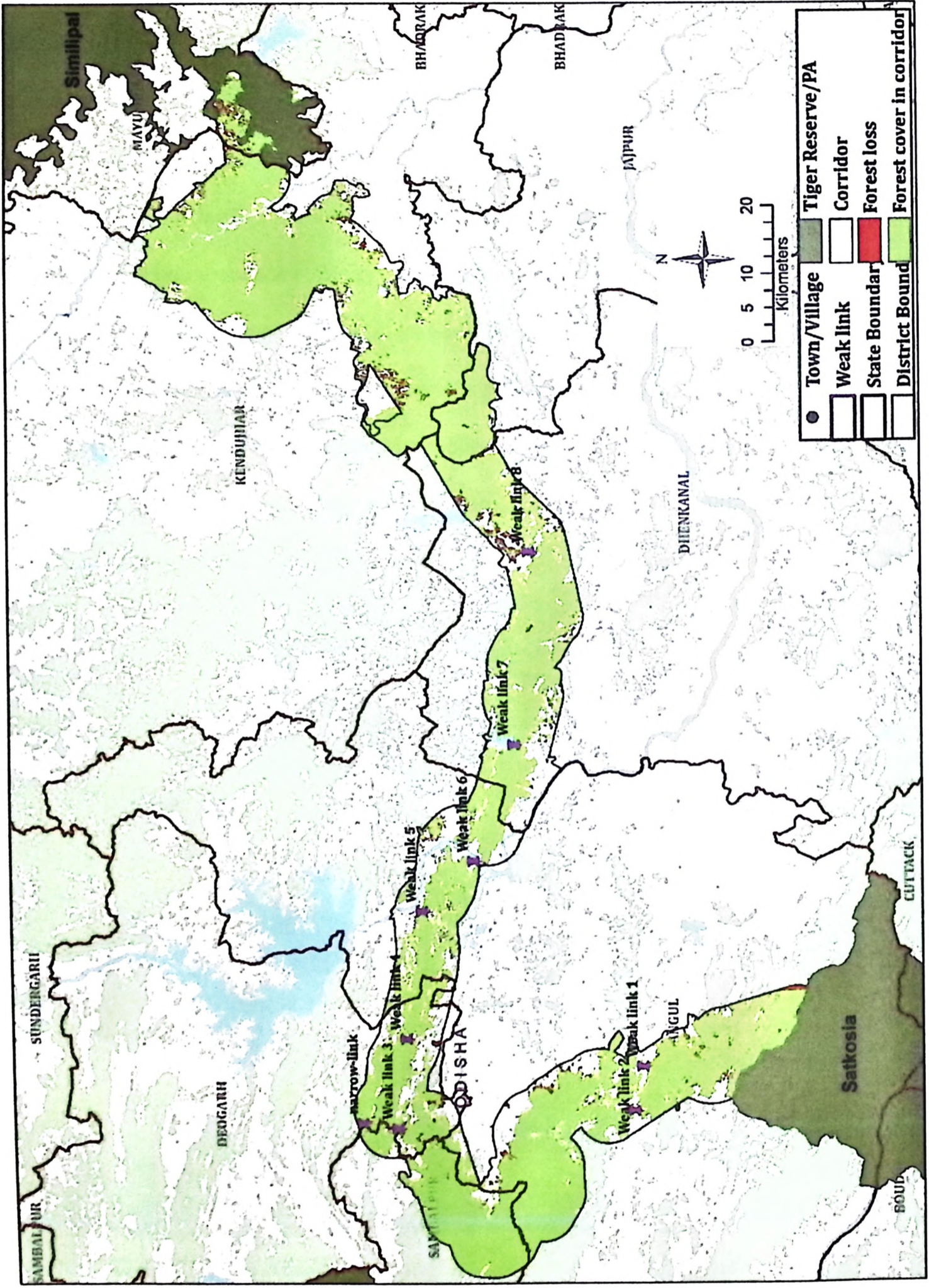


Figure 3-32: Forest cover change in Simlipal-Satkosia corridor during 1995-2016

b) Geographic and demographic change analysis

Nighttime lights change analysis

The area of the nighttime lights increased all over the corridor at a rate of 10% per year from 1995 (Table 3-6 and Figure 3-33). As a result of the rate at which development has taken place in the region, the number of nightlight patches in the entire corridor increased from nine to 84. Further, there was a reduction in the inter-patch distance, from 100 km in 1995 to 28 km in 2016 (Table 3-7), indicating that small urban patches were merging into continuous urban areas and fragmentation of new patches.

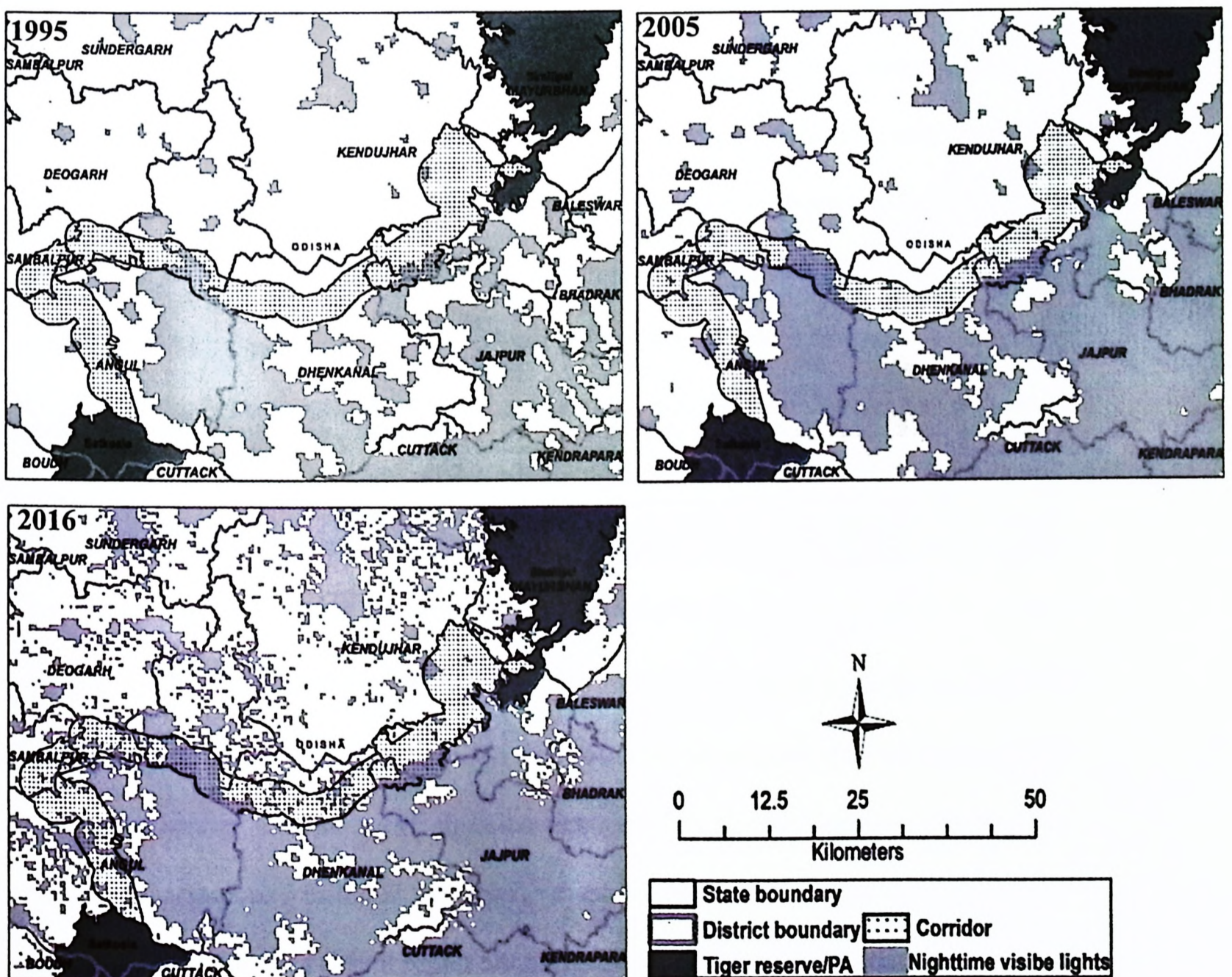


Figure 3-33: Growth in nighttime lights area during 1995–2016 in Simlipal–Satkosia corridor

Demographic changes

Demographic analysis of the villages in the corridor indicates that there was a 35% change in the population in a 20-year span of time (Table 3-8). The population grew at a rate of 2% per year.

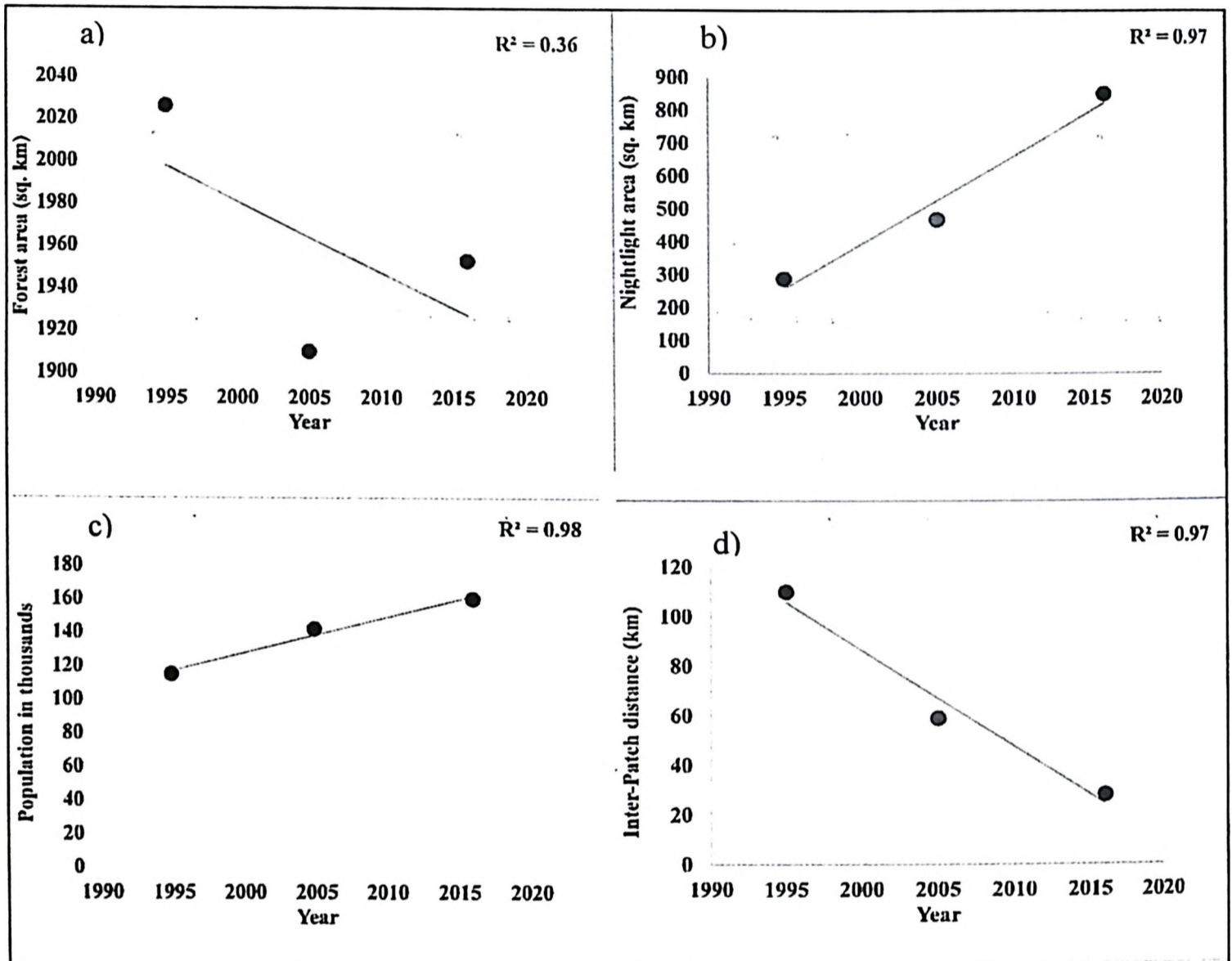


Figure 3-34: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches Simlipal-Satkosia corridor

c) Threats and weak link

Simlipal has the only meaningful population of tigers in the entire state. Safeguarding the connectivity between Satkosia and the other adjacent forest patches is crucial. Recently, tiger signs have been discovered in the nearby Hadagarh Wildlife Sanctuary. This suggests that a population of tigers may be established in the future in this area. The tiger densities of the two protected areas are reported to be low, but they are known to sustain a variety of

other carnivore and herbivores species such as the leopard, gaur, sambar and barking deer. The reserves also have potential habitat to support a good number of tigers, but a safe dispersal route for individuals to form a demographically stable population.

Odisha is one of the most mineral-rich states of India. Compared with other forest linkages in the country, this corridor has the largest number of infrastructure elements. Four national highways, two state highways and a few other roads cut across the corridor. There are eight locations where the connectivity is weak or completely broken (Table 3-13)

The corridor is highly fragmented, and at places only thin forest strips are remaining. Immediate action is required at these locations to maintain this corridor (Annexure II). It is important to address the mitigation measures in these weak links (weak links 1, 2, 4 and 5) as there is no alternative linkage in the landscape connecting Simlipal with Satkosia. Vegetation restoration, traffic regulations such as speed control and temporary blocking of traffic, especially during the night, and construction of underpasses or overbridges should be carried out according to the findings of a ground survey. Another major threat to this corridor is the presence of Talchar coalfield, to the north of Satkosia, in Angul District. The coalfield occupies a large area near the corridor and has a substantial overlap with the forest patches, which have a significant wildlife presence. Also, a part of the coalfield lies within the 10-km buffer of the corridor, threatening it further. One patchier corridor extends along the Brahmini River up to Satkosia. To ensure that this linkage is maintained, further infrastructure developments in the forest area should not be encouraged.

Table 3-13 List of weak links in Simlipal–Satkosia corridor

S.No	Name	Nearby landmark	Latitude	Longitude	Problem and Importance
1	Weak link 1	Durgapur range Near Katada Handapa range	20 54.19N	084 50.18E	Connectivity is only through the linear strip of forests. Cut by NH-42 and Canal
2	Weak link 2	near Kadalimunda	20 54.97915N	084 46.50E	Fragmented forest NH-42 and a canal is passing Connectivity is fragmented
3	Weak link 3	Reamal range near Kendupal Reamal range near	21 13.46N	084 45.57E	and narrow less than optimal width around 2km Crucial link to maintain the link bet ween two forest
4	Weak link 4	Talaranijharan village	21 12.58N	084 52.96E	patches, Dissected by NH-200 Linear strip of less than 0.2 is left
5	Weak link 5	Kaniha forest range Middle of kaniha and	21 11.00N	085 03.54E	Dissected by NH-200 and Baudabeda nalam road Corridor is broken due to water stream , high water levels can create temporal blockage in the connectivity
6	Weak link 6	talchar forest range	21 06.79N	084 46.08E	Width of linkage is less than 0.6 km
7	Weak link 7	Mahabirod forest range Kamakhyanagar	21 03.33N	085 17.28E	Disturbed by several linear infrastructure due to presence of reservoir Connectivity is patchy and surrounded by agricultural and human habitation
8	Weak link 8	(West) forest range	21 0125.92N	85 33 50.86E	

3.3.2.6. Guru Ghasidas–Lawalong

The corridor is 218 km long, stretching from Guru Ghasidas National Park, in Chhattisgarh, to Lawalong Wildlife Sanctuary, in Jharkhand. The contiguous forest patches of forest divisions of Guru Ghasidas National Park, Surajpur, Tamorpingla, Balrampur, Semarsot Wildlife Sanctuary, Palamau, Latehar, Garhwa and Medini Nagar (Table 3-4 and Figure 3-35) form it. The forest canopies of these divisions are good and provide continuous structural connectivity up to Lawalong Wildlife Sanctuary. There are around 180 villages in the corridor.

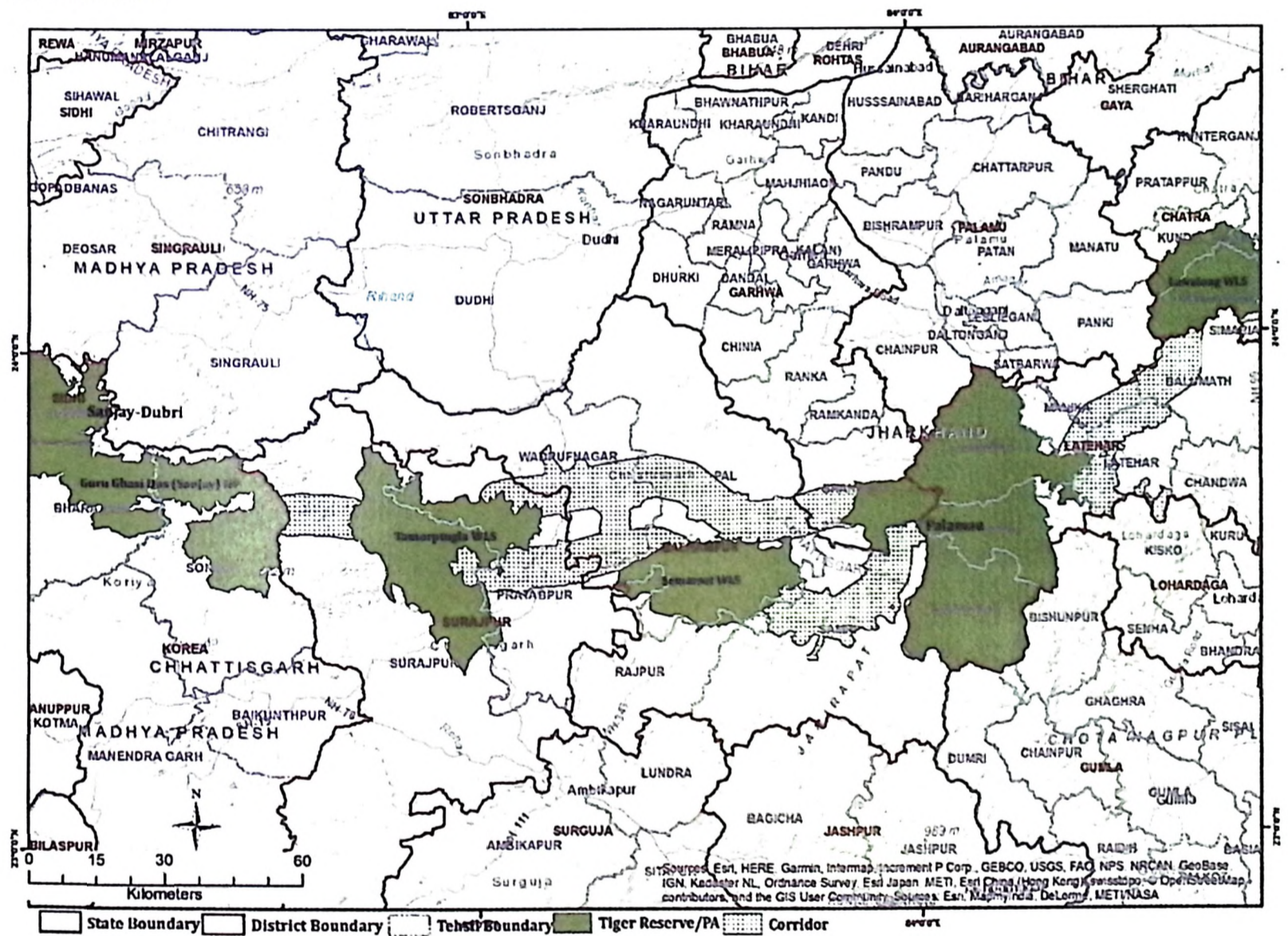


Figure 3-35: Location map of Guru Ghasidas–Lawalong corridor, central India

a) Forest cover change

The corridor has lost 37 km² (3%) of forest cover in the last 20 years (Table 3-5 and Figure 3-37).

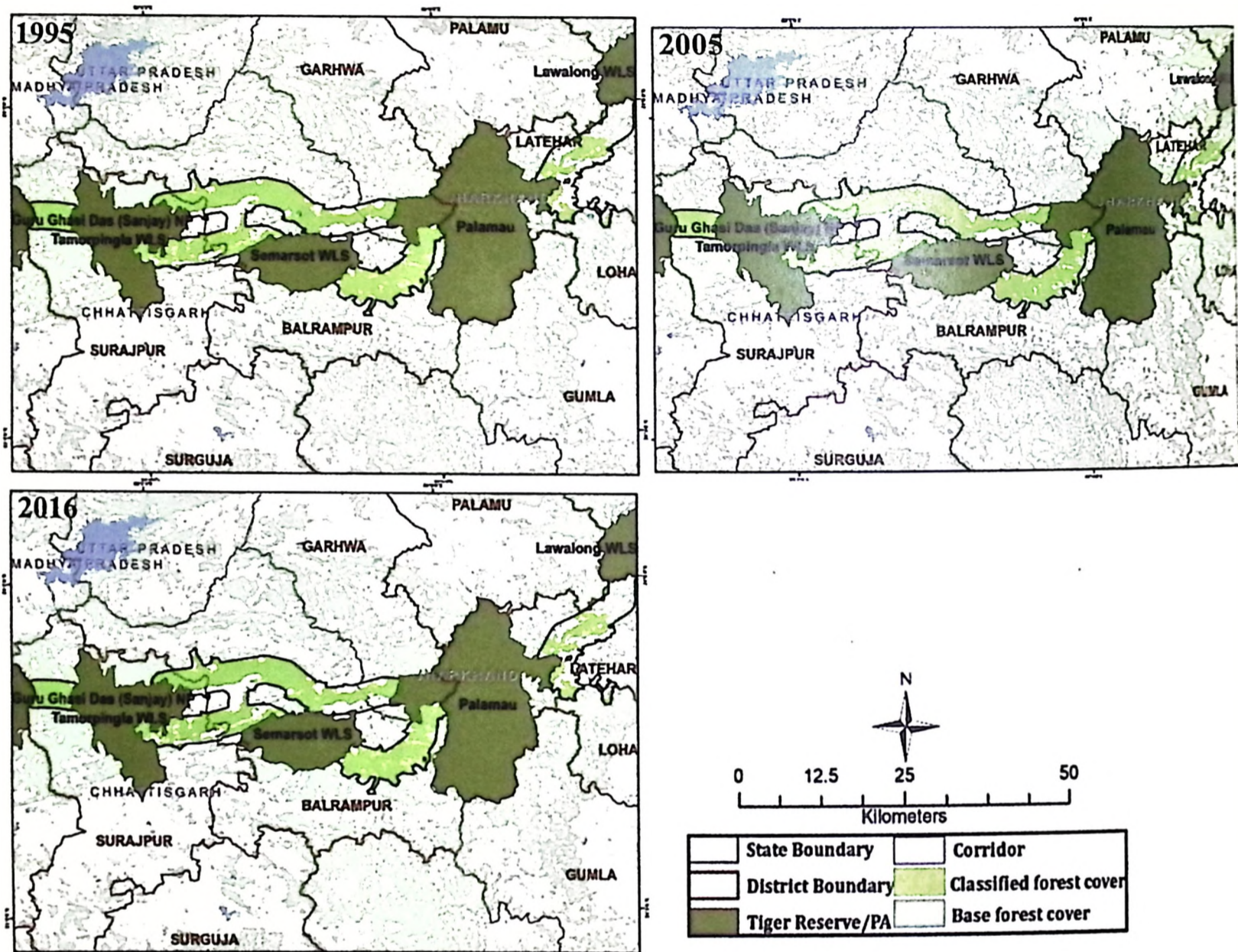


Figure 3-36: Forest cover in Guru Ghasidas–Lawalong corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

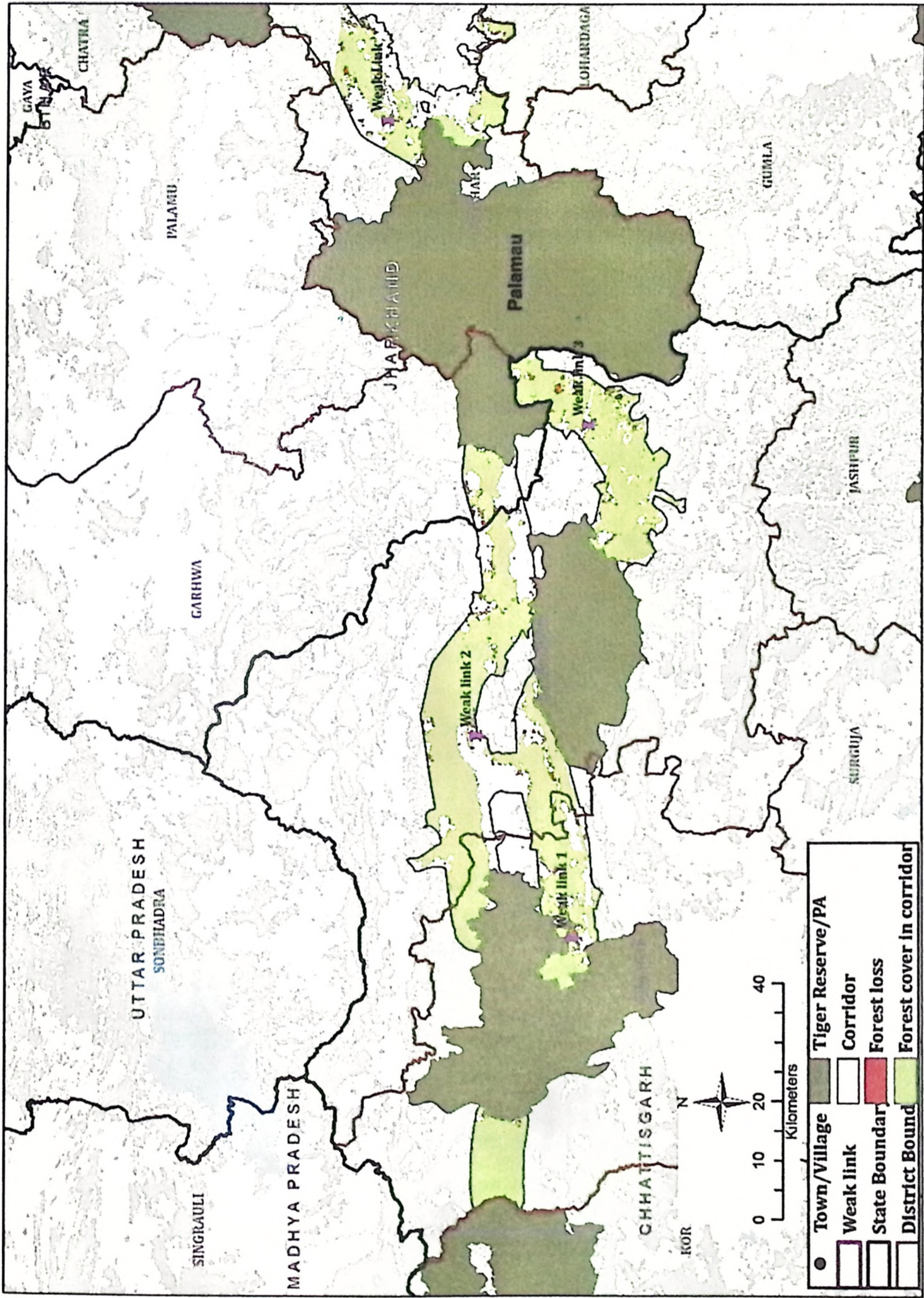


Figure 3-37: Forest cover change in Guru Ghasidas-Lawalong corridor during 1995-2016

b) Geographic and demographic change analysis

Nighttime lights change analysis

The nighttime lights data show that there was an increasing trend in the urban patches from 1995, but the growth was not noticeable till 2005, after which there was an exponential increase (Figure 3-38). The urban patches in the corridor region grew more than 10-fold after 2005. The number and extent of these patches are increasing, as indicated by the inter-patch distance reducing from 187 km to 30 km during 2005–2016 (Table 3-7).

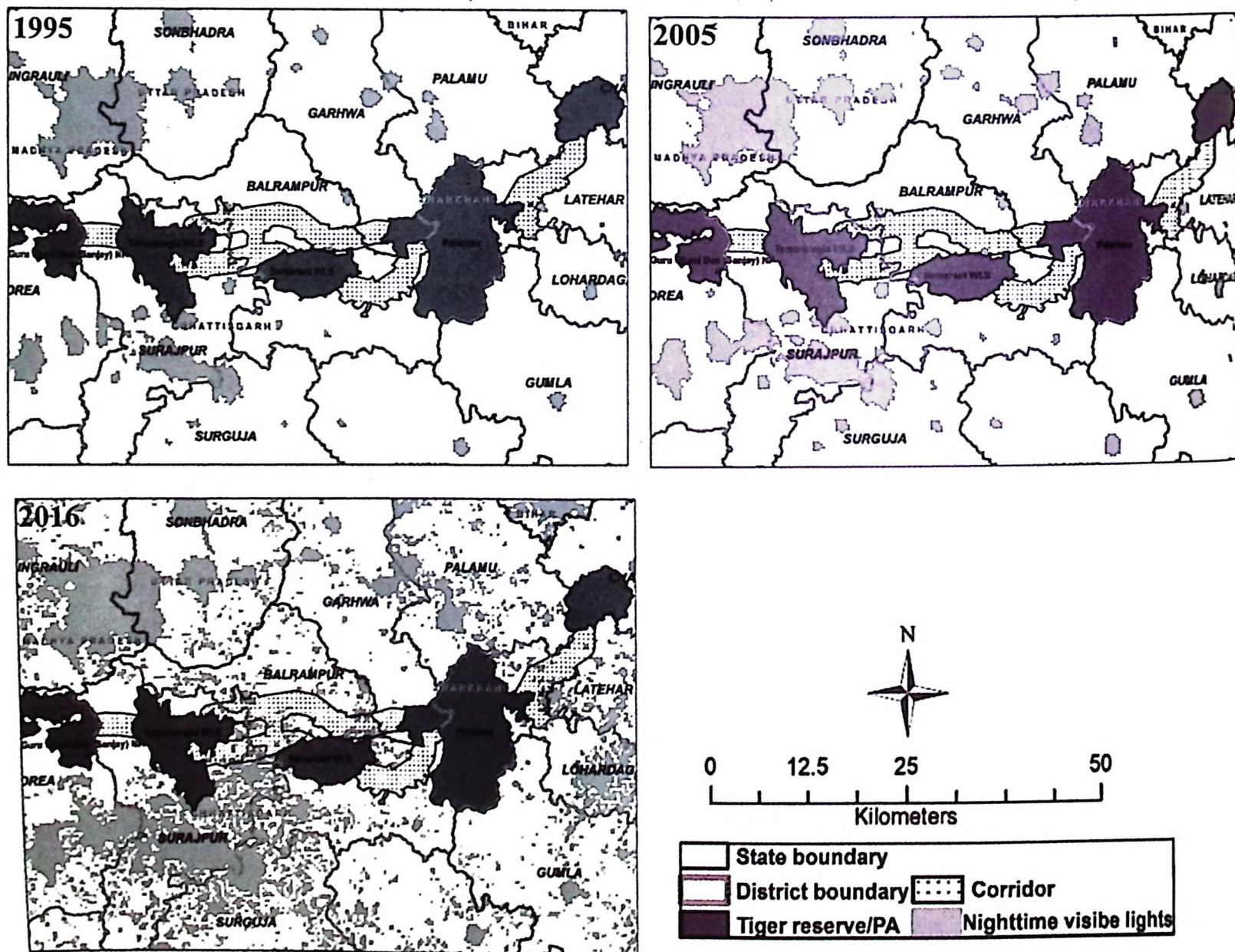


Figure 3-38: Growth in nighttime lights area during 1995–2016 in Guru Ghasidas–Lawalong corridor

Demographic changes

The human population in the corridor increased considerably from 1995. There was an overall growth of 47% in the two decades since then. The population growth during 1995–2005 was 1.8% per year, and the growth during 2005–2016 was 2.4% per year (Table 3-8). The total number of households in the region increased by 6.

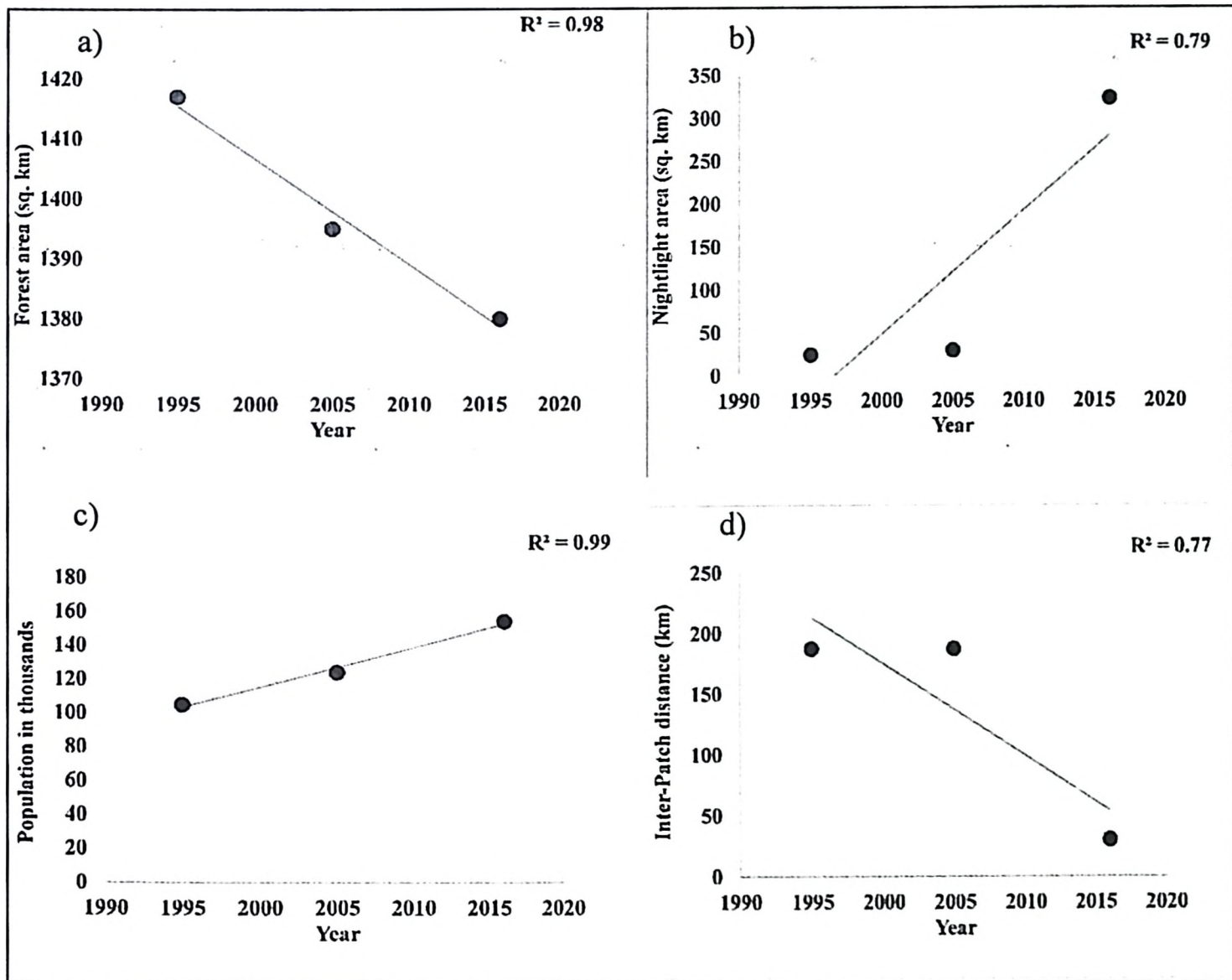


Figure 3-39: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches Guru Ghasidas–Lawalong corridor

b) Threats and weak link

Four weak links have been identified in the corridor (Table 3-14). All the four locations are crucial for maintaining the connectivity as the corridor is highly fragmented at these locations. If the fragmentation is not addressed, the corridor might get disconnected. These weak links are surrounded by agricultural fields (Annexure II).

Table 3-14: List of weak links in Guru Ghasidas–Lawalong corridor

S.No	Name	Location	Latitude	Longitude	Problem
1	Weak link 1	Ghui range, chirwan pat forest	23 32.78N	083 02.09E	Linkage is less than half a km, cut by road Only link to join two corridor links, narrow linkage
2	Weak link 2	Near Wadrufnagar forest range	23 41.48N	083 22.58E	disturbed by linear alignments
3	Weak link 3	West of Chando range forest	23 30.42N	083 53.87E	Narrow link of less than 0.5 km
4	Weak link 4	Ramchoura forest in balrampur range	23 48.52N	084 25.39E	Narrow link of less than 0.5 km

3.3.2.7. Pench–Satpura–Melghat

This corridor links the three major wildlife source areas of central India, the Pench, Satpura and Melghat tiger reserves. This is the second longest corridor identified in the landscape, having a total length of 443 km. The corridor passes through the fragmented forest patches of Chindwara Forest Division and North Betul Forest Division, after which it gets bifurcated into two habitat linkages. One habitat linkage connects Pench Tiger Reserve with the forests of Satpura through North Betul Forest Division. The other linkage connects Pench to Melghat Tiger Reserve through the forest patches of North Betul and parts of Harda and West Betul divisions. Another potential corridor exists to the north. The corridor is formed by the large, contiguous forests of the Hosangabad, Harda and Khandwa forest divisions of

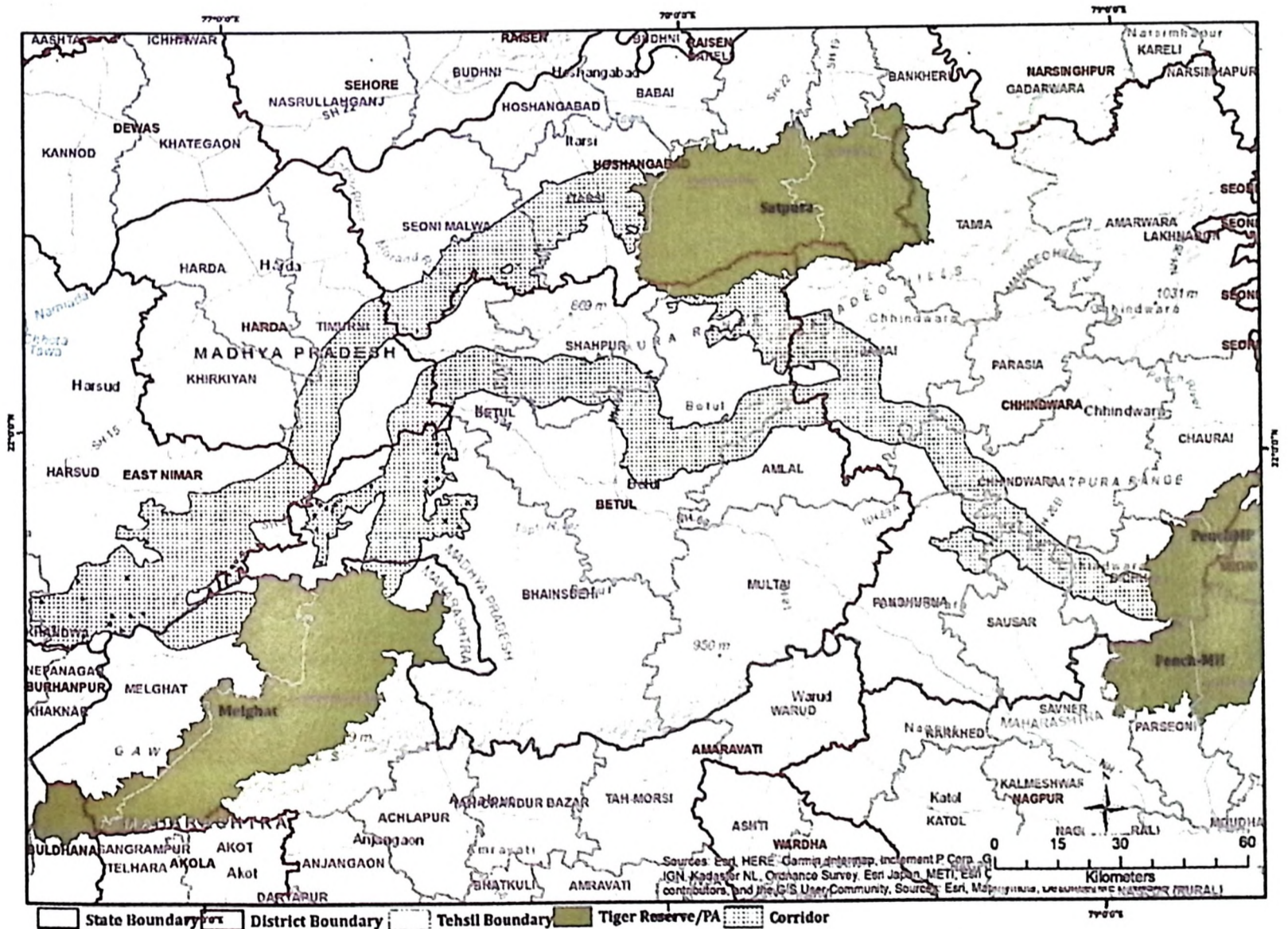


Figure 3-40: Location map of Pench–Melghat–Satpura corridor, central India

Madhya Pradesh (Table 3-4 and Figure 3-40). Around 270 notified human habitations (villages) are present in the corridor.

a) Forest cover change

The total forest area lost in the corridor region since 1995 in a period of 20 years is estimated to be 142 km² (4%) (Figure 3-41 and Figure 3-42). Most of the deforestation occurred during the decade 1995–2005, contributing 3% of the total forest loss (Table 3-5).

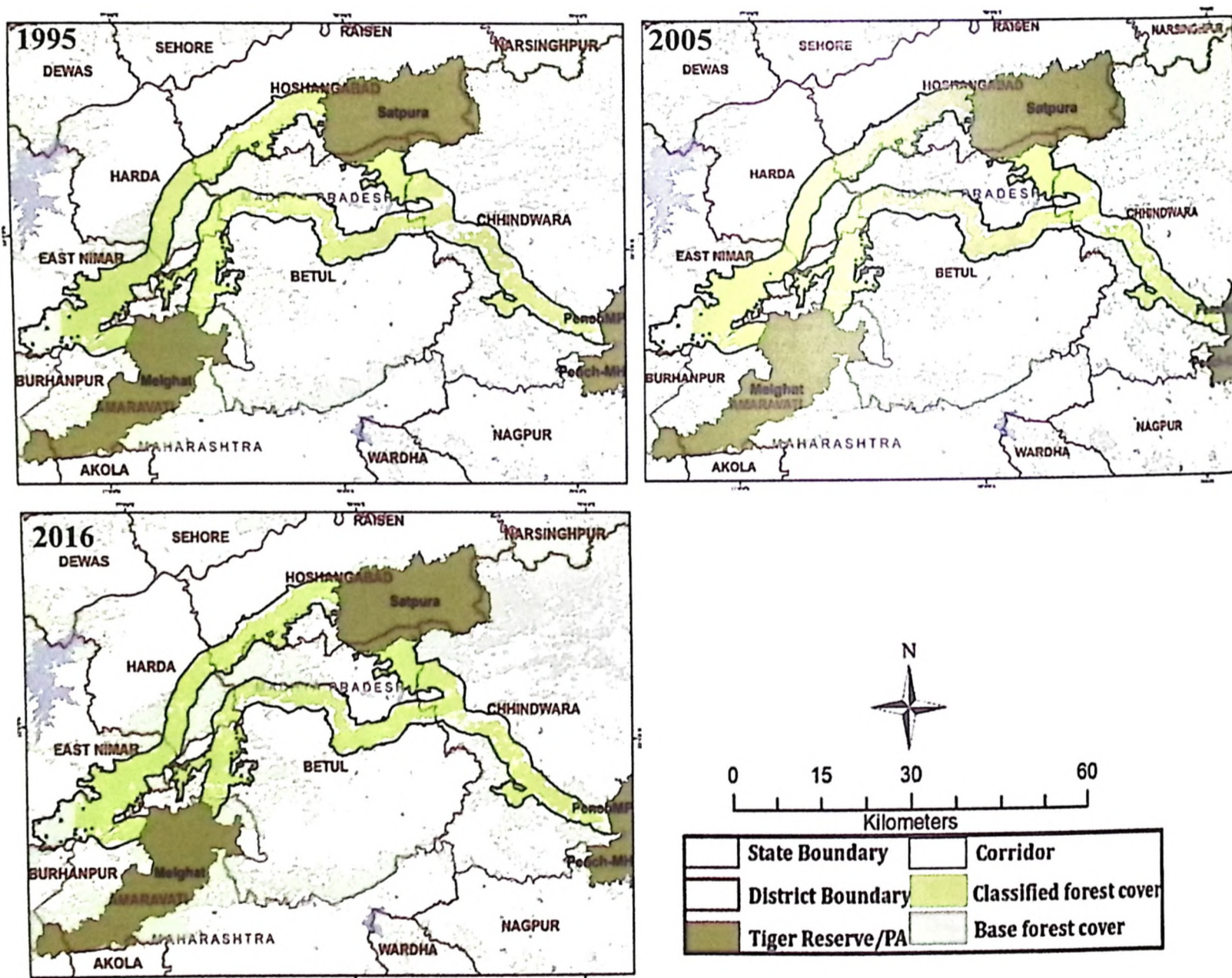


Figure 3-41: Forest cover in Pech-Melghat-Satpura corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

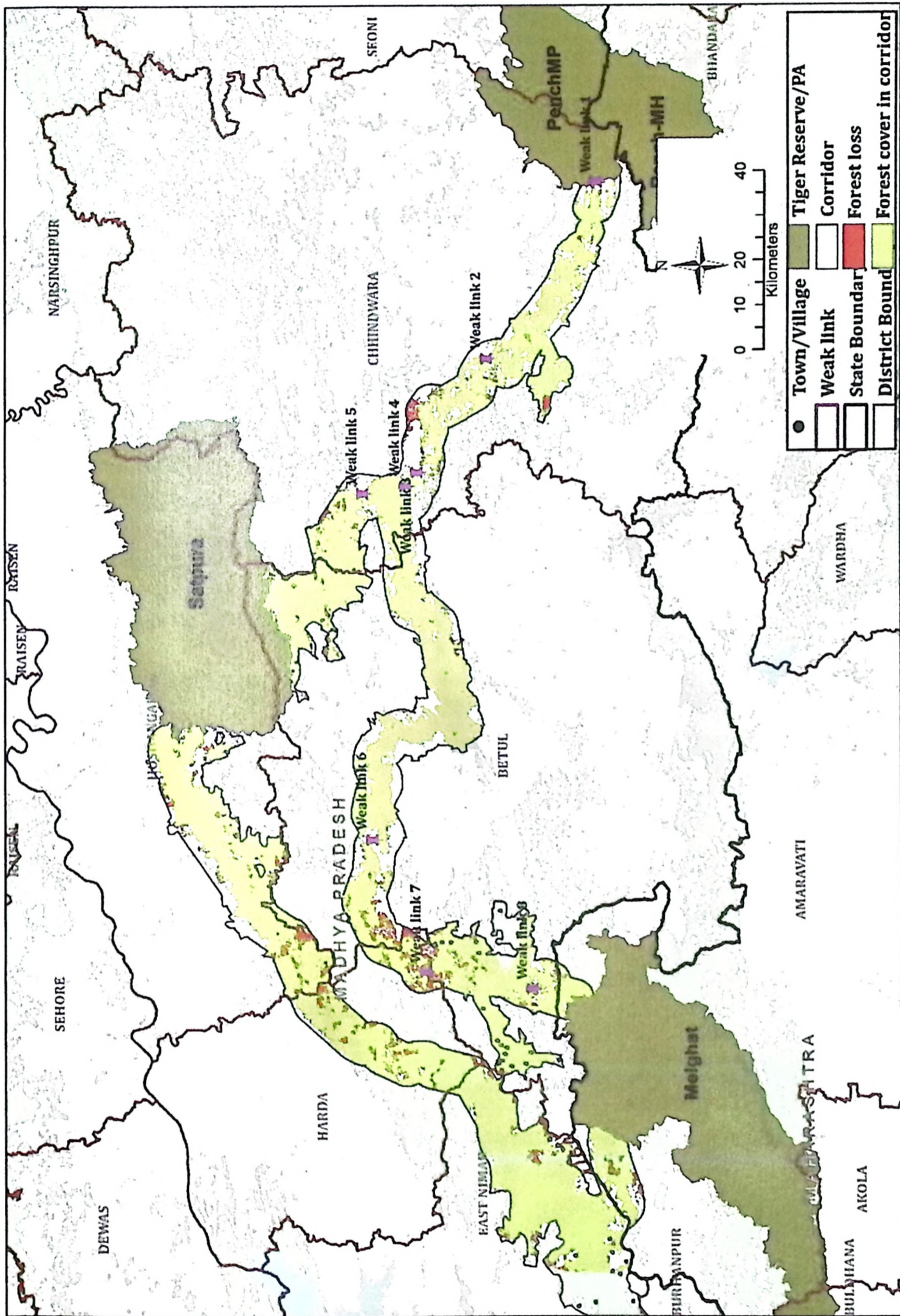


Figure 3-42: Forest cover change in Pench-Melghat-Satpura corridor during 1995-2016

b) Geographic and demographic change analysis

Nighttime lights change analysis

The corridor has seen an increase of 83% in the extent of nighttime lights since 1995 (Figure 3-43). The area expanded by 230 km² in the first decade, i.e. 1995–2005, contributing 50% of the total (Table 3-6). There was a decreasing trend in the distance between urban patches, from 50 km to 40 km, in the two decades (Table 3-7).

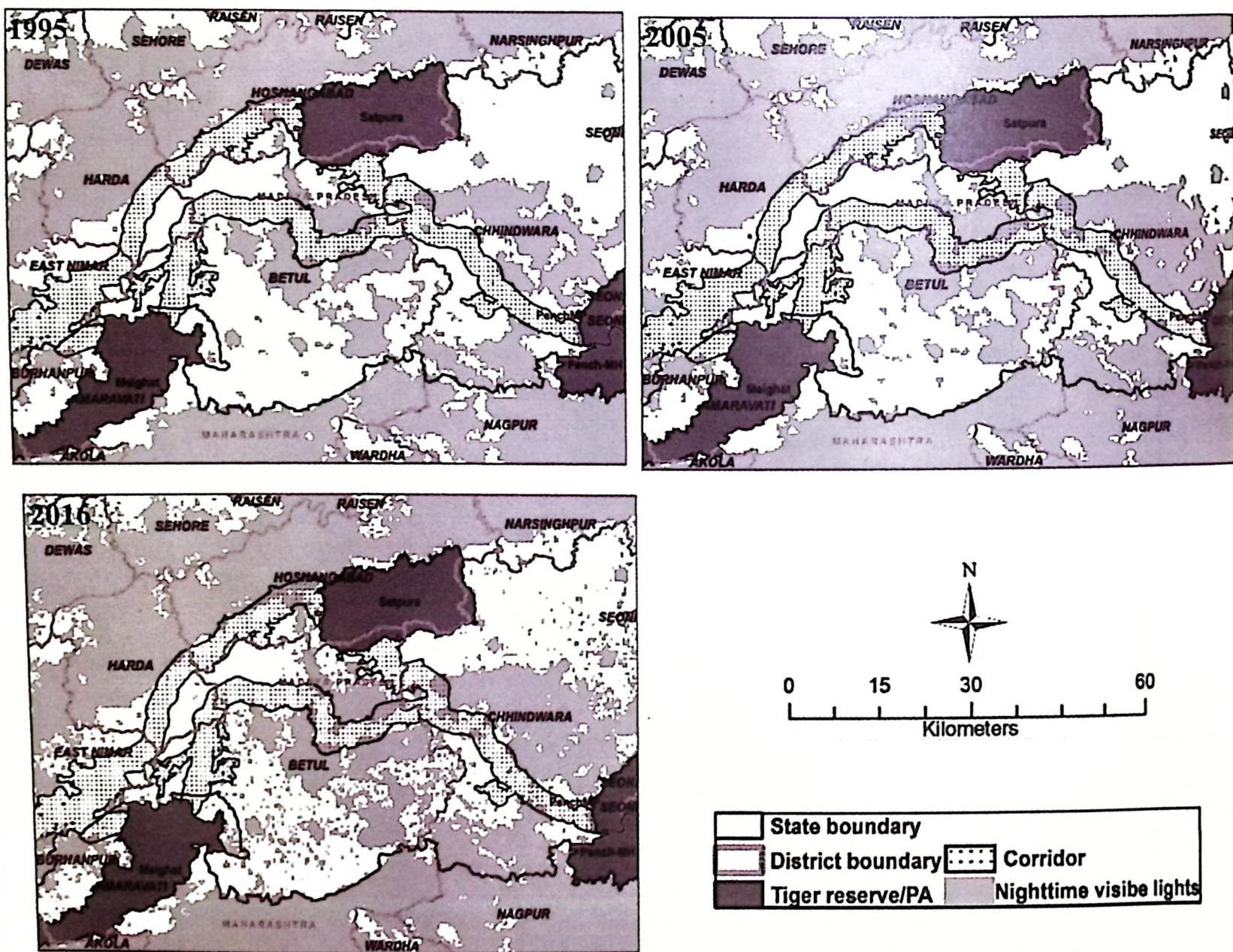


Figure 3-43: Growth in nighttime lights area during 1995–2016 in the Pench–Melghat–Satpura corridor

Demographic change

The human population of the villages in the corridor increased by 55%—65,000 individuals were added to the population since 1995. This increasing trend of the population has also resulted in a 79% increase in the number of households in the area (Table 3-8).

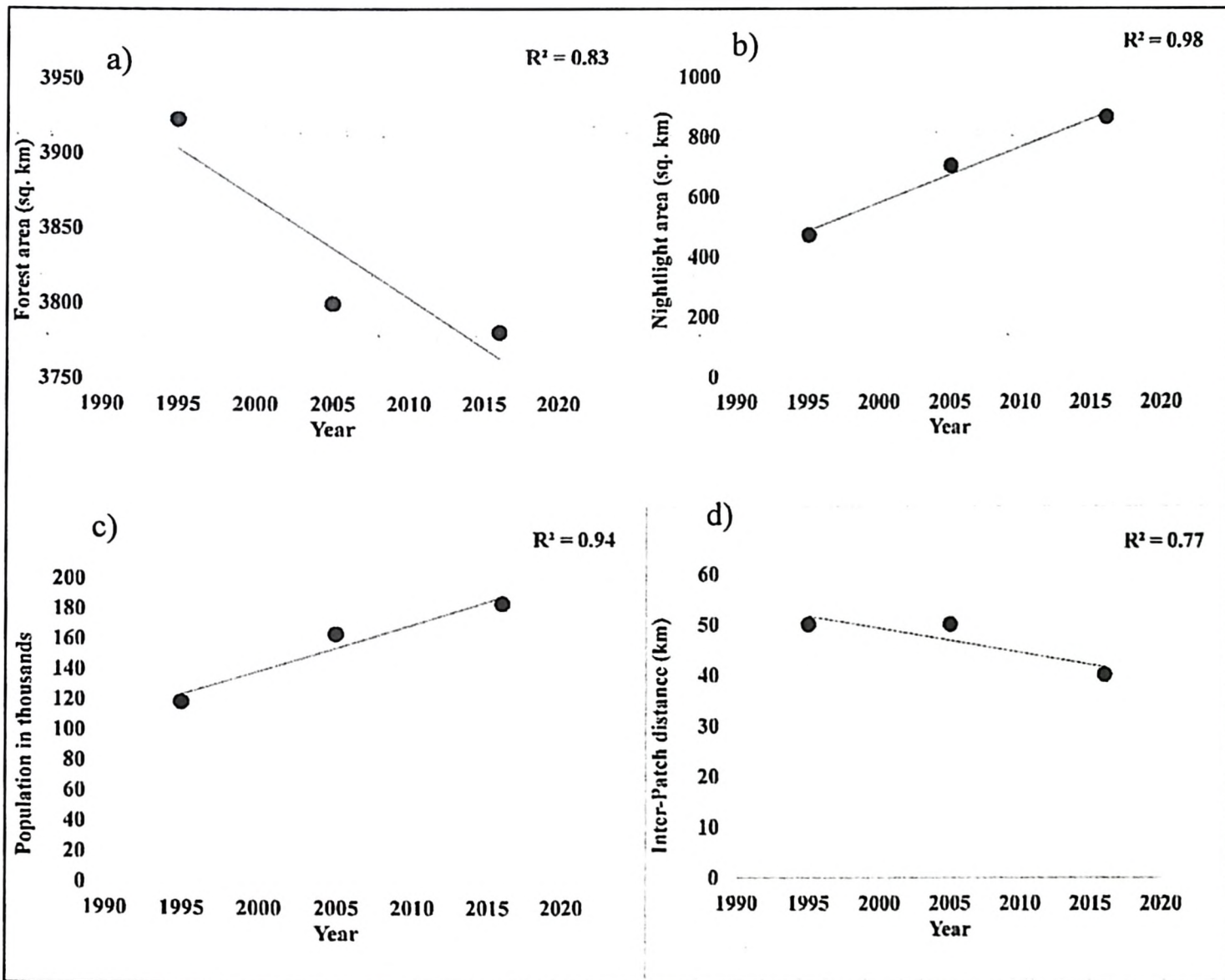


Figure 3-44: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches in PENCH–MELGHAT–SATPURA CORRIDOR

c) Threats and weak link

Eight weak links were detected in the corridor (Table 3-15 and Annexure II). Weak links 3 and 4 are present in the fragmented landscape, where the forest connectivity is highly disrupted by agriculture. The vegetation cover of this area needs to be regenerated as soon as possible to safeguard the connectivity. The area south of Satpura Reserve is disturbed by coal-mining activities, and the crucial part of the corridor is affected. These mining activities need to be observed by the forest department, and restorative measures need to be implemented to avoid permanent damage to the forest land of the corridor.

Table 3-15: List of weak links in PENCH–SATPURA–MELGHAT CORRIDOR

S.No	Name	Nearby landmark	Latitude	Longitude	Problem
1	Weak link 1	In Kanhan forest range			Fragmented connectivity, less than 0.5 km width. Only linkage connecting PENCH with the nearby forest
2	Weak link 2	Near Shankarpur beat in saori range forest	21 55.09N	078 43.46E	Highly fragmented, surrounded by agriculture field
3	Weak link 3		22 03.44N	078 28.74E	Road cutting the forest patch
4	Weak link 4		22 04.78N	078 26.98E	Highly fragmented with agricultural field all over
5	Weak link 5	In Jamai range	22 09.94N	078 25.93E	Degraded forest patch, Corridor width is less than 1.5 km, cut by SH-19B
6	Weak link 6	Shahpur forest range	22 08.14N	077 41.64E	Narrow corridor- less than 1 km width with degraded forest
7	Weak link 7	Between Jhirna-Hurra Malgajari village	22 01.34N	077 24.92E	Fragmented landscape, corridor is almost broken
8	Weak link 8	Taodi forest range	21 48.12N	077 23.04E	Link is only connected through a water body, surrounded by agricultural fields

3.3.2.8. Kanha–Nawegaon–Nagzira–Tadoba–Indravati

This is the longest identified corridor. It runs through 14 forest divisions of Madhya Pradesh, Chhattisgarh, Maharashtra and Telangana, in the central Indian landscape (Table 3-4 and Figure 3-45). The total length of the corridor is 705 km. It connects several protected areas in one stretch, from Kanha Tiger Reserve (Madhya Pradesh) to Nawegaon, Nagzira, Tadoba (Maharashtra) and Indravati (Chhattisgarh). The corridor is fragmented at several places, and only stepping-stone connectivity exists. A total of 446 villages are present in the corridor.

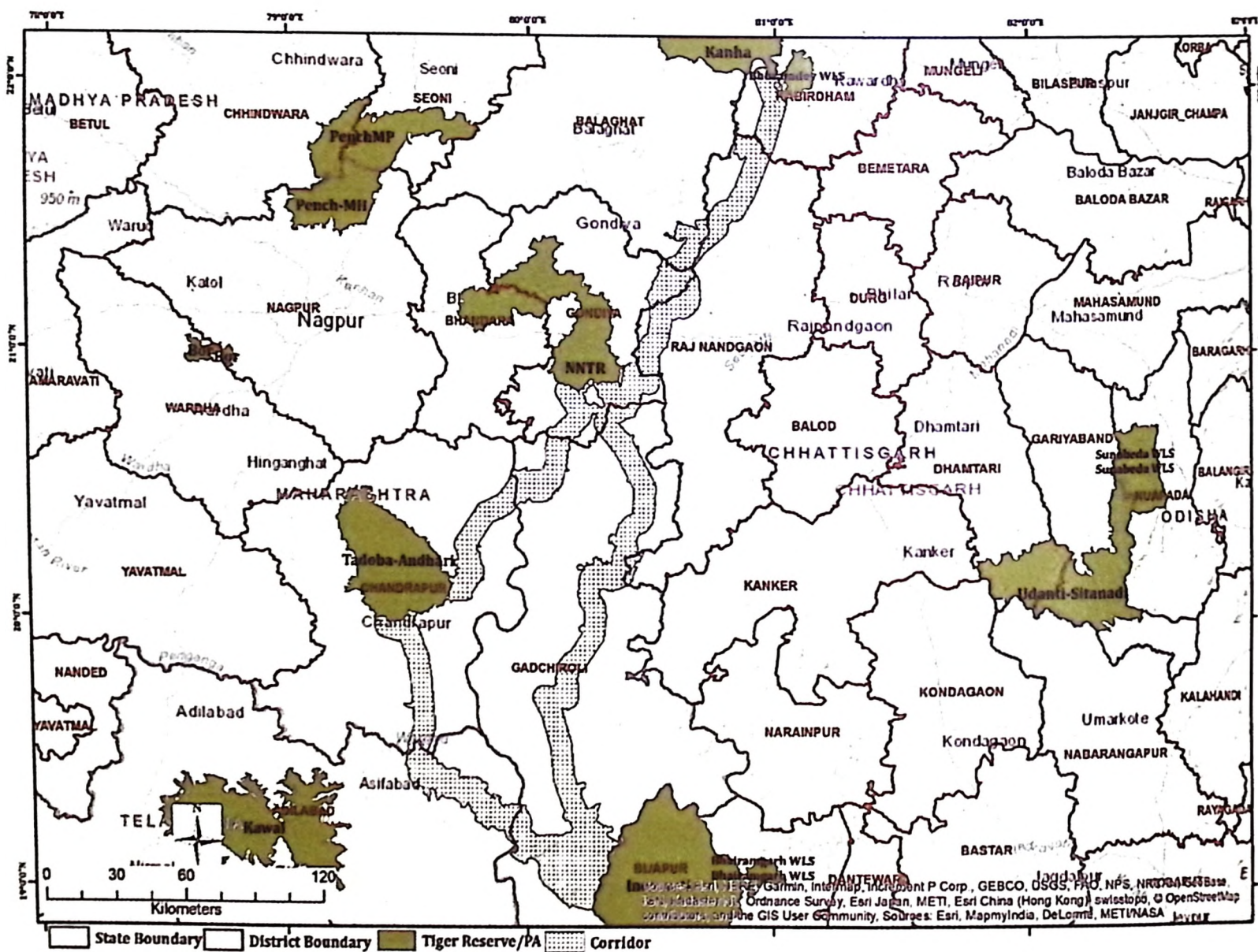


Figure 3-45: Location map of Kanha–Nawegaon–Nagzira–Tadoba–Indravati corridor, central India

a) Forest cover change

Around 9% of the forest cover disappeared in the last two decades, amounting to a loss of 517 km² of forest area in the corridor. The period from 2005 to 2016 was the most detrimental to the green cover. Six percent of the forest was lost during this period (Table 3-5 and Figure 3-46).

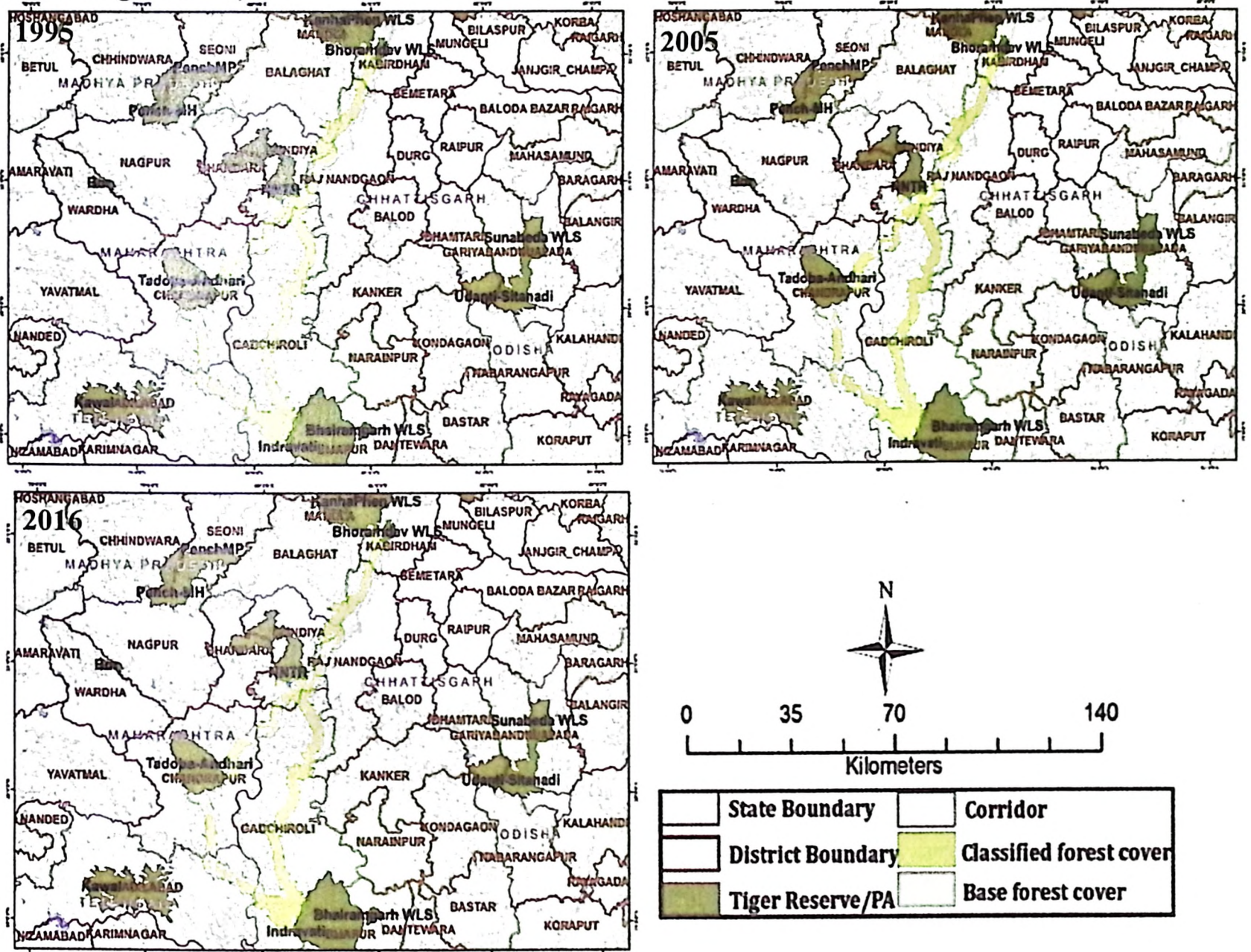


Figure 3-46: Forest cover in Kanha–Nawegaon–Nagzira–Tadoba–Indravati corridor classified using Landsat TM satellite data of 1995, 2005 and 2016

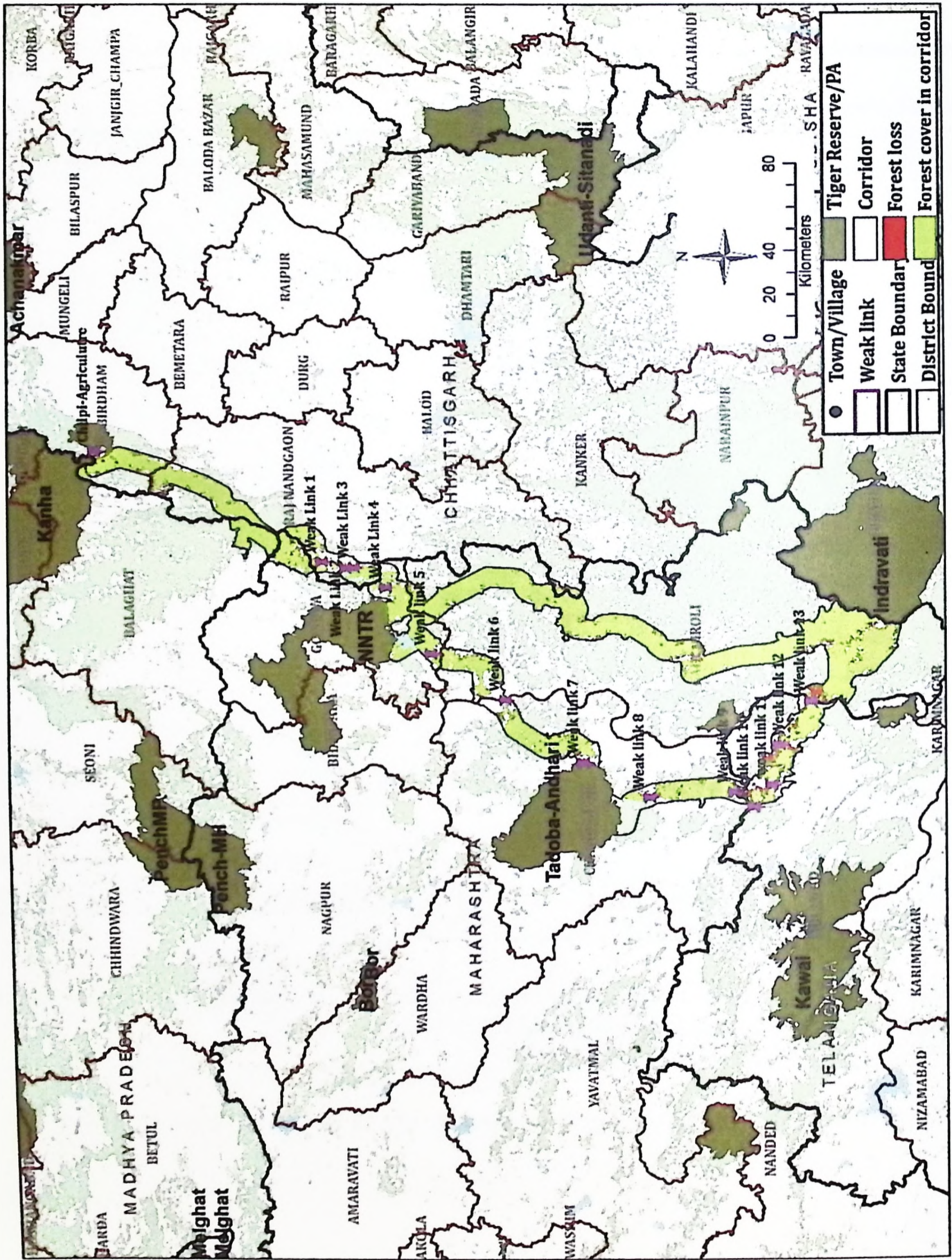


Figure 3-47: Forest cover change in Kanha-Indravati corridor during 1995-2016

b) Geographic and demographic change analysis

Nighttime lights change analysis

The area falls within rapidly growing districts in terms of size and development. The urban area has grown by 866 km² (Table 3-6). The urban area has grown at an annual rate of around 8.5% over 20 years. This urban expansion has resulted in the inter-patch distance decreasing from an average of 78 km to 34 km (Table 3-7 and Figure 3-48).

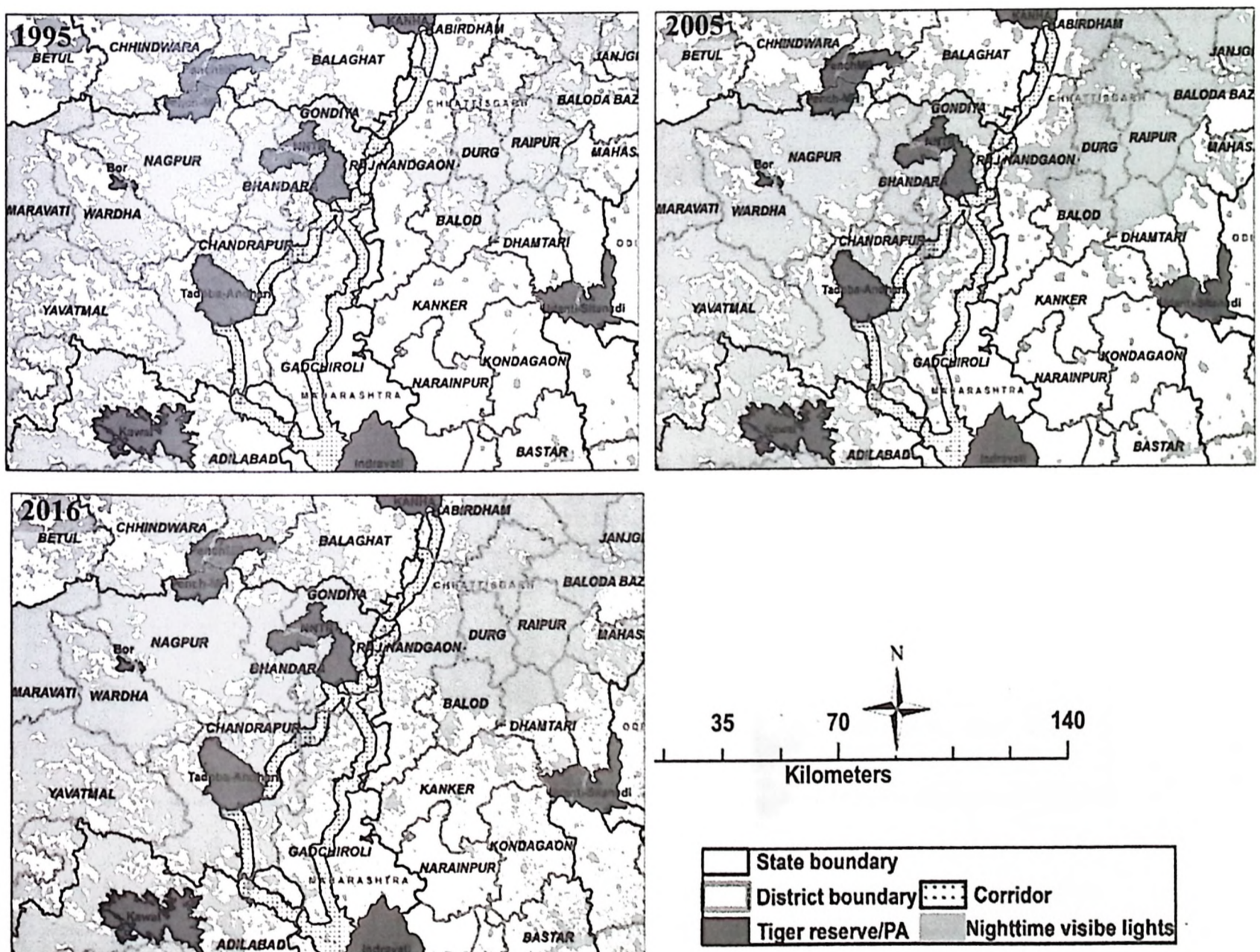


Figure 3-48: Growth in nighttime lights area during 1995-2016 in Kanha-Nawegaon-Nagzira-Tadoba-Indravati corridor

Demographic changes

The human population of the villages in the corridor increased 44% since 1995. The population increase was highest during 1995–2005, with a growth rate of 3.1% per year (Table 3-8). The growth of the population has also resulted in an increase in the number of households in the area, 63% in two decades.

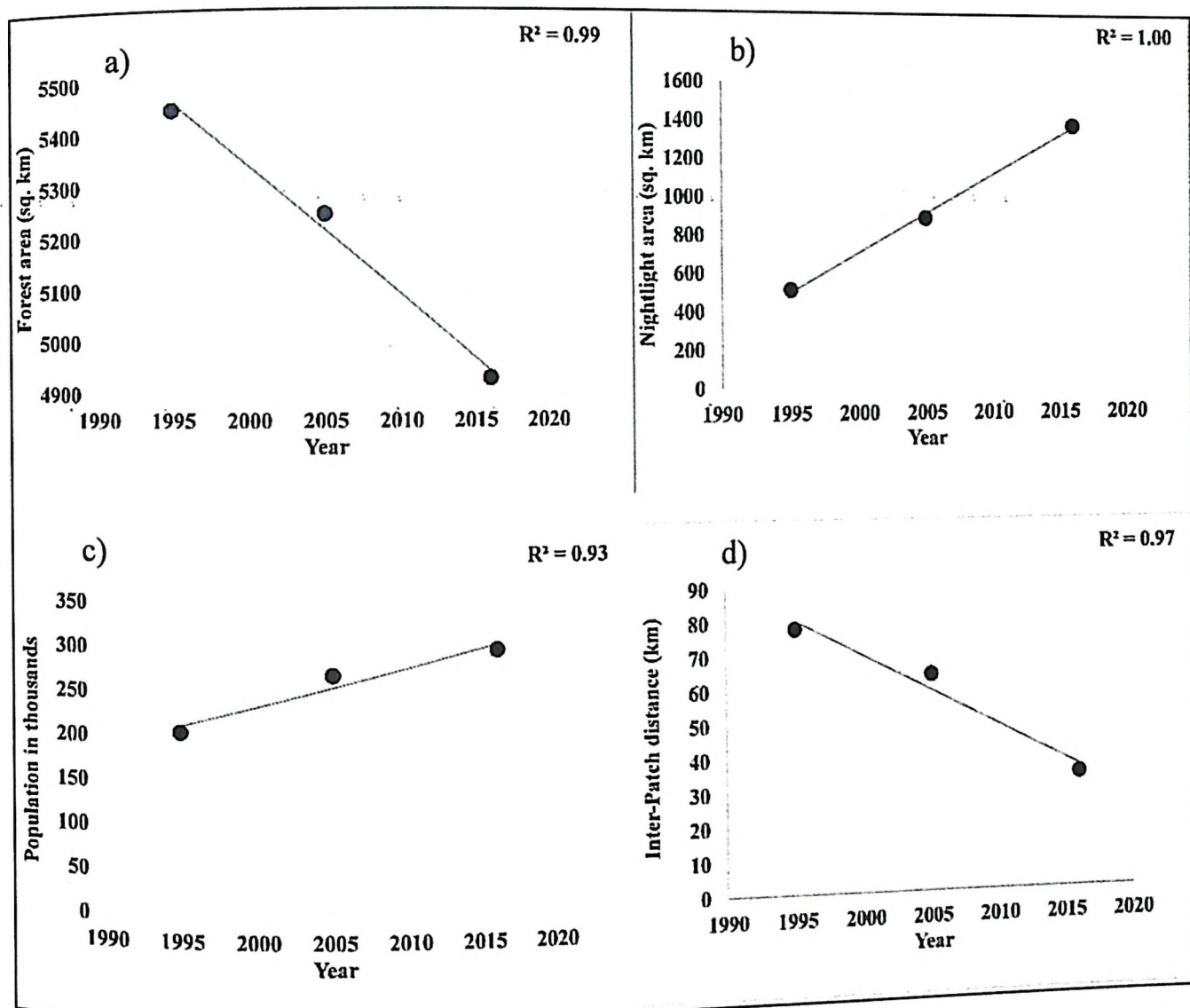


Figure 3-49: Comparison of trends in a) forest loss b) nightlight area c) demographic and d) inter-patch distance in urban patches in Kanha–Nawegoan–Nagzira–Tadoba–Indravati corridor

3.3.3. Forest loss and major drivers of change

A regression analysis was performed to model the relationship between forest cover loss and variables associated with it. The linear regression also helped in investigating the relationship and effects of variables at two scales: 1) in district by comparing the data pertaining to districts from where corridor is passing 2) within corridor region. The drivers of change are diverse but largely associated with developing areas which least developed over time due to mineral resources, population growth and development determining the land use land cover affecting the connection.

Table 3-17: Result of correlation between variables in district versus in corridor

	<i>Forest loss (district)</i>	<i>Forest loss (corridor)</i>	<i>Change in nightlight (district)</i>	<i>Change in nightlight (corridor)</i>	<i>Growth in population (district)</i>	<i>Growth in population (corridor)</i>
<i>Forest loss (district)</i>	1					
<i>Forest loss (corridor)</i>	0.79	1				
<i>Change in nightlight (district)</i>	0.78	-0.01	1			
<i>Change in nightlight (corridor)</i>	0.16	-0.25	0.93	1		
<i>Growth in population (district)</i>	0.83	0.26	0.79	0.45	1	
<i>Growth in population (corridor)</i>	0.27	0.56	-0.19	0.04	0.31	1

Table 3-16: List of weak links in Kanha–Nawegoan–Nagzira–Tadoba–Indravati corridor

S.No	Name	Nearby landmark	Latitude	Longitude	Problem
1	Weak link 1	Bagrekasa forest	21 08.71N	080 32.74E	Less than optimal width of corridor ~0.6km
2	Weak link 2	In Baghnadi forest range	21 03.07N	080 31.10E	Existing road fragmented and degraded forest patches
3	Weak link 3	In baghnadi range (Jobe-forest)	21 01.08N	080 31.19E	Corridor is broken, 1.5 & 0.9 km distance from nearby forest patches
4	Weak link 4	Chichgarh forest	20 53.80814N	080 25.96E	Highly fragmented forest, 0.5 km of corridor width is left
5	Weak link 5	In Gothangaon forest	20 43.18N	080 08.58E	Highly fragmented forest, 0.5 km of corridor width is left
6	Weak link 6	Fringes of Bramhpuri forest	20 25.82N	079 56.50E	Corridor is broken, intensive agriculture landscape, forest patches are around 6-8 km apart
7	Weak link 7	Forest of Sawali range	20 07.47N	079 40.27E	Corridor is broken, intensive agriculture landscape, forest patches are around 3-6 km apart
8	Weak link 8	fragmented-disturbed forest	19 52.21N	079 31.36E	Narrow width of corridor~3 km, highly fragmented with various roads cutting across
9	Weak link 9	Near tomta village, Dhaba forest range	19 33.06N	079 32.76971E	Connectivity is broken, the nearest forest patch is 3 km apart
10	Weak link 10	Weak_link	19 22.85N	079 44.99E	
11	Weak link 11	weak_link	19 15.84N	079 56.36E	Connectivity is broken, nearest forest patch is at a distance of 2 km approx. matrix is full of agriculture field and settlements
12	Weak link 12				Linkage is almost broken surrounded by agricultural field

3.3.3. Forest loss and major drivers of change

A regression analysis was performed to model the relationship between forest cover loss and variables associated with it. The linear regression also helped in investigating the relationship and effects of variables at two scales: 1) in district by comparing the data pertaining to districts from where corridor is passing 2) within corridor region. The drivers of change are diverse but largely associated with developing areas which least developed over time due to mineral resources, population growth and development determining the land use land cover affecting the connection.

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<i>Forest loss (corridor)</i>	0.79	1				
<i>Change in nightlight (district)</i>			1			
<i>Change in nightlight (corridor)</i>	0.78	-0.01		1		
<i>Growth in population (district)</i>	0.16	-0.25	0.93		1	
<i>Growth in population (corridor)</i>	0.83	0.26	0.79	0.45		1
	0.27	0.56	-0.19	0.04	0.31	

3.3.3.1. Change in forest cover

There was a significant relationship ($R= 0.55, p=0.2$) between the forest loss in the corridors and the overall forest loss at the district level. The relationship improved after the Guru Ghasidas–Lawalong corridor data were excluded from the analysis ($R= 0.79, p=0.1$). The forest loss in a corridor is governed by the overall changes in the green cover at the district level, and the trends in the two areas are similar. In the case of the Gurughasidas–Lawalong corridor, the overall loss of forest cover in the district was greater than the change in the corridor. According to the *Indian State of Forest Report 2017*, forest cover was lost in other parts of the district due to mining, road widening and tree-felling activities of local people.

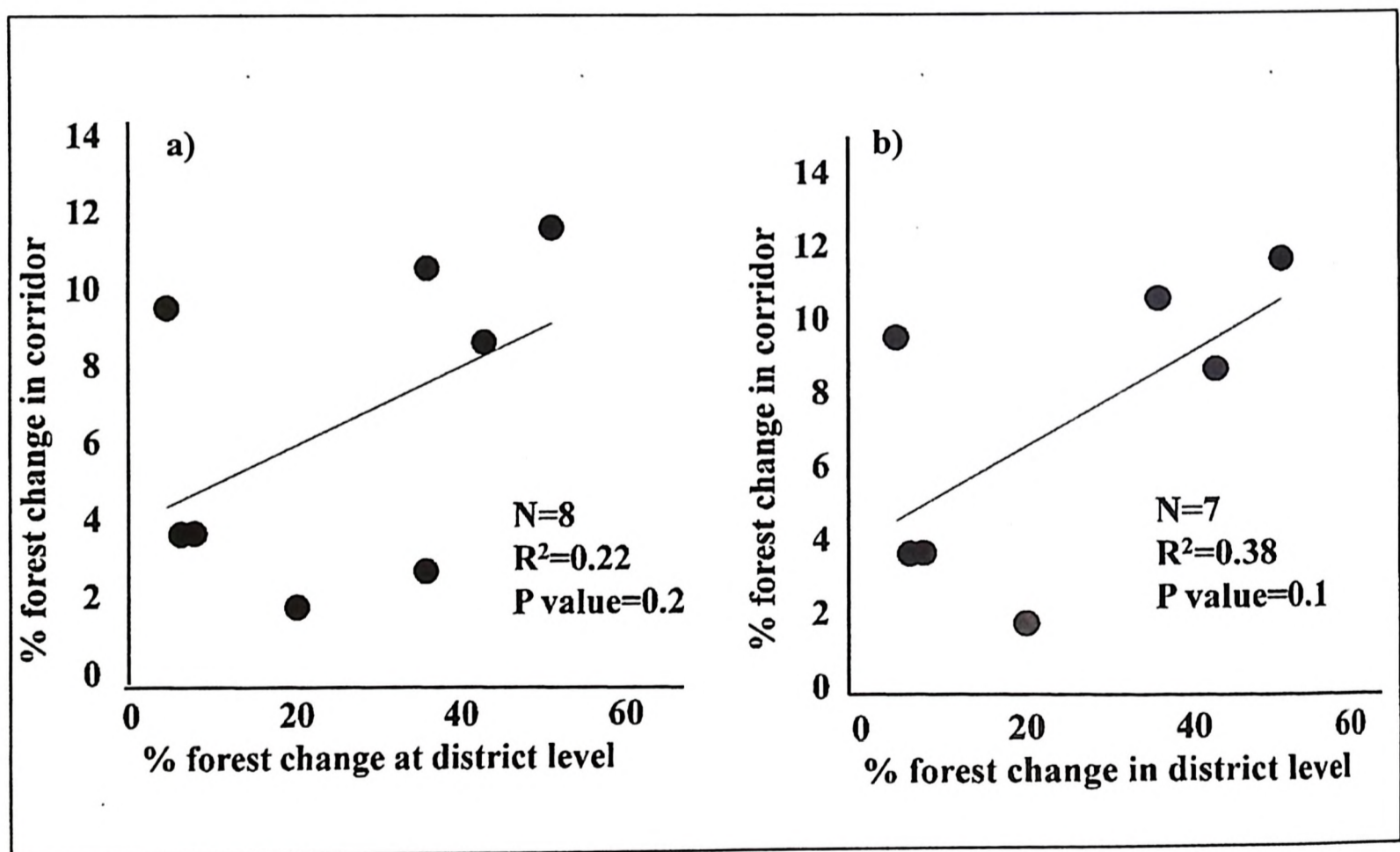


Figure 3-50: Changes in forest cover in districts versus change in forest cover in corridor: (a) before and (b) after removing outlier values

3.3.3.2. Growth in urbanisation

Analysis of the growth of the nighttime light areas revealed that the urbanisation in the districts and the urbanisation in the corridor follow similar trends. Regression analysis of the growth in the extent of nighttime lights in the districts and in the corridor showed a statistically significant relationship ($R=0.92$, $p=0.002$) after the Kanha–Achanakmar corridor data were excluded. The Kanha–Achanakmar data were excluded from the analysis because most of the villages in the corridor were electrified after 2011 (rural electrification scheme) and thus their existence was not captured by the nighttime lights data of the

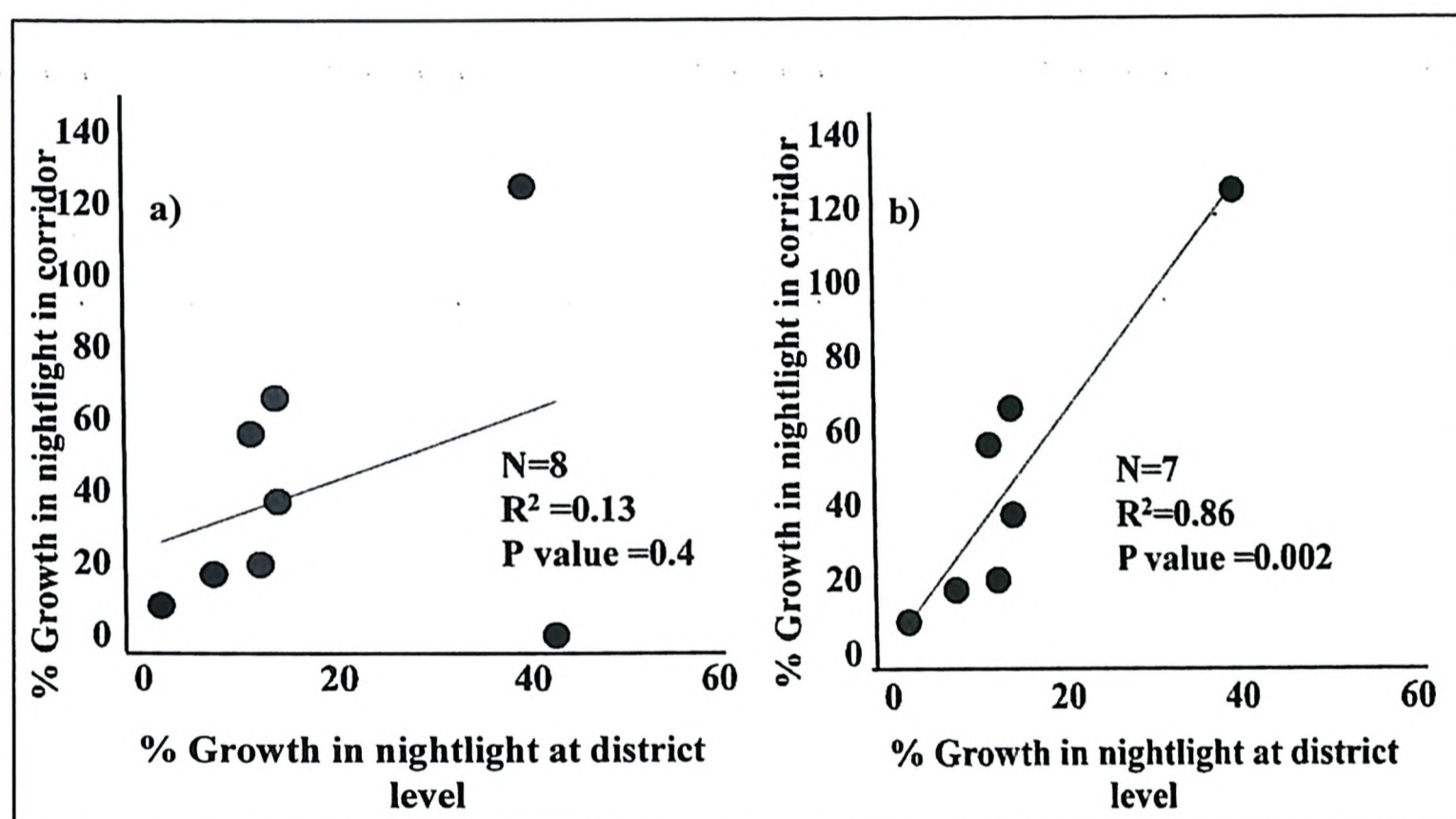


Figure 3-51: Growth of nighttime lights in districts versus growth of nighttime lights in corridor: (a) before and (b) after removing outlier values

3.3.3.3. Growth in population

Regression analysis of the demographic data of the district and those of the corridor identified no relationship. This was expected, as populations tend to grow in urban areas compared with rural areas because of better employment, higher living standards and better

educational and medical facilities. Therefore, an urban population increase does not necessarily lead to a growth in the population of the rural areas nearby but is an underlying driver of deforestation through expansion of agriculture, industrial growth or other developmental activities.

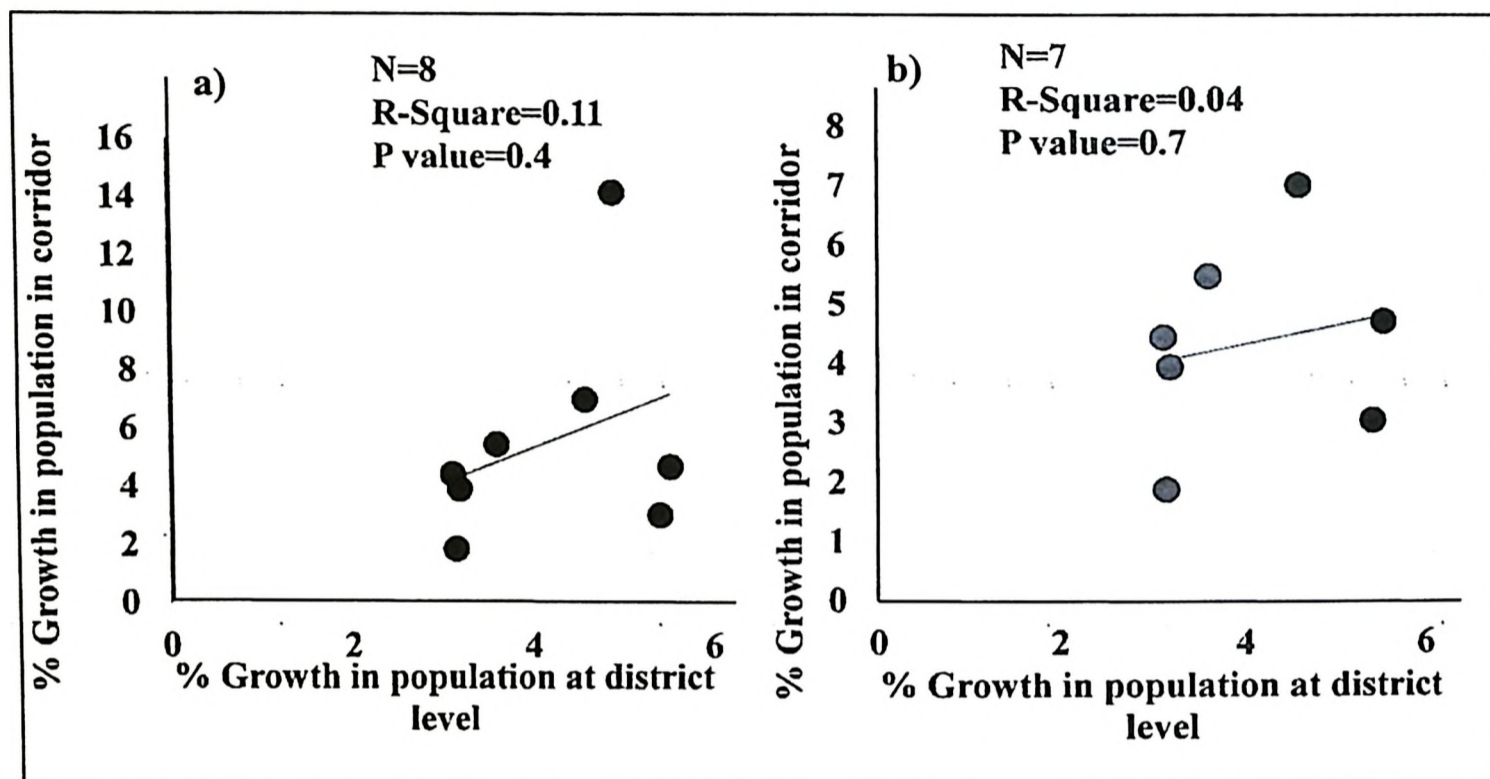


Figure 3-52: Growth in population in districts versus growth of population in corridor: (a) before and (b) after removing outlier values

3.3.3.4. Forest loss versus growth in nighttime lights

Linear regression of the forest loss with the growth in the nighttime lights in the districts showed a significant relationship with $R=0.78$, $p=0.1$. The relationship is improved after the data of the districts of the Bandhavgarh–Sanjay Dubri corridor, where there is substantial forest loss without much growth in the nighttime lights, were excluded. The R^2 -value of 0.7 explains the 70% level of variations in the deforestation ($p=0.02$). The loss in green cover in the Bandhavgarh–Sanjay Dubri region is due to fragmentation of forest patches caused by increasing agricultural activities, while the growth of nighttime lights in the district is mainly because of coal mining and the associated development of infrastructure.

The mean inter-patch distance of the urban patches within the corridors had a decreasing trend over time. The trend clearly revealed an increase in patchiness in the corridors, with small urban areas being converted into either large clusters or contiguous urban sprawls.

Figure 3-54 shows the temporal trend of the inter-patch distance of the corridors.

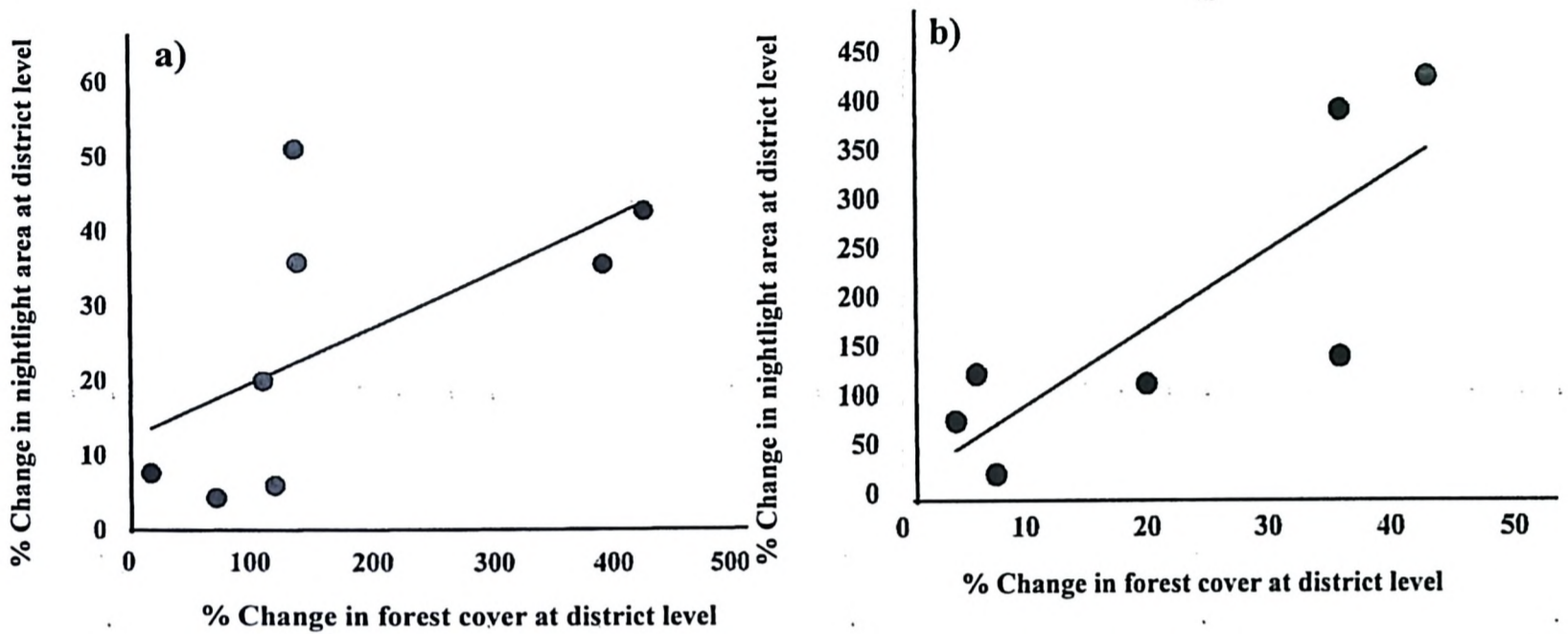


Figure 3-53: Growth in nighttime lights versus forest loss: (a) with outlier and (b) after removing outlier in districts

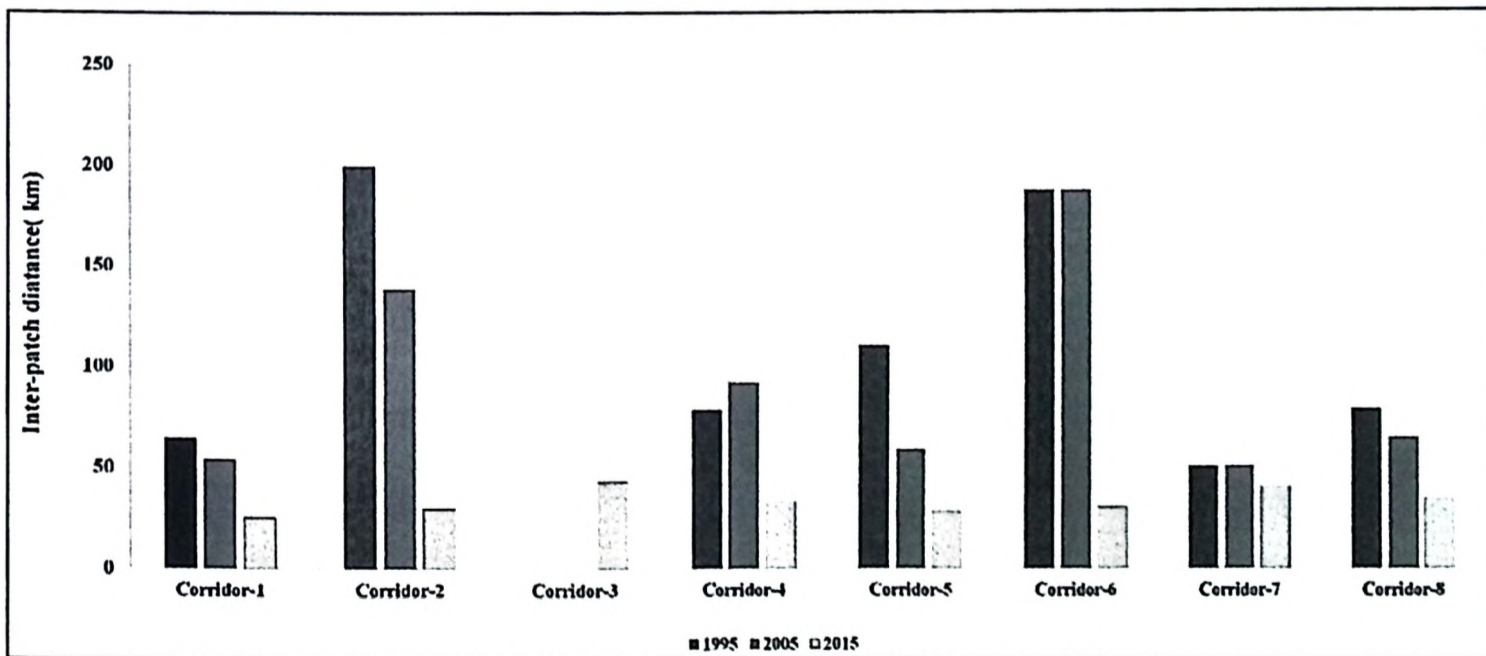


Figure 3-54: Decrease in inter-patch distance in nightlight patches in corridors

3.3.3.5. Forest loss versus growth in population

A regression model of the forest loss with the change in urban population showed a strong relationship ($R=0.83$, $p=0.01$). The growth of the population explained 70% of the variability of the dependent variable (i.e., forest loss).

Linear regression of the forest loss in the corridors against the population growth in that region over time yielded similar results. The relationship was weak ($R^2=0.3$), but the p value was 0.1. The model reveals that the increasing population is one of the major drivers of the forest cover loss.

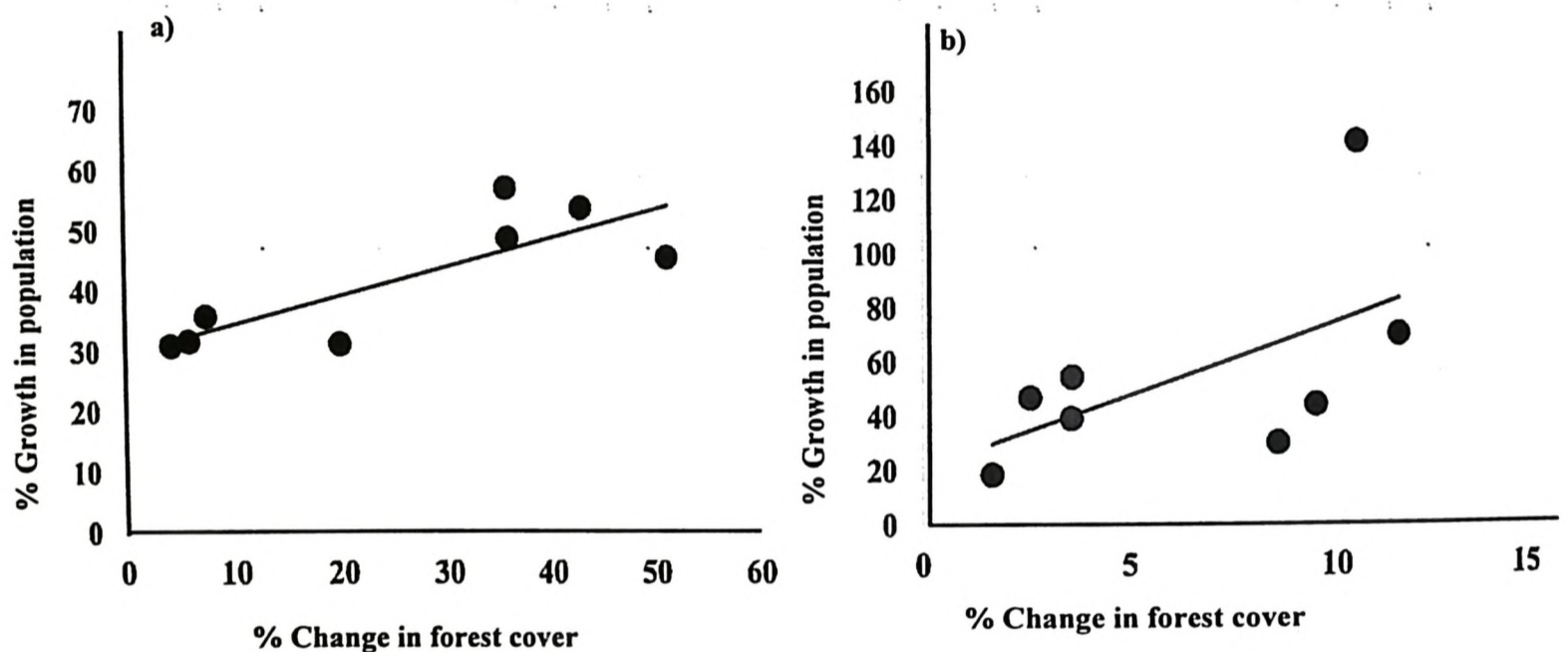


Figure 3-55: Growth in population versus forest loss: (a) in districts and (b) in corridor

3.3.3.6. Change in forest cover versus Economic growth (Gross domestic product)

The result indicate that economic growth does not necessarily govern forest loss in the district and have very less explanatory power. It is clearly depicted by the trends that district with GDP values less than or equal to 100 crores were facing forest loss while district having GDP more than 100 crores were more stable in terms of forest loss (Figure 3-56). This shows that economic growth factor have less explanatory power in identifying the causes behind deforestation. The trend further reveals that as soon as the district's economic growth

increases, dependency on natural resources decreases. This is further strengthened by exploring the sectors contributing to economic growth which shows a decline in contribution from the primary sector in a district's overall economic growth (Annexure-III).

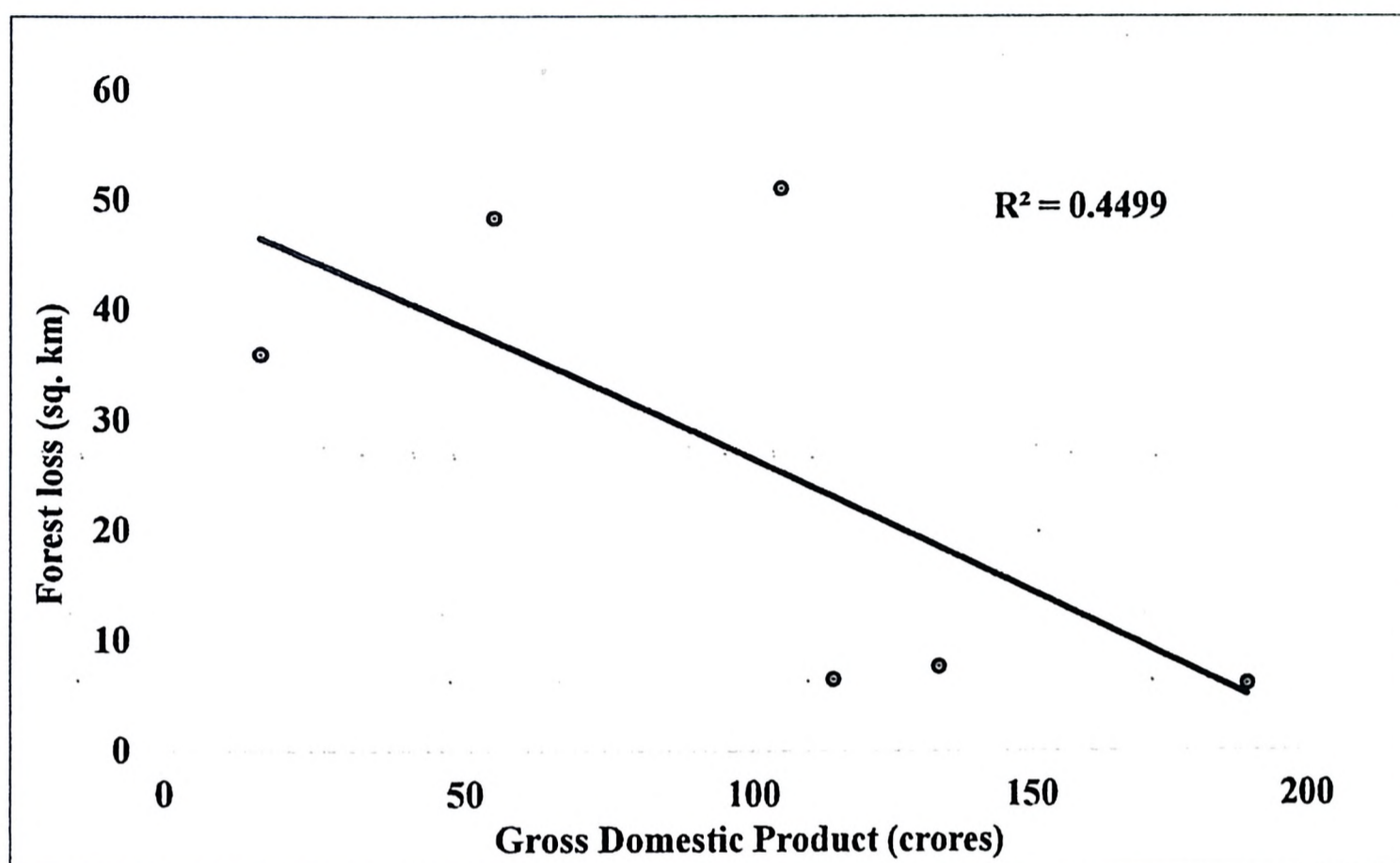


Figure 3-56: Change in forest cover versus economic growth (Gross Domestic Product)

3.4. Summary of Results

The variables responsible for changes in forest cover at district level govern significantly deforestation locally along with some proximate drivers. Regression analysis presented in table 23 depicts that depending on the magnitude and nature, some drivers affect directly to forest loss like expansion in nightlights while population plays indirect role in decreasing forest cover. Nightlight expansion was statistically significant in both the models, indicating forest losses due to development activities and infrastructure development.

Based on the results it can be concluded that both socio-economic and demographic factors are of importance for forest losses in districts while their effect may vary at corridor level.

3.5. Discussion

All corridors indicate consistent trends in forest cover change (Figure 3-57), demographic (Figure 3-58), geographic (Figure 3-59) and in inter-patch distances (Figure 3-60). Forest cover reduced in all the corridors quite rapidly worst being the case of Kanha-NNTR-Tadoba-Indravati corridor, similarly the urban proliferation was also maximum in this corridor. Though the corridor passes through the contiguous forest patches (Figure 3-46) which provides high hopes of its survival for long term if the pinch points (Table 3-16) indicated are addressed on time. The inter-patch distance in nightlights patches is a measure of fragmentation and proliferation of new urban-semi urban patches. The maximum semi urbanization was observed in Gurughasidas-Lawalong corridor. The number of weak links varies from 4 to 12 in the corridors in the landscape. These weak links provide useful pinch points where connectivity is likely to get disjunction in future. These weak links are important for maintaining the corridor connectivity in the landscape and provide an important base for prioritizing conservation investments. All corridors indicate change in structural connectivity. However, the total forest loss in terms of area was 7% on average. Most of the forest loss occurred due to development of villages, mining, linear infrastructure which has caused fragmentation and disturbance in the corridor area. There is negative relationship between district wise GDP (Gross development product) and forest cover loss in districts having GDP \geq 100 crores whereas districts with GDP $<$ 100 crores showed positive trend indicating that as the economic growth increases dependency on forest resources decreases (Figure 3-56). According to the recent study done at global scale “Economic growth in poor countries increases environmental depletion, but that the effect disappears or reverts for developed economies”, (Cuaresma et al 2017). Location of corridor will be an important factor in deciding future of their persistence. No clear-cut trend emerged as a driver of change except that population growth depending on natural resources and need

for development for basic facilities. The development in these villages in the corridor is causing erosion of connectivity. The major disruption and weak links are formed because of the developmental activities occurring in these villages.

The trend forecasting in corridors is difficult though most of the variables about population development and forest losses have shown negative trend but those all depends on complex intermix of socio-political processes driving the development in a given area. Development largely is not ecologically sensitive thus resulting in isolation of patches and compromising future of our natural areas. There is an urgent need to develop ecologically sensitive district development plans to ensure the sustenance of wildlife as well as our well-being.

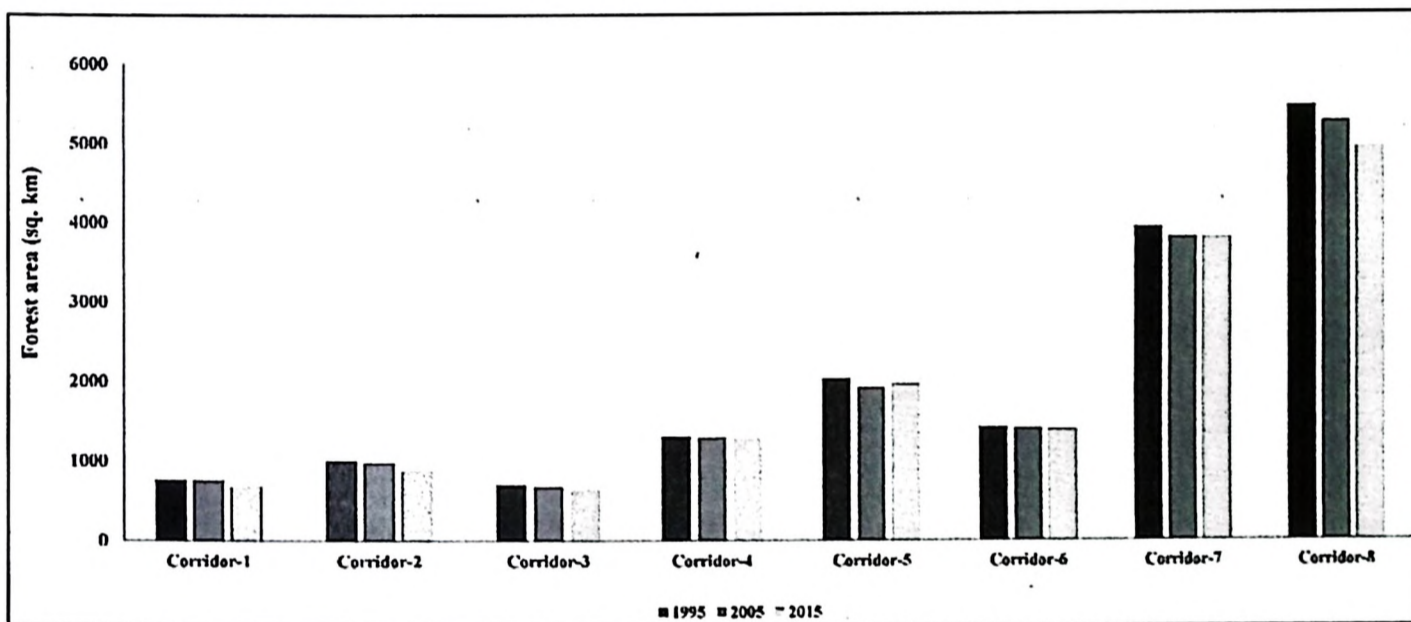


Figure 3-57: Change in forest cover across corridors

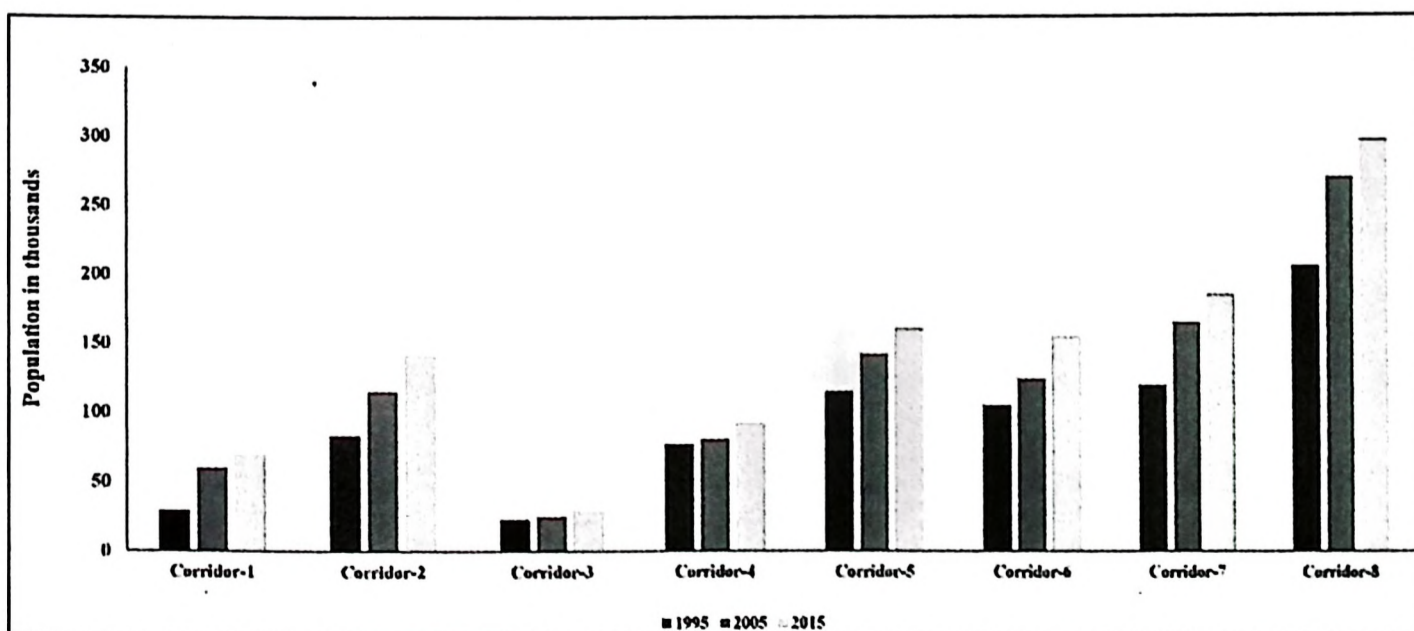


Figure 3-58: Growth in population across corridors

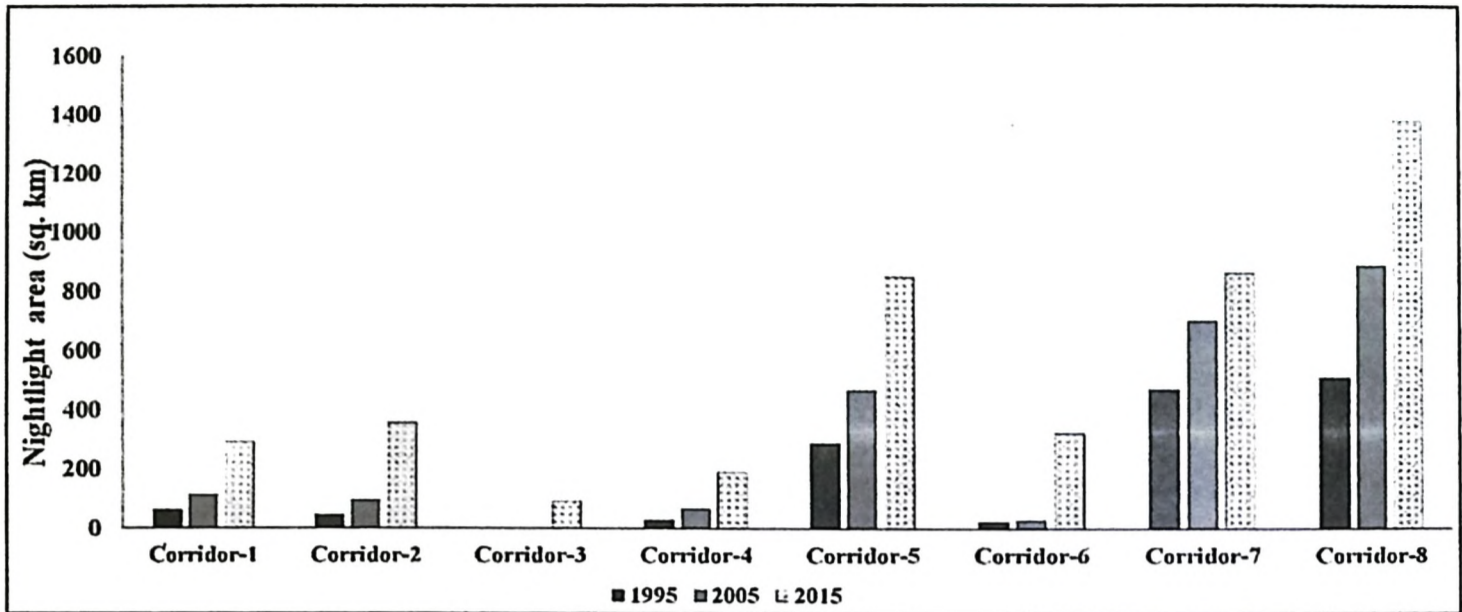


Figure 3-59: Growth in nightlight area across corridors

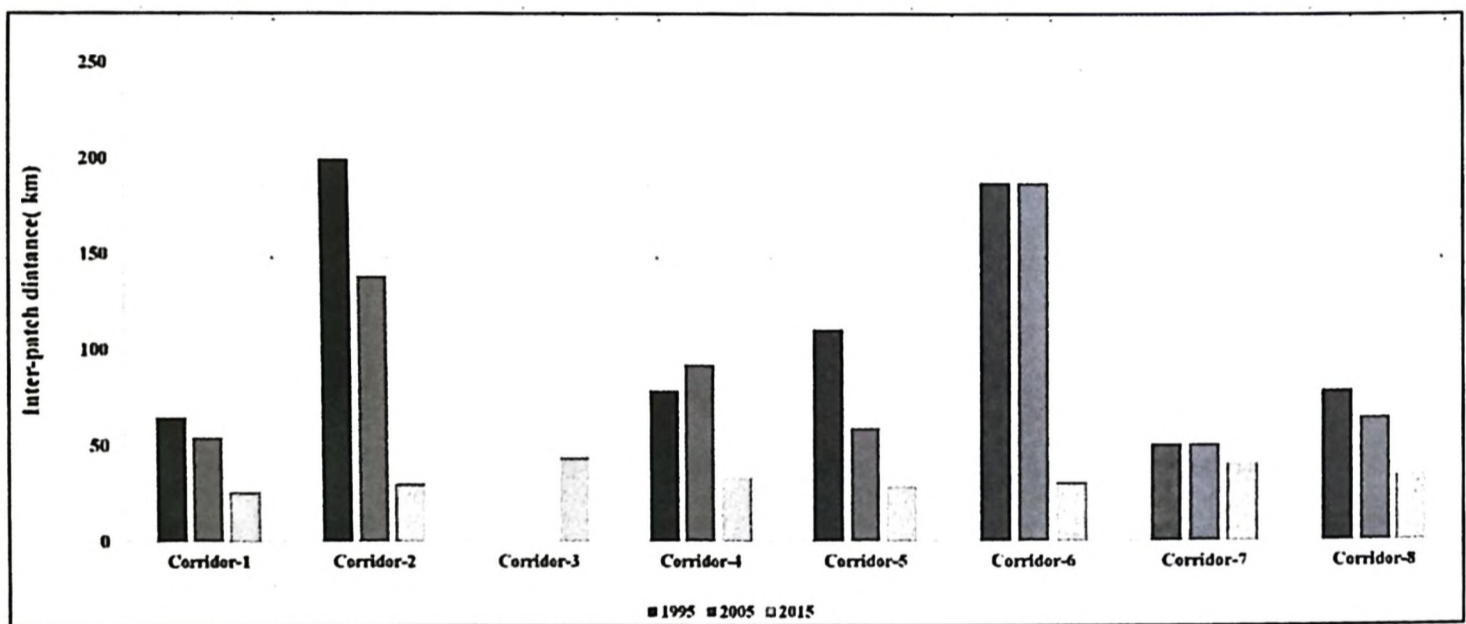


Figure 3-60: Reduction in inter-patch distance in urban patches across corridors

Corridor-1 Bhandhavgarh-Achanakmar Corridor-3 Kanha-Achanakmar Corridor-5 Simlipal-Satkosa Corridor-7 Pench-Satpura-Melghat
 Corridor-2 Bhandhavgarh-Sanjaydubri Corridor-4 Kanha-Pench Corridor-6 Gurughasidas-Lawalong Corridor-8 Kanha-NNTR-Tadoba-Indravati

3.6. Conclusion

Kanha-Pench Corridor

Establishment of forest policy by British's in 1864 laid the foundation for the conservation of forest lands and their associated resources including wild life. The initial laws were framed to have custodial powers over forestlands and managing them for timber. Timber was the major source of revenue for the government and its protection led to the control of government over forests and management of their resources. Forest shrinkage happened due to the indiscriminate felling of trees for railway construction, clearing of forests for agriculture and from cultivation practices such as from swidden cultivation, (land is cleared by slashing and burning vegetation) detrimental to forests and their structures (Rangrajan 1996) . In 1878, areas important for timber were declared as reserved forest strictly banning felling, lopping, burning activities. Access to forests was limited for public to avoid harm from human use activities such as livestock and cattle grazing, protection of forest from fires, execution of trespassers and limited use of roads inside forests for common people were added to the law. The attitude was completely to protect forest from fires with wide interest for timber production. Until this time, less concern was drawn for wildlife and the forest areas were open for game hunting. The attitude towards wildlife changed later when many of species started depleting and improved attitude towards preservation of wildlife. Apart from hunting, threats from wider changes in land use become major concern for forest protection and for wildlife preservation. Species were affected by the spread of cultivation and human use of forests except few that were able to survive in government controlled forests due to protection and less human intervention. Another major damaging human activity was cultivation practices that destruct forests and their quality. Therefore, forest areas that area not for commercial forest activities, suitable for wildlife laid the foundation for conservation around 1900.

Central Indian landscape being highly populated and with growing developmental demands is continually facing modifications in land uses-land covers. The protected areas in the landscape are connected by the reserved forest patches but are under stress due to developmental activities and increasing anthropogenic pressure on their periphery. Forest areas connecting Kanha TR and Pench TR are one of the most crucial connection for wildlife movement and is the most studied and discussed during the last one decade. The connectivity between the two protected areas creates a crucial dispersal route for most of the wild species residing in this area. The landscape is rich in biodiversity, and harbours a variety of large carnivores and herbivores; many of which are endangered. The area has good population of tigers, leopards, sloth bear, dhole, hyena, jackal and, wolf along with many herbivores such as gaur, nilgai and sambar. The corridor link allows tigers from Kanha to disperse in other parts of the landscape, especially to Pench and further to Satpura TR. The tiger population in Pench was able to recover because of new immigrants 'from Kanha through this corridor (Personal discussion with Prof. Qamar Qureshi). The corridor is also crucial for gaur movement because of intact continuous strands of forest patches, which is preferred by gaur for their movement. Although the corridor is currently connected through continuous forest patches, but these patches are getting fragmented and succumbing to long-term anthropogenic pressures. This may be the result of patterns of forest use due to biophysical conditions or historical forest use patterns by humans (Meghna et al. 2016). Large number of people living in close vicinity of these forests largely depends on agriculture and forest resources. There is also a high grazing pressure on these areas from the nearby village livestock.

In 2010, All India tiger monitoring report, this corridor was identified as one of the major linkages connecting the Kanha (source population) with other tiger reserves and tiger occupied Protected Areas in Central India. In 2010, Vattakaven, Qureshi et al. and Jenna et al. in 2014 highlighted the pressures due to developmental activities in this connectivity and identified the critical areas for conservation actions. The most severe threats to the corridor was from the road and railway infrastructure. Presence of national highway NH-7 near Pench tiger reserve and two other roads connecting Keolari- Balaghat, Nainpur to Balaghat running parallel to Nainpur railway line are main threats for the animal dispersal in this corridor. Wildlife mortality is recorded on these roads, highlighting hindrance in animal dispersal in these sections of the corridor. Thereafter, NHAI came up with the widening plan of NH-7(44), which might have further affected the dispersal and the potential of becoming a total barrier for corridor connectivity. This drew immediate attention of the conservation practitioners and wildlife enthusiasts. The highway is one of the important road connections from south to north India facilitating the livelihood of many. Because of lack of appropriate mitigation planning, the work in this stretch remain uncompleted for almost ten years. In 2016, road ministry following the directives of Bombay High Court sanctioned construction of underpasses for safe wildlife movement based on the recommendations of Wildlife Institute of India and National Tiger Conservation Authority. These passages were recently surveyed and found to be in functional use by the wildlife species. Records of species using the underpass is an encouraging sign that conservation can go hand in hand with developmental requirement with appropriate mitigation measures. Recently, Vodafone along with Grow-Trees has initiated to restore a part of Kanha-Pench wildlife corridor near Sijhora range in Madhya Pradesh by creating a private forestland to offset its carbon footprint. The initiative is to protect around 100 hectares of land by planting

trees over the next three years restoring land by afforestation to safeguard corridor connectivity for future in this area.

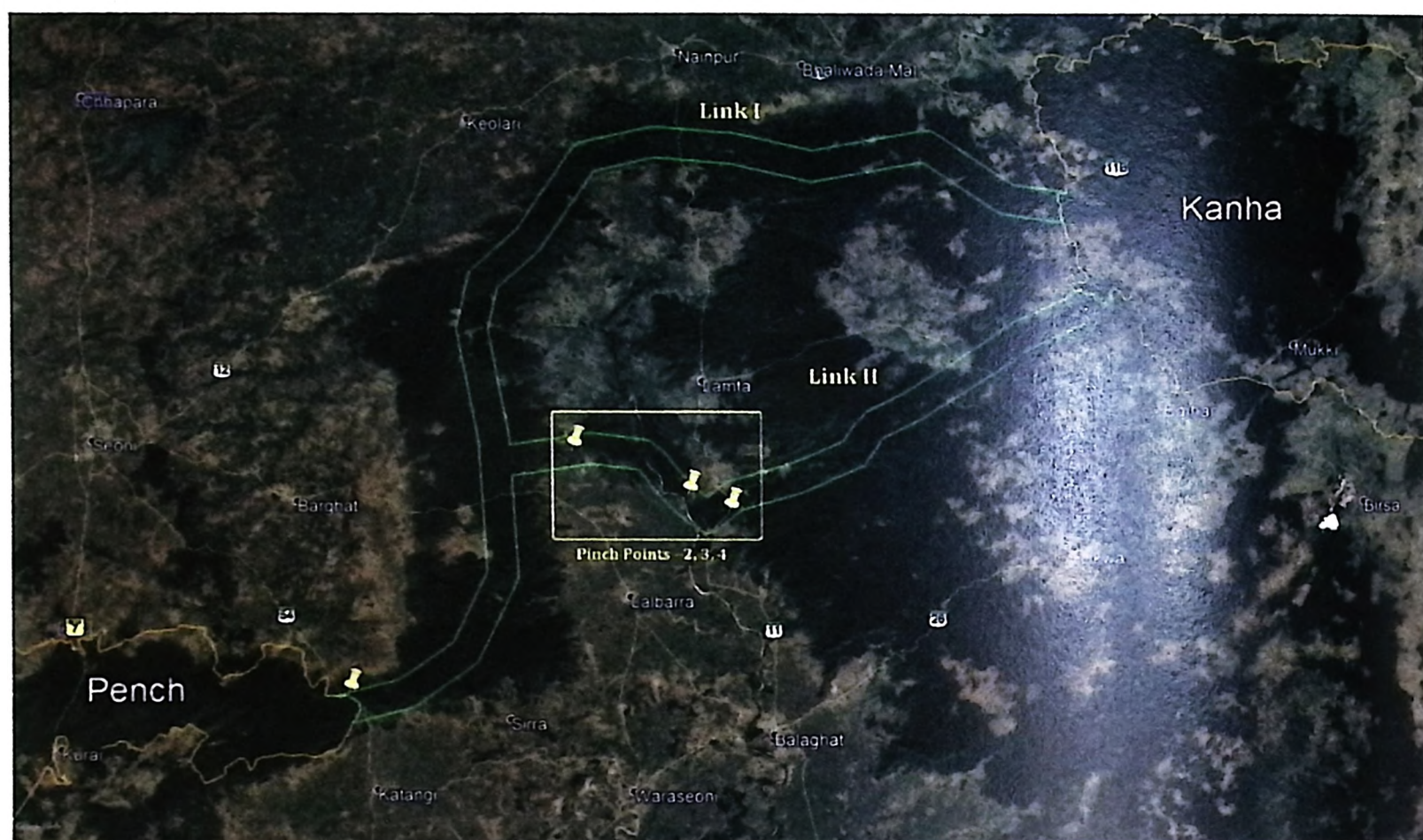


Figure 3-61 Locations of weak links Kanha-Pench corridor in central India

Kanha-Pench is also connected through the other link forming an alternative connectivity (Fig 3-62). Apart from the mitigation of NH-7 (44), the other parts of the corridor also needs attention (Link-II), the section of the corridor is significantly fragmented and stressed around the three weak points (2, 3 and 4) in North Balaghat Division (Annexure II). Here, four of the state highways cross the corridor, especially SH-11, which crosses Balaghat Forest Division near Mohgaon Khurd and Amoli village. The forest patches are fragmented by the presence of these road and railway networks. These linear infrastructure are detrimental for wildlife movement, causing deaths on the tracks and hindering the movements. To sustain the entire corridor connectivity between Kanha-Pench it is crucial now to also safeguard and mitigate this part (Link-II) of the corridor by implementing regulations for safe passage of wild animals and by developing the fragmented area through forest restorative measures.

However, it took more than a decade to materialize the mitigation action on ground for NH-7(44) with the contribution from managers, civil society and other conservation activists. This learning might be helpful in planning mitigation and incorporating them beforehand with the developmental projects coming up in wildlife important areas or in corridors. It is of immense importance that conservationists, infrastructure developers and civil society should gather on a single platform to exchange views on their requirements and their interest to develop mutually beneficial and economic plans.

India's present policy structure; including Indian forest Act (1927), Wildlife protection Act (1972), forest conservation Act (1980), the environment Protection act (1986), The biodiversity Act (2002) and National wildlife Action Plan (2002-2016) provide essential framework and support to protect the wildlife species and their habitat inside the protected areas. National wildlife Action Plan (2002-2016) was formulated to focus on stringing and enhancing the protected area network to conserve the endangered wildlife and their habitat and to put control on illegal trade of wildlife products. However, for long-term survival of wild populations, it is crucial that these protected areas remain connected with each other through corridors. Therefore, it is important to conserve and regulate not only habitats inside PA's but also outside protected areas. Wildlife corridors provide a potential solution to reduce adverse effects of habitat fragmentation by facilitating movement of wide-ranging animals across landscapes, but cannot be considered as an alternative for primary habitat loss. With careful planning, mitigation strategy and management, corridors can assist in long-term persistence of wild populations, along with delivering other environmental and social advantages without hindering human development in a landscape.

For wildlife populations, Central India is one of the most fragmented landscapes though having a good protected area network, which is scattered in this human dominated landscape. Wildlife populations living in these protected areas are small and their long-term persistence depends on immigrants that disperse through corridor connectivity. Current corridor habitats are tenuous, narrow, and many are under severe threats (Table 3-18). Linear infrastructure development, agriculture expansion, construction of dams, unmanaged forest loss, etc. are making these corridors highly vulnerable especially at certain regions – the “pinch points”. Therefore, urgent actions are required to address these pinch points, otherwise functionality of corridors, as a conduit for wildlife movement in the future is questionable. There are around 49 pinch points highlighted in the present study (Table 3-18) where immediate actions are required to safeguard the future of this connectivity’s in the central Indian landscape. Fate of these corridor also depends on timely executing the mitigation measures on ground before it is too late and movement behaviour of species changes in the landscape (Chloe et al 2015). A probable measure to restore the connectivity is habitat restoration by using agroforestry/plantation options with local participation. Encouraging locals to opt for agroforestry by providing them with subsidies or by leasing land for corridor conservation could help sustain the linkages for long term in the landscape. Pinch points fragmented due to linear developments can be addressed by implementation of appropriate engineering structures that crease safe passage ways for wildlife through legislative and policy on road regulations.

However, corridor management and design depends highly on operational scale and purpose, therefore area specific plans are required for effective management. National Tiger Conservation Authority (NTCA), under the aegis of the wildlife protection act-1972(under sections 38O (g) and 38V (3b)) guide state forest departments to prepare tiger conservation plans (TCP) to ensure “protection of tiger reserve habitat and areas linking one protected

areas to another allowing dispersal of wild animals through site-specific habitat inputs”. This provide a promising platform for the conservation and management of corridors on ground. The protected areas staff already have adequate training and perception towards wildlife conservation, thus their experience can help put corridor conservation goals in place with much less effort and investment. Some of the tiger reserves has already included corridor conservation in their plans such as Similpal, Kanha, Palamau and Melghat and Tadoba. Kanha and Melghat has decided to address the restoration of weak links after ground trothing of the identified corridor. Action plan of Simlipal and Taodba is more precise where corridors and adjoining areas are identified for restoration and for mitigation of disturbances in the habitat corridor. However, corridor conservation is now included in the management and conservation plans by the Tiger Conservation Plans of Tiger Reserves but it is also important that district development plans should also account these areas as this will help in preparing strategic plans that plan development keeping conservation as one of the objectives in mind.

From 49 pinch points, around 11 locations are affected due to the presence of linear infrastructure of national and state highways, crucial points where connectivity is likely to be at risk (Figure 3-62 & Table 3-18). The threat from these linear infrastructures can be minimized by adopting regulatory or prescriptive measures or by on-site engineering solutions (WII, 2016). Onsite engineering solutions include construction of under passes or over passes to allow the movement of wild species. Land bridge, canopy bridge, glider poles, viaduct, and box culvert are some of the solutions, which can be adopted based on the site feasibility. Along with this, management of local traffic in terms of control of speed, volume of vehicles and by planting vegetation along animal passageways while putting wildlife barriers along the rest of the road to channelize movement only from designated passages can also encourage animals to cross the road safely.

At 31 locations connectivity is highly fragmented as width of the natural vegetation is less than 3 km, recommended for minimal corridors caused due to disjunct forest patches within agriculture matrix. To safeguard the connectivity in these pinch points, it is essential to restore the natural vegetation cover in these pinch points by re-vegetation these sections of corridors by native species and by protection the present natural cover from encroachment. This would call for involvement of the local communities; any government owned land where restoration is required should be treated on priority by the local administration and forest department through reviewing of tree cutting practices, reducing biotic pressures on the forest fragments, and safeguarding the area from encroachment. This can be done by fencing the corridor not only to avoid negative interactions with locals but also to protect the forestland from local disturbances. Private land where corridor is weak, should be restored by motivating owners either by taking their land on lease by the government or by engaging private companies for plantation with appropriate compensation so as not to infringe on local livelihoods. Afforestation can be enhanced through the Campa Aforestation scheme and by taking grants from private sector through carbon credits.

At 3 pinch points the corridor is threatened due to the presence of canals/reservoir where high water levels can hinder wildlife movement, regulation in releasing of water in time and volume is essential.

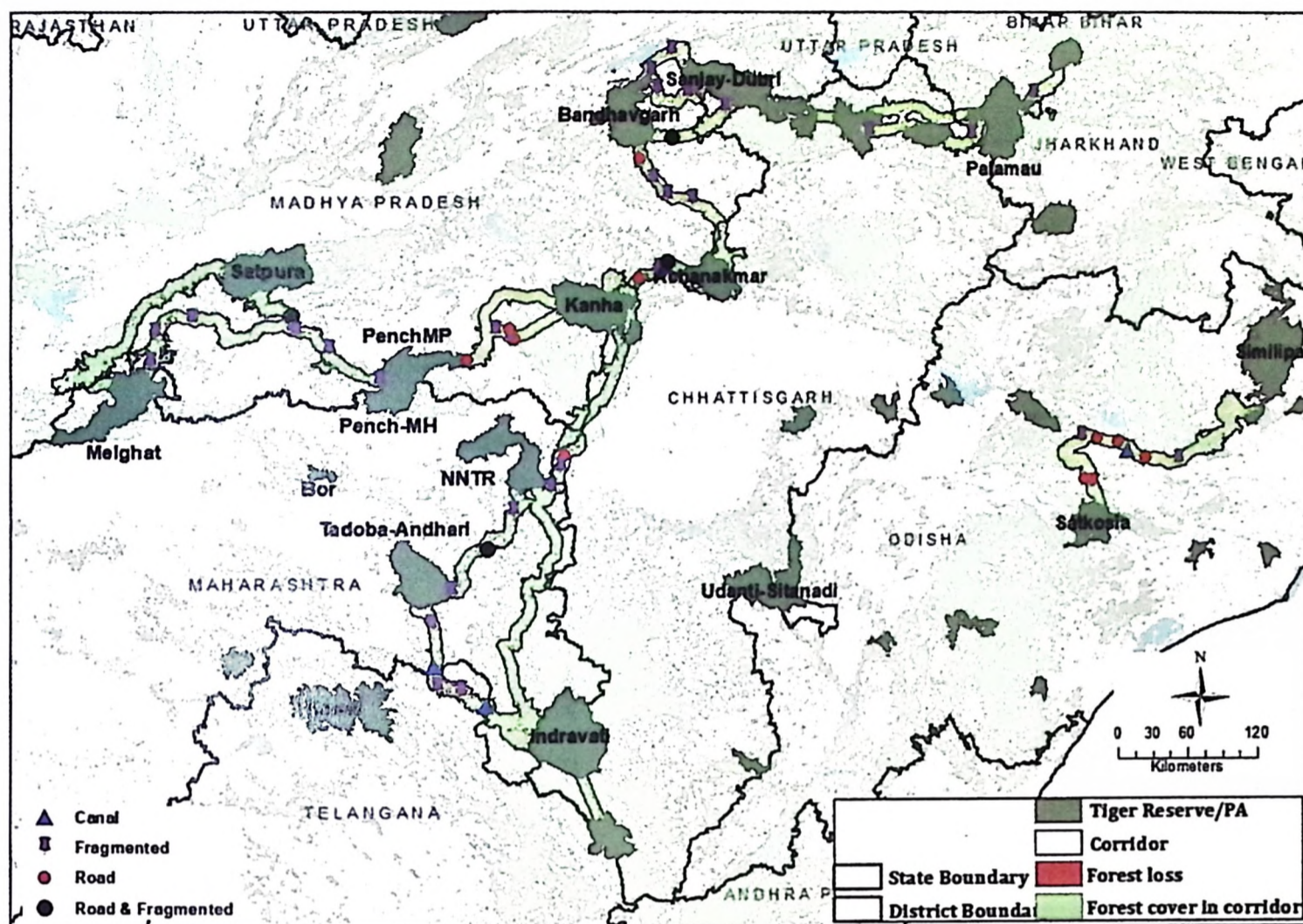


Figure 3-62 Locations of weak links and associated problems in the identified corridor in central India

Kanha-NNTR-Tadoba-Indravati Corridor

The corridor connects the four important tiger reserves in Central India, these protected areas harbours some of most important wild species such as tigers, leopards, dhole, and gaur that require metapopulation structure to persist for the long-term in the landscape. Corridor connectivity among these protected areas is crucial to allow movement of these wildlife species. The corridor is found to be deteriorating continuously, though the parks are connected through the contiguous forest patches of Madhya Pradesh, Chhattisgarh and Maharashtra. But these patches are getting affected severely at few points due to road broadening and fragmentation. Around 11 pinch points are identified which if addressed appropriately can safeguard the long-term connectivity between these protected areas. The corridor is fragile due to scattered forest patches within agriculture matrix or have large inter

patch distance between these forests, especially between NNTR-Tadoba and from Tadoba to Indrāvati. These locations are emerging as corridor gaps and can only be addressed by restorative inputs. These gaps can impede movement of sensitive species that need contiguous natural cover to move; large ranging species such as tigers and leopard might not get affected but can increase chances of negative interactions with humans and their death. Therefore, it is essential that vegetation cover is restored at these weak locations. Other weak location in the corridor is caused due to intersection with Highway and which might become a barrier for species movement due to fast moving vehicle and traffic volume, if wildlife underpass of appropriate height (6-8m) are constructed at appropriate sites that can assist animals to traverse these barriers.

Table 3-18: List of weak links in corridor, their location, and site specific problems that need immediate mitigation.

S.NO	CORRIDOR	NAME	NEARBY LANDMARK	PROBLEM
1	Bhandhavgarh-Achanakmar	Weak link 1 (23 21 54.16 N, 081 08 41.24E)	Pali range (Umaria)	Corridor is traversed by NH-78 – needs wildlife passages.
2		Weak link 2 (23 12 44.53N, 081 15 23.63E)	Ahirkawa range (Annupur) near Lamro	Corridor width is less than 0.5 km Surrounded by agriculture fields- needs restoration through plantation and protection.
3		Weak link 3 (23 05 26.10N, 081 22 18.17E)	Shahdol range (South shahdol)	Corridor width is less than 0.3 km- needs land acquisition with restoration.
4		Weak link 4 (23 03 24.72N, 081 34 27.62E)	Shahdol range (South shahdol)	Corridor width is less than 0.3 km - needs land acquisition with restoration.
5	Bhandhavgarh-Sanjay dubri-Gurughasidas	Weak link 1 (23 31 09.78 N, 081 24 33.06 E)	Gohparu range (South shahdol) near amjhor village	Corridor is connected through degraded forest with less than 0.6 km width SH -9 crossing the forest patch - needs wildlife passage ways as well as land acquisition and restoration.
6		Weak link 2 (23 44 29.89 N, 081 50 54.10 E)	Kuwarpur range (Mahendragarh) near badhwar village	Fragmented forest patches within agriculture matrix , needs protection and restoration of present natural cover
7		Weak link 3 (24 01 03.55 N, 081 14 06.87 E)	Beohari West range (North shahdol) near tikhwa village	Corridor width is less than optimum ~0. 0.8 km., need maintain the width of the corridor by restoration inputs

8		Weak link 4 (23 52 48.40 N, 081 17 17.48 E)	Godawal range (North shahdol) Near jhalra village	Linkage is almost broken, high agricultural activities. Agroforestry can help build the cover for safe passage of wildlife
9		Weak link 5 (23 51 26.77 N, 081 32 05.06 E)	Amjhor range (North shahdol)	Highly fragmented patches, safeguarding the present natural cover can ensure its persistence
10		Weak link 6 (24 10 17.09 N, 081 24 22.82 E)	Beohari East range (North shahdol)	Almost broken connectivity needs restoration through agroforestry.
11	Kanha- Achanakmar	Weak link 1 (22 28.20 N, 081 08.10 E)	Mawai range (East mandla)	Fragmented forest patches surrounded by agriculture and road, sustainability of this connectivity depends if overpass/underpass can be constructed along with afforestation.
12		Weak link 2 (22 30.22N, 081 17.49E)	South samnapur (Dindori) forest range	Forest patches are connected by narrow strip of forest of around 0.15 m width, surrounded by agriculture. Promoting agroforestry measures in this landscape would be beneficial
13		Weak link 3 (22 30.10N, 081 19.13E)	Border of south samnapur (Dindori) forest range	
14		Weak link 4 (22 32.18N, 081 18.24E)	Border of Bajag range (Dindori) near Kadawani village	Connectivity is fragmented at many places and is left connected through thin strips of width less than 0.15 km. Area is full of agriculture fields SH-9 cuts the corridor at several places. Agroforestry with local participation can help restore the connectivity in this landscape
15		Weak link 5 (22 34.95N, 081 21.97E)	Bajag range (Dindori)	
17		Kanha-Pench	Weak link 1 (21 51.28N, 079 46.71E)	Ari, near rukhad
18	Weak link 2 (22 04.12N, 079 59.8E)		Lal Bara range (South Balaghat)	Corridor width is less than 3 km , forest clearing further aiding fragmentation. Afforestation and agroforestry wherever possible can help safeguard this connection from further deterioration.
19	Weak link 3 (22 01.57N, 080 06.43E)		South lamta (North Balaghat)	Highly fragmented patch, 4 linear structure including SH-11 and Railway line. Regulatory measures for traffic as well as underpasses can be helpful to maintain this section of corridor
20	Weak link 4 (22 05.33N, 080 06.74E)		South lamta (North Balaghat) near Amoli	
21	Simlipal-Satkosia	Weak link 1 (20 54.19N, 084 50.18E)	Durgapur range Near Katada	Corridor is almost broken due to NH-42 and railway line. Forest is connected via thin strip. Promoting green cover through agroforestry and regulatory measures for road is the only
22		Weak link 2 (20 54.97N, 084 46.50E)	Handapa range near Kadalimunda	

				option left to reconnect this section of corridor
23		Weak link 3 (21 13.46N, 084 45.57E)	Reamal range near Kendupal	Fragmented patchy landscape with agriculture and human habitation, agroforestry measures can revive the green cover in this section to maintain the corridor.
24		Weak link 4 (21 12.58N, 084 52.96E)	Reamal range near Talaranijharan village	Crucial link to maintain the link bet ween two forest patches, NH-200 traversing through the forest patch. Construction of underpass/overpass can maintain the link.
25		Weak link 5 (21 11.00N, 085 03.54E)	Kaniha forest range	Linear strip of less than 0.2 is left Dissected by NH-200 and Baudabeda nalam road
26		Weak link 7 (21 03.33N, 085 17.28E)	Mahabirod forest range	Width of linkage is less than 0.6 km Disturbed by several linear infrastructure due to presence of reservoir
27		Weak link 8 (21 0125.92N, 85 33 50.86E)	Kamakhyanagar (West) forest range	Connectivity is patchy and surrounded by agricultural and human habitation. Improving natural cover by adopting agroforestry plantation is required.
28	Gurughaisdas- Lawalong	Weak link 1 (23 32.78N, 083 02.09E)	Ghui range, chirwan pat forest	Linkage is less than half a km, cut by road. Regulatory measure to control traffic on road with improving green cover along the road could help to maintain this section
29		Weak link 2 (23 30.42N, 083 53.87E)	West of Chando range forest	This section of corridor have fragmented forest patches within agriculture matrix, this part of corridor can be improved with agroforestry plantation to maintain the connection.
30		Weak link 3 (23 48.52N, 084 25.39E)	Ramchoura forest in balrampur range	Narrow link of less than 0.5 km , surrounded by agricultural fields, fencing the forest patch and enhancing green cover in the surrounding can help safeguard this section for future.
31	Pench-Satpura- Melghat	Weak link 1	In Kanhan forest range	Fragmented connectivity, less than 0.5 km width. Only linkage connecting Pench with the nearby forest
32		Weak link 2 (21 55.09 N, 078 43.46 E)	Near Shankarpur beat in Saori range forest	Highly fragmented, surrounded by agriculture field Road cutting the forest patch
33		Weak link 3 (22 03.44 N, 078 28.74 E)		Highly fragmented with agricultural fields Few forest patches are present which are needed to connect through agroforestry and plantations to create a stepping stone corridor
34		Weak link 4 (22 04.78 N, 078 26.98 E)		

35		Weak link 5 (22 09.94 N, 078 25.93 E)	In Jamai range	Degraded forest patch, Corridor width is less than 1.5 km , traversed by SH-19B. Need to have wildlife passages and more of green cover.
36		Weak link 6 (22 08.14 N, 077 41.64 E)	Shahpur forest range	Narrow corridor-less than 1 km width with degraded forest within fragmented landscape. Afforestation can help join the forest patches for animal movement.
37		Weak link 7 (22 01.34 N, 077 24.92 E)	Between Jhirna-Hurra Malgajari village	
38		Weak link 8 (21 48.12 N, 077 23.04 E)	Taodi forest range	Link is only connected through a water body, surrounded by agricultural fields. Increasing green cover along the water body and promoting agroforestry can safeguard this link for future.
39	Kanha-NNTR-Tadoba-Indravati	Weak link 1 (21 08.71 N, 080 32.74 E)	Bagrekasa forest	Less than optimal width of corridor ~0.6km, another threat is road that traverse the corridor, construction of underpass/ overpass can help sustain the connectivity for long.
40		Weak link 2 (21 03.07 N, 080 31.10 E)	In Baghnadi forest range	Fragmented and degraded forest patches, needs restorative inputs
41		Weak link 3 (20 53.80 N, 080 25.96 E)	Chichgarh forest	Highly fragmented forest, 0.5 km of corridor width is left. Agroforestry
42		Weak link 4 (080 25.96 E, 080 08.58 E)	In Gothangaon forest	Highly fragmented forest, 0.5 km of corridor width is left. Agroforestry option can help to restore the connectivity
43		Weak link 5 (080 08.58 E, 079 56.50 E)	Fringes of Bramhpuri forest	Corridor is broken, intensive agriculture, forest patches are around 6-8 km apart. Agroforestry or plantation either by land procurement or along the banks of water body can help forming a stepping stone corridor
44		Weak link 6 (20 07.47 N, 079 40.27 E)	Forest of Sawali range	Corridor is broken, intensive agriculture landscape, forest patches are around 3-6 km apart. Critical to connect with Tadoba with other forest areas, artificial stepping stone corridor with agroforestry plantation is required to connect it with nearby forest patches
45		Weak link 7 (19 52.21 N, 079 31.36 E)	fragmented-disturbed forest	Narrow width of corridor~3 km, highly fragmented with various roads cutting across. Forest restoration and regulatory

				measures for roads crossing from the patch by speed control, closure of roads at night etc. should be implemented for safe movement of wild species.
46		Weak link 8 (19 33.06 N, 079 32.76 E)	Near tomta village, Dhaba forest range	Connectivity is broken, the nearest forest patch is 2-3 km apart matrix is full of agriculture field and settlements. Stepping stone corridor by promoting agroforestry and plantation for making a stepping stone corridor
47		Weak link 9 (19 22.85 N 079 44.99 E)	Weak_link	
58		Weak link 10 (19 15.84 N, 079 56.36 E)	weak_link	
49		Weak link 11		Linkage is almost broken surrounded by agricultural field. Agroforestry and plantation can potentially protect this connectivity

In a developing country like India with an increasing human population every hungry for more resources, it is important for the Government to balance the need for today with security for tomorrow. Due to poverty and struggle for livelihoods, conservation is not the immediate priority of communities. In such a scenario, securing the future of our natural heritage as well as that of local communities is the mandate of the Government. An essential element for securing biodiversity persistence in landscapes is to permit natural geneflow between isolated fragmented populations across a sea of human dominated landscape. Investment in managing viable habitat corridors is an essential element for conservation in the Anthropocene. As economic status of local communities improves and the more pressing demands of survival are addressed local people will show interest in conservation. Till that period of time the responsibility of balancing conservation needs along with development lies with the larger society and country level Governance. The fragile planet requires constant care and corridors a one of the essential part of this care that we need to provide for long term ecological security.

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5. ANNEXURE-I

FORM-1: CARNIVORE SIGN SURVEY DATA SHEET

Forest Division:

Start Time:

Starting Latitude:N

End Latitude:N

Total distance covered (km):

Range:

End Time:

Starting Longitude:E

End Longitude:E

Time spent in other activities (Resting etc.):

Date:

Beat:

Trail Id:

Observers	Name	Designation	Phone No.
1			
2			

Sl. No.	Time	Latitude			Longitude			Sign Type ²	Species	Age of Track/sign ^{**}	Remarks
		Deg.	Min.	Sec.	Deg.	Min.	Sec.				
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											
19											

In case of Direct sighting, observer should mention the Age, Sex and Individual number in the Remarks column.
¹Sign types:- Scat/Pedlets/Dung-SCT/PLI/DNG, Pugnmark, Track-PT, Vocalization-VC, Rake-RK, Scrape-SCR, Rolling-RL, Spray-SPR, Digging-DIG, KIB-K, Scat & Scape-SS
²Age of Track & Sign: Very Fresh- VF, Fresh- F, Old-O, Very Old- VO
 Note: 1. If you get more sign than these, then enter it on another datasheet.

FORM 2: LINE TRANSECT DATA SHEET

Forest Division: _____ **Range:** _____ **Date:** _____
Transact ID: _____ **Transact Bearing:** _____ **Transact length (Km):** _____
Start time: _____ **Forest type:** _____ **Terraina type:** _____
Start Latitude: N **End time:** _____ **Young:** _____
End Latitude: N **Start Longitude: E** **Total no. (Adult & young):** _____
End Longitude: E **Weather: Sunny (/) Cloudy (/) Rain (/)** **Phone No.** _____

Observers	Name	Designation
1		
2		

S. No.	Time	Latitude			Longitude			Species	Total no. (Adult & young)	Young	Angular Sighting Distance	Compass bearing		Forest type	Terrain type	Remarks
		Deg.	Min.	Sec.	Deg.	Min.	Sec.					Animal	Walk			
1																
2																
3																
4																
5																
6																
7																
8																
9																
10																
11																
12																
13																
14																
15																
16																
17																
18																

*Species for which data need to be collected- Chital, Sambar, Nilgai, Elephant, Gaur, Barasingha, Chousingha, Blackbuck, Chinkara, Wild boar, Langur, Peacock, Hare, Livestock etc. (all animal sightings).
Instructions:

1. The start and end time of the transect must be recorded.
2. The format of GPS location should be in Degree-minute-second.
3. The walk bearing and animal bearing should be written while walking the 2km transect (the walk bearing and transect bearing can be different if line transect is passing through hill or different terrain).

FORM-4: SAMPLING FOR UNGULATE PELLETS / DUNG

Observer:

Date:

Forest division:

Range:

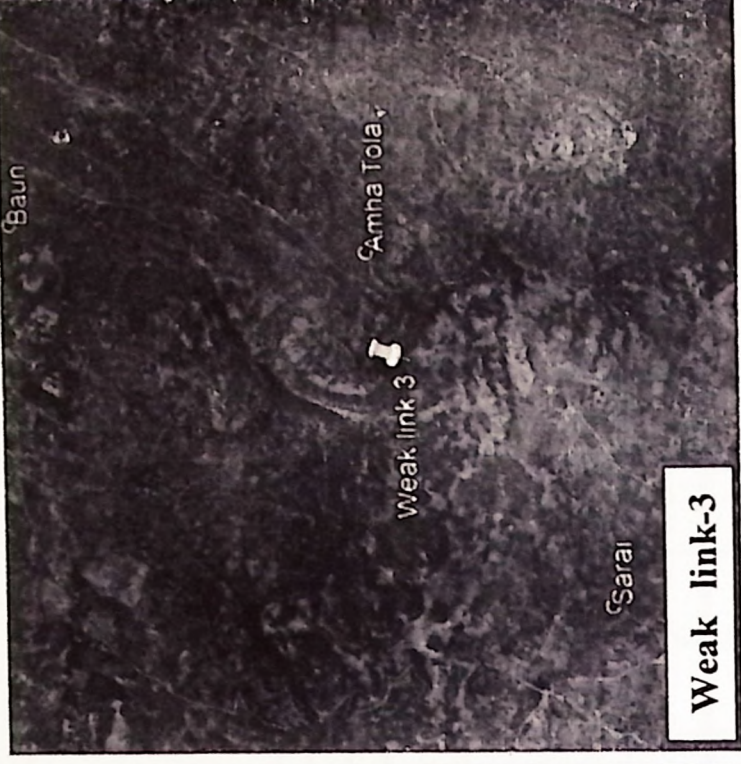
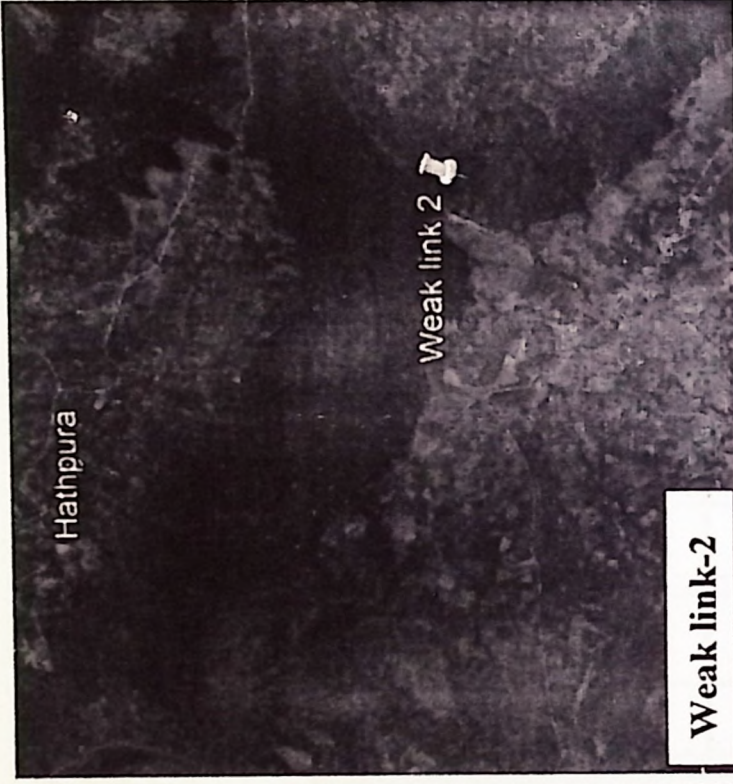
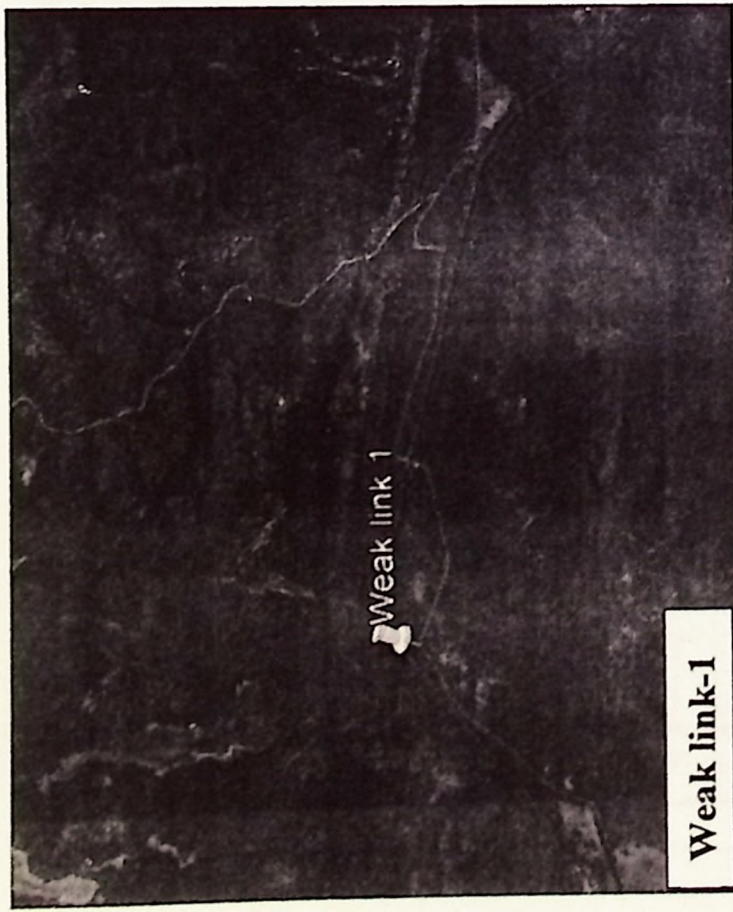
Beat:

Transect line Number

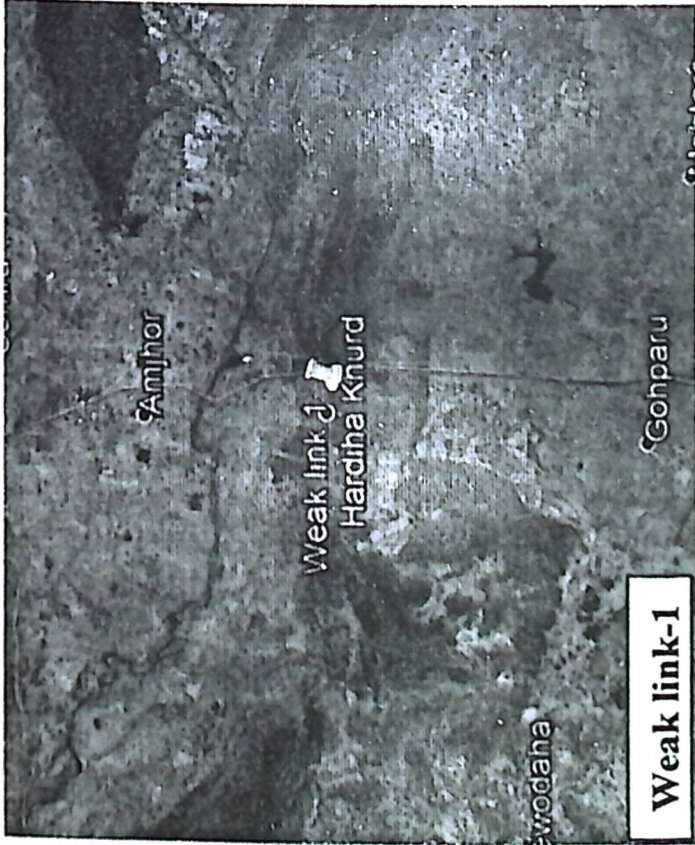
Plot No.	Chital	Sambar	Wild pig	Migai	Elephant	Gaur	Brsingha	Barking deer	Chinkara	Chousingha	Hare	Mouse deer	Blackbuck	Langur	Macaque	Hog deer	Wild buffalo	Peafowl	Rhinoceros	Other wild animal	Cattle/buffalo	Sheep/goat	Other domestic animal	
1																								
2																								
3																								
4																								
5																								
6																								
7																								
8																								
9																								
10																								

1. Do goat/sheep graze the sampled plot? Yes / No. _____
 If Pellets exceed 1000 then enter them as 999.

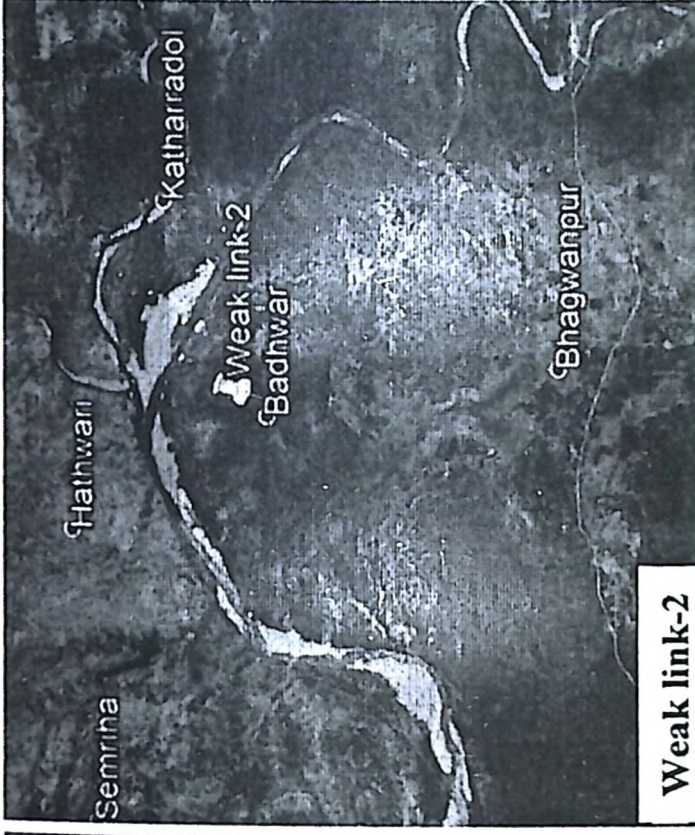
6. Annexure-II Bhandhavgarh-Achanakmar Corridor



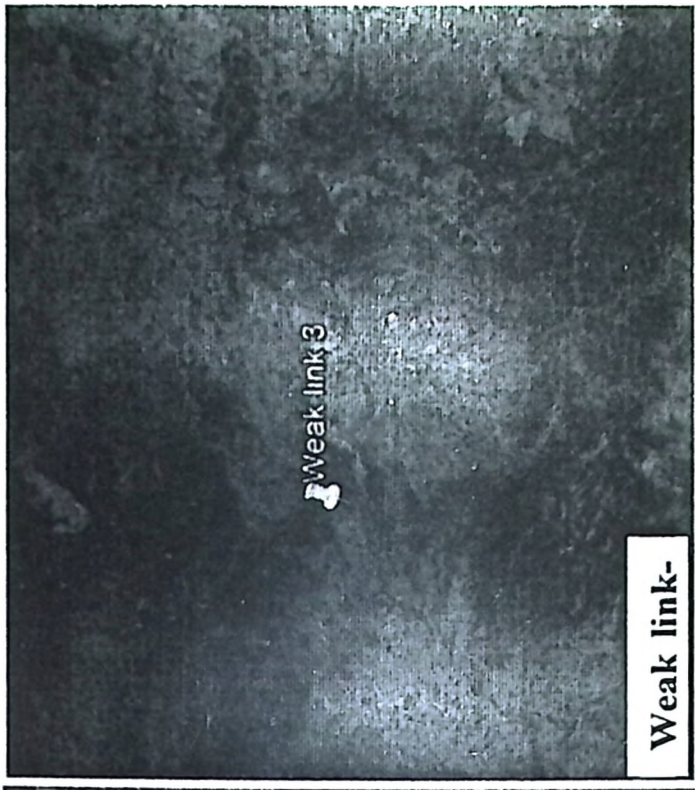
Bhandhavgarh-Sanjay-dubri-Gurughasidas



Weak link-1



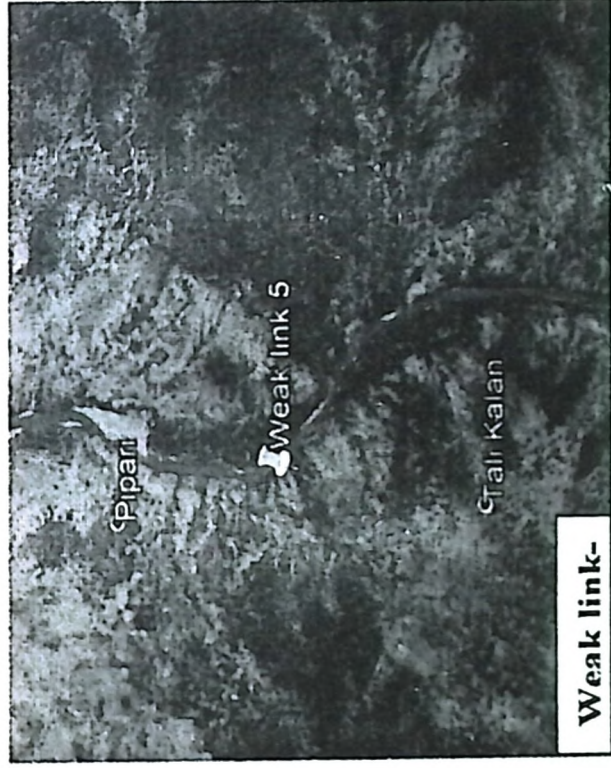
Weak link-2



Weak link-

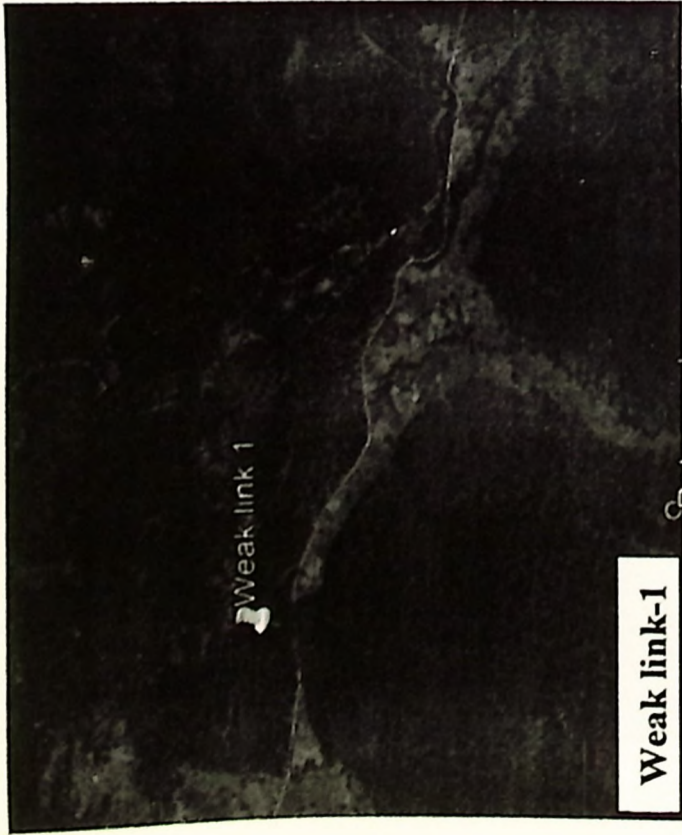


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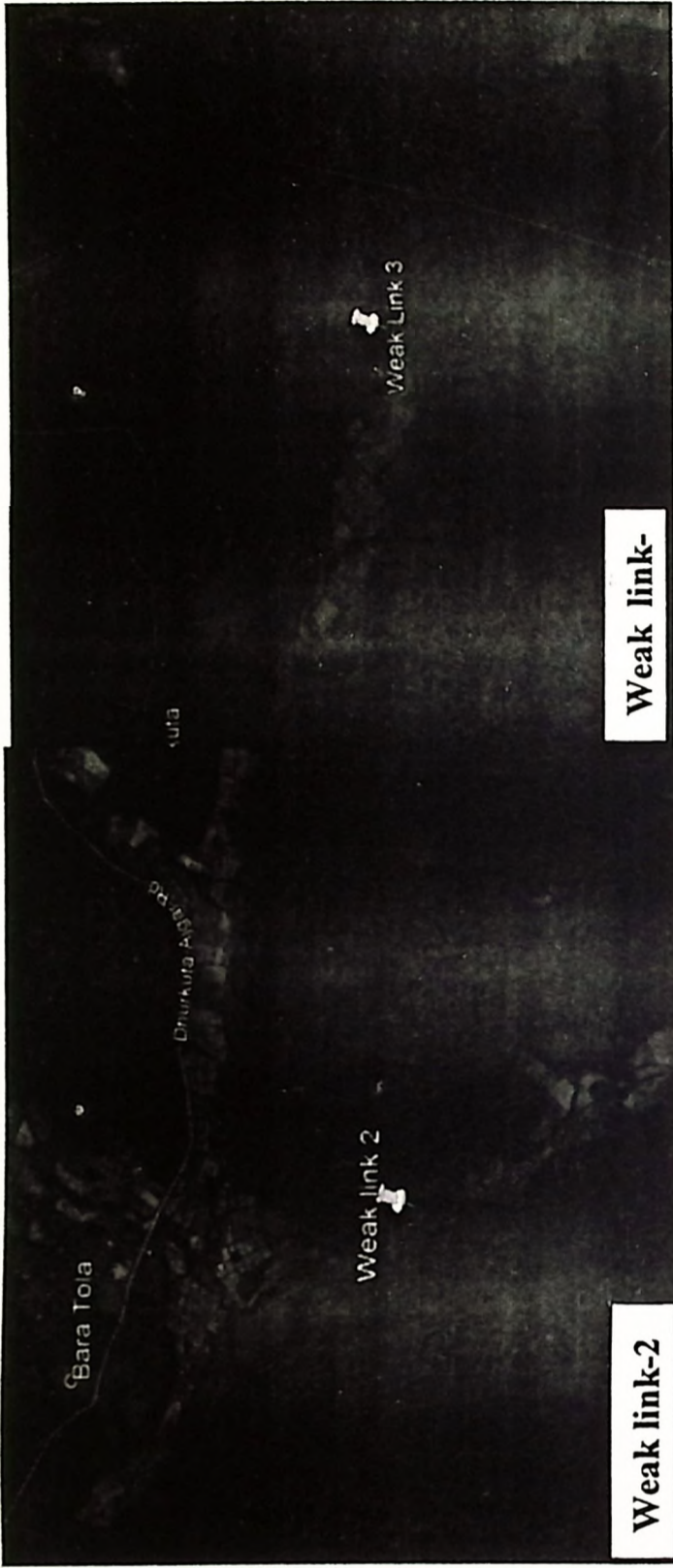


Weak link-

Kanha-Achanakmar

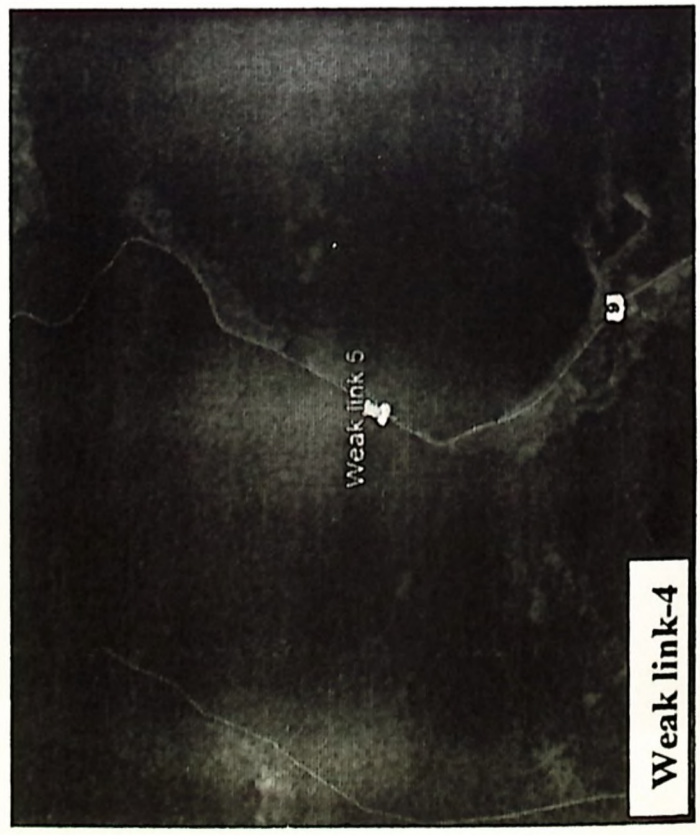


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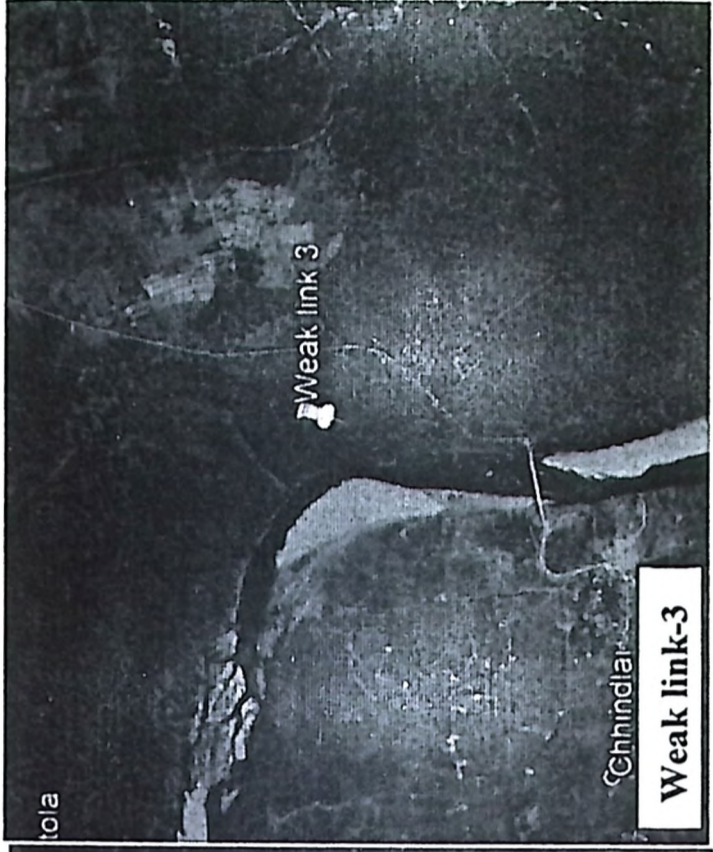
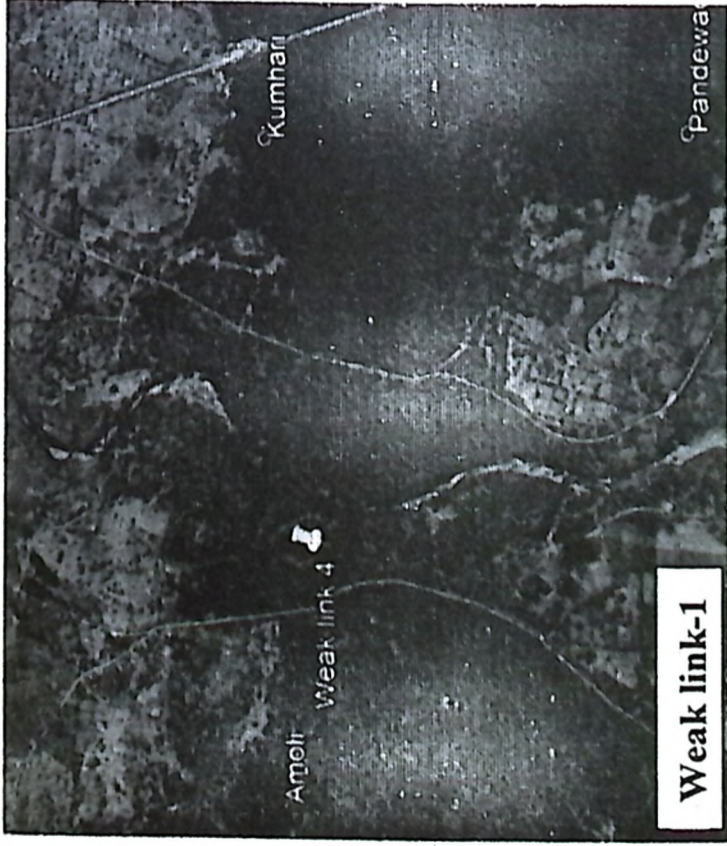
Weak link-2

Weak link-

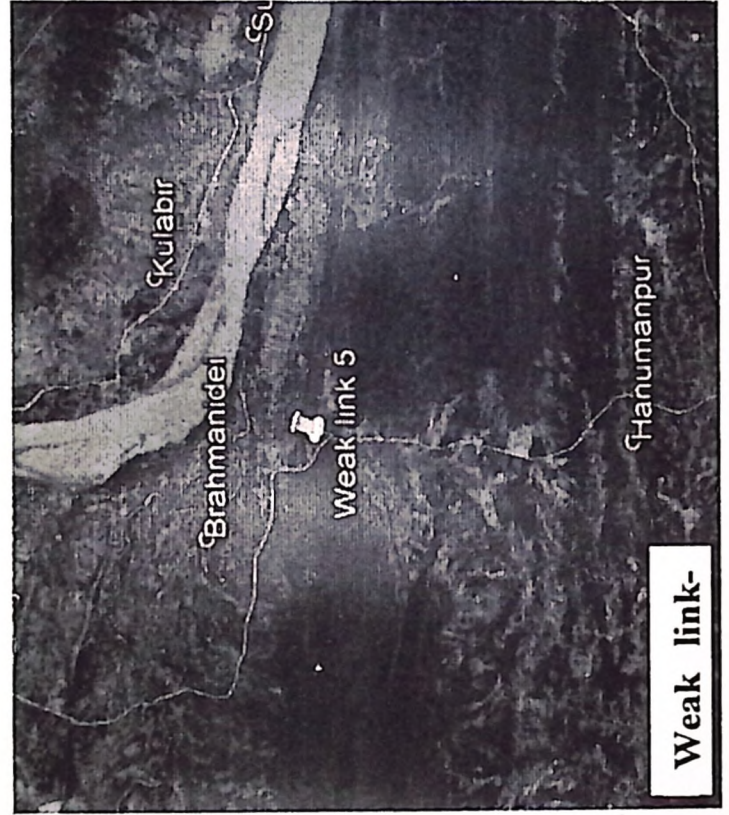
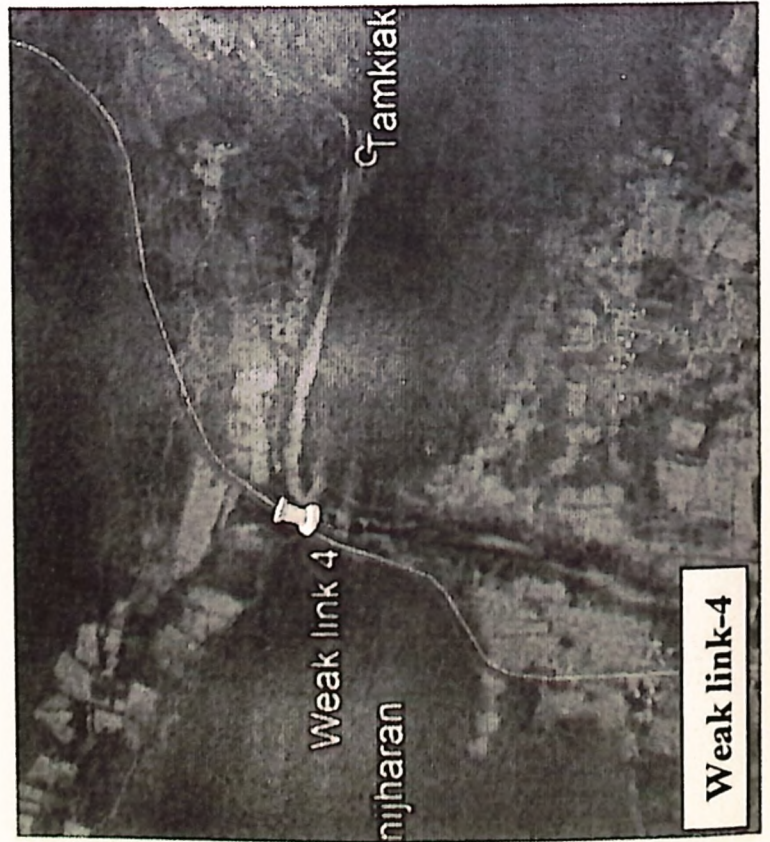
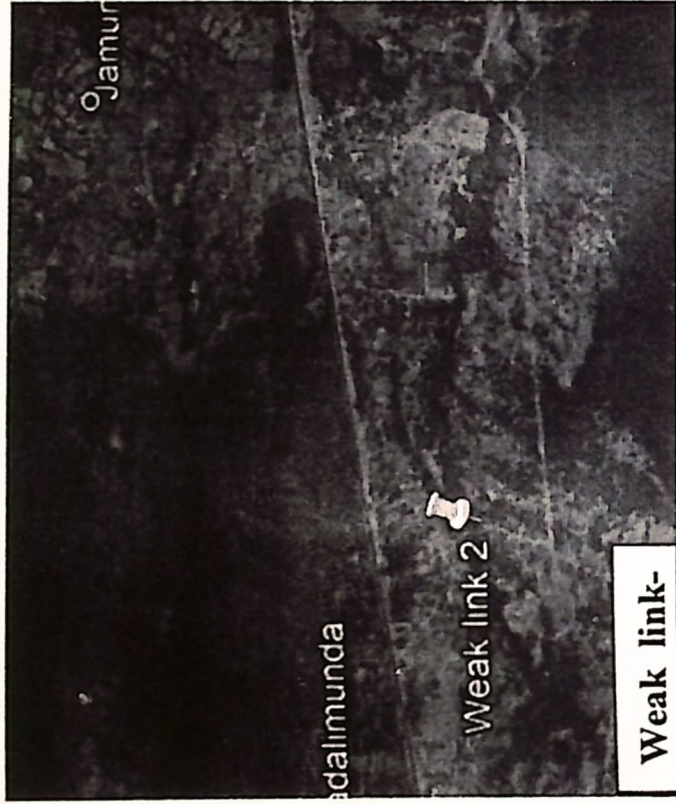


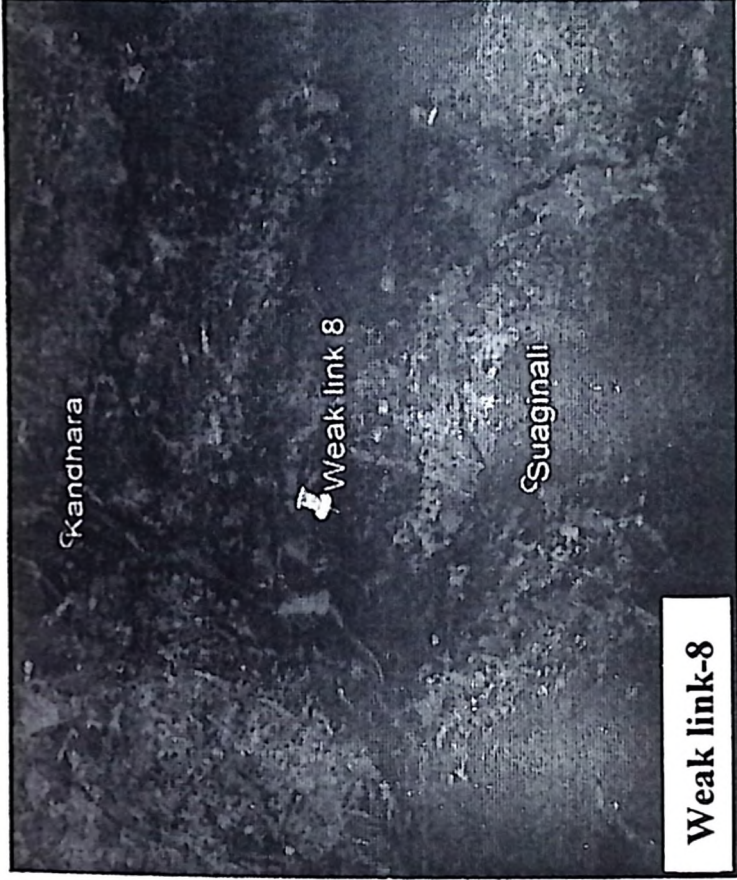
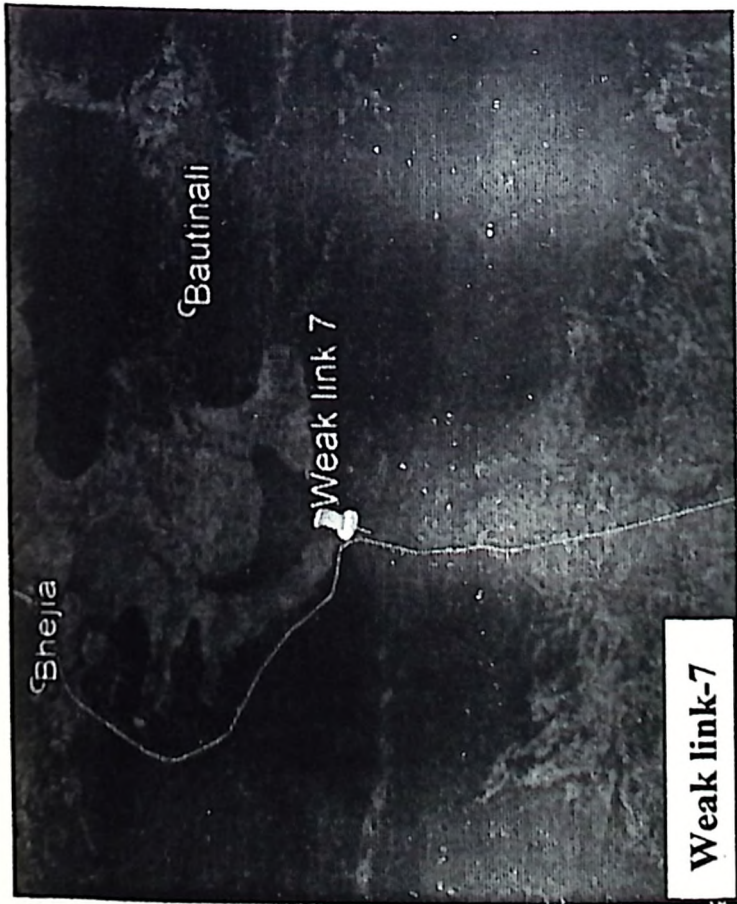
Weak link-4

Kanha-Pench



Simlipal-Satkosia

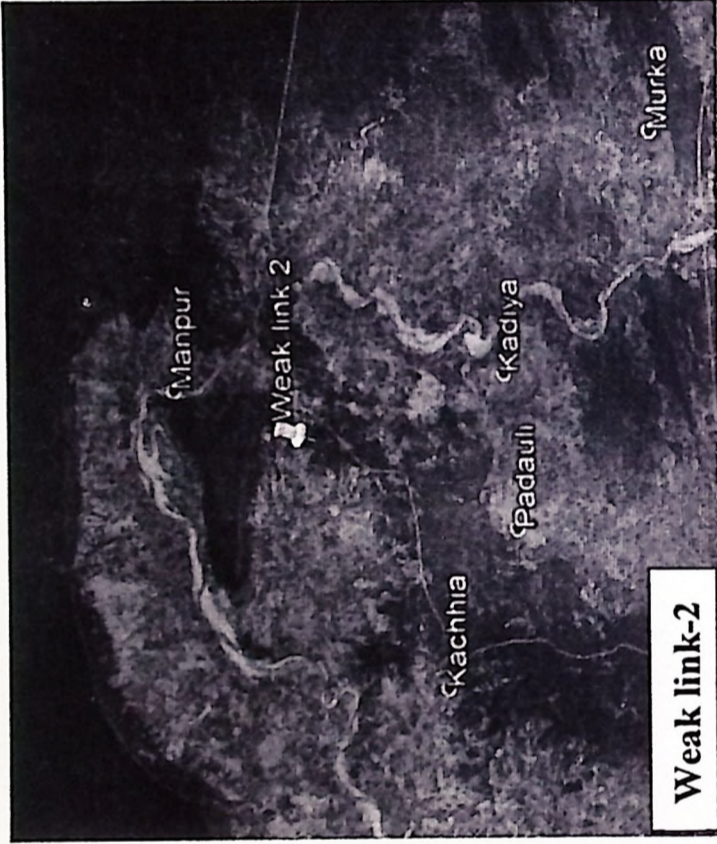




Gurughasidas-Lawalong



Weak link-1



Weak link-2

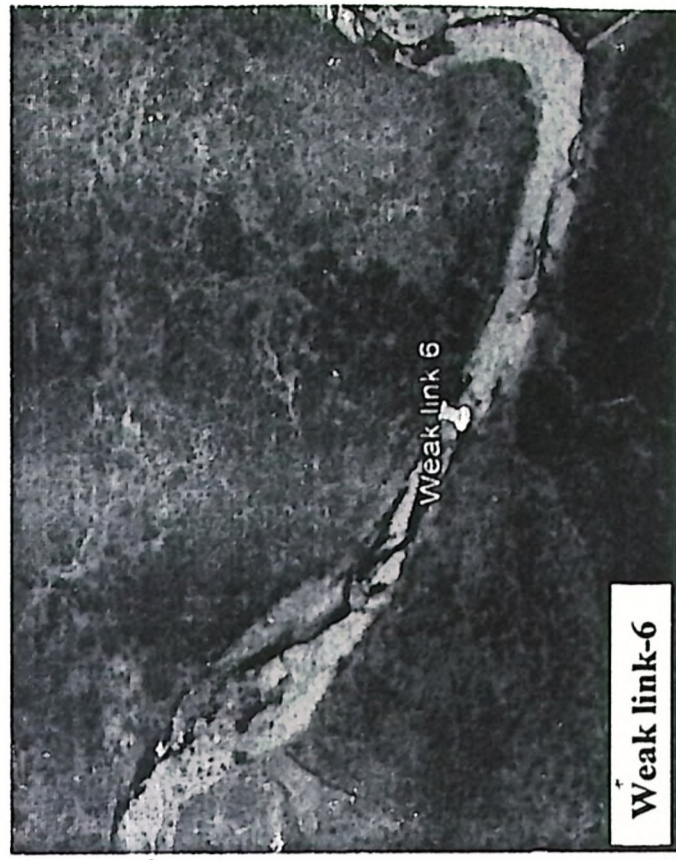


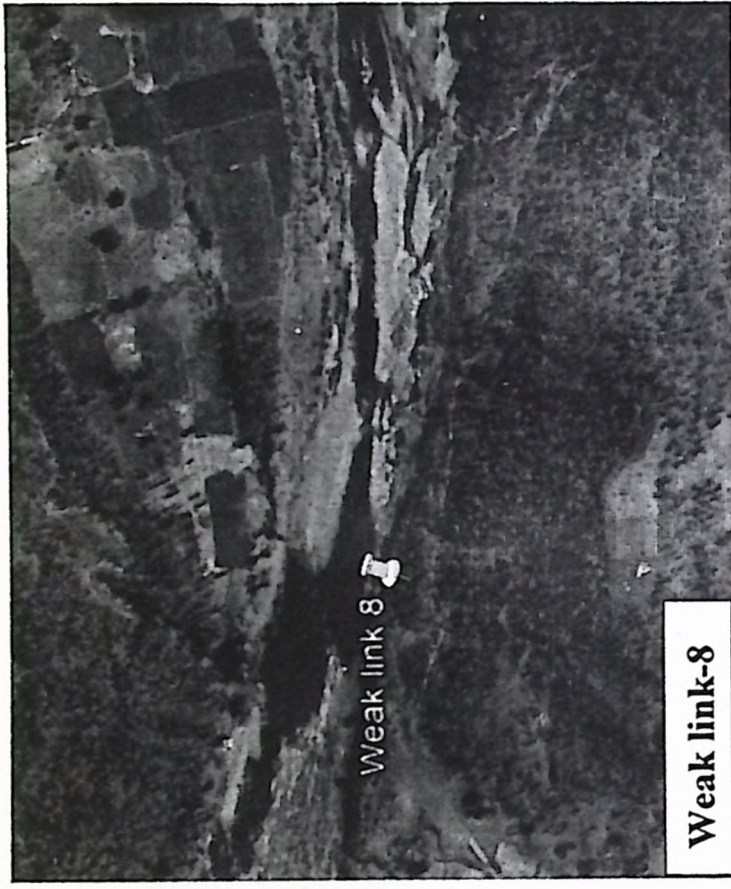
Weak link-3



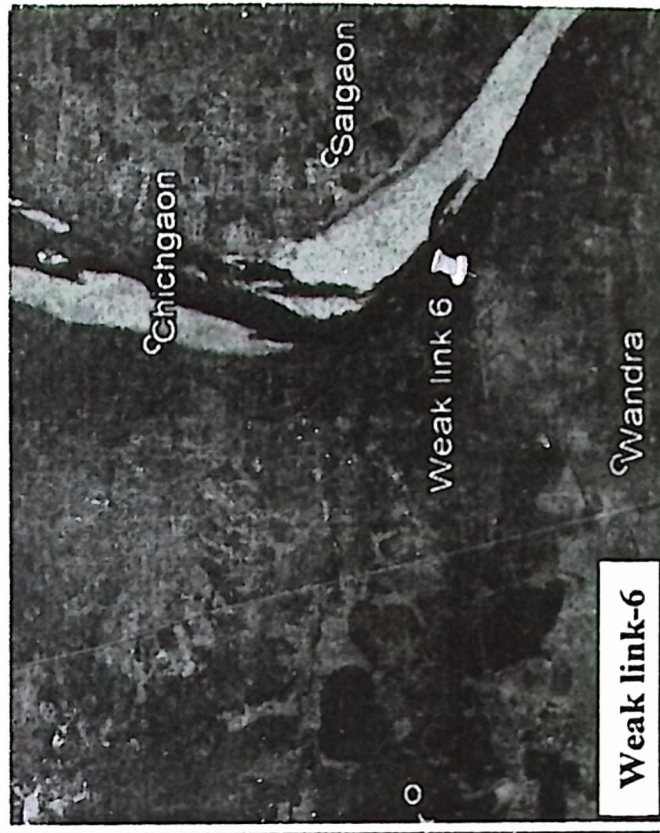
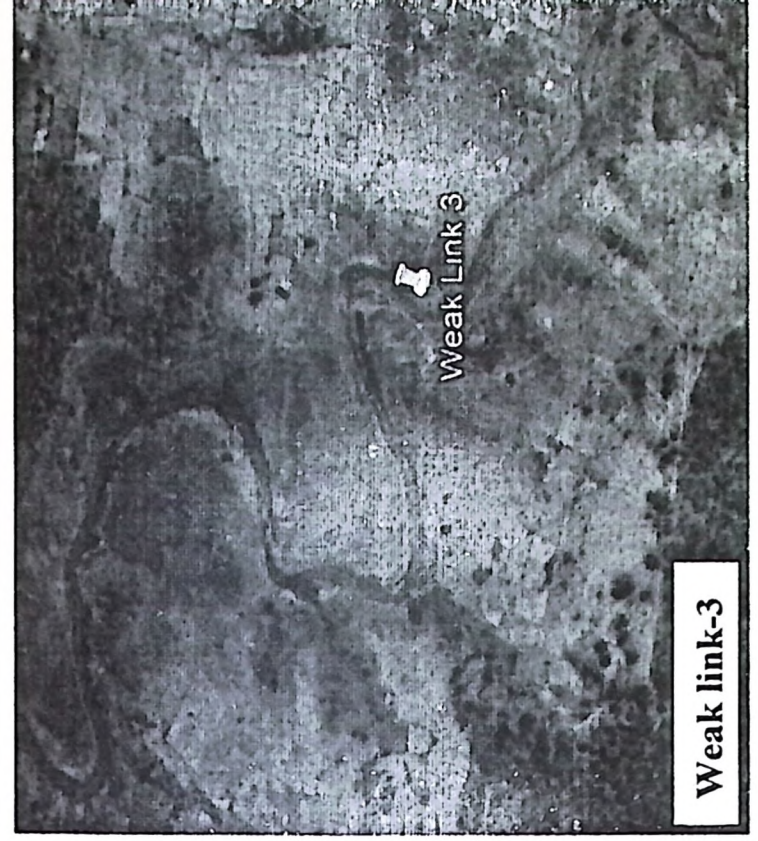
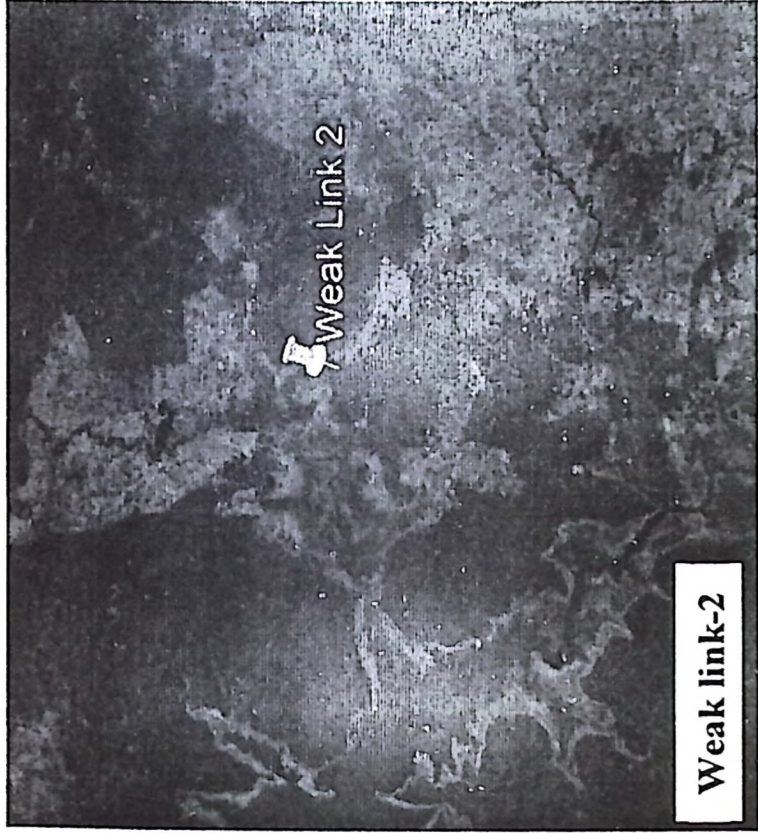
Weak link-4

Pench-Satpura-Melghat





Kanha-NNTR-Tadoba-Indravati

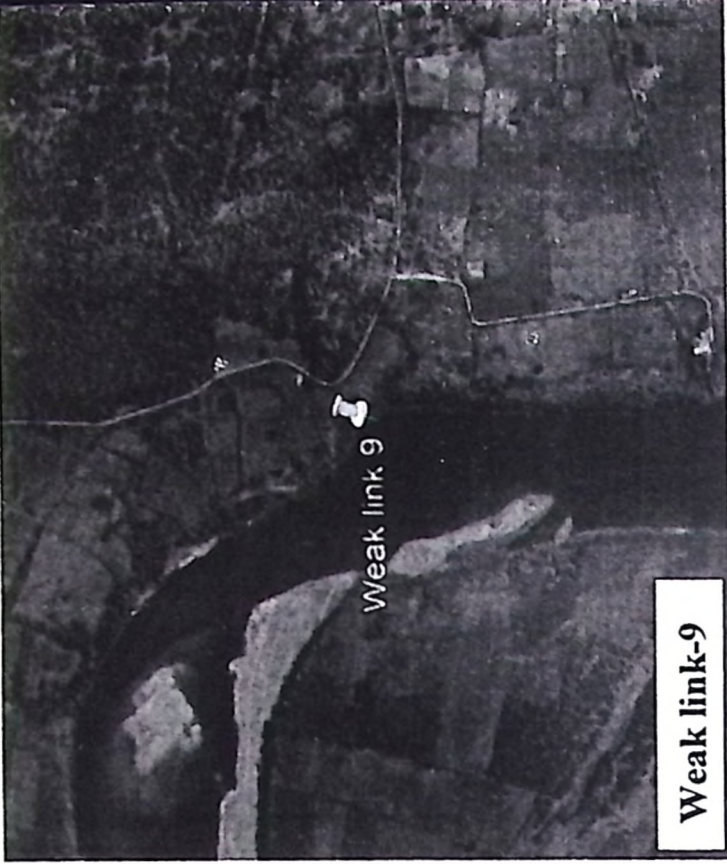




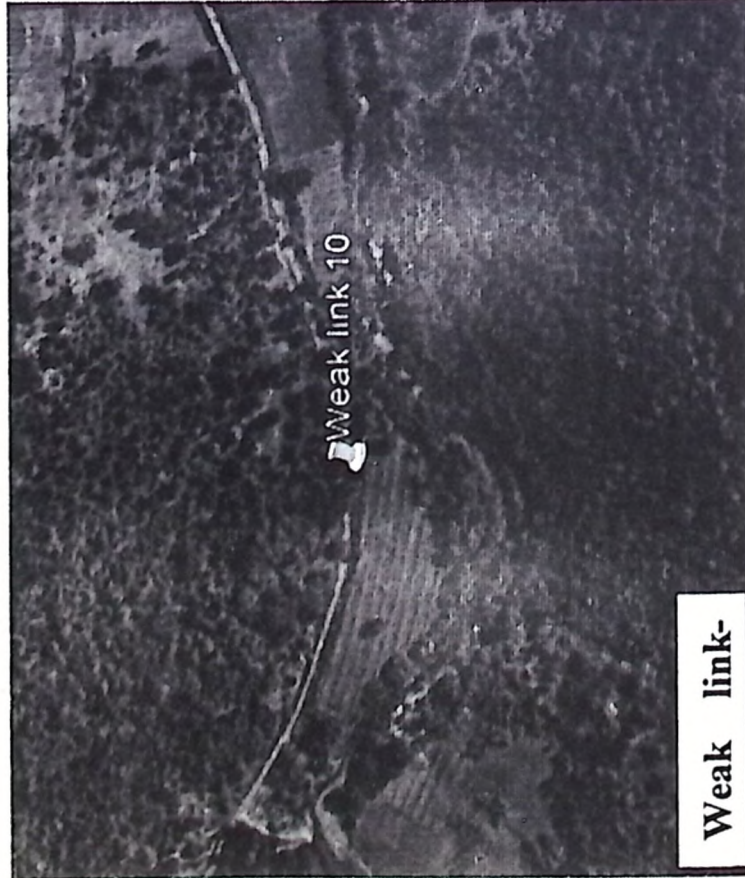
Weak link-7



Weak link-8



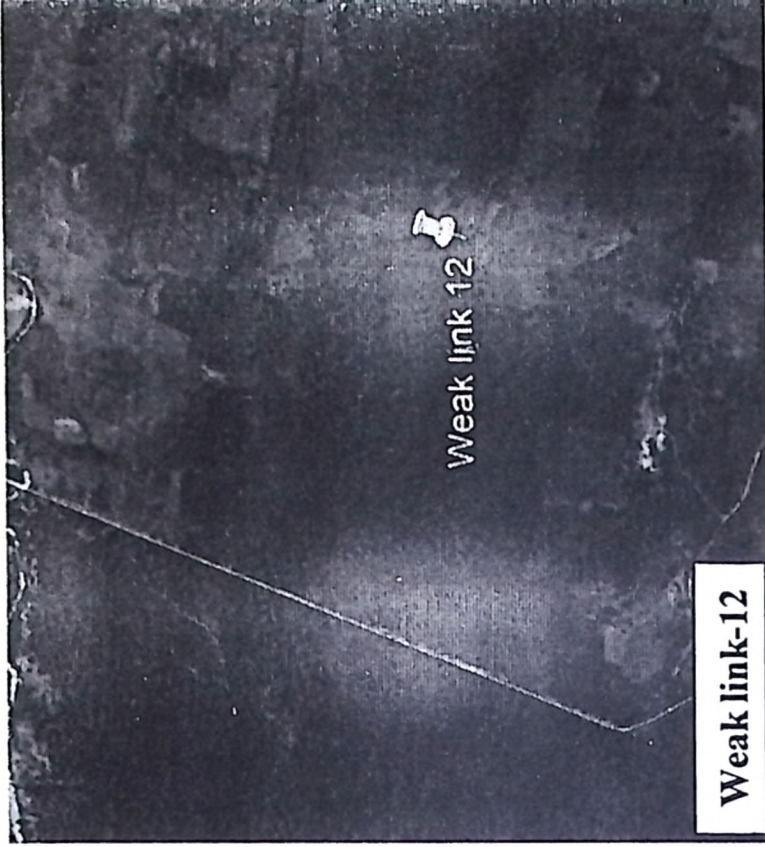
Weak link-9



Weak link-



Weak link-11



Weak link-12

7. Annexure-III

Andhra Pradesh

Sectorwise Gross District Domestic Product (GDDP) for the Year: 1999-2000 (At 1999 – 2000 Prices) (Rs Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unregd. MFG.	Electricity, Gas & W.supply	Construction	Trade, Hotels & Restaurants	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Srikulam	68026	4749	5827	4864	36897	20094	16802	6656	14725	34036	3412
2	Vizianagaram	84392	4411	4871	2325	15983	4370	11613	3933	14379	26892	4522
3	Visakapatnam	99221	6881	13798	8113	147712	124019	23693	16490	54949	138210	13301
4	Eastgodavari	267820	9352	24167	38832	166744	93305	73438	18459	30516	143683	3493
5	Westgodavari	285049	6718	44700	2855	63682	45328	18354	21840	19355	106094	2998
6	Krishna	255647	6239	73045	8516	63109	34666	28443	16250	38369	99506	13116
7	Guntur	307100	7659	21800	11325	45169	33830	11339	20818	38923	96342	5257
8	Prakasam	138011	6932	21192	7078	32697	14565	18132	10557	34402	53268	2382
9	Nellore	108392	5251	51726	629	50180	26680	23500	12375	29153	53592	4396
10	Chittoor	162953	7764	1787	5290	54380	24908	29472	19038	32411	58760	5608
11	Cuddapah	105743	6009	952	4184	54486	32436	22050	16880	24434	42992	1722
12	Anantapur	125646	6452	4149	1726	50909	4540	46369	22402	28426	52209	9968
13	Kurnool	144882	6597	1178	11493	25024	9575	15450	14744	29891	57644	2321
14	Mahabubnagar	102004	7196	7144	126	29056	12436	16620	17813	35284	40063	1306
15	Rangareddy	121041	4021	2480	2587	192286	180013	12274	17191	62873	110854	9165
16	Hyderabad	24531	2369	0	0	117827	103360	14467	31273	59302	60816	101369
17	Medak	118170	4677	3175	2146	259202	253658	5543	16368	17520	130165	664
18	Nizamabad	97874	4437	5262	59	38635	28016	10620	15269	15188	36472	933
19	Adilabad	77178	6591	3213	49688	14560	7890	6670	8296	19695	49069	1355
20	Karimnagar	173265	6544	4712	102287	31953	20461	11493	22250	29643	104806	2091
21	Warangal	129740	6650	4427	5347	26205	7152	19054	19234	25139	46584	10093
22	Khammam	126938	7394	5704	85777	18881	7591	11290	10632	20588	78875	1465
23	Nalgonda	129357	5857	13544	3961	77839	43478	34360	23909	29394	67577	2133

Source: Directorate of Economics and Statistics, Govt of Andhra Pradesh

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total DDP	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	Srikakulam	9917	122	2489	15055	29696	13088	38571	288130	25297	11390
2	Vizianagaram	6630	369	2697	14728	25712	13428	38413	263685	22509	11714
3	Visakapatnam	65742	630	7324	31093	66220	58982	63069	791736	37835	20926
4	Eastgodavari	42925	292	8646	35129	56319	30020	74368	950767	48956	19421
5	Westgodavari	20117	369	9143	29783	44915	21393	60788	739800	37980	19479
6	Krishna	53879	1249	12563	37093	66504	43960	72503	861547	41530	20745
7	Guntur	27330	3024	12088	35129	56482	29637	72478	790562	44550	17745
8	Prakasam	10311	223	6532	23456	36758	20496	46116	450411	30435	14799
9	Nellore	14434	382	7761	21056	32487	22607	43096	457515	26523	17250
10	Chittoor	17313	307	9846	27165	43596	31287	62052	539557	37067	14556
11	Cuddapah	12337	100	5407	17565	29645	17545	42275	382276	25751	14845
12	Anantapur	13878	364	9693	22692	39749	27885	56711	472859	36049	13117
13	Kurnool	15956	240	9357	21601	36238	20228	57414	454810	34754	13086
14	Mahabubnagar	10337	143	5570	21056	35649	18313	48619	379676	34803	10909
15	Rangareddy	24282	798	11728	20183	69757	31219	66231	746697	34343	21742
16	Hyderabad	109408	283	25260	56839	138787	93325	99950	921340	37569	24524
17	Medak	14174	92	4869	17674	26495	17740	35008	668138	26328	25378
18	Nizamabad	9824	396	3998	17783	25068	12389	34054	317641	23204	13689
19	Adilabad	7108	48	4226	15819	27789	27359	34335	346328	24476	14150
20	Karimnagar	17504	154	5956	19310	38676	33439	54432	647023	34549	18728
21	Warangal	14665	460	6467	20510	36953	16016	55254	423743	32109	13197
22	Khammam	12935	326	5728	16910	29493	29475	43646	494770	25470	19426
23	Nalgonda	11518	272	5320	19965	35633	14099	50322	490701	32182	15248

Source: Directorate of Economics and Statistics, Govt of Andhra Pradesh

Chhattisgarh

Sector wise Gross District Domestic Product (GDDP) for the year: 1999-00

(At 1999 – 2000 Prices)

Sr. No.	Distri ct Name	Agric ul- tur e	Forestry & Logging	Fishin g	Mining & Quarrying	Manufa- cturing MFG.	Regi- stered MFG.	Un regd . MFG.	Electricity, Gas & W.supply	Constru- ction	Trade,Hotels & Resta- urants	Railway s
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Koriya	14532	2810	347	30052	6576	5215	1360	521	3127	8965	2977
2	Surguja	59631	6342	481	24262	19446	15423	4023	1617	6572	14614	335
3	Jashpur	30184	1952	1051	1	13991	11097	2894	375	2670	5250	0
4	Raigarh	29885	2942	2789	2185	21325	16913	4412	1145	5994	16234	2486
5	Korba	16702	2201	4850	236687	18904	14993	3911	125224	5846	16668	1106
6	Janjgir- Champa	35219	2681	79	1252	19317	15320	3996	1908	4547	15087	3428
7	Bilaspur	54432	4260	2117	1143	33321	26428	6893	3042	12096	35078	15506
8	Kawardha	21323	1648	1011	1	4379	3473	906	488	1899	6377	0
9	Rajnangaon	44950	2940	2596	112	23822	18894	4928	1155	6195	18555	3441
10	Durg	84971	4194	5637	17169	76068	60331	15737	4057	16839	56713	15295
11	Raipur	64248	6634	4401	8231	91772	72786	18986	4981	19190	71014	10061
12	Mahasamun d	24774	2070	1962	33	11169	8859	2311	1033	3204	10522	504
13	Damtari	19802	2365	1198	5	15000	11897	3103	935	2637	11071	595
14	Kanker	21944	2195	146	5	8422	6680	1742	853	2707	5628	0
15	Baster	32574	7002	212	30	14872	11795	3077	1058	6317	12429	1607
16	Dantewara	30006	4226	35	20163	3173	2517	657	1102	3277	3407	2104

Source: Directorate of Economics and Statistics, Govt of Chhattisgarh

Sector wise Gross District Domestic Product (GDDP) for the year: 1999-00

(In lakhs)

Sr. No.	District Name	Transport by other means	Stores	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total I D D P	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	Koriya	1195	11	585	1714	5093	3065	8099	89667	5764	15556
2	Surguja	3188	57	911	3847	11384	6980	23535	183201	19236	9524
3	Jashpur	661	23	220	855	4328	2656	9835	74052	7337	10093
4	Raigarh	1920	122	1252	3275	9197	6278	19427	126457	12419	10183
5	Korba	5425	45	1536	2731	10045	5784	13112	466865	9890	47205
6	Janjgir-Champa	2366	60	686	2180	8622	4236	13453	115122	12930	8904
7	Bilaspur	7196	298	4061	7940	17237	11125	29105	237956	19632	12121
8	Kawardha	625	1	267	834	3618	1740	5967	50178	5765	8705
9	Rajnangaon	2237	239	1408	3940	9666	6451	17955	145661	12605	11556
10	Durg	13174	297	6323	13121	28931	17237	38124	398149	27630	14410
11	Raipur	21015	739	9223	17849	29849	17802	45458	422467	29597	14274
12	Mahasamund	1353	91	876	2152	6311	2843	9010	77907	8528	9136
13	Damtari	2342	93	701	2022	4549	2822	8674	74812	6927	10801
14	Kanker	289	23	492	1244	3745	3006	9856	60555	6387	9481
15	Baster	2675	190	875	2899	8552	6533	18842	116666	12828	9095
16	Dantewara	241	14	168	1029	4542	3063	8604	85155	7083	12023

Source: Directorate of Economics and Statistics, Govt of Chhattisgarh

Sector wise Gross District Domestic Product (GDDP) for the year: 2004-05

(At 2004 – 2005 Prices)

(In Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unregd. MFG.	Electricity, Gas & W.supply	Construction	Trade,Hotels & Restaurants	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Koriya	12053	3314	761	42741	12328	10708	1620	649	4421	12448	2667
2	Surguja	58005	7109	1522	28600	36457	31666	4792	1804	11355	17489	300
3	Jashpur	25565	1972	590	649	26230	22783	3448	492	4562	6340	0
4	Raigarh	33590	2907	4078	26069	39981	34726	5255	1652	9762	30952	2227
5	Korba	14294	3254	2995	350533	35441	30783	4658	102230	7867	25078	991
6	Janjgir-Champa	35046	2505	3745	2526	36215	31455	4760	2444	7125	19142	3072
7	Bilaspur	51329	4190	5062	3147	62471	54260	8211	3942	17473	44932	13893
8	Kawardha	16316	2060	1789	438	8209	7130	1079	539	3053	6897	0
9	Rajnangana	41504	2932	2285	939	44663	38792	5870	1459	9694	22783	3083
10	Durg	93035	3707	7080	14157	142613	123868	18745	4906	23675	72189	13704
11	Raipur	77395	6683	4604	11328	172086	149471	22615	5950	26258	96707	9015
12	Mahasamund	29217	2063	3769	368	20940	18188	2752	1449	4886	13030	451
13	Damtari	23105	2581	2917	63	28122	24426	3696	1027	4260	14367	533
14	Kanker	25771	2374	805	400	15790	13715	2075	1266	4828	7264	0
15	Baster	37645	8267	2122	100	27882	24217	3665	1362	10499	16933	1440
16	Dantewara	26049	5023	327	28901	5950	5168	782	1700	5372	4468	1885

Source: Directorate of Economics and Statistics, Govt of Chhattisgarh

Sector wise Gross District Domestic Product (GDDP) for the year : 2004-05

(In Lakhs)

1	2	14	15	16	17	18	19	20	21	22	23
1	Koriya	2142	11	1251	2248	6073	3888	9997	116991	6270	18659
2	Surguja	5783	59	1952	5046	13255	10560	30817	230114	21733	10588
3	Jashpur	1374	23	473	1122	5054	4356	13322	92124	7817	11786
4	Raigarh	3825	125	2688	4295	11151	8241	23697	205239	13628	15060
5	Korba	8987	46	3292	3581	12098	7826	16865	595375	11062	53821
6	Janjgir-Champa	3030	62	1470	2859	10086	5699	16996	152022	14179	10721
7	Bilaspur	10227	305	8724	10414	21597	13835	35130	306672	21427	14312
8	Kawardha	721	1	574	1093	4217	2158	7222	55287	6176	8951
9	Rajnangao	2982	245	3026	5168	11579	8299	22043	182684	13765	13271
10	Durg	16166	305	13581	17210	37269	20906	45993	526494	30051	17520
11	Raipur	42231	757	19768	23410	39746	23126	56790	615853	32525	18935
12	Mahasamu	2777	93	1880	2823	7384	3632	11008	105770	8907	11875
13	Damtari	3678	96	1503	2651	5494	4027	11291	105715	7640	13837
14	Kanker	702	23	1054	1632	4362	3856	11828	81953	7014	11684
15	Baster	3974	195	1881	3802	9985	8273	22151	156511	14049	11141
16	Dantewara	746	14	361	1350	5245	4649	11252	103291	7653	13496

Source: Directorate of Economics and Statistics, Govt of Chhattisgarh

Maharashtra

-SECTORWISE GROSS DISTRICT DOMESTIC PRODUCT - 2013-14

{AT CONSTANT (2004-05) PRICE

(In Crore)

Sr. No.	District	Agriculture	Forestry & Logging	Fisheries	Agriculture & Allied Activity	Mining & Quarrying	PRIMARY SECTOR	Manufacturing		Construction	Electricity, Gas & Water.Sly.	SECONDARY SECTOR	Industry
								Registered	Un-Registered				
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Mumbai *	1132	388	439	1959	22	1981	15501	14427	10769	5349	46048	46069
2	Thane	390	855	308	1553	48	1600	24928	7295	6887	2070	41180	41228
3	Raigad	300	473	73	846	18	864	7092	929	1739	717	10478	10496
4	Ratnagiri	397	381	137	915	24	938	1879	540	1426	450	4295	4319
5	Sindhudurg	494	345	58	897	13	910	265	299	633	109	1306	1319
	KONKAN DIV.	2712	2442	1014	6169	125	6293	49666	23491	21454	8696	103307	103432
6	Nashik	6115	552	19	6686	34	6720	6938	2150	3093	700	12881	12915
7	Dhule	1684	190	9	1883	9	1892	710	507	773	497	2487	2496
8	Nandurbar	689	156	23	867	7	874	510	215	310	55	1090	1097
9	Jalgaon	3008	387	4	3400	8	3408	2104	930	1664	552	5249	5257
10	Ahmednagar	2838	592	10	3441	15	3456	3270	1327	1751	433	6780	6796
	NASHIK DIV.	14335	1878	65	16277	74	16351	13532	5129	7589	2237	28487	28561
11	Pune	3807	828	100	4735	45	4780	28139	4668	8371	696	41873	41918
12	Satara	2334	456	1	2790	19	2809	2333	846	1582	475	5236	5255
13	Sangli	2976	467	0	3443	20	3463	2558	926	1128	496	5108	5128
14	Solapur	2314	530	4	2848	20	2868	4309	1438	1879	274	7901	7921
15	Kolhapur	2956	538	0	3494	29	3523	6558	1906	1964	481	10910	10939
	PUNE DIV.	14386	2819	106	17311	133	17443	43897	9785	14924	2422	71028	71161
16	Aurangabad	2320	332	9	2661	9	2670	6296	933	2309	314	9852	9861
17	Jalna	1773	285	1	2058	12	2070	765	302	581	102	1750	1762
18	Parbhani	1551	172	5	1728	16	1743	82	264	603	126	1075	1090
19	Hingoli	584	123	4	712	10	722	77	153	239	46	515	525
20	Beed	1847	292	3	2142	25	2168	282	384	808	317	1791	1817
21	Nanded	1649	364	30	2043	26	2068	497	573	1122	218	2410	2435
22	Osmanabad	1649	225	7	1881	7	1889	357	285	440	124	1207	1214
23	Latur	2087	427	7	2521	7	2529	383	446	951	167	1947	1955

	AURANGABAD DIV.	13460	2221	65	15746	112	15858	8740	3339	7054	1415	20547	20659
24	Buldhana	1582	253	23	1857	11	1868	837	352	699	171	2060	2070
25	Akola	1223	156	14	1394	17	1411	622	364	867	223	2076	2093
26	Washim	1398	119	20	1537	7	1545	243	135	237	62	676	683
27	Amravati	1677	324	19	2020	12	2032	210	552	1325	364	2450	2462
28	Yavatmal	1256	393	44	1694	860	2553	408	445	1180	183	2215	3075
	AMRAVATI DIV.	7136	1246	120	8502	906	9408	2319	1848	4307	1004	9478	10384
29	Wardha	757	206	16	979	7	987	816	297	836	152	2101	2109
30	Nagpur	768	366	75	1209	578	1788	6043	1943	4643	992	13621	14200
31	Bhandara	460	231	57	748	115	863	462	411	632	95	1599	1714
32	Gondia	272	241	42	555	5	560	542	461	732	55	1790	1795
33	Chandrapur	880	356	39	1275	1737	3012	1182	688	1512	510	3891	5629
34	Gadchiroli	275	252	13	540	7	547	100	164	297	78	640	647
	NAGPUR DIV.	3413	1652	242	5307	2449	7756	9145	3964	8653	1881	23643	26093
	MAHARASHTRA	55441	12258	1613	69311	3799	73110	127299	47556	63981	17654	256491	260289

Sr. No.	District	Railway	Transport by other means & Warehousing	Storage	Communication	Trade, Hotel & Restaurant	Banking & Insur.	R.Estate, O.Dwell B/S	Public Adm.	Other Services	SERVICE SECTOR	TOTAL G.D.P.	Population (000)	Per Capita District Domestic Product (Rs)
1	Mumbai	1319	13636	80	16343	35034	42061	34890	6418	11137	160918	208946	16052	130169
2	Thane	1368	5748	73	9285	16061	20705	19386	3644	5614	81884	124665	10368	120238
3	Raigad	115	1370	36	1241	2806	2055	1942	769	1206	11540	22881	2562	89318
4	Ratnagiri	34	477	3	917	1529	1197	978	371	789	6293	11526	1917	60133
5	Sindhudurg	9	186	1	493	726	1066	504	224	515	3724	5940	978	60757
6	KONKAN DIV.	2845	21417	192	28279	56155	67085	57699	11425	19261	264359	373959	31876	117315
7	Nashik	346	1242	13	1831	5393	4792	3428	2003	2250	21299	40900	5967	68546
8	Dhule	19	410	4	503	1721	1508	977	406	842	6391	10770	1989	54138
9	Nandurbar	40	169	2	191	850	577	625	202	462	3117	5081	1495	33996
10	Jalgaon	542	758	7	1178	3543	3087	2174	808	1799	13895	22552	4311	52312
11	Ahmednagar	51	753	8	1296	3774	3640	2486	1217	1829	15054	25291	4647	54428
12	NASHIK DIV.	998	3333	33	4998	15281	13604	9690	4636	7182	59756	104594	18408	56818
13	Pune	399	3118	37	4958	10654	12649	15383	4599	4690	56488	103141	8973	114949
14	Satara	38	722	5	793	2428	3675	1621	555	1228	11065	19110	3192	59864
15	Sangli	58	540	7	937	2497	3972	1736	502	1223	11471	20042	2999	66822
16	Solapur	206	860	11	1181	4408	3750	2448	869	1827	15559	26329	4536	58044
17	Kolhapur	20	937	4	1448	4020	6882	2861	829	1645	18646	33079	4135	80006
18	PUNE DIV.	721	6178	64	9316	24006	30928	24048	7355	10613	113229	201700	23835	84624
19	Aurangabad	23	670	5	998	3144	2341	2202	878	1405	11667	24189	3453	70056
20	Jalna	13	224	3	243	1234	729	827	350	557	4178	7998	1852	43192
21	Parbhani	52	199	2	313	1364	892	767	358	729	4675	7493	1800	41632
22	Hingoli	17	95	1	113	646	425	440	151	336	2225	3463	1125	30777
23	Beed	11	328	3	307	1560	989	1115	404	928	5645	9604	2475	38798
24	Nanded	36	428	4	580	2319	1675	1684	597	1338	8662	13140	3335	39394
25	Osmanabad	3	247	1	237	853	805	861	335	544	3886	6981	1695	41193
26	Latur	13	355	3	382	1893	1141	1194	417	1022	6421	10897	2410	45208
27	AURANGABAD DIV.	168	2545	22	3174	13013	8997	9091	3490	6860	47359	83765	18145	46163
28	Buldhana	30	326	3	419	1759	1439	1174	444	827	6422	10350	2574	40205

25	Akola	101	373	5	619	1925	1573	721	404	890	6611	10097	1947	51868
26	Washim	11	112	1	148	632	406	1075	159	338	2883	5103	1167	43715
27	Amravati	62	569	5	662	2593	2165	2220	691	1389	10355	14837	3089	48039
28	Yavatmal	16	409	4	407	2010	1422	1014	523	984	6790	11559	2819	40998
	AMRAVATI DIV.	220	1789	18	2255	8920	7005	6204	2222	4428	33061	51947	11596	44795
29	Wardha	110	214	3	373	1162	1116	778	386	710	4853	7941	1441	55108
30	Nagpur	588	1527	22	2533	6762	6712	4547	2076	2994	27761	43170	5106	84549
31	Bhandara	30	135	1	214	925	829	553	300	505	3493	5954	1295	45994
32	Gondia	88	167	3	279	1072	529	559	242	521	3460	5810	1358	42777
33	Chandrapur	125	475	3	574	1813	1350	1277	741	1255	7614	14518	2442	59454
34	Gadchiroli	2	56	1	164	463	317	490	271	457	2223	3410	1086	31399
	NAGPUR DIV.	942	2574	33	4137	12198	10854	8204	4017	6444	49403	80803	12727	63487
	MAHARASHTRA	5895	37836	362	52160	129573	138472	114936	33146	54787	567167	896767	116589	76917

Sector wise Gross District Domestic Product (GDDP) for the year: 1999 – 2000 (At 1999 – 2000 Prices)
(In Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG	Registered MFG	Un regd. MFG	Electricity, Gas & Water.SI y.	Construction	Trade, Hotel & Restaurant	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Mumbai *	68952	3448	23448	132	1427662	1155287	272376	256812	223076	815619	42471
2	Thane	82420	6945	14086	1052	798564	547542	251023	61954	142657	448581	44070
3	Raigad	59952	3665	4489	123	310533	288171	22362	31238	36022	164677	3719
4	Ratnagiri	42633	3143	6851	213	58652	46574	12078	17175	29534	48537	1088
5	Sindhudurg	46034	1671	3130	380	13024	5643	7381	3589	13111	15486	277
6	Nashik	256034	7244	674	1488	288410	231784	56625	26164	64063	191793	11144
7	Dhule	29835	2593	464	106	42612	31052	11560	5976	16004	33247	621
8	Nandurbar	59188	2523	270	81	7668	0	7668	2066	6415	15357	1286
9	Jalgaon	229316	5000	1785	341	87266	66570	20696	21848	34461	87032	17447
10	Ahmednagar	184937	6686	479	162	124208	85885	38323	14020	36262	105602	1655
11	Pune	295232	7450	1839	2404	791462	697296	94166	26713	173385	454051	12836
12	Satara	173447	5007	1063	57	88186	68017	20169	13133	32762	76688	1232
13	Sangli	186224	4021	958	996	70780	45265	25514	10294	23375	70028	1864
14	Solapur	161521	5362	374	534	108814	47931	60883	10461	38918	93105	6644
15	Kolhapur	218699	5500	809	1450	160836	103443	57393	15275	40684	122672	647
16	Aurangabad	107206	3371	823	866	194607	176464	18143	12341	47828	119466	746
17	Jalna	64211	1711	614	641	24353	15363	8990	4192	12044	26319	425
18	Parbhani	75972	1714	881	97	13678	7093	6584	4971	12484	23978	1669
19	Hingoli	36898	1112	27	322	5106	0	5106	1751	4950	10891	558
20	Beed	132043	2949	898	42	17674	7229	10445	12540	16742	32771	340
21	Nanded	96700	4229	1063	599	34647	17808	16839	8653	23243	41660	1161
22	Osmanabad	71191	1769	326	24	14947	6511	8436	4994	9119	22559	97
23	Latur	78582	2561	873	221	20106	8754	11352	6791	19703	30087	424
24	Buldhana	88715	2736	2297	430	20949	11190	9758	6692	14483	31196	982

25	Akola	75212	1513	579	155	30695	21336	9360	8824	17963	33448	3238
26	Washim	39991	997	1001	188	6216	2715	3501	2157	4902	11884	363
27	Amravati	185380	4438	996	239	22614	8450	14164	14150	27436	46445	1990
28	Yavatmal	109130	7333	1163	42105	20601	9102	11499	7502	24437	40505	504
29	Wardha	60137	6848	930	361	24567	17022	7545	5792	17318	25836	3536
30	Nagpur	114726	5241	2081	45118	181007	133159	47847	39183	96180	134616	18939
31	Bhandara	44701	5326	3252	3928	30327	15076	15251	3765	13082	23933	969
32	Gondia	43010	7089	6360	588	28528	2844	25684	2235	15170	22470	2819
33	Chandrapur	72245	12614	5918	90975	41395	24778	16617	20060	31329	50920	4011
34	Gadchiroli	30200	34535	667	149	5344	1326	4018	3357	6152	11997	57

Source: Directorate of Economics and Statistics, Govt of Maharashtra

Sectorwise Gross District Domestic Product (GDDP) for the year: 1990 – 2000 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	TOTAL D.D.P.	Population (00)	Per Capita Income (Rs)
1	2	14	15	16	17	18	19	20	21	22	23
1	Mumbai *	460616	6541	143844	856953	533305	235827	338701	5437409	115197	47201
2	Thane	153505	5876	78394	421854	298832	133889	182883	2875560	78692	36542
3	Raigad	32426	1727	17574	41879	47722	28240	39576	823564	21600	38129
4	Ratnagiri	15009	227	21533	24378	22195	13636	28444	333247	16647	20019
5	Sindhudurg	6861	29	12906	21727	12523	8217	16670	175636	8527	20597
6	Nashik	37251	1445	26462	97625	80734	73613	78069	1242213	48694	25511
7	Dhule	13286	354	7685	30732	30305	14936	29056	257811	16701	15437
8	Nandurbar	3912	76	3349	11754	21437	7414	16353	159149	12857	12378
9	Jalgaon	22373	683	17650	62885	64208	29675	58155	740126	35992	20564
10	Ahmednagar	22635	650	18324	74166	68039	44713	65501	768038	39567	19411
11	Pune	89628	3036	50460	257718	226948	169001	161022	2723184	70219	38782
12	Satara	21764	390	19750	74880	48190	20405	45421	622376	27541	22598
13	Sangli	16917	1615	13428	80923	46705	18428	45011	591565	25272	23408
14	Solapur	25508	842	18759	76399	64402	31938	62865	706447	37595	18791
15	Kolhapur	26788	760	20031	140210	66872	30464	59124	910822	34423	26460
16	Aurangabad	22473	470	12710	47696	40035	32273	47974	690885	28256	24451
17	Jalna	7046	228	5211	14843	19587	12848	18478	212752	15797	13468
18	Parbhani	7766	253	5096	18165	22132	13157	23640	225653	14920	15124
19	Hingoli	2439	40	2582	8666	13943	5540	11196	106021	9676	10957
20	Beed	11247	255	8248	20151	34406	14835	31772	336915	21173	15913
21	Nanded	13816	257	10723	34118	47544	21951	42641	383007	28139	13611
22	Osmanabad	8032	90	6422	16405	15726	12308	19941	203951	14571	13997

Sector wise Gross District Domestic Product (GDDP) for the year: 1999 – 2000 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total DD P	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	DUMKA	2623	24	2395	1763	3863	5317	12078	137281	11771	11663
2	JAMTARA	1490	14	1608	1268	2777	3821	6822	76877	6948	11065
3	DEOGHAR	4892	29	3557	3798	6344	5706	19162	175943	12397	14192
4	GODDA	1553	2	1838	1722	5958	3832	12291	106407	11147	9545
5	PAKUR	2995	5	865	587	3910	2464	7130	132940	7464	17810
6	SAHEBGANJ	3646	22	1759	1584	2896	3810	10259	160752	9869	16288
7	HAZARIBAGH	13333	91	7065	7479	10103	25918	33807	377306	24228	15573
8	KODERMA	3197	41	1365	1651	3299	3115	6933	73634	5312	13861
9	CHATRA	2027	13	1048	780	3770	5979	8696	82753	8418	9830
10	GIRIDIH	5960	0	3646	3753	8313	7264	22898	201066	20259	9925
11	BOKARO	7894	13	6252	6416	13588	12611	23164	305249	18911	16142
12	DHANBAD	18873	691	12314	12071	23778	14548	41236	563778	25499	22110
13	RANCHI	17334	164	15860	18590	31462	66423	45017	518367	29626	17497
14	LOHARDAGA	1018	30	967	495	1498	1643	4304	43308	3878	11168
15	GUMLA	1169	48	2055	1245	3610	3927	7102	110274	8855	12453
16	SIMDEGA	743	30	1369	791	2293	2496	4598	63035	5471	11522
17	PALAMU	3392	28	3519	2987	12676	8680	14820	163555	16355	10000
18	LATEHAR	1179	10	1267	1020	4328	2963	5231	67738	5967	11352
19	GARHWA	1842	5	1572	972	4627	3537	8015	90833	11014	8247
20	E. SINGHBHUM	14318	351	13545	13475	30346	15327	36396	417127	21094	19774
21	W. SINGHBHUM	4205	135	4001	2908	7941	5991	14675	207767	13127	15828
22	SARAYKELA KHARSAWA	3237	105	2941	2508	6844	5166	10586	141021	9030	15617

Sr No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG	Registered MFG	Un regd. MFG	Electricity, Gas & Water.S	Construction	Trade, Hotel & Restaurant	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Mumbai *	68952	3448	23448	132	1427662	1155287	272376	256812	223076	815619	42471
2	Thane	82420	6945	14086	1052	798564	547542	251023	61954	142657	448581	44070
3	Raigad	59952	3665	4489	123	310533	288171	22362	31238	36022	164677	3719
4	Ratnagiri	42633	3143	6851	213	58652	46574	12078	17175	29534	48537	1088
5	Sindhudur	46034	1671	3130	380	13024	5643	7381	3589	13111	15486	277
6	Nashik	256034	7244	674	1488	288410	231784	56625	26164	64063	191793	11144
7	Dhuie	29835	2593	464	106	42612	31052	11560	5976	16004	33247	621
8	Nandurbar	59188	2523	270	81	7668	0	7668	2066	6415	15357	1286
9	Jalgaon	229316	5000	1785	341	87266	66570	20696	21848	34461	87032	17447
10	Ahmednagar	184937	6686	479	162	124208	85885	38323	14020	36262	105602	1655
11	Pune	295232	7450	1839	2404	791462	697296	94166	26713	173385	454051	12836
12	Satara	173447	5007	1063	57	88186	68017	20169	13133	32762	76688	1232
13	Sangli	186224	4021	958	996	70780	45265	25514	10294	23375	70028	1864
14	Solapur	161521	5362	374	534	108814	47931	60883	10461	38918	93105	6644
15	Kolhapur	218699	5500	809	1450	160836	103443	57393	15275	40684	122672	647
16	Aurangabad	107206	3371	823	866	194607	176464	18143	12341	47828	119466	746
17	Jalna	64211	1711	614	641	24353	15363	8990	4192	12044	26319	425
18	Parbhani	75972	1714	881	97	13678	7093	6584	4971	12484	23978	1669
19	Hingoli	36898	1112	27	322	5106	0	5106	1751	4950	10891	558
20	Beed	132043	2949	898	42	17674	7229	10445	12540	16742	32771	340
21	Nanded	96700	4229	1063	599	34647	17808	16839	8653	23243	41660	1161
22	Osmanabad	71191	1769	326	24	14947	6511	8436	4994	9119	22559	97
23	Latur	78582	2561	873	221	20106	8754	11352	6791	19703	30087	424
24	Buldhana	88715	2736	2297	430	20949	11190	9758	6692	14483	31196	982
25	Akola	75212	1513	579	155	30695	21336	9360	8824	17963	33448	3238
26	Washim	39991	997	1001	188	6216	2715	3501	2157	4902	11884	363

27	Amravati	185380	4438	996	239	22614	8450	14164	14150	27436	46445	1990
28	Yavatmal	109130	7333	1163	42105	20601	9102	11499	7502	24437	40505	504
29	Wardha	60137	6848	930	361	24567	17022	7545	5792	17318	25836	3536
30	Nagpur	114726	5241	2081	45118	181007	133159	47847	39183	96180	134616	18939
31	Bhandara	44701	5326	3252	3928	30327	15076	15251	3765	13082	23933	969
32	Gondia	43010	7089	6360	588	28528	2844	25684	2235	15170	22470	2819
33	Chandrapur	72245	12614	5918	90975	41395	24778	16617	20060	31329	50920	4011
34	Gadchiroli	30200	34535	667	149	5344	1326	4018	3357	6152	11997	57

Source : Directorate of Economics and Statistics , Govt of Maharashtra

Sector wise Gross District Domestic Product (GDDP) for the year: 1990 – 2000 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	TOTAL D.D.P.	Population (00)	Per Capita Income (Rs)
1	2	14	15	16	17	18	19	20	21	22	23
1	Mumbai *	460616	6541	143844	856953	533305	235827	338701	5437409	115197	47201
2	Thane	153505	5876	78394	421854	298832	133889	182883	2875560	78692	36542
3	Raigad	32426	1727	17574	41879	47722	28240	39576	823564	21600	38129
4	Ratnagiri	15009	227	21533	24378	22195	13636	28444	333247	16647	20019
5	Sindhudurg	6861	29	12906	21727	12523	8217	16670	175636	8527	20597
6	Nashik	37251	1445	26462	97625	80734	73613	78069	1242213	48694	25511
7	Dhule	13286	354	7685	30732	30305	14936	29056	257811	16701	15437
8	Nandurbar	3912	76	3349	11754	21437	7414	16353	159149	12857	12378
9	Jalgaon	22373	683	17650	62885	64208	29675	58155	740126	35992	20564
10	Ahmednagar	22635	650	18324	74166	68039	44713	65501	768038	39567	19411
11	Pune	89628	3036	50460	257718	226948	169001	161022	2723184	70219	38782
12	Satara	21764	390	19750	74880	48190	20405	45421	622376	27541	22598
13	Sangli	16917	1615	13428	80923	46705	18428	45011	591565	25272	23408
14	Solapur	25508	842	18759	76399	64402	31938	62865	706447	37595	18791
15	Kolhapur	26788	760	20031	140210	66872	30464	59124	910822	34423	26460
16	Aurangabad	22473	470	12710	47696	40035	32273	47974	690885	28256	24451
17	Jalna	7046	228	5211	14843	19587	12848	18478	212752	15797	13468
18	Parbhani	7766	253	5096	18165	22132	13157	23640	225653	14920	15124
19	Hingoli	2439	40	2582	8666	13943	5540	11196	106021	9676	10957
20	Beed	11247	255	8248	20151	34406	14835	31772	336915	21173	15913
21	Nanded	13816	257	10723	34118	47544	21951	42641	383007	28139	13611
22	Osmanabad	8032	90	6422	16405	15726	12308	19941	203951	14571	13997
23	Latur	11574	215	7391	23254	20109	15334	34720	271944	20354	13361

24	Buldhana	10586	268	9220	29319	34588	16331	29211	298002	21854	13636
25	Akola	12566	645	9547	32054	26637	14827	29103	297006	15897	18683
26	Washim	2775	28	3415	8270	15135	5858	12252	115433	9995	11549
27	Amravati	17835	664	14077	44105	44677	25385	47515	497945	25446	19568
28	Yavatmal	12487	381	9686	28972	40603	19235	34025	398669	24079	16557
29	Wardha	6876	247	7867	22745	21784	14196	23656	242695	12093	20069
30	Nagpur	44240	1906	35562	136747	85618	76293	94758	1112214	39436	28203
31	Bhandara	4760	109	5198	16900	19122	11034	17423	203828	11136	18303
32	Gondia	4005	295	5036	10779	19763	8879	18028	195053	11778	16560
33	Chandrapur	13122	273	11234	27509	33351	27243	37914	480113	20225	23738
34	Gadchiroli	1483	64	4868	6467	11633	9973	16843	143787	9529	15090

Sector wise Gross District Domestic Product (GDDP) for the year : 2004 – 2005 (At 2004 – 2005 Prices)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG	Registered MFG	Unregd. MFG	Electricity, Gas & Water Supply.	Construction	Trade, Hotel & Restaurant	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Mumbai *	64968	2770	25545	49	1631837	1263119	368718	347640	245426	1239835	51224
2	Thane	127673	6087	7004	881	932890	622640	310250	88720	156949	688125	53153
3	Raigad	65540	3505	4724	2741	379990	351544	28446	27729	39631	260951	4486
4	Ratnagiri	55351	3044	16521	2679	59088	43463	15624	18222	32493	73078	1312
5	Sindhudurg	57334	1602	2934	1589	17529	8137	9392	4062	14424	22786	334
6	Nashik	412647	6790	749	301	396913	324404	72509	27780	70482	331013	13441
7	Dhule	55596	2310	448	63	40449	24021	16427	6434	17607	45901	749
8	Nandurbar	111788	1947	194	16	9567	0	9567	2344	7058	25466	1551
9	Jalgaon	262819	4173	1497	324	81446	52794	28652	23244	37914	111506	21043
10	Ahmednagar	222526	6489	571	233	131693	80808	50884	6921	39895	143599	1996
11	Pune	346812	6994	1228	84	1028355	908875	119480	29163	190756	753790	15481
12	Satara	190573	4853	868	633	90841	63908	26933	14155	36044	103425	1487
13	Sangli	183919	3890	509	256	71208	38178	33031	11902	25717	88916	2248
14	Solapur	222141	5344	482	31	118402	41898	76505	11430	42817	132386	8013
15	Kolhapur	219188	5213	1030	1818	170070	94226	75843	17322	44760	166635	781
16	Aurangabad	120336	2837	1078	901	217127	188499	28628	13431	52620	171178	899
17	Jalna	66616	1613	512	423	19447	6441	13006	4418	13251	31162	513
18	Parbhani	70265	1159	299	97	15239	7170	8069	5312	13735	30507	2013
19	Hingoli	49269	1207	313	59	6371	0	6371	1938	5446	15839	673
20	Beed	127943	2829	1187	2340	17524	3783	13741	13075	18419	42441	410
21	Nanded	105370	3630	1461	1195	30630	8225	22405	9408	25572	51909	1401
22	Osmanabad	67558	1623	128	47	17158	6636	10522	5261	10033	28466	117
23	Latur	81893	2495	479	105	21839	7323	14516	7174	21677	40299	511
24	Buldhiana	71395	2451	1868	255	24533	13175	11358	7321	15934	40008	1184
25	Akola	47079	932	468	244	39139	27935	11204	9673	19762	46561	3906
26	Washim	48583	991	862	244	5307	828	4478	2588	5393	15196	438

27	Amravati	119091	2663	1172	592	25095	7400	17694	15457	30185	52395	2400
28	Yavatmal	78728	2762	1294	54332	21741	6909	14831	8037	26885	48046	608
29	Wardha	61521	4175	868	536	28917	19017	9900	6222	19053	34619	4265
30	Nagpur	121734	3817	2402	58769	200090	134954	65137	41127	105816	194061	22842
31	Bhandara	52711	4507	3617	6761	43574	24092	19482	4039	14392	37731	1169
32	Gondia	27629	5179	3883	315	35695	3765	31931	2473	16689	29245	3400
33	Chandrapur	57482	14526	4388	118127	59725	38079	21646	21028	34468	72696	4838
34	Gadchiroli	26010	16932	1023	163	7713	2735	4979	3526	6768	11966	69

Source: Directorate of Economics and Statistics, Govt of Maharashtra

Sector wise Gross District Domestic Product (GDDP) for the year : 2004 – 2005 (At 2004 – 2005 Prices)

(In Lakhs)

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	TOTAL D.D.P.	Population (00)	Per Capita Income (Rs)
1	2	14	15	16	17	18	19	20	21	22	23
1	Mumbai *	615436	9132	254938	1103973	1053100	263646	402905	7312424	130885	55869
2	Thane	210476	7528	141957	543455	531914	149683	212477	3858972	87539	44083
3	Raigad	45585	2120	29402	53950	62925	31572	45789	1060643	23138	45839
4	Ratnagiri	19795	293	34290	31405	27853	15244	32374	423044	17653	23965
5	Sindhudurg	8744	48	20376	27990	15068	9186	19190	223199	9029	24719
6	Nashik	50115	1530	44275	125766	107329	82297	89637	1761062	52763	33377
7	Dhule	15784	383	12790	39591	36731	16698	33057	324589	17918	18116
8	Nandurbar	7070	162	5486	15142	25363	8289	18537	239982	13678	17545
9	Jalgaon	30221	828	29404	81012	78391	33175	67033	864031	38688	22333
10	Ahmednagar	30322	795	30682	95544	83926	49988	74429	919611	42241	21770
11	Pune	121368	4071	88261	332006	430922	188937	186137	3724366	77240	48218
12	Satara	29447	507	31325	96464	60625	22813	51430	735492	29271	25127
13	Sangli	22520	1215	22453	104249	59273	20602	51245	670122	27079	24747
14	Solapur	34340	1107	31036	98422	79905	35706	72348	893911	40515	22064
15	Kolhapur	36888	565	33646	180626	89944	34058	67476	1070019	37038	28890
16	Aurangabad	29151	539	21595	61444	54245	36080	55149	838611	30587	27417

17	Jalna	9562	284	8382	19122	23849	14363	21352	234868	16855	13935
18	Parbhani	9163	365	8432	23401	26544	14709	27189	248428	16078	15452
19	Hingoli	4342	141	4132	11163	16489	6193	12846	136420	10295	13251
20	Beed	15018	319	13035	25960	40701	16585	36231	374017	22569	16572
21	Nanded	18473	358	17473	43952	56939	24541	49153	441464	30138	14648
22	Osmanabad	10771	172	10138	21134	18887	13760	22582	227835	15504	14695
23	Latur	15746	288	11995	29957	24704	17143	39397	315703	21793	14487
24	Buldhana	13877	410	14793	37770	41784	18257	33323	325162	23356	13922
25	Akola	15634	758	15870	41294	33616	16577	33457	324969	17222	18870
26	Washim	4901	58	5459	10653	18066	6549	13848	139136	10651	13063
27	Amravati	23896	669	22654	56819	55425	28380	54138	491030	27480	17868
28	Yavatmal	16845	282	15450	37324	48864	21504	38910	421611	25680	16418
29	Wardha	9206	173	12666	29302	26839	15870	27129	281360	12976	21684
30	Nagpur	59903	2676	59744	176165	127008	85293	110007	1371455	43588	31464
31	Bhandara	5364	132	8271	21771	22877	12336	19881	259135	11848	21872
32	Gondia	6512	532	8215	13886	23701	9927	20663	207943	12496	16641
33	Chandrapur	17869	344	18221	35439	40883	30456	44058	574548	21801	26354
34	Gadchiroli	2017	90	7632	8332	13729	11149	18946	136063	10069	13513

Madhya Pradesh

Per Capita Income at constant price (2004 – 2005 prices)

(In Lakhs)

S.N.	District	2004-05	2005-06	2006-07	2007-08
1	Sheopur	11916	12010	12078	12314
2	Morena	11049	11366	11831	12093
3	Bhind	10063	11006	10855	11251
4	Gwalior	21569	22132	23614	23845
5	Datia	13021	13785	14077	14373
6	Shivpuri	11419	11709	11486	11226
7	Guna	12615	13233	13720	14055
8	Tikamgarh	10618	10605	10535	10469
9	Chhatarpur	11886	11978	11884	11890
10	Panna	11343	11830	11924	11998
11	Sagar	13291	13832	14706	14997
12	Damoh	13351	14242	15490	15232
13	Satna	12927	13406	13956	14183
14	Rewa	10523	10864	11430	11613
15	Umaria	11047	11619	12069	12385
16	Shahdol	16746	17279	18302	18908
17	Sidhi	21588	20990	22534	22661
18	Neemuch	17841	17281	18578	19003
19	Mandsaur	17314	16095	18431	18491
20	Ratlam	18001	18158	20196	20935
21	Ujjain	19709	20579	23170	23182
22	Shajapur	13684	13798	14600	15000
23	Dewas	14282	14914	16267	16741
24	Jhabua	9261	9694	9800	10500
25	Dhar	13256	13411	15118	15640
26	Indore	34442	35097	38711	40557
27	West Nimar	11449	11378	12490	13029
28	Barwani	9433	9468	10156	10484
29	East Nimar	13070	13605	14467	15212
30	Rajgarh	12721	13024	13452	13928
31	Vidisha	13806	14084	15063	14340
32	Bhopal	28265	30096	33378	36111
33	Sehore	13379	13809	13777	14209
34	Raisen	12944	13356	14149	14558
35	Betul	13530	14391	15673	15438
36	Harda	13994	17906	19066	19881
37	Hoshangabad	18418	19856	21600	22719
38	Katni	15812	16581	17354	17785

39	Jabalpur	21890	22316	24558	25495
40	Narsimhapur	13466	13804	14474	14756
41	Dindori	9193	9687	9961	10770
42	Mandla	9709	10087	10153	10472
43	Chhindwara	17448	18007	19935	20757
44	Seoni	11560	12508	13322	13727
45	Balaghat	13019	13793	14682	15412
	MP	15442	15927	17073	17572

*(p) Provisional, (Q) Quick

Per Capita Income at constant price (2004 – 2005 prices)

Rs (Lakhs)

S.N.	District	2008-09	2009-10	2010-11	2011-12 (P)	2012-13 (Q)
1	Sheopur	13310	14268	14390	16457	17549
2	Morena	13678	14420	15346	16529	17650
3	Bhind	13627	14848	14913	15816	17607
4	Gwalior	27967	30008	31864	33913	36223
5	Datia	16383	18050	18680	20454	23442
6	Shivpuri	13262	14231	14126	16850	16828
7	Guna	15913	16848	17406	19422	22047
8	Tikamgarh	12977	13480	13281	15187	16107
9	Chhatarpur	13718	14554	15275	16805	17674
10	Panna	12896	13790	14762	15887	16884
11	Sagar	17167	18496	18202	20210	22395
12	Damoh	17250	18209	17743	18747	20495
13	Satna	15792	16908	17336	18670	20093
14	Rewa	12659	13172	13799	15136	16590
15	Umaria	12713	13555	15173	15913	17798
16	Shahdol	20645	21127	22550	23708	25779
17	Sidhi	24876	25400	27739	27477	30085
18	Neemuch	21094	21700	23262	24514	27475
19	Mandsaur	19980	20910	22385	24600	27477
20	Ratlam	22395	23892	24131	26037	29011
21	Ujjain	25331	27780	27911	29409	32567
22	Shajapur	16058	17627	17818	19068	20797
23	Dewas	17789	19563	19748	22015	24454
24	Jhabua	12639	13302	13329	15276	16735
25	Dhar	17348	18746	18837	20441	22095

26	Indore	44978	48231	49327	52827	55348
27	West Nimar	13815	15106	16070	18319	18197
28	Barwani	12145	12975	13551	15581	17446
29	East Nimar	15800	16602	17635	19884	22129
30	Rajgarh	15066	16291	16330	17599	19598
31	Vidisha	16729	18148	18149	19082	20818
32	Bhopal	37639	41947	44231	47433	49979
33	Sehore	15200	17383	16518	18511	19909
34	Raisen	16069	17561	16656	18917	21374
35	Betul	17119	18490	19865	20427	22483
36	Harda	20517	23124	24964	25932	32421
37	Hoshangabad	23735	26121	26616	28749	30393
38	Katni	19621	19739	21240	23240	24620
39	Jabalpur	31399	34465	36486	38956	41462
40	Narsimhapur	15804	17306	17763	18100	20649
41	Dindori	11905	12905	13921	15735	18715
42	Mandla	11862	12175	12892	13659	14123
43	Chhindwara	21468	24404	25555	27657	30884
44	Seoni	14856	15765	16959	18479	21275
45	Balaghat	16067	17846	18415	19265	21739
	MP	19462	20959	21706	23447	25463

Madhya Pradesh- Per Capita Income at constant price (2004 – 2005 prices)

(In Lakhs)

S. N.	District	Agricul- ture	Forestry & Logging	Fishing	Mining & Quarrying	Manufa- cturing MFG.	Regi- stered MFG.	Un regd. MFG.
1	2	3	4	5	6	7	8	9
1	Sheopur	59401	8888	593	104	6760	4534	2226
2	Morena	103471	6373	72	622	44639	31565	13074
3	Bhind	94581	4111	138	210	38663	27730	10933
4	Gwalior	93141	6466	259	1416	101265	72224	29041
5	Data	68825	1772	152	11	16858	11574	5284
6	Shivpuri	116704	12187	694	961	23683	15553	8130
7	Guna	208019	10537	1338	41	45348	31277	14072
8	Tikamgarh	82057	5952	878	87	23900	15589	8311
9	Chhatarpur	91576	7722	1143	2258	31603	19913	11690
10	Panna	68159	6098	533	1310	18807	12801	6006
11	Sagar	145891	12818	288	6569	77463	37707	39756

12	Damoh	73377	8610	1027	2691	43765	21941	21824
13	Satna	90022	7671	1388	16343	83640	57166	26474
14	Rewa	91641	6061	1286	5674	50435	32187	18247
15	Umaria	23069	10327	578	6381	8850	5802	3048
16	Shahdol	79453	10006	2412	160558	37526	24302	13224
17	Sidhi	105899	12211	790	397004	33578	22601	10977
18	Neemuch	87062	6292	213	3702	23333	16458	6875
19	Mandsaur	174818	7055	1243	2444	29824	20513	9311
20	Ratlam	154683	6391	309	648	46139	34151	11987
21	Ujjain	202394	7463	245	433	113796	83243	30553
22	Shajapur	144483	8477	983	705	25444	17407	8037
23	Dewas	169263	9703	739	2007	73377	52889	20488
24	Jhabua	127298	7054	1340	2562	16193	10797	5396
25	Dhar	198701	8006	2907	2105	94477	69231	25247
26	Indore	141606	7657	1547	60	321220	232054	89166
27	West Nimar	123955	6859	728	4520	42094	30055	12039
28	Barwani	115604	5527	185	26	21819	14800	7019
29	East Nimar	152061	14876	919	2889	56931	37815	19116
30	Rajgarh	132227	8999	709	695	28641	19440	9201
31	Vidisha	125286	6205	447	68	24238	15770	8469
32	Bhopal	65039	5190	602	43	214184	171384	42800
33	Sehore	127723	10748	867	2633	16664	10637	6027
34	Raisen	119144	9611	847	5602	60199	44299	15900
35	Betul	119150	12238	588	15576	27450	18616	8834
36	Harda	101494	4757	793	14365	8808	5524	3284
37	Hoshangabad	117093	6139	599	81	54251	41507	12744
38	Katni	50271	4880	1172	8594	53786	34904	18882
39	Jabalpur	218796	9897	1282	4954	213034	154625	58409
40	Narsimhapur	86461	5128	310	7989	19364	11813	7551
41	Dindori	36427	7008	411	145	6924	4543	2380
42	Mandla	47581	12108	917	180	14132	9707	4425
43	Chhindwara	265685	15607	597	82777	44068	29868	14200
44	Seoni	111232	14088	1019	28	16820	10989	5830
45	Balaghat	80040	22191	2153	24140	46830	29287	17543
	M P	5190862	387965	38237	792209	2400826	1676794	724032

Per Capita Income at constant price-2012-2013 (2004 – 2005 prices)

(In Lakhs)

S.N.	District	Electricity, Gas & W.supply	Constru-ction	Trade,Hotels & Resta-urants	Railways	Transport by other means	Storage
1	2	10	11	12	13	14	15
1	Sheopur	1941	11478	17976	449	1501	500
2	Morena	6456	53471	50140	2272	14131	1052
3	Bhind	6972	40550	40742	736	4569	468
4	Gwalior	29639	97971	119261	11187	49925	1519
5	Datia	2419	26781	23950	2551	2201	296
6	Shivpuri	7298	36356	44323	853	5501	566
7	Guna	6121	57700	58943	4965	7659	863
8	Tikamgarh	7158	44062	33324	1229	4231	393
9	Chhatarpur	8710	65246	50385	469	9594	577
10	Panna	2791	22541	23410	327	2106	186
11	Sagar	6896	72565	83683	13948	17110	734
12	Damoh	3453	38419	40300	3683	3793	242
13	Satna	10307	67698	75716	11373	17642	967
14	Rewa	15011	46723	58543	477	20792	283
15	Umaria	9038	17195	11455	3918	1879	57
16	Shahdol	18278	61367	47830	9808	8989	401
17	Sidhi	103339	44715	35435	2919	12849	432
18	Neemuch	2987	24854	36455	2110	5576	330
19	Mandsaur	21650	39364	56185	4257	5707	480
20	Ratlam	4570	40202	63552	22086	7925	1056
21	Ujjain	27946	74765	96926	11142	12356	1259
22	Shajapur	4619	41407	51226	3760	4714	892
23	Dewas	5808	36554	45654	526	7434	898
24	Jhabua	3681	38223	29259	1860	5286	301
25	Dhar	5777	41855	55875	57	7048	655
26	Indore	12278	180063	268620	8696	190022	3383
27	West Nimar	12761	40742	53178	198	5147	368
28	Barwani	2707	17432	39260	16	3579	209
29	East Nimar	5304	54359	68953	9125	8936	1522
30	Rajgarh	9877	41863	39129	1156	4647	239
31	Vidisha	2859	46829	44831	3117	3550	660
32	Bhopal	9039	168360	173049	15456	68341	1247
33	Sehore	10535	25118	33469	1540	4984	339
34	Raisen	2157	39327	32853	1468	4600	617

35	Betul	57955	39483	37067	15901	7355	354
36	Harda	1413	12735	18657	3202	2155	229
37	Hoshangabad	17835	54116	54185	31850	6914	1097
38	Katni	2295	48821	49895	18945	9130	405
39	Jabalpur	17960	134585	153669	22394	59288	843
40	Narsimhapur	5935	21652	39693	4435	4207	541
41	Dindori	708	5524	9239	0	1062	57
42	Mandla	2050	31632	21477	3089	2134	167
43	Chhindwara	10949	71134	69001	6105	14918	591
44	Seoni	7501	38666	34904	817	5358	205
45	Balaghat	5791	46352	50914	1666	3536	459
	M P	520777	2260856	2542591	266137	650379	28941

Per Capita Income at constant price (2004 – 2005 prices)

(In Lakhs)

S.N.	District	Communi- cation	Banking & Insurance	Real, Owner ship of Dwel. B.Ser.& Legal	Public Adminis- tration	Other Services	Total DDP
1	2	16	17	18	19	20	21
1	Sheopur	2781	4647	3464	7250	11183	21
2	Morena	9243	16463	12419	21714	43445	138915
3	Bhind	7872	13558	8523	20760	39569	385985
4	Gwalior	28785	85782	85681	52014	81894	322023
5	Datia	5274	7413	5268	12540	19376	846205
6	Shivpuri	8304	17349	8406	22337	33300	195689
7	Guna	9253	22302	19831	22807	38753	338823
8	Tikamgarh	6415	13191	6894	15408	28546	514482
9	Chhatarpur	9522	18771	9051	20561	38326	273725
10	Panna	3807	8453	5000	12562	21153	365513
11	Sagar	14882	41470	24359	33190	56657	197243
12	Damoh	8026	12534	12097	15126	26707	608523
13	Satna	13549	31121	35866	25978	52924	293849
14	Rewa	12379	39131	26020	33680	57321	542205
							465456

15	Umaria	2781	8315	2547	6949	13324	126662
16	Shahdol	10260	26398	10218	22947	44419	550870
17	Sidhi	6827	85140	10338	20144	38053	909673
18	Neemuch	6444	13375	21763	9373	22490	266358
19	Mandsaur	10279	15163	36918	14703	32444	452532
20	Ratlam	12456	26092	47605	19746	38101	491561
21	Ujjain	19810	44206	83671	29278	60406	786095
22	Shajapur	7920	12549	9818	15416	32688	365101
23	Dewas	8380	22730	17692	17439	33729	451933
24	Jhabua	6818	12718	5197	20554	33791	312134
25	Dhar	8812	28737	15774	29412	46918	547114
26	Indore	60802	264088	451821	56487	166585	2134936
27	West Nimar	10423	19413	15698	24054	38423	398559
28	Barwani	5245	13146	9470	12296	22734	269257
29	East Nimar	10768	29088	18090	21881	38199	493901
30	Rajgarh	6683	12106	8341	14523	32822	342657
31	Vidisha	7470	14323	17967	16172	32041	346063
32	Bhopal	59545	280428	175859	91705	107201	1435289
33	Sehore	7019	12794	9569	14673	26359	305035
34	Raisen	6846	10792	6414	16489	27931	344897
35	Betul	9857	19718	7525	21539	38672	430428
36	Harda	4114	12305	7112	6418	10863	209420
37	Hoshangabad	13021	23112	16357	21737	33849	452238
38	Katni	9176	20223	36769	11769	27831	353961
39	Jabalpur	49123	102245	79742	47863	96718	1212392
40	Narsimhapur	7345	13283	5833	14089	27023	263287
41	Dindori	2071	4570	1163	8856	12633	96797
42	Mandla	4324	10134	2455	20240	26096	198717
43	Chhindwara	14210	27896	31330	29644	55918	740433
44	Seoni	7249	12595	8807	19919	32617	311823
45	Balaghat	8898	13528	10254	23760	44813	385325
	M P	545066	1543395	1444996	1016003	1844848	21474088

Sectorwise Gross District Domestic Product (GDDP) for the year : 1999 - 2000 (At 1999 - 2000 Prices)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unreg. MFG.	Electricity, Gas & W.supply	Construction	Trade, Hotels & Restaurants	Railways
		3	4	5	6	7	8	9	10	11	12	13
1	Sheopur	26039	1459	22	28	2958	1791	1167	706	2281	8460	292
2	Morena	52513	2257	71	73	19579	14289	5290	2387	11923	23360	1480
3	Bhind	44791	1968	46	55	16225	11564	4661	2555	9238	19043	479
4	Gwalior	42892	1621	82	214	43527	31917	11609	11405	18249	56434	7285
5	Datia	28183	890	37	142	7167	4642	2525	863	5323	11184	1661
6	Shivpuri	63024	2761	184	252	10141	6047	4094	2826	7225	20781	556
7	Guna	65875	1813	56	82	19281	13264	6017	2385	11999	27776	3233
8	Tikamgarh	48659	2031	701	112	10801	6363	4438	2822	8757	15542	800
9	Chhatarpur	54453	3223	1429	316	14101	8090	6011	3820	13355	23665	305
10	Panna	29616	2095	70	2017	7969	5060	2909	1074	4480	10962	213
11	Sagar	55379	3342	360	142	29250	16847	12403	2614	14466	39725	9083
12	Damoh	37726	1819	292	1294	16490	9445	7045	1314	9246	18991	2399
13	Satna	47046	3596	768	7417	33682	23400	10281	4031	14044	35819	7406
14	Rewa	50109	3417	1070	2993	21367	13015	8352	5798	10728	27576	311
15	Umaria	12226	1783	416	2282	4011	2567	1444	3606	3417	5388	2551
16	Shahdol	39748	4284	1577	60654	16763	10778	5984	7018	13013	22575	6387
17	Sidhi	46647	6031	128	148679	14909	9492	5417	41645	9809	16744	1901
18	Neemuch	43076	1033	33	2334	9896	6510	3386	1625	4939	17416	1374
19	Mandsaur	88946	1700	571	144	13332	8398	4934	8679	9471	26596	2772
20	Ratlam	78506	1636	80	82	20280	14686	5594	1572	7990	30141	14383
21	Ujjain	103189	2084	81	171	48796	37158	11639	10961	14811	45932	7256
22	Shajapur	80855	1881	75	71	11398	6740	4658	1728	9895	24241	2449
23	Dewas	62668	3800	201	57	31034	22331	8703	1934	7265	21618	342
24	Jhabua	39434	2259	275	1089	6955	4038	2916	1329	9062	13820	1211
25	Dhar	72879	2657	271	322	38142	29264	8878	2618	10023	26747	37
26	Indore	61509	2135	149	509	134359	99908	34451	4745	31308	127804	5663
27	West Nimar	45759	2413	148	74	17784	12733	5051	4940	9721	25119	129

28	Barwani	24130	1659	63	52	9291	6090	3202	1017	3464	18605	11
29	East Nimar	66986	4111	129	64	27177	19579	7599	2191	11900	32532	5942
30	Rajgarh	61230	1894	65	54	13230	8610	4619	3887	9846	18549	753
31	Vidisha	65963	2075	105	62	10069	6079	3990	1006	10685	21084	2030
32	Bhopal	22963	1583	391	88	85429	69847	15581	3217	29249	82795	10065

Sectorwise Gross District Domestic Product (GDDP) for the year : 1999 – 2000 (At 1999 – 2000 Prices)

(In Lakh)

																				(Rs.)
I	2	14	15	16	17	18	19	20	21	22	23									
1	Sheopur	676	90	432	563	1264	2425	5170	52866	5417	9759									
2	Morena	5953	258	1395	4082	3969	8018	18475	155794	15483	10062									
3	Bhind	1810	124	1178	3769	2783	8376	17067	129506	13972	9269									
4	Gwalior	17756	414	5166	17859	32570	19619	33136	308228	15845	19453									
5	Datia	797	83	829	1810	1837	4653	8495	73955	6120	12084									
6	Shivpuri	1920	161	1290	3470	3053	7207	14831	139681	13987	9987									
7	Guna	2672	213	1466	4471	7976	8167	17624	175091	16168	10829									
8	Tikamgarh	1310	98	952	2490	2354	5523	13141	116093	11664	9953									
9	Chhatarpur	3235	172	1499	3771	2526	7824	17171	150865	14304	10547									
10	Panna	670	42	553	1701	1931	4607	9359	77358	8327	9290									
11	Sagar	6168	178	2449	7209	8978	12733	25869	217945	19685	11072									
12	Damoh	1258	67	1284	2167	5074	5398	12668	117486	10570	11115									
13	Satna	6305	290	2256	7257	13088	9295	23722	216022	18135	11912									
14	Rewa	6658	76	2044	8128	9070	13539	24994	187876	19147	9813									
15	Umaria	433	16	443	2779	976	2619	5775	48722	5024	9699									
16	Shahdol	2471	132	1614	4449	3164	7865	19927	211640	15383	13758									
17	Sidhi	2785	116	1070	5969	3472	7487	17083	324475	17680	18353									
18	Neemuch	2178	71	1038	2578	9423	3429	9853	110297	7076	15586									
19	Mandsaur	2556	86	1679	3528	16564	5679	14149	196451	11515	17061									
20	Ratlam	3020	271	2086	6449	20268	7427	16846	211038	11810	17869									
21	Ujjain	5071	345	3232	9757	35902	10519	26985	325093	16644	19533									
22	Shajapur	1811	248	1231	2614	3833	5698	15540	163565	12543	13040									
23	Dewas	2658	204	1381	4298	6396	6458	15274	165588	12697	13041									
24	Jhabua	1945	71	1198	2407	1949	6908	15777	105689	13569	7789									
25	Dhar	2509	154	1403	4894	5807	10177	21083	199721	16881	11831									
26	Indore	50667	1003	10549	42048	180010	21193	64524	738176	23790	31029									
27	West Nimar	1742	91	1631	5491	6455	8678	17211	147387	14829	9939									
28	Barwani	1578	50	812	2216	4073	4155	10468	81645	10468	7799									
29	East Nimar	3798	368	1811	3598	6650	8908	17265	193428	16720	11569									
30	Rajgarh	1646	58	1063	2746	2996	5516	15238	138769	12174	11399									
31	Vidisha	2331	160	1224	3002	7089	5777	14948	147609	11803	12506									
32	Bhopal	22291	361	10618	36683	52459	33287	42118	433597	17758	24416									

Sr. No.	District Name	Agriculture	Forest & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unregistered MFG.	Electricity, Gas & W.supply	Construction	Trade, Hotels & Restaurants	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
33	Sehore	59378	3038	606	22	7479	4195	3283	4114	4992	15835	1003
34	Raisen	52465	2412	261	213	23748	18290	5458	743	7816	15560	956
35	Betul	49464	4128	285	5654	12470	8064	4406	23746	9439	17410	10355
36	Harda	25655	1995	19	2	3926	2044	1882	539	2531	8768	2085
37	Hoshangabad	50756	2005	463	223	18495	12706	5789	6952	11377	25553	20742
38	Katni	29811	2241	1366	6296	21615	14064	7551	827	9703	23535	12338
39	Jabalpur	37067	2845	1992	332	66191	45123	21068	6816	24000	72677	14583
40	Narsimhapur	52128	1892	74	75	8667	4719	3948	2310	3395	18679	2888
41	Dindori	19786	3410	124	282	3278	2037	1241	242	1098	4307	0
42	Mandla	22469	4353	264	49	6301	4008	2293	902	8537	10098	2011
43	Chhindwara	89444	3805	379	30831	20421	13634	6787	4179	14688	32579	3976
44	Seoni	41874	5648	747	67	7519	4361	3158	2903	9406	16570	532
45	Balaghat	50564	6093	2328	11974	19113	11180	7933	2198	10426	23915	1085

Source : Directorate of Economics and Statistics , Govt of Madhya Pradesh

Sector wise Gross District Domestic Product (GDDP) for the year: 2004 – 2005 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unreg. MFG.	Electricity, Gas & W.supply	Construction	Trade, Hotels & Restaurants	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Sheopur	26222	1345	45	23	2868	1597	1271	1024	2965	9098	329
2	Morena	52906	2514	68	292	14992	9268	5725	3446	15547	25031	1663
3	Bhind	42480	2196	24	123	14606	9397	5209	3697	12052	20404	539
4	Gwalior	41564	1814	68	419	40204	27369	12835	16278	23674	61023	8189
5	Datia	26549	991	63	162	6814	3957	2857	1259	6918	11949	1867
6	Shivpuri	59629	2963	434	689	9994	4957	5037	3921	9392	22329	624
7	Guna	67616	1908	544	305	19682	12800	6882	3298	15617	29887	3634
8	Tikamgarh	43397	2215	739	887	10928	5276	5652	4001	11382	16613	900
9	Chhatarpur	56375	3620	977	894	14755	7033	7722	4819	17374	25408	343
10	Panna	37106	2221	439	3067	8493	4832	3661	1533	5823	11684	240
11	Sagar	60833	3841	457	265	27037	15253	11784	3746	18805	42753	10210
12	Damoh	40525	1998	530	1733	15010	7905	7106	1881	12079	20261	2696
13	Satna	51457	3849	1187	6880	33953	21836	12117	5616	18277	38582	8325
14	Rewa	48899	3728	1048	2881	22151	11352	10799	8153	13999	29689	349
15	Umaria	12756	2659	364	2670	4115	2314	1801	5097	4442	5764	2868
16	Shahdol	36699	4897	1699	69440	16849	9392	7457	10023	16946	24186	7180
17	Sidhi	49535	6465	391	169198	15325	7978	7346	58462	12784	18021	2137
18	Neemuch	39405	1141	160	2299	9885	6015	3869	1656	6420	18851	1545
19	Mandsaur	66317	1894	273	190	13118	7633	5485	12250	12372	28534	3116
20	Ratlam	59234	1818	313	121	20158	13861	6297	2254	10385	32402	16168
21	Ujjain	69140	2323	212	1727	48332	35701	12631	15563	19249	49344	8156
22	Shajapur	64993	2093	310	253	11227	5565	5663	2467	12924	25951	2752
23	Dewas	58824	3134	421	278	28060	18036	10024	2788	9443	23274	385
24	Jhabua	45798	2517	443	409	7447	4086	3361	1931	11834	14763	1361
25	Dhar	77002	2942	1131	833	33857	23894	9963	3149	13092	28988	41
26	Indore	54577	2767	779	895	119821	82026	37795	6764	40525	139155	6366
27	West Nimar	55567	2663	294	445	17044	11519	5525	7039	12696	26953	145

28	Barwani	32658	1837	75	128	8723	5159	3564	1461	4503	20011	12
29	East Nimar	57503	10285	121	470	25225	17443	7782	2811	15509	34826	6680
30	Rajgarh	54577	2099	422	333	13014	7468	5546	5513	12856	19899	846
31	Vidisha	63881	2346	265	285	9876	5308	4569	1473	13940	22659	2282
32	Bhopal	22103	1752	180	734	92020	74552	17468	4695	37860	90025	11314

Source: Directorate of Economics and Statistics, Govt of Madhya Pradesh

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total DD P	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	Sheopur	834	118	920	867	1545	2735	5610	56551	6098	9274
2	Morena	7248	329	2886	4317	4928	9165	20074	165405	17080	9684
3	Bhind	2226	151	2447	3816	3387	9162	18375	135685	14952	9075
4	Gwalior	23063	511	11610	20017	41233	23048	36019	348734	17595	19820
5	Datia	979	100	1734	1976	2226	5221	9344	78152	6680	11699
6	Shivpuri	2359	193	2725	3776	3674	8522	16171	147393	15599	9449
7	Guna	3349	266	3104	4740	9728	9005	19202	191885	18027	10644
8	Tikamgarh	1659	124	1967	2819	2974	6342	14222	121170	13038	9293
9	Chhatarpur	4065	204	3195	4395	3339	8477	18603	166844	15957	10456
10	Panna	811	72	1127	1968	2345	5049	10177	92154	9185	10033
11	Sagar	7892	231	5326	7932	10998	14083	28322	242731	21557	11260
12	Damoh	1536	78	2749	3494	6054	6163	13905	130693	11480	11385
13	Satna	8043	335	4933	8091	16528	10715	25792	242563	20253	11977
14	Rewa	8413	95	4475	9599	11075	14818	26767	206142	21322	9668
15	Umaria	526	20	951	3121	1161	2961	6288	55762	5499	10140
16	Shahdol	2991	155	3413	4871	3943	9765	21467	234524	16593	14134
17	Sidhi	3443	156	2271	6549	4237	8363	18266	375604	20181	18612
18	Neemuch	2655	92	2212	2880	11435	3965	10790	115393	7706	14974
19	Mandsaur	3107	121	3633	3933	19870	5669	15474	189872	12661	14997
20	Ratlam	3751	333	4515	6556	24428	8251	18337	209024	13056	16010
21	Ujjain	6275	421	6935	10667	43508	12288	29604	323745	18300	17691
22	Shajapur	2185	304	2597	2677	4674	6298	17046	158752	13859	11455

23	Dewas	3224	281	2983	4556	8290	7281	16770	169992	14120	12039
24	Jhabua	2419	82	2693	2955	2427	7901	16863	121844	14899	8178
25	Dhar	2999	190	2977	5938	7552	11548	23043	215282	18827	11435
26	Indore	64095	1224	22855	58407	226557	24930	74811	844527	27256	30985
27	West Nimar	2111	112	3420	4524	7916	9746	18893	169567	16580	10227
28	Barwani	1892	64	1693	3026	4904	5020	11302	97309	11796	8250
29	East Nimar	4719	469	3968	7180	8408	9351	19018	206542	18081	11423
30	Rajgarh	1984	69	2275	2979	3829	6089	16751	143535	13526	10612
31	Vidisha	2872	207	2657	3237	8738	6602	16275	157594	13056	12071
32	Bhopal	28939	444	23657	76890	71171	39504	45550	546837	20504	26670

Source: Directorate of Economics and Statistics, Govt of Madhya Pradesh

Sector wise Gross District Domestic Product (GDDP) for the year : 2004 – 2005 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unregd MFG.	Electricity, Gas & W.supply	Construction	Trade,Hotels & Restaurants	Railways
1	2	3	4	5	6	7	8	9	10	11	12	13
33	Sehore	58095	2756	477	197	7522	3619	3903	5848	6489	17003	1128
34	Raisen	48939	3033	421	598	22931	16669	6261	1095	10159	16752	1074
35	Betul	47032	5563	210	6735	11815	6452	5364	32873	12329	18661	11640
36	Harda	23145	2356	94	164	3971	1718	2254	771	3290	9429	2344
37	Hoshangabad	45643	2641	440	1096	19061	12073	6988	9887	14812	27371	23315
38	Katni	27343	2793	1419	6905	22392	13498	8894	1203	12612	25260	13868
39	Jabalpur	49088	2862	2046	1177	68897	44172	24726	9765	31092	78403	16393
40	Narsimhapur	52859	2319	228	182	9136	4148	4987	3286	4379	19944	3247

41	Dindori	19534	3253	169	96	3449	1659	1790	358	1427	4569	0
42	Mandla	23562	5773	506	255	6592	3670	2922	1039	11182	10760	2261
43	Chhindwara	91761	4515	291	35311	18825	11032	7793	5978	19113	34947	4469
44	Seoni	38994	6713	638	252	7880	3996	3884	4137	12291	17774	598
45	Balaghat	44303	7880	2138	16447	19528	10355	9173	3149	13597	25545	1219

Source: Directorate of Economics and Statistics, Govt of Madhya Pradesh

Jharkhand-

Sector wise Gross District Domestic Product (GDDP) for the year : 1999 - 2000

(At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unregd MFG.	Electricity, Gas & W.supply	Construction	Trade, Hotels & Restaurants	Railways
		3	4	5	6	7	8	9	10	11	12	13
1	DUMKA	49855	1341	2565	4504	52225	47471	4754	1176	8904	16756	4282
2	DEOGHAR	18230	634	2154	4961	59673	54241	5432	2553	7188	13907	4599
3	GODDA	22359	574	1197	2925	27954	25407	2547	671	4126	7734	227
4	PAKUR	16518	381	1077	22360	51770	47053	4717	303	2736	6818	727
5	SAHEBGANJ	11834	784	1795	16199	65286	59339	5947	1139	5255	12041	5165
6	HAZARIBAGH	30316	4712	2932	70460	53709	47222	6487	14934	22105	30799	5507
7	KODERMA	4885	1015	689	7753	10945	9946	999	1247	4930	10685	1694
8	CHATRA	12892	4164	537	2075	21699	19724	1975	375	2693	5698	74
9	GIRIDIH	22158	2909	1177	11577	44324	40284	4040	1370	15158	18791	4515
10	BOKARO	4432	1328	2989	47460	79078	71875	7203	16145	19609	23506	7699
11	DHANBAD	9870	347	2274	175291	62437	56748	5689	13614	36722	51523	18885
12	RANCHI	73118	2921	2956	19489	81012	73630	7382	7571	27579	42772	8253
13	LOHARDAGAJA	11331	814	776	1283	8369	7605	764	144	1455	3731	176
14	GUMLA	69545	2519	1782	3472	29701	26995	2706	72	2628	8480	1158
15	PALAMU	45021	6696	1588	4958	44133	40116	4017	1651	9251	17536	6852
16	GARHWA	18482	3508	682	3030	20692	18805	1887	447	2758	7496	1021
17	E. SINGHBHUM	23769	2253	2393	14991	118804	107980	10824	4932	28513	39651	9181
18	W. SINGHBHUM	58970	5937	2781	13359	89465	81319	8146	3764	15549	21267	18386

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total DDP	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	DUMKA	3513	36	2103	2274	4729	5459	16627	176349	17092	10318
2	DEOGHAR	4179	28	1868	2849	4518	3412	16858	147611	11320	13040
3	GODDA	1327	2	966	1292	4243	2292	10813	88702	10179	8714
4	PAKUR	2558	5	455	441	2784	1468	6273	116674	6816	17118
5	SAHEBGANJ	3114	22	924	1188	2062	2274	9026	138108	9012	15325
6	HAZARIBAGH	11389	88	3709	5609	7195	15472	29742	308678	22123	13953
7	KODERMA	2731	40	717	1239	2349	1864	6100	58883	4851	12138
8	CHATRA	1732	13	551	585	2685	2594	7650	66017	7687	8588
9	GIRIDIH	5092	0	1915	2815	5921	4332	20145	162199	18499	8768
10	BOKARO	6743	13	3284	4813	9677	7531	20379	254686	17268	14749
11	DHANBAD	16119	673	6466	9056	16934	8689	36278	465178	23284	19978
12	RANCHI	14806	160	8330	13946	22406	28171	39605	393095	27052	14531
13	LOHARDAG A	869	29	508	372	1067	984	3787	35695	3541	10080
14	GUMLA	1633	77	1798	1527	4204	3834	10294	142724	13082	10910
15	PALAMU	3904	36	2513	3006	12111	6849	17640	183745	20383	9015
16	GARHWA	1574	5	826	729	3295	2117	7052	73714	10057	7330
17	E. SINGHBHU M	12229	342	7113	10109	21611	9147	32020	337058	19262	17499
18	W. SINGHBHU M	6358	233	3648	4063	10529	6659	22224	283192	20232	13997

Source : Directorate of Economics and Statistics , Govt of Jharkhand

Sector wise Gross District Domestic Product (GDDP) for the year: 2000 - 2005
(At 2004 – 2005 Prices)

(In Lakhs)

Sr. No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unregd. MFG.	Electricity, Gas & W.supply	Construction	Trade, Hotels & Restaurants	Railways
		3	4	5	6	7	8	9	10	11	12	13
1	DUMKA	41288	1309	365	2830	35397	31895	3502	732	8672	14696	3928
2	JAMTARA	19178	929	322	2034	19921	18113	1808	526	5063	8277	2826
3	DEOGHAR	22110	1058	578	5358	63208	57141	6066	2731	11089	19067	7255
4	GODDA	27118	958	322	3159	29610	26766	2845	718	6366	10603	358
5	PAKUR	20034	636	289	24151	54836	49569	5268	324	4220	9347	1146
6	SAHEBGANJ	14354	1309	481	17497	69153	62511	6642	1219	8106	16509	8148
7	HAZARIBAGH	36769	7866	787	76105	56994	49749	7245	15976	34104	42225	8688
8	KODERMA	5924	1694	185	8374	11593	10477	1115	1334	7605	14650	2673
9	CHATRA	15636	6951	144	2242	22984	20778	2205	401	4154	7812	117
10	GIRIDIH	26874	4856	315	12504	46949	42437	4512	1465	23383	25763	7122
11	BOKARO	5375	2217	802	51261	83762	75717	8045	17271	30251	32227	12145
12	DHANBAD	11971	579	610	189330	66136	59781	6355	14564	56649	70638	29791
13	RANCHI	88685	4876	793	21050	85810	77565	8244	8099	42544	58642	13018
14	LOHARDAGA	13743	1359	208	1385	8865	8012	853	154	2244	5115	278
15	GUMLA	56069	2488	329	2295	19231	17403	1828	48	2481	7063	1116
16	SIMDEGA	28279	1717	149	1455	12229	11034	1194	31	1573	4572	710
17	PALAMU	33897	6952	205	3992	34672	31366	3307	1316	10592	17769	8057
18	LATEHAR	20705	4226	222	1364	12075	10894	1180	450	3679	6271	2751

19	GARHWA	22415	5856	183	3273	21918	19810	2108	478	4254	10275	1610
20	E. SINGHBHUM	28829	3761	642	16191	125842	113752	12090	5276	43986	54361	14483
21	W. SINGHBHUM	50572	6971	450	7749	53935	48414	5521	2163	13555	16937	15578
22	SARAYKELA KHARSAWA	20950	2939	296	6680	40828	37251	3576	1864	10431	12218	13427

Source: Directorate of Economics and Statistics, Govt of Jharkhand

Odisha

Sector wise Gross District Domestic Product (GDDP) for the year : 1999 – 2000 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	Distri ct Name	Agricul - ture	Forestr y & Logging	Fishing	Mining & Quarryin g	Manufa- cturing MFG.	Regi- stered MFG.	Un- re- gd MFG.	Electricit y, Gas & W.suppl y	Constr- u- ctio n	Trade, Hote ls & Resta- urants	Railway s
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Anugul	32244	5159	1451	95692	119051	115397	3654	20454	10470	10719	1269
2	Baleshwa r	47083	631	13785	99	17000	12293	4707	5203	7871	15839	2886
3	Bargarh	74461	2309	2215	993	11486	6013	5473	3195	4779	9701	413
4	Bhadrak	28271	184	4700	1	2677	988	1689	2927	3622	11087	1982
5	Balangir	49295	2932	1081	296	6308	2467	3841	3817	13184	10599	3946
6	Baudh	17302	2425	375	55	1405	-19	1423	355	1922	1981	5
7	Cuttack	41343	1496	1364	149	15262	7035	8227	12051	19604	58387	5087
8	Debagarh	16696	2963	765	79	829	0	829	1111	2564	1183	5
9	Dhenkana l	30240	3300	1184	597	7257	4324	2933	4136	11042	9575	1029
10	Gajapati	19006	4688	345	56	984	14	970	1168	4803	4281	145
11	Ganjam	66727	5981	5223	223	12320	2495	9825	11362	28813	37108	2303
12	Jagatsing hapur	22479	252	7146	4	12674	10245	2428	3113	8369	10331	988
13	Jajapur	25892	1377	1121	23398	4603	1720	2883	4417	11040	17646	1874
14	Jharsugu da	21265	384	1084	41868	10249	7858	2391	2710	7014	7203	4839
15	Kalahandi	61105	4819	1296	148	5226	2101	3125	4024	8281	9258	749
16	Kandham al	27417	10842	35	399	3878	68	3810	1355	11217	3756	4
17	Kendrapa ra	29356	471	3510	8	2033	-39	2072	4070	7230	10477	193
18	Kendujhar	60478	5881	847	18278	22757	17746	5011	4266	8160	10282	1300
19	Khordha	37597	1175	1959	129	13150	8844	4307	14889	19712	39060	15648
20	Koraput	44838	3569	390	3683	15478	13339	2138	6969	15720	9853	2779
21	Malikangiri	28434	6373	527	84	630	-28	658	1642	3253	1909	0

22	Mayurbhanj	65990	8340	2811	364	19109	1305	17803	4890	13338	13940	1619
23	Nabarangapur	44255	4677	314	253	3873	1984	1889	1486	6213	7312	19
24	Nayagarh	20823	3952	760	10	3041	95	2946	1433	4677	6061	73
25	Nuapada	27205	3512	395	103	1339	229	1110	803	4469	3172	239
26	Puri	42349	260	10474	4	2723	304	2420	3877	5536	16172	3036
27	Rayagada	25079	5340	90	249	15492	14099	1393	2758	8467	6912	2138
28	Sambalpur	47798	6896	1237	102	17369	10188	7180	7214	11178	10359	2596
29	Sonapur	26788	790	484	13	1654	0	1654	547	2052	3335	55
30	Sundargarh	54603	9414	753	15947	91189	86842	4346	6116	16658	21078	15465

Source: Directorate of Economics and Statistics, Govt of Orissa

Sector wise Gross District Domestic Product (GDDP) for the year: 1999 – 2000 (At 1999 – 2000 Prices)

(In Lakhs)

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total GDP	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	Anugul	4898	44	1673	3144	8065	6919	14801	336052	11165	30100
2	Baleshwar	6207	127	3838	7369	12378	13174	27961	181450	19809	9160
3	Bargarh	4056	104	1502	3734	8024	4437	17521	148930	13308	11191
4	Bhadrak	4633	84	2137	4120	7380	6374	17421	97602	13029	7491
5	Balangir	3842	80	1926	3699	9090	9948	21640	141682	13270	10677
6	Baudh	418	7	428	945	2141	1850	4702	36314	3662	9918
7	Cuttack	17666	693	7309	17261	21631	27984	48919	296205	22926	12920
8	Debagarh	581	3	352	546	1522	1765	4235	35201	2690	13086
9	Dhenkanal	5488	65	1682	3098	6668	7236	19780	112375	10531	10671
10	Gajapati	1031	7	992	1284	3139	2502	10354	54786	5111	10720
11	Ganjam	14503	279	5728	11673	23538	18959	57961	302701	31022	9758

12	Jagatsinghapur	7893	47	2120	3726	6906	7583	16757	110388	10560	10453
13	Jajapur	8874	85	2431	4262	8739	8230	26050	150040	15937	9415
14	Jharsuguda	2631	74	1191	1548	4751	3893	7848	118552	5021	23611
15	Kalahandi	3018	32	1748	2984	8200	6800	18274	135962	13088	10388
16	Kandhamal	1493	7	1455	1441	3836	4213	9665	81011	6348	12762
17	Kendrapara	4235	14	1929	3492	7164	5945	21059	101186	12840	7881
18	Kendujhar	8465	47	2461	3469	11222	8868	21848	188631	15332	12303
19	Khordha	13422	271	7694	23673	23580	41272	40403	293635	18242	16096
20	Koraput	4474	124	1834	3138	8576	8590	20419	150434	11622	12944
21	Malikangiri	563	3	364	430	2671	2112	4267	53264	4932	10799
22	Mayurbhanj	6225	81	3559	5431	15644	12204	26818	200364	21793	9194
23	Nabarangapur	1457	22	727	1114	5324	3228	11372	91645	10014	9152
24	Nayagarh	2385	10	988	2074	4677	4157	11552	66671	8558	7791
25	Nuapada	1069	23	725	1127	2985	2401	6395	55962	5235	10690
26	Puri	6113	103	2407	5275	9895	10840	24496	143563	14783	9711
27	Rayagada	2380	97	1219	1771	5351	4100	12614	94057	8163	11523
28	Sambalpur	4755	96	2159	5048	8563	9370	15819	150560	9198	16369
29	Sonapur	765	16	412	986	3104	2094	6327	49420	5341	9253
30	Sundargarh	9381	94	4621	8533	17412	11698	29357	312319	17981	17369

Source: Directorate of Economics and Statistics, Govt of Orissa

Sector wise Gross District Domestic Product (GDDP) for the year: 2004 – 2005 (At 1999 – 2000 Prices)

(In Lakhs)

No.	District Name	Agriculture	Forestry & Logging	Fishing	Mining & Quarrying	Manufacturing MFG.	Registered MFG.	Unreg. d. MFG.	Electricity, Gas	Construction	Trade, Hotels & Restaurants	Railways
		3	4	5	6	7	8	9	10	11	12	13
1	Anugul	37132	5388	1454	169307	179831	175756	4075	37499	7976	17719	1858
2	Baleshwar	58367	659	15929	419	35752	29781	5971	7063	7421	27233	3726
3	Bargarh	56750	2412	2257	1805	12478	6571	5908	4564	5820	15845	613
4	Bhadrak	46956	193	6581	5	1317	-791	2108	3974	3415	19250	2560
5	Balangir	49755	3062	1718	661	7647	3592	4055	5495	17076	16597	5554
6	Baudh	21237	2533	606	237	1989	101	1888	570	3250	2814	1
7	Cuttack	63408	1563	1676	524	20614	11403	9211	17223	19306	94330	6574
8	Debagarh	12049	3094	691	227	884	0	884	1587	3123	1839	8
9	Dhenkanal	33182	3446	1507	510	9983	6762	3221	7583	8411	15668	1506
10	Gajapati	22275	4897	242	395	1078	14	1064	1862	5416	6508	172
11	Ganjam	82960	6247	6506	677	15595	4768	10826	18104	32491	56227	2730
12	Jagatsinghapur	37771	264	6742	393	64525	61757	2768	4450	8242	16329	1277
13	Jajapur	36892	1438	919	52739	6832	3662	3169	6313	10872	29273	2422
14	Jharsuguda	13997	402	832	68100	16065	13452	2613	3871	8541	11137	7188
15	Kalahandi	59641	5034	1867	342	5255	2099	3157	5973	9630	13841	1113
16	Kandhamal	34454	11324	298	1094	5168	103	5065	2176	18970	5649	1
17	Kendrapara	39159	492	3116	34	2416	173	2243	5817	7120	17351	249
18	Kendujhar	82667	6143	1253	58290	34949	28717	6233	6345	7427	19921	1306
19	Khordha	53272	1227	4791	578	28348	23998	4350	23526	15913	68006	2093
20	Koraput	49447	3728	492	8121	77577	75085	2492	9668	16836	14873	3378
21	Malkangiri	24556	6656	731	313	752	35	716	2279	3484	2878	0
22	Mayurbhanj	76481	8711	2331	686	30863	5617	25246	6653	15584	22649	2318

23	Nabarangapur	40448	4884	581	843	5022	2947	2075	2062	6654	10817	23
24	Nayagarh	25271	4127	1389	75	3011	39	2972	2265	3776	10001	97
25	Nuapada	22893	3669	447	226	1567	441	1126	1193	5198	5002	355
26	Puri	62022	272	11147	286	2996	550	2446	6126	4469	26439	4063
27	Rayagada	31304	5578	241	628	31642	30062	1580	3826	9068	10308	2599
28	Sambalpur	40077	7203	1090	1041	24200	16356	7844	10307	13612	15743	3856
29	Sonapur	26447	825	1308	44	1669	-51	1720	787	2657	5435	77
30	Sundargarh	50032	9832	1309	25646	110881	106984	3897	7505	15732	36082	2111
												9

Sector wise Gross District Domestic Product (GDDP) for the year: 2004 – 2005 (At 1999 – 2000 Prices) (In Lakhs)

Sr. No.	District Name	Transport by other means	Storage	Communication	Banking & Insurance	Real, Ownership of Dwel. B.Ser.& Legal	Public Administration	Other Services	Total GDP	Population (In '00)	Per Capita Income (Rs.)
1	2	14	15	16	17	18	19	20	21	22	23
1	Anugul	12734	79	3161	4743	11322	7660	17652	515514	11953	43130
2	Baleswar	12192	239	6571	12146	16863	14528	35905	255015	21271	11989
3	Bargarh	8024	165	2800	5983	9515	4865	20984	154881	13815	11211
4	Bhadrak	9101	159	3659	6790	10158	7029	22371	143519	14066	10204
5	Balangir	7195	128	3290	5856	11512	13148	27254	175949	13595	12942
6	Baudh	1123	9	739	1375	2442	2108	5702	46733	3902	11976
7	Cuttack	33177	1322	12380	26050	27873	29403	60203	415624	24549	16930
8	Debagarh	1150	4	657	875	1757	1936	5072	34953	2860	12220
9	Dhenkanal	14267	118	3178	4672	9141	8012	23591	144777	10982	13183
10	Gajapati	2011	18	1751	1962	4006	2727	12318	67637	5366	12604
11	Ganjam	28281	759	10112	17842	34603	20661	68952	402744	32968	12216
12	Jagatsingha pur	14823	90	3591	5624	8479	7968	20622	201188	10600	18980
13	Jajapur	16666	162	4118	6433	10574	8647	32059	226358	16958	13348
14	Jharsuguda	5205	116	2221	2480	5799	4269	9400	159623	5272	30277
15	Kalahandi	6610	45	3200	4523	10279	8118	23825	159296	13980	11394

16	Kandhamal	4004	9	2515	2095	4274	4801	11720	108553	6797	15971
17	Kendrapara	7953	26	3267	5270	8596	6247	25916	133029	13432	9904
18	Kendujhar	19466	62	4230	4731	12387	10006	27389	296571	16290	18206
19	Khordha	26373	476	14704	37345	26747	49499	48643	420387	20048	20969
20	Koraput	9955	250	3315	4464	14574	9771	24024	250473	12231	20478
21	Malkangiri	1254	7	658	612	4131	2403	5020	55733	5300	10516
22	Mayurbhanj	12937	104	5614	7628	10949	14756	33015	251277	23268	10799
23	Nabarangapur	3241	44	1314	1585	8063	3672	13379	102631	10835	9472
24	Nayagarh	4686	17	1888	3272	5969	4985	13907	84736	8841	9585
25	Nuapada	2342	32	1327	1708	3712	2867	8337	60873	5471	11126
26	Puri	12011	180	4601	8321	11985	13001	29492	197411	15591	12662
27	Rayagada	5295	196	2203	2520	8846	4663	14840	133758	8657	15452
28	Sambalpur	9407	152	4025	8089	10826	10276	18946	178849	9723	18395
29	Sonapur	1432	26	704	1561	3782	2768	7969	57489	5596	10273
30	Sundargarh	17876	97	9150	13219	21034	11742	32382	383639	19064	20124

Source: Directorate of Economics and Statistics, Govt of Orrisa