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Biodiversity Co-benefits of Land Sparing and Land Sharing Strategies for Tiger Conservation in Central India

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Abstract

India is celebrating the 53rd anniversary of Project Tiger, which began in 1973 with the establishment of nine designated tiger reserves. During this period, the tiger population has increased by 33% and 58 tiger reserves have been declared, comprising two management units: core zone and buffer zone, following land sparing and land sharing frameworks respectively. To create inviolate core areas, village relocation programmes are being carried out and so far, more than 170 villages have been relocated from the tiger reserves. Surprisingly, despite the large number of village relocations, there has been a notable gap in studies addressing the resulting changes in land cover and biodiversity distribution. We analysed tiger conservation-induced land use land cover (LULC) change from 1989 to 2019 and performed ensemble modelling of 103 species (26 mammals, 38 birds and 39 trees) to characterise biodiversity, focusing on the core and buffer zones in the Panna Tiger Reserve, Central India. We then used Generalised linear models to analyse the response of biodiversity to changes in LULC. The results showed a significant increase in total forest cover, despite being surrounded by intensive agricultural areas. This relates to the core area, which supports high biodiversity, while in the buffer areas, only the land units with high terrain complexity, away from human settlements, support high biodiversity. We conclude that while land sparing is effective for biodiversity conservation, the combination of land-sparing and land-sharing approaches maybe the most practical option for balancing conservation goals and livelihood of people in the forest landscapes.

1. Introduction

Protected areas (PAs), covering one-sixth of the world's terrestrial surface, play a crucial role in decelerating biodiversity loss (Chape et al. 2005; Geldmann et al. 2019). Despite exemplary conservation efforts, biodiversity continues to decline (Gatiso et al. 2022). To halt this trend, the UN Convention on Biological Diversity (CBD) has been adopted by 196 nations in recent decades. Its Strategic Plan for Biodiversity 2011–2020 set the Aichi targets of protecting 17% of terrestrial areas and 10% of marine ecosystems (Convention on Biological Diversity, 2010). The most recent and ambitious initiative, the Global Biodiversity Framework (GBF), was agreed upon by CBD signatory countries in December 2022. This framework includes Target 3, which aims to conserve at least 30% of land, inland water, and marine ecosystems in protected and conserved areas by 2030, known as the 30 × 30 target (Dudley 2023).

The success of PAs is usually assessed on the basis of species diversity, the coverage of endemic and threatened species, management plans, staff availability and boundaries (Rodrigues et al. 2004; Jachmann 2008), under the assumption that PAs provide adequate protection once established. India has also, institutionalised the Management Effectiveness Evaluation (MEE) process, and every four years all tiger reserves and selected PAs are evaluated and ranked based on multiple criteria (Mathur et al. 2009). However, there is a lack of temporal analysis of how conditions within the PA have changed as a result of protection and management actions taken (Craigie et al. 2010). Such information is essential for policy makers to understand the status and ensure the delivery of the conservation benefits of PAs (Brooks et al. 2006; Margules & Pressey 2000). Therefore, the effectiveness of PAs in conserving

biodiversity is often questioned due to a lack of critical data (Rodrigues et al. 2004; Chape et al. 2005; Laurance et al. 2012; Brooks et al. 2006; Jetz et al. 2012; Kindsvater et al. 2018).

The management strategies of protected areas are largely based on the concepts of land sparing (LSP) and land sharing (LSH). Under land sparing, an area is separated from other land uses for conservation purposes. While land sharing advocates wildlife-friendly agriculture to promote biodiversity and agriculture within the same area (Kremen 2015; Pywell et al. 2015). Conservationists have debated the concept of LSP and LSH for many years, and the controversy was reignited after the articles by Green et al. 2005 and Balmford et al. 2005. These articles were based on a theoretical model and argued that LSP was more effective for biodiversity conservation. However, the success of LSP depends on the type of ecosystem and species considered (Bignal & McCracken 1996).

Globally, large-bodied vertebrates are a focus of conservation concern, and these species are generally sensitive to anthropogenic pressures, so LSH strategies may not always be effective. Fritz et al. 2003 observed a negative correlation between the expansion of cultivated land and proxies for medium sized mammal density in northern Zimbabwe. Similarly, LSP was concluded to be more effective for mega-herbivore and top-predator conservation (Boudron 2014) Nevertheless, land sparing for protected areas can sometimes pose a significant threat to marginalised local communities, leading to conflict (Andersson et al. 2013). Several studies suggest that LSH may be a more promising strategy for biodiversity conservation, particularly in regions such as southwest Ghana, northern India and southern Uganda, with minimal negative impacts on the abundance and diversity of birds and trees (Phalan et al. 2011; Hulme et al. 2013; Wright et al. 2012). Given the escalating global demand for food and the unprecedented expansion of agricultural land in developing countries – a trend projected to continue until 2050 (Green et al. 2005; Balmford et al. 2005; Gibbs et al. 2010) – the potential benefits of LSH appear increasingly relevant.

Biodiversity conservation in developing countries, such as India, faces the challenge of a rapidly growing population and associated pressures, with many millions of people living near or within PAs (Dinerstein et al. 2017). The conservation challenges are therefore also different from other countries where PAs are located in areas of low human density and low biodiversity value, such as China, the USA and Brazil (Pimm et al. 2018). In India, the Wildlife Protection act 1972, Project Tiger-1973, and the 2006 Amendment to the Wildlife Protection Act 1972 provided the legal backing for the protection of wildlife and laid groundwork for future conservation initiatives (Das 2019). Currently, there are 58 tiger reserves under Project Tiger program of Government of India to save the flagship species while benefiting the overall value of biodiversity and human well-being. Tiger reserves cover 2.3% of the country's geographical area and receive the highest level of protection within the PA network. Tiger reserves are divided into two management units: the core and the buffer. The core area is legally protected from human intervention, ensuring its preservation as a strictly reserved space (LSP). Surrounding this core is the buffer zone, which consists of a mix of forest and non-forest lands. This buffer area is managed as a multiple-use zone (LSH), allowing for various uses while still supporting the conservation objectives of the reserve.

Within the core regions of the tiger reserves, conservation-induced relocation has been undertaken to improve habitat and resolve ongoing human-wildlife conflict (Karanth 2002). Nearly 257 villages from the core areas of tiger reserves tiger reserves have been relocated to date (NTCA 2024). Village relocation for conservation purposes dates back to the 1960s (Rangarajan & Shahabuddin 2006), but since then it has been a controversial issue among conservationists, and there is a lack of long-term post-relocation studies (Lasgorceix & Kothari 2009). A few studies have documented the social aspect of village relocation, focusing on people-centric affairs (Shahabuddin & Shah 2003; Sharma 2003; Ganguly 2004; Wilshusen et al. 2002; Brockington 2003), but the ecological view of environmental impacts or the effectiveness of relocation on biodiversity conservation is not considered (Rajpoot & Chauhan 2018). Hence, to address these gaps, we investigated the long-term LULC changes as a result of village relocation and protection status and assessed its relationship with biodiversity in the context of LSP and LSH frameworks.

2. Methodology

2.1 Study site

Our study area, the Panna Tiger Reserve (PTR), was declared India's 22nd tiger reserve in 1994. PTR constitutes a core area of 576 km^2 and a buffer zone of 1021 km^2 located in north-central Madhya Pradesh. It is part of a landscape consisting of an isolated forest patch of 3,500 km^2 in the Vindhya hill range (Jhala et al. 2008). During the last decade, in 2011, PTR was notified as a Biosphere Reserve by the Union Ministry of Environment, Forest and Climate Change (MoEFCC). In October 2020, UNESCO included PTR in the Man and Biosphere Programme (MAB). Between 1986 to 2008, conservation efforts in PTR led to the voluntary relocation of fourteen villages to establish inviolate core areas. These villages were relocated outside the forest and resettled in the fringe areas of nearby towns and villages. The sizes of the relocated villages ranged from 10 to 200 hectares, and the process typically took 3 to 10 years. Currently, only three villages remain in the north-western part of the core. The Ken River flows 55 km inside PTR and forms a natural boundary between these villages and the eastern part of the core (Fig. 1).

PTR has a rugged topography with elevations ranging from 123 meters to 566 meters and a varying slope of 0° to 48°. PTR receives approximately 1100 mm of annual rainfall and temperatures range from 7°C to 45°C. The vegetation type of PTR is broadly categorised as dry deciduous forest, with the tablelands occupied by savannah grasslands, short grass woodlands and slopes supporting mixed forests.

2.2 Patterns of land use land cover

We used multi-temporal Landsat satellite images of the study area downloaded from the USGS Earth Explorer site (https://earthexplorer.usgs.gov) for four decades. We used unsupervised classification using the fuzzy logic k-means clustering algorithm; the fuzzy k-means classifies the image into different

fuzzy clusters (Bezdek 1973). The classification was done in ERDAS IMAGINE software; all images were classified into six classes, i.e. dense forest, open forest, scrubland, water, cropland/agriculture and bare land (Online Resource 1). We then tested the accuracy of the classified images against ground data, expert knowledge and historical imagery using the accuracy assessment tool in ERDAS IMAGINE. The overall accuracy and the KAPPA coefficient were assessed for each classified image (Jensen 1996; Cohen 1960).

2.3 Change analysis

LULC change detection can quantify temporal effects using multi-temporal data by identifying the conversion of different LULC classes (Singh 1989; Pielke et al. 2011). LULC change is a primary driver of global change and has significant impacts on ecosystem processes, biological cycles and biodiversity (Behera et al. 2012). To understand the trends in land use and land cover in the PTR, we performed a change detection analysis following the post-classification comparison technique in ERDAS IMAGINE software (Zewdie & Csaplovies, 2015). We used classified images of 1989, 1999, 2009 and 2019 for change detection, first to identify the decadal change; then to visualise the overall change patterns. We compared images from 1989–2019 and the land use land cover transition matrix was generated. The transition matrix was further devided into six classes for better visualisation (Online Resource 2).

2.4 Biodiversity assessment

We calculated the biodiversity of three taxonomic groups, trees, birds and mammals. Mammals and birds have been widely studied globally in relation to forest age, structure and composition (Drapeau et al. 2000; Gil-Tena et al. 2007; Malcolm & Ray 2000; Sobral et al. 2017). In addition, trees with bird and mammal assemblages increase the surrogacy of biodiversity (Kati et al. 2004; Larsen et al. 2012; Leal et al. 2010). In this study, we defined a biodiversity value as the standardised sum of tree, mammal and bird alpha diversity (Lecina-Diaz et al. 2018).

2.4.1 Species occurrence data

To predict the alpha diversity of taxonomic groups, we used species occurrences recorded during the winter season from 2019 to 2021. The data collection was done by a team consisting of researchers, forest department officials and field assistants. For tree species occurrence, we used 3117 data points collected using the systematic line transect, representing 39 species. In 2020, a total of 285 transects of 1 km length, randomly located within a grid size of 4sq.km. were walked and vegetation plots were established at 250-meter intervals. Distance sampling was used for birds following stratified random sampling, we sampled 135 points with three replicates using a fixed radius of 50 meters for dense forest and 100 meters for open forest. A total of 654 records were collected for 38 species in 2021. In addition, a grid-based survey was conducted for mammal species and 343 camera traps were deployed in year 2019 with a grid size of 2*2 km covering the core and buffer zone of the PTR. A total of 4287 camera trap images representing 26 species were used. All sampling points were spatially explicit and non-overlapping (Online Resource 3).

2.4.2 Habitat covariates

We used a set of remotely sensed continuous biotic and abiotic environmental variables. Six covariates including elevation, slope, land surface temperature (LST), normalised difference vegetation index (NDVI), normalised difference water index (NDWI) and distance to village were used at 30-meter spatial resolution and tested for multicollinearity using variance inflation factors (VIF) in the 'USDM' package in R (Naimi et al. 2015). SRTM DEM data were used for elevation and slope calculations, to represent terrain conditions (Farr et al. 2007). We calculated LST from LANDSAT 8 data, NDVI & NDWI using the Sentinel 2A dataset to represent habitat variability. It is also worth noting that the agricultural areas of the PTR are not under the jurisdiction of the Forest Department, so we were not able to collect ground data on species occurrence from these areas, but Euclidean distance from village was included as an explanatory variable (Greenspan et al. 2020; Ndao et al. 2022). These variables have been used in previous distribution modelling studies, and their ability to represent habitat complexity has been demonstrated (Bobrowski et al. 2018; Manyangadze et al. 2016; Bonthoux et al. 2018; Wen et al. 2015 Khan et al. 2016; Thinley et al. 2019). We selected the same set of covariates for all models to ensure comparability of results.

2.4.3 Modeling alpha diversity

We predicted alpha diversity for each taxonomic group using species presence data and environmental variables at a spatial resolution of 30-meter. We used the ensemble modelling approach of the BIOMOD2 package in the R environment to obtain robust species occurrence and environment relationships (Thuiller et al. 2013). BIOMOD2 is a species distribution modelling platform that allows multi-model ensemble modelling, calibration and prediction for single and multiple species. We used three methods: two regression techniques (generalised linear model, GLM; generalised additive model, GAM) and one machine learning technique (random forest, RF). These three techniques are widely used in species distribution modelling, GLM uses parametric functions. In contrast, GAM uses non-parametric smooth functions to allow for non-linearity between response and predictors. RF is a modification of the bootstrap aggregation approach, which builds a consensus tree from the average of a large number of uncorrelated classification trees (Thuiller et al. 2003; Valavi 2021; Liu et al. 2009).

We used 1000 pseudo-absence points per species in a randomised fashion to run the species distribution model (SDM). Our aim was to enhance model specificity, and random selection of pseudo-absences has been shown to achieve this (Barbet-Massin et al. 2012 and Marini et al. 2009). As our study is limited to a protected area with evenly distributed data points, the random method was considered the most appropriate. We then used a randomly selected 70% of the presence-absence data for prediction, while keeping 30% of the data for model validation (Araujo et al. 2005; Franklin 2009; Thuiller et al. 2009; Barbet-Massin et al. 2012; Elith et al. 2006).

Three runs were performed for each SDM, in order to limit the computational requirements while still achieving stable results (Thuiller et al. 2016). For each technique, we kept the setting that produced the highest receiver operator curve (ROC) value during cross-validation. We calculated ROC and the true skill

statistic (TSS) via cross-validation and used them as an indicator to assess model performance (Huettmann et al. 2017). For all three taxonomic groups, the performance of the best-fitting model was assessed against the defined thresholds of TSS > 0.5 and ROC > 0.8 (Hill et al. 2017; Mi et al. 2017).

To improve the predictive performance of all SDM algorithms, we combined the predictions of GLM, GAM and RF using an ensemble model for each species that met predefined ROC thresholds. We evaluated the model predictions using the TSS validation technique. The TSS ranges from − 1 to + 1, where + 1 is considered a perfect match between the observed and expected distributions, whereas a value < 0 defines a model with a predictive performance no better than random (Liu et al. 2009). The spatial predictions of alpha diversity were then visually assessed for validation.

2.4.4 Biodiversity mapping

Biodiversity combines the alpha diversity of trees, mammals and birds at 30-meter spatial resolution. The alpha diversity of all taxonomic groups had different ranges, so we rescaled the actual values proportionally between 0 and 1 using the 'climateStability' package in R (Owens & Guralnick 2019). Once all predicted alpha diversity layers were rescaled, we added the pixel-wise values of the rasters using the raster calculator tool in ArcGIS Pro 2021 (Lecina-Diaz et al. 2018) to map biodiversity.

2.5 Biodiversity response to LULC change classes and physical factors

We ran a logistic regression model to analyse the association of LULC change classes and physical factors with biodiversity. Generalised linear models were fitted using the R function 'glm' in RStudio for each taxonomic group and biodiversity, assuming a Gaussian distribution (GLM, McCullagh & Nelder 1989). We wanted to examine the relationship between predictor and response variables at different scales, so we ran separate models for the whole PTR, core, buffer, areas around relocated villages and existing villages. We kept the predictor variables the same for all models to avoid omitted variable bias. To perform the analysis and visualise the results of the GLMs, we used the 'raster', 'ggplot2', 'ggeffects', 'ggpmisc' and 'reshape2' packages in the R environment (Hijmans et al. 2015; Villanueva et al. 2019; Aphalo 2016). We conducted the comparative analysis of biodiversity and LULC change at two levels: first at the core and buffer, and then at the micro-scale, which includes areas around relocated and existing villages (settlements where people currently reside). For the micro-scale, the boundary was established by creating a 1 km buffer around agricultural fields.

3. Results

3.1 Land use land cover pattern

The results of LULC classification in six classes for the years 1989, 1999, 2009 and 2019 were obtained with overall accuracy of > 83% and kappa statistics of > 0.78. The overall trend of LULC in the PTR shows that there has been a significant increase in dense forest cover, while open forest and scrub forest show

a decreasing trend, and other classes did not show much variation. We extracted the LULC map for both the core & buffer areas and the area statistics reveal a similar trend to the overall PTR. However, in the core region, the changes in area exhibit a continuous pattern, whereas in the buffer region, the pattern is irregular. The LULC trend in areas around relocated villages and existing villages was similar to the core and buffer, respectively; only the cropland/agriculture in areas around relocated villages decreased to 0 in the last year 2019 due to the village relocation program.

3.2. Land use land cover change

The decadal conversion of LULC classes shows the increase in forest classes and decrease in shrubland (Fig. 2a, Supplementary materials 4–5). Overall results show that forest areas which have remained the same are mainly located on the higher slopes, which are generally less accessible to humans. In the PTR, the forest cover class has increased significantly as a result of protection measures. Since the relocation of the villages, the pressure on the adjacent forest has also been reduced and the forest cover has improved. The relocated villages were developed as grasslands, which are not explicitly categorised in this study due to limitations of spectral variation in the historical imagery; therefore, it has been merged with scrubland.

3.3 Biodiversity values

The results of species distribution modelling for each species were highly accurate in terms of ROC and TSS, which were > 0.8 and > 0.5 (Online Resource 6). To produce the ensemble model, the best performing algorithms were ranked by TSS score and combined using a weighted average of TSS scores to predict species distribution at 30-meter resolution (Tanaka et al. 2020). Once the ensemble model for species was constructed, alpha diversity was predicted for each taxonomic group. For trees, it ranged from 0 to 31; for mammal and bird species, it ranged from 0 to 26 (Online Resource 7). The alpha diversity of tree and mammal species was estimated to be highest in the core region of the PTR and in some small pockets in the buffer region; however, the distribution of birds did not show much variation.

The lowest alpha diversity of birds was estimated near the steep slopes, with other areas showing moderate to high alpha diversity. Overall, all three taxonomic groups follow a similar distribution of alpha diversity. In addition, total biodiversity was calculated by summing the three alpha diversity layers, which range from 0 to 72 (Fig. 2b). The highest overall biodiversity was predicted for the core region of the PTR, similar to the alpha diversity, while the lowest remains in the agricultural and bare land. The mean biodiversity for the core region and the areas around the relocated villages were 31.85 and 34.95 respectively. At the same time, it was estimated to be 18.16 and 18.23 for the PTR buffer and areas around existing villages respectively, indicating that the LSP framework supports more biodiversity compared to LSH in this region.

3.4 Biodiversity response to LULC change classes and physical factors

The results of the GLMs showed a strong positive relationship between biodiversity and forest remains the same class, followed by forest gain (Fig. 3). Forest degradation also showed a positive relationship with biodiversity. The area of degraded forest in the PTR is surrounded by the forest remains the same and forest gain classes and despite its degraded state several species are using it. It is also noteworthy that during the study period we did not find significant conversion of forest areas to other land uses, and the forest degradation class includes conversion of dense to open forest and dense/open to scrub land. Other variables including non-forest remains the same, other changes, elevation and slope showed a negative relationship with biodiversity, while no significant effect of agriculture to scrub land class was observed. We then tested the relationship between alpha-diversity of each taxonomic group and the explanatory variables; the results show a similar trend of relationship as biodiversity, only alpha-diversity of birds did not show strong relationships. We used recent biodiversity data, while the predictor variables included were both historical and recent. Historical biodiversity data would have allowed a straightforward comparison, but in the absence of such data we assumed that landscape change and the resulting response would explain the species response from past to recent.

3.5 Biodiversity response in different protection framework

To understand the partial effects of variables under different management strategies, we extracted data for core & buffer and for areas around relocated & existing villages. A similar trend was observed in core and areas around relocated villages, where the biodiversity tested to be positively related to forest remains the same, forest gain and degraded forest class, respectively. However, the significance of the variables varied in both regions; in the areas around relocated villages, other variables apart from elevation and slope were found to be insignificant. While in the core, non-forest remains the same, agriculture to scrubland and other changes class were insignificant. This is due to the higher protection status of these areas.

In PTR buffers and areas around existing villages, forest remains the same, forest gain, forest degradation and altitude show a slightly positive relationship with biodiversity, while other variables show a negative or no relationship. In buffer areas, anthropogenic pressure on these forests is higher compared to the core, and elevated areas are relatively difficult for villagers to access, thus supporting biodiversity. For the PTR buffer, all variables were found to be highly significant, while agriculture to scrub, other changes and non-forest remains the same classes were found to be insignificant (Fig. 4).

We also analysed the relationship of alpha diversity of different taxonomic groups with the explanatory variables and there was no significant difference in their response. The results of the GLMs showed a similar trend in the relationship for all levels (whole PTR, core, buffer, areas around relocated and existing villages). Furthermore, biodiversity showed a strong positive relationship with forest classes in the LSP framework compared to LSH.

4. Discussion

Our study is the first attempt to quantify conservation-induced LULC changes and their relationship with biodiversity in the Indian context. The change patterns of LULC were irregular indicating that these forests are still in the early stages of succession and have a long way to go to reach climax. We analysed the alpha diversity of three taxonomic groups and biodiversity, which showed a similar relationship to the LULC change classes. The classes 'forest remains the same" showed a strong positive relationship with biodiversity and alpha diversity followed by 'forest gain' class. This illustrates that secondary forests support less biodiversity than primary forests (Barlow et al. 2007; Laurance 2007). In the PTR core and areas around relocated villages, biodiversity has a strong positive relationship with forest classes compared to the buffer and areas around existing villages, but most of the change classes were found to be insignificant under LSP. This suggests that the drivers of biodiversity under LSP are acting at the micro scale and due to protection status; all forested and non-forested areas have a similar relationship with biodiversity.

PTR has been rated 'Very Good' in the MEE for the last four cycles, including the period of local tiger extinction (MEE 2006, MEE 2010). Therefore, we need to assess the effectiveness of PAs in terms of specific weights for biodiversity, habitat quality, forest health, conservation of threatened species, and management effectiveness in managing or controlling disturbances. Our approach in this study can be replicated with the inclusion of more taxa to assess conservation effectiveness under an umbrella species conservation framework in other systems. However, we acknowledge that generating multi-taxa data on a regular basis is challenging and in some cases is impossible. We therefore recommend a surrogate approach or multi-taxa sampling at defined intervals to generate long-term data. Our study provides a foundation for further research, suggesting the inclusion of biodiversity beyond PAs, long-term biodiversity data collection, integration of climatic variables, consideration of social and ecological aspects of village relocation, and exploration of political dimensions to better understand the complexity of human-environment interactions to support future conservation efforts.

While earlier studies have reported a decline in biodiversity within PAs, particularly in the tropics (Gaston et al. 2008; Laurance et al. 2012; Geldmann et al. 2013), our results show that PTR as a PA supports significant biodiversity and that the LSP framework is more effective in biodiversity conservation. Following the local extinction of the tiger population in 2009, active recovery efforts in PTR has ensured viable population with current population estimate of 60 tigers (Krishnamurthy et al. 2016, Dutta & Krishnamurthy 2024). The villages relocated from inside the core were developed as grasslands and these areas now provide grazing grounds for the herbivores. LSP, hence, has played a major role in the successful reintroduction of the tiger population, as evidenced by the fact that the tigers have also colonized and established their home ranges within the relocated areas. This study provides strong evidence of the effectiveness of flagship species conservation with community support in promoting overall biodiversity conservation.

Similar patterns were observed in the tiger landscapes across India and its four neighboring countries, where core areas exhibited low levels of fragmentation in forest patches underscoring their effectiveness (Sabu et al. 2024). Lamba et al. documented the positive impact of tiger reserves on forest

protection by avoiding forest loss, especially in central India (Lamba et al. 2023). Additionally, a landscape level study encompassing 65 study areas reports increasing bird and mammal diversity in and around PAs suggesting biodiversity co-benefits are not limited to PAs but also enhance nearby unprotected sites (Brodie et al. 2023).

Global targets for biodiversity conservation, i.e. the Aichi target of protecting 30% of the world's land, will also need to promote sustainable, high-yield agriculture to meet human needs. Thus, the conventional notion of large-scale land conservation may not be feasible in a real-world scenario. Especially if the increased demand for food is to be met by developing countries (Balmford et al. 2005) with rich biodiversity and high population densities. Therefore, based on the current study, we advocate an integrated landscape approach with a mosaic of land management (LSP & LSH). This approach also takes into account the conservation of smaller habitat patches surrounded by an agricultural matrix. The LSH and LSP approaches are complementary and potential solutions to the same problem. Given that most species now occur in fragmented habitats (Fahrig 2003), conserving land in these fragments will not only improve habitat quality but also act as a stepping stone to facilitate species movement. It can also facilitate the spread of threats and diseases if not adequately protected.

The PTR is surrounded by high-intensity agricultural land to the north and south and has fragmented connectivity to the east and west. The area is rich in mineral resources, with an open-pit diamond mine operated by the National Mineral Development Corporation (NMDC) adjacent to the core boundary of the PTR, and another proposed diamond mining project in the nearby Buxwaha forest. In addition, the Ken-Betwa Link Project (KBLP), India's first river interlinking project under the National Perspective Plan, is proposed to be developed in the PTR, affecting habitat status and connectivity (Vasudeva et al. 2022). However, all these development projects also provide livelihood opportunities for local people and are essential for a nation’s development. Such challenges are prevalent in the tropics as most countries are developing and resources are limited, making it important to find a balance between development and conservation. This study provides a general indicator for using land sparing and land sharing as combined contributions to meet both biodiversity conservation and human well-being.

Declarations

CRediT authorship contribution statement

Kamana Pokhariya: Conceptualization, Methodology, Data curation, Software, Visualization, Writing-Reviewing and Editing. Ajay Singh: Conceptualization, Data curation. Supratim Dutta: Data curation. Zainab Khan: Data curation. Ramesh Krishnamurthy: Conceptualization, Methodology, Reviewing- Editing and Supervision.

Declaration of competing interest

The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

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Data Availability

The data will be made available upon reasonable request.

References

1. Aphalo, P. J. (2016). ggpmisc: An R package.
2. Andersson, J., de Garine-Wichatitsky, M., Cumming, D., Dzingirai, V., & Giller, K. (Eds.). (2017). Transfrontier conservation areas: People living on the edge. Taylor & Francis.
3. Arau´jo, M. B., Pearson, R, G., Thuiller, W., Erhard, M. 2005. Validation of species-climate impact models under climate change. Global Change Biol. 11: 15041513 https://doi.org/10.1111/j.1365-2486.2005.01000.x
4. Balmford, A., Bennun, L., Ten Brink, B., Cooper, D., Côté, I. M., et al. (2005). The convention on biological diversity's 2010 target. *Science*, *307*(5707), 212-213 https://doi.org/10.1126/science.1106281
5. Balmford, A., Green, R. E., & Scharlemann, J. P. (2005). Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology*, *11*(10), 1594-1605 https://doi.org/10.1111/j.1365-2486.2005.001035.x
6. Barbet-Massin, M., Jiguet, F., Albert, C. H., & Thuiller, W. (2012). Selecting pseudo-absences for species distribution models: How, where and how many?. Methods in ecology and evolution, 3(2),

327-338 https://doi.org/10.1111/j.2041-210X.2011.00172.x

7. Behera, M. D., Borate, S. N., Panda, S. N., Behera, P. R., & Roy, P. S. (2012). Modelling and analysing the watershed dynamics using Cellular Automata (CA)–Markov model–A geo-information based approach. *Journal of earth system science*, *121*(4), 1011-1024 https://doi.org/10.1007/s12040-012-0207-5
8. Bezdek JC (1973) Guzzy mathematics in pattern classification. PhD dissertation, Cornell University, Ithaca, NY
9. Bignal, E. M., & McCracken, D. I. (1996). Low-intensity farming systems in the conservation of the countryside. *Journal of Applied Ecology*, 413-424 https://doi.org/10.2307/2404973
10. Bobrowski, M., Bechtel, B., Böhner, J., Oldeland, J., Weidinger, J., et al. (2018). Application of thermal and phenological land surface parameters for improving ecological niche models of Betula utilis in the Himalayan Region. *Remote Sensing*, *10*(6), 814 https://doi.org/10.3390/rs10060814
11. Bonthoux, S., Lefèvre, S., Herrault, P. A., & Sheeren, D. (2018). Spatial and temporal dependency of NDVI satellite imagery in predicting bird diversity over France. *Remote Sensing*, *10*(7), 1136 https://doi.org/10.3390/rs10071136
12. Baudron, F., Andersson, J. A., Corbeels, M., & Giller, K. E. (2012). Failing to yield? Ploughs, conservation agriculture and the problem of agricultural intensification: An example from the Zambezi Valley, Zimbabwe. Journal of Development Studies, 48(3), 393-412 https://doi.org/10.1080/00220388.2011.587509
13. Brodie, J. F., Mohd-Azlan, J., Chen, C., Wearn, O. R., Deith, M. C., Ball, J. G., ... & Luskin, M. S. (2023). Landscape-scale benefits of protected areas for tropical biodiversity. *Nature*, *620*(7975), 807-812. https://doi.org/10.1038/s41586-023-06410-z
14. Brockington, D., 2003. Injustice and conservation: is local support necessary for sustainable protected areas? Policy Matters 12, 22–30
15. Brooks, T. M., Mittermeier, R. A., Da Fonseca, G. A., Gerlach, J., Hoffmann, M., et al. (2006). Global biodiversity conservation priorities. *science*, *313*(5783), 58-61 https://doi.org/10.1126/science.1127609
16. Chape S., Harrison J., Spalding M., Lysenko I. 2005. Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences 360:443–455 https://doi.org/10.1098/rstb.2004.1592
17. Cohen J (1960) A coefficient of agreement for nominal scales. Educ Psychol Meas 20:37–46. doi:10.1177/001316446002000104 https://doi.org/10.1177/001316446002000104
18. Craigie, Ian D., Baillie, J., Balmford, A., Carbone, C., Collen, B., Green, E, R., et al. "Large mammal population declines in Africa's protected areas." *Biological conservation* 143, no. 9 (2010): 2221-2228 https://doi.org/10.1016/j.biocon.2010.06.007
19. Das, S. (2019). 5 Forest governance in India. Environmental Policy in India.

20. Decision, X. (2010). 2, The strategic plan for biodiversity 2011–2020 and the Aichi biodiversity targets. In *Proc. Conf. Parties Convention Biol. Diversity*
21. Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., et al. 2017. An ecoregion-based approach to protecting half the terrestrial realm. BioScience 67, 534–545 https://doi.org/10.1093/biosci/bix014
22. Drapeau, P., Leduc, A., Giroux, J., Savard, J, L., and Vickery, W, L., 2000. Landscape-Scale Disturbances and Changes in Bird Communities of Boreal Mixed-Wood Forests. Ecological Mono 70:423–444 https://doi.org/10.1890/0012-9615(2000)070[0423:LSDACI]2.0.CO;2
23. Dudley, N. (2023). What Does the Global Biodiversity Framework Mean for Protected and Conserved Areas?. In Managing Protected Areas: People and Places (pp. 11-30). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-40783-3_2
24. Dutta, S., & Krishnamurthy, R. (2024). Successful conservation translocation: Population dynamics of tiger recovery in Panna Tiger Reserve, Central India. *Ecological Solutions and Evidence*, *5*(2), e12337. https://doi.org/10.1002/2688-8319.12337
25. Elith*, J., H. Graham*, C., P. Anderson, R., Dudík, M., Ferrier, S., et al. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, *29*(2), 129-151 https://doi.org/10.1111/j.2006.0906-7590.04596.x
26. Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., et al. 2007, The shuttle radar topography mission https://doi.org/10.1029/2005RG000183
27. Fahrig, L. (2003). Effects of habitat fragmentation on biodiversity. Annual review of ecology, evolution, and systematics, 487-515 https://doi.org/10.1146/132419
28. Franklin J. (2009) Mapping species distributions - spatial inference and prediction. Cambridge: Cambridge University Press
29. Fritz, H., Saïd, S., Renaud, P. C., Mutake, S., Coid, C., & Monicat, F. (2003). The effects of agricultural fields and human settlements on the use of rivers by wildlife in the mid-Zambezi valley, Zimbabwe. Landscape ecology, 18, 293-302 https://doi.org/10.1023/A:1024411711670
30. Ganguly, V. 2004. Conservation, Displacement and Deprivation. Maldhari of Gir Forest of Gujarat. Indian Social Institute, New Delhi
31. Gaston, K. J., Jackson, S. F., Cantú-Salazar, L., & Cruz-Piñón, G. (2008). The ecological performance of protected areas. *Annual review of ecology, evolution, and systematics*, 93-113
32. Gatiso, T. T., Kulik, L., Bachmann, M., Bonn, A., Bösch, L., et al. (2022). Effectiveness of protected areas influenced by socio-economic context. *Nature Sustainability*, 1-8 https://doi.org/10.1038/s41893-022-00932-6
33. Geldmann, J., Manica, A., Burgess, N. D., Coad, L., & Balmford, A. (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *Proceedings of the National Academy of Sciences*, *116*(46), 23209-23215 https://doi.org/10.1073/pnas.1908221116
34. Geldmann, J., Barnes, M., Coad, L., Craigie, I. D., Hockings, M., et al. (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*,

161, 230-238 https://doi.org/10.1016/j.biocon.2013.02.018

35. Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., & Foley, J. A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences, 107(38), 16732-16737 https://doi.org/10.1073/pnas.0910275107
36. Gibson, L., Lynam, A, J., Bradshaw, C, J, A., He, F., Bickford, P, D., et al. 2013. Near-complete extinction of native small mammal fauna 25 years after forest fragmentation. Science 341: 1508–1510 https://doi.org/10.1126/science.1240495
37. Gil-Tena, A., Saura. S., and Brotons., L. 2007. Effects of forest composition and structure on bird species richness in a Mediterranean context: Implications for forest ecosystem management. Forest Ecology and Management 242:470–476 https://doi.org/10.1016/j.foreco.2007.01.080
38. Green, R. E., Cornell, S. J., Scharlemann, J. P., & Balmford, A. (2005). Farming and the fate of wild nature. *science*, *307*(5709), 550-555 https://doi.org/10.1126/science.1106049
39. Greenspan, E., Montgomery, C., Stokes, D., Wantai, S., & Moo, S. S. B. (2020). Prioritising areas for conservation action in Kawthoolei, Myanmar using species distribution models. *Journal for Nature Conservation*, *58*, 125918 https://doi.org/10.1016/j.jnc.2020.125918
40. Halley, J.M., V. Sgardeli & N. Monokrousos. 2013. Species area relationships and extinction forecasts. Ann. N. Y. Acad. Sci. 1286: 50–61 https://doi.org/10.1111/nyas.12073
41. Hijmans, R. J., Van Etten, J., Cheng, J., Mattiuzzi, M., Sumner, M., et al. M. R. J. (2015). Package 'raster'. *R package*, *734*
42. Hill, L., Hector, A., Hemery, G., Smart, S., Tanadini, M., et al. (2017). Abundance distributions for tree species in Great Britain: A two-stage approach to modeling abundance using species distribution modeling and random forest. *Ecology and evolution*, *7*(4), 1043-1056 https://doi.org/10.1002/ece3.2661
43. Hulme, M. F., Vickery, J. A., Green, R. E., Phalan, B., Chamberlain, D. E., Pomeroy, D. E., ... & Atkinson, P. W. (2013). Conserving the birds of Uganda's banana-coffee arc: land sparing and land sharing compared. PloS one, 8(2), e54597 https://doi.org/10.1371/journal.pone.0054597
44. Jachmann, H. (2008). Monitoring law-enforcement performance in nine protected areas in Ghana. *Biological Conservation*, *141*(1), 89-99 https://doi.org/10.1016/j.biocon.2007.09.012
45. Jensen JR (1996) Introductory digital image processing: a remote sensing perspective. Prentice Hall, New Jersey
46. Jetz, W., McPherson, J. M., & Guralnick, R. P. (2012). Integrating biodiversity distribution knowledge: toward a global map of life. *Trends in ecology & evolution*, *27*(3), 151-159 https://doi.org/10.1016/j.tree.2011.09.007
47. Jhala, Y.V., Gopal, R., and Qureshi, Q. (Eds) (2008) Status of tigers, co-predators and prey in India.National Tiger Conservation Authority and Wildlife Institute of India.TR08/001 pp. 164
48. Karanth, U. K. (2002). Mitigating human-wildlife conflicts in southern Asia. Making parks work: strategies for preserving tropical nature, 250-264

49. Kati, V., Devillers, P., Dufrêne, M., Legakis, A., Vokou, D., et al. (2004). Testing the value of six taxonomic groups as biodiversity indicators at a local scale. *Conservation biology*, *18*(3), 667-675 https://doi.org/10.1111/j.1523-1739.2004.00465.x
50. Kindsvater, H. K., Dulvy, N. K., Horswill, C., Juan-Jordá, M. J., Mangel, M., et al. (2018). Overcoming the data crisis in biodiversity conservation. *Trends in Ecology & Evolution*, *33*(9), 676-688 https://doi.org/10.1016/j.tree.2018.06.004
51. Khan, G., Khan, B., Qamer, F. M., Abbas, S., Khan, A., et al. (2016). Himalayan ibex (Capra ibex sibirica) habitat suitability and range resource dynamics in the Central Karakorum National Park, Pakistan. *Journal of King Saud University-Science*, *28*(3), 245-254 https://doi.org/10.1016/j.jksus.2016.04.006
52. Kremen, C. (2015). Reframing the land-sparing/land-sharing debate for biodiversity conservation. *Annals of the New York Academy of Sciences*, *1355*(1), 52-76 https://doi.org/10.1111/nyas.12845
53. Krishnamurthy, R., Cushman, S. A., Sarkar, M. S., Malviya, M., Naveen, M., et al. (2016). Multi-scale prediction of landscape resistance for tiger dispersal in central India. *Landscape ecology*, *31*(6), 1355-1368 https://doi.org/10.1007/s10980-016-0363-0
54. Lamba, A., Teo, H. C., Sreekar, R., Zeng, Y., Carrasco, L. R., & Koh, L. P. (2023). Climate co-benefits of tiger conservation. Nature Ecology & Evolution, 7(7), 1104-1113 https://doi.org/10.1038/s41559-023-02069-x
55. Larsen, F. W., Bladt, J., Balmford, A., and Rahbek, C. 2012. Birds as biodiversity surrogates: will supplementing birds with other taxa improve effectiveness? Journal of Applied Ecology 49:349–356 https://doi.org/10.1111/j.1365-2664.2011.02094.x
56. Lasgorceix A., Kothari A (2009) Displacement and relocation of protected areas: a synthesis and analysis of case studies. Econ Polit Wkly EPW xliv(49) http://dx.doi.org/10.2307/25663860
57. Laurance, W.F., Useche, D.C., Rendeiro, J., Kalka, M., Bradshaw, J. A. C., et al. 2012. Averting biodiversity collapse in tropical forest protected areas. Nature 489: 290–294 https://doi.org/10.1038/nature11318
58. Leal, I. R., Bieber, A. G. D., Tabarelli, M., & Andersen, A. N. (2010). Biodiversity surrogacy: indicator taxa as predictors of total species richness in Brazilian Atlantic forest and Caatinga. *Biodiversity and Conservation*, *19*(12), 3347-3360 https://doi.org/10.1007/s10531-010-9896-8
59. Lecina-Diaz, J., Alvarez, A., Regos, A., Drapeau, P., Paquette, A., et al. (2018). The positive carbon stocks–biodiversity relationship in forests: co-occurrence and drivers across five subclimates. *Ecological Applications*, *28*(6), 1481-1493 https://doi.org/10.1002/eap.1749
60. Liu, C., White, M., Newell G (2009) Measuring the accuracy of species distribution models: a review. In: Anderssen RS, Braddock RD, Newham LTH, editors. Proceedings 18th World IMACs/MODSIM Congress. Cairns, Australia. pp. 4241–4247.
61. Liu, Q., Liu, G., Huang, C., & Xie, C. (2015). Comparison of tasselled cap transformations based on the selective bands of Landsat 8 OLI TOA reflectance images. *International Journal of Remote Sensing*, *36*(2), 417-441 https://doi.org/10.1080/01431161.2014.995274

62. Lüdecke, D. (2018). ggeffects: Tidy data frames of marginal effects from regression models. *Journal of Open Source Software*, *3*(26), 772 https://doi.org/10.21105/joss.00772
63. Malcolm, J. R., & Ray, J. C. (2000). Influence of timber extraction routes on central African small-mammal communities, forest structure, and tree diversity. *Conservation Biology*, *14*(6), 1623-1638 https://doi.org/10.1111/j.1523-1739.2000.99070.x
64. Manyangadze, T., Chimbari, M. J., Gebreslasie, M., Ceccato, P., & Mukaratirwa, S. (2016). Modelling the spatial and seasonal distribution of suitable habitats of schistosomiasis intermediate host snails using Maxent in Ndumo area, KwaZulu-Natal Province, South Africa. *Parasites & vectors*, *9*(1), 1-10 https://doi.org/10.1186/s13071-016-1834-5
65. Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature*, *405*(6783), 243-253 https://doi.org/10.1038/35012251
66. Marini, M. Â., Barbet-Massin, M., Lopes, L. E., & Jiguet, F. (2009). Major current and future gaps of Brazilian reserves to protect Neotropical savanna birds. Biological Conservation, 142(12), 3039-3050 https://doi.org/10.1016/j.biocon.2009.08.002
67. Mathur, VB., AK. Nayakand NA., Ansari. 2019 Fourth Cycle of Management. Effectiveness Evaluation (MEE) of Tiger. Reserves in India, 2018, National Tiger Conservation Authority and Wildlife Institute of India, Ministry of Environment Forest and Climate Change, Government of India, Pp. 212
68. McCullagh, P., Nelder, J.A., 1989. Generalised Linear Models, second ed. Chapman & Hall, London.
69. McCullagh, P., & Nelder, J. A. (2019). *Generalised linear models*. Routledge.
70. Mi, C., Huettmann, F., Guo, Y., Han, X., & Wen, L. (2017). Why choose Random Forest to predict rare species distribution with few samples in large undersampled areas? Three Asian crane species models provide supporting evidence. *PeerJ*, *5*, e2849 https://doi.org/10.7717/peerj.2849
71. Mitchell, M. G. E., Bennett, E. M., & Gonzalez, A. (2013). Linking landscape connectivity and ecosystem service provision: Current knowledge and research gaps. Ecosystems, 16, 894–908 https://doi.org/10.1007/s10021-013-9647-2
72. Naimi, B. (2015). USDM: Uncertainty analysis for species distribution models. R package version 1.1–15. *R Documentation http://www. rdocu-mentation. org/packages/usdm*.
73. Ndao, B., Leroux, L., Hema, A., Diouf, A. A., Bégué, A., et al. (2022). Tree species diversity analysis using species distribution models: A Faidherbia albida parkland case study in Senegal. *Ecological Indicators*, *144*, 109443 https://doi.org/10.1016/j.ecolind.2022.109443
74. Newmark, W.D. 1987. A land-bridge island perspective on mammalian extinctions in western North American parks. Nature 325: 430–432 https://doi.org/10.1038/325430a0
75. Newmark, W.D. 1995. Extinction of mammal populations in Western North-American national-parks. Conserv. Biol. 9: 512–526.
76. Owens, H. L., & Guralnick, R. (2019). climateStability: an R package to estimate climate stability from time-slice climatologies. *Biodiversity Informatics*, *14*, 8-13.

77. Phalan, Ben, Malvika Onial, Andrew Balmford, and Rhys E. Green. "Reconciling food production and biodiversity conservation: land sharing and land sparing compared." science 333, no. 6047 (2011): 1289-1291 https://doi.org/10.1126/science.1208742

78. Pielke Sr, R. A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., et al. (2011). Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(6), 828-850 https://doi.org/10.1002/wcc.144

79. Pimm, S.L., Jenkins, C.N., Li, B.V., 2018. How to protect half of Earth to ensure it protects sufficient biodiversity. Sci. Adv. 4, eaat2616 https://doi.org/10.1126/sciadv.aat2616

80. Protected Planet Report 2018 (UNEP-WCMC IUCN & NGS, 2018)

81. Pywell, R. F., Heard, M. S., Woodcock, B. A., Hinsley, S., Ridding, L., et al. (2015). Wildlife-friendly farm-ing increases crop yield: Evidence for ecological intensification. Proceedings of the Royal Society B: Biological Sciences, 282 https://doi.org/10.1098/rspb.2015.1740

82. Rajpoot, S. S., & Chauhan, M. S. (2018). Research Need on Environmental Gains in Conservation-Induced Relocation. In *Environmental Pollution* (pp. 15-25). Springer, Singapore https://doi.org/10.1007/978-981-10-5792-2_2

83. Rangarajan, M., Shahabuddin, G., 2006. Displacement and relocation from protected areas: Towards a biological and historical synthesis. Conservation and Society 4, 359–378

84. Rodrigues, A. S., Akcakaya, H. R., Andelman, S. J., Bakarr, M. I., Boitani, L., et al. (2004). Global gap analysis: priority regions for expanding the global protected-area network. *BioScience*, *54*(12), 1092-1100 https://doi.org/10.1641/0006-3568(2004)054[1092:GGAPRF]2.0.CO;2

85. Sabu, M. M., Pasha, S. V., Reddy, C. S., Singh, R., & Jaishanker, R. (2022). The effectiveness of Tiger Conservation Landscapes in decreasing deforestation in South Asia: A remote sensing-based study. *Spatial Information Research*, *30*(1), 63-75. https://doi.org/10.1007/s41324-021-00411-8

86. Shaffer, M.L. 1981. Minimum population sizes for species conservation. Bioscience 31: 131–134 https://doi.org/10.2307/1308256

87. Shahabuddin, G., Shah, A., 2003. Relocation of people from wildlife areas: Socio-economic and ecological issues. Economic and Political Weekly 38, 4945–4946 http://dx.doi.org/10.2307/4414307

88. Sharma, A., 2003. Displacement from wildlife protected areas: Implications for conservation and livelihoods. The case of Kuno Wildlife Sanctuary, Madhya Pradesh. Social Change 33, 89–114 https://doi.org/10.1177/004908570303300307

89. Singh, A. (1989). Review article digital change detection techniques using remotely-sensed data. *International journal of remote sensing*, *10*(6), 989-1003 https://doi.org/10.1080/01431168908903939

90. Sobral, M., Silvius, K. M., Overman, H., Oliveira, L. F., Raab, T. K., et al. (2017). Mammal diversity influences the carbon cycle through trophic interactions in the Amazon. *Nature ecology & evolution*, *1*(11), 1670-1676 https://doi.org/10.1038/s41559-017-0334-0

91. Tanaka, K. R., Torre, M. P., Saba, V. S., Stock, C. A., & Chen, Y. (2020). An ensemble high-resolution projection of changes in the future habitat of American lobster and sea scallop in the Northeast US continental shelf. *Diversity and Distributions*, *26*(8), 987-1001 https://doi.org/10.1111/ddi.13069
92. Terborgh, J., K. Feeley, M. Silman, Nuñez, P., Balukjian, B. 2006. Vegetation dynamics of predator-free land-bridge islands. J. Ecol. 94: 253–263
93. Terborgh, J., van Schaik, C., Davenport, L., Rao, M. (Eds.), Making Parks Work: Strategies for Preserving Tropical Nature. Island Press, Washington, DC, pp. 250–264
94. Thinley, P., Norbu, T., Rajaratnam, R., Vernes, K., Wangchuk, K., et al. (2019). Population abundance and distribution of the endangered golden langur (Trachypithecus geei, Khajuria 1956) in Bhutan. *Primates*, *60*(5), 437-448 https://doi.org/10.1007/s10329-019-00737-w
95. Thuiller, W., Arau´jo, MB., Lavorel, S. (2003) Generalised models versus classification tree analysis: a comparative study for predicting spatial distributions of plant species at different scales. Journal of Vegetation Science (in press)
96. Thuiller, W., Georges, D., Engler, R. (2013) BIOMOD2: Ensemble platform for species distribution modeling. R package version 2.1. 7/r560
97. Thuiller, W., Georges, D., Engler, R., Breiner, F., Georges, M. D., et al. (2016). Package 'biomod2'. *Species Distrib. Model. within an ensemble Forecast. Framew*
98. Thuiller, W., Lafourcade, B., Engler, R., Araújo, MB., (2009) BIOMOD - a platform for ensemble forecasting of species distributions. Ecography 32: 369–373 (Version 1.1–7.00). doi:10.1111/j.1600-0587.2008.05742.x https://doi.org/10.1111/j.1600-0587.2008.05742.x
99. Valavi, R., Guillera-Arroita, G., Lahoz-Monfort, J. J., & Elith, J. (2021). Predictive performance of presence-only species distribution models: a benchmark study with reproducible code. *Ecol. Monogr*, *92*, e01486 https://doi.org/10.1002/ecm.1486
100. Vandermeer, J., & Perfecto, I. (2007). The agricultural matrix and a future paradigm for conservation. Conservation Biology, 21, 274–277 https://doi.org/10.1111/j.1523-1739.2006.00582.x
101. Vasudeva, V., Upgupta, S., Singh, A., Sherwani, N., Dutta, S., et al. (2022). Conservation Prioritisation in a Tiger Landscape: Is Umbrella Species Enough?. *Land*, *11*(3), 371 https://doi.org/10.3390/land11030371
102. Vimal, R., Navarro, L. M., Jones, Y., Wolf, F., Le Moguédec, G., et al. (2021). The global distribution of protected areas management strategies and their complementarity for biodiversity conservation. *Biological Conservation*, *256*, 109014 https://doi.org/10.1016/j.biocon.2021.109014
103. Wen, L., Saintilan, N., Yang, X., Hunter, S., & Mawer, D. (2015). MODIS NDVI based metrics improve habitat suitability modelling in fragmented patchy floodplains. *Remote Sensing Applications: Society and Environment*, *1*, 85-97 https://doi.org/10.1016/j.rsase.2015.08.001
104. Wilshusen, P., Brechin, S.R., Fortwangler, C., West, P.C., 2002. Reinventing a square wheel: Critique of a resurgent "protection paradigm" in international biodiversity conservation. Society and Natural Resources 15, 17–40 https://doi.org/10.1080/089419202317174002

105. Wright, H. L., Lake, I. R., & Dolman, P. M. (2012). Agriculture—a key element for conservation in the developing world. Conservation letters, 5(1), 11-19 https://doi.org/10.1111/j.1755-263X.2011.00208.x

106. Zewdie, W., & Csaplovies, E. (2015). Remote sensing based multi-temporal land cover classification and change detection in northwestern Ethiopia. *European Journal of Remote Sensing*, *48*(1), 121-139 https://doi.org/10.5721/EuJRS20154808

Figures

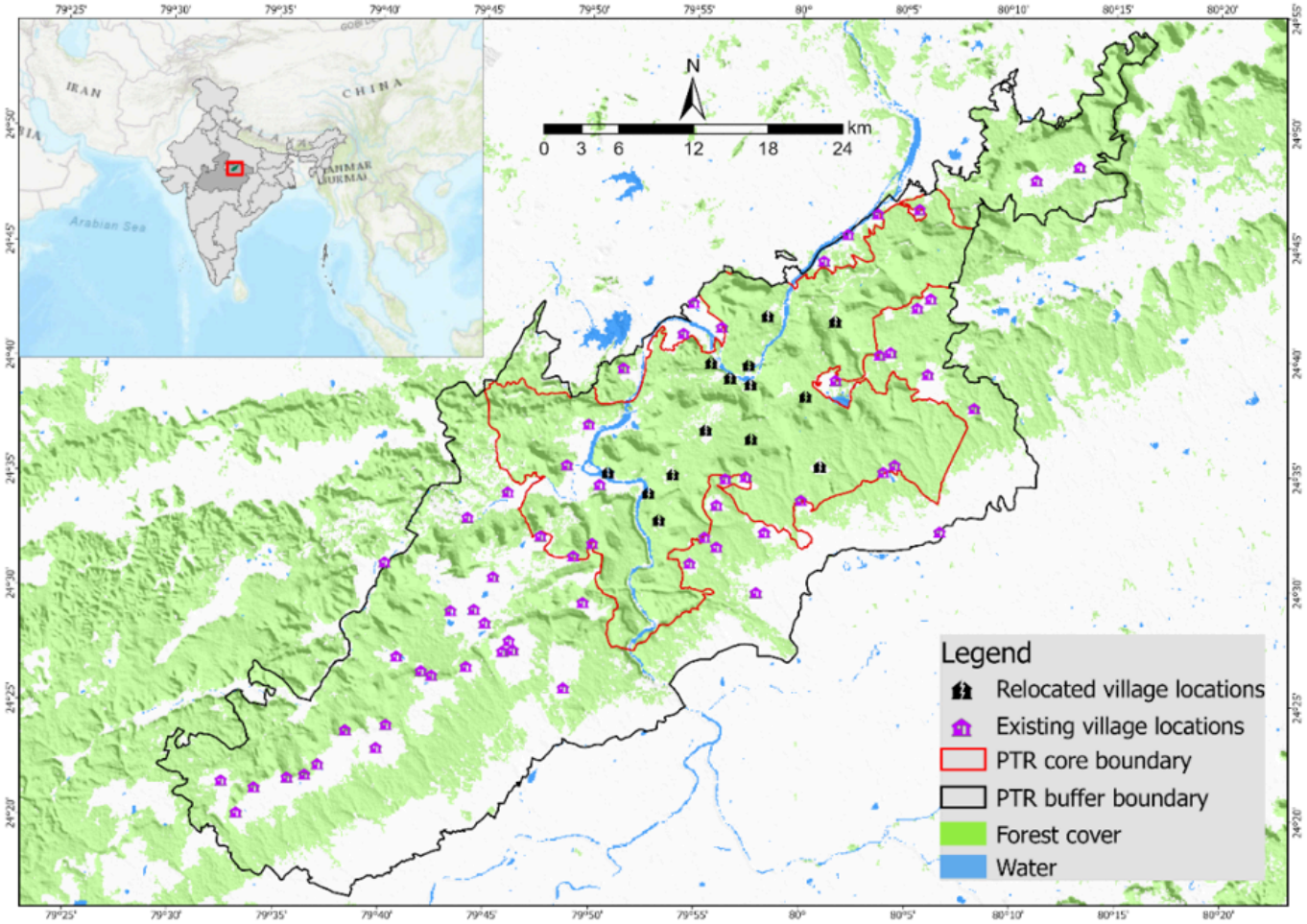


Figure 1

Study area map of Panna Tiger Reserve with the location of existing and relocated villages

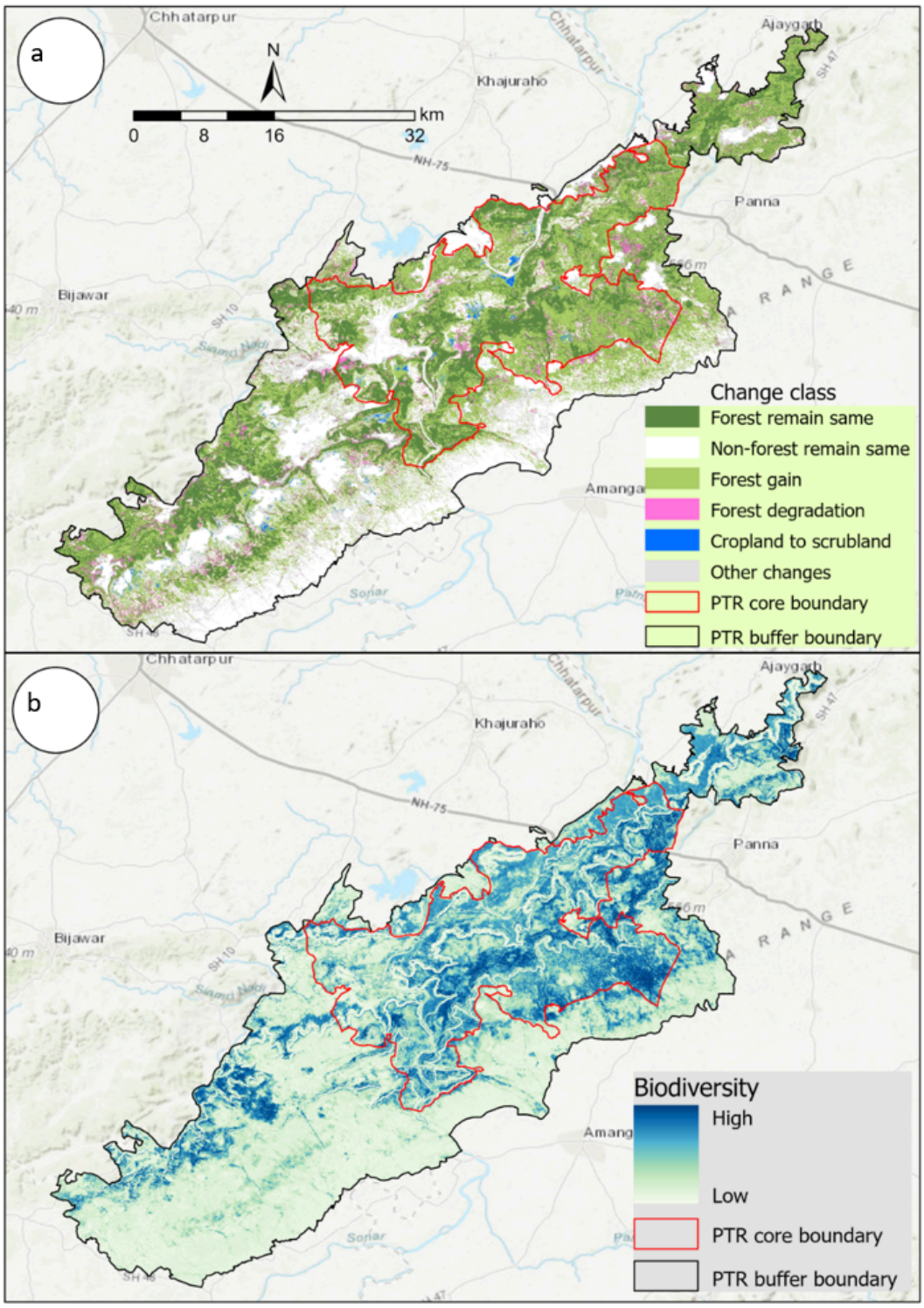


Figure 2

(a) LULC change classes distribution in Panna Tiger Reserve **(b)** Distribution of predicted biodiversity in Panna Tiger Reserve

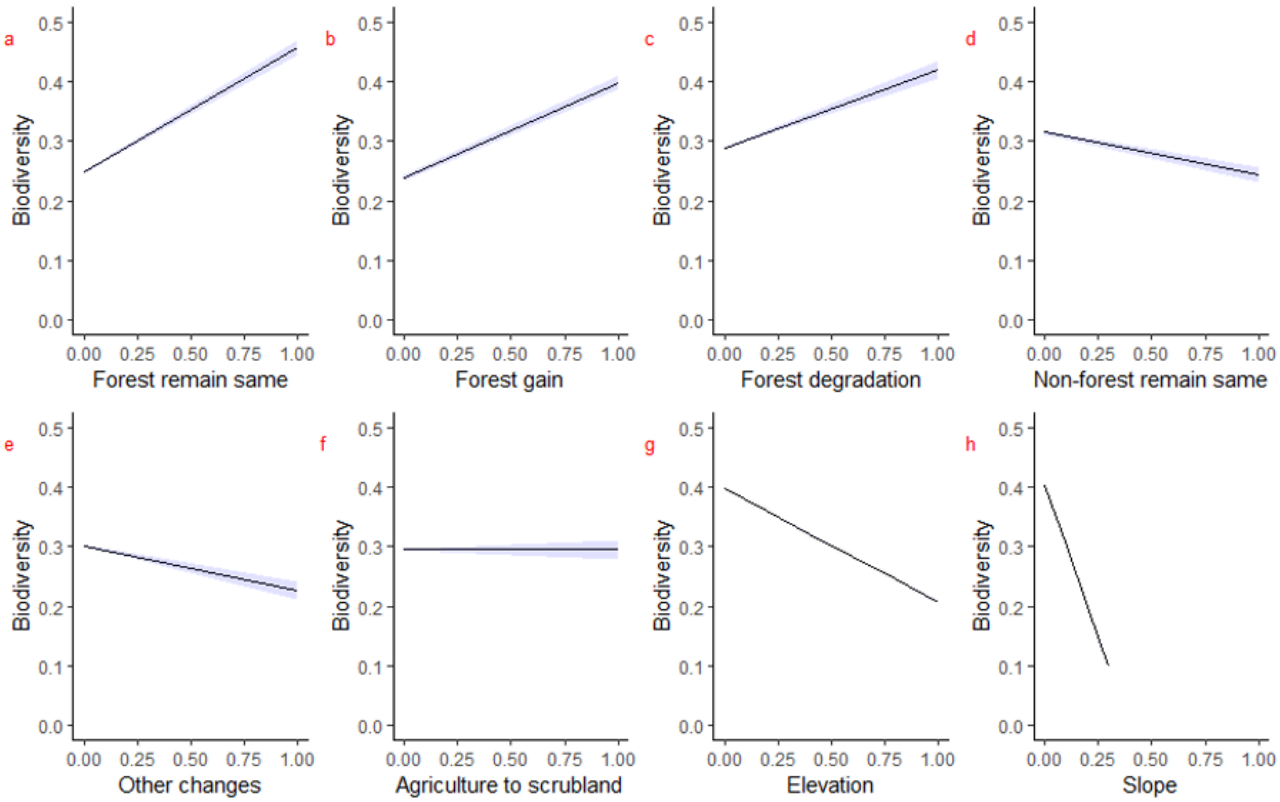


Figure 3

GLM results explaining the partial effect of explanatory variable on predicted biodiversity

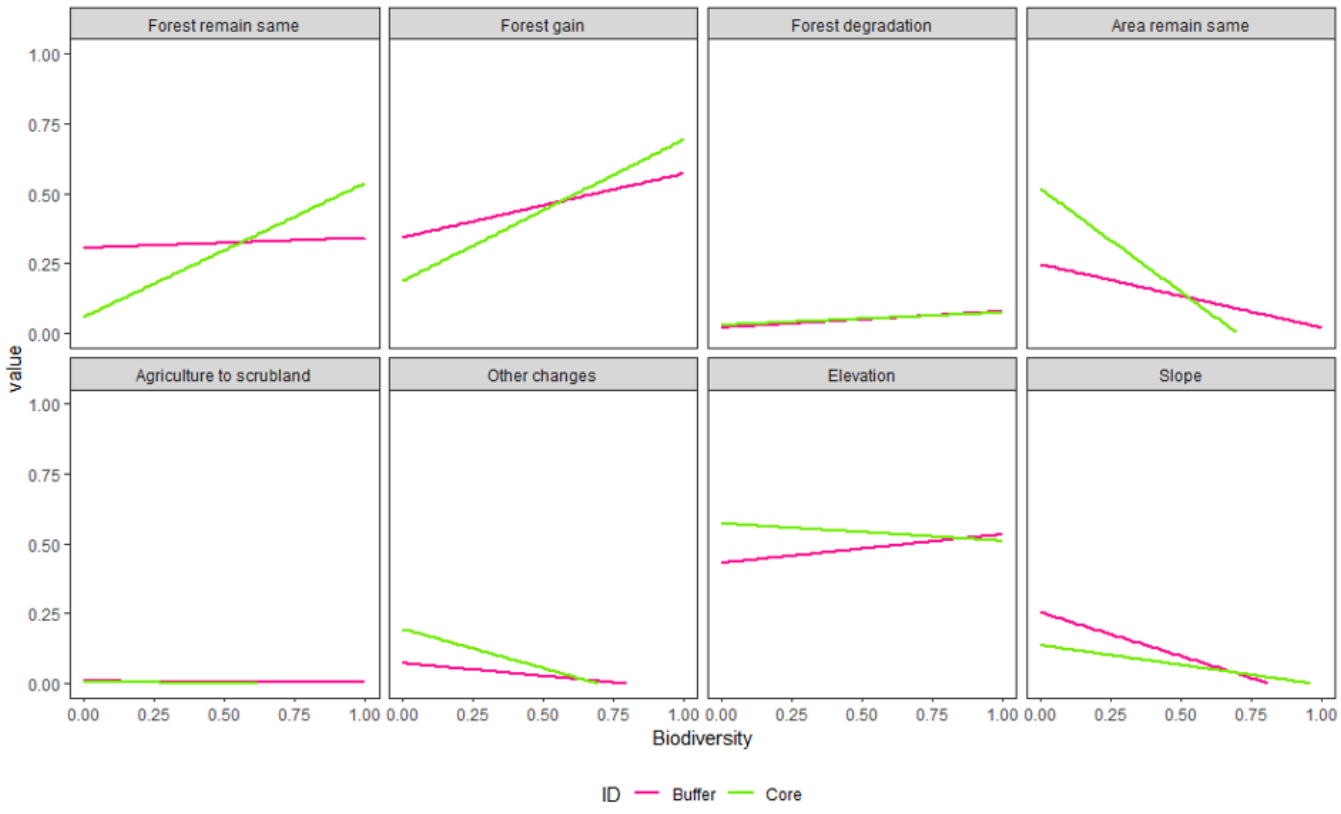


Figure 4

GLM results representing partial effect of explanatory variable on biodiversity in core and buffer region of Panna Tiger Reserve

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