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Bits and pieces: Forest fragmentation by linear intrusions in India

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ABSTRACT

Linear infrastructure development is an important driver of forest fragmentation leading to habitat and biodiversity loss as well as disruption of critical ecosystem processes. The tropical forests of India are increasingly impacted by infrastructure development. Little quantitative information is available on the extent of fragmentation due to linear infrastructure on these habitats. Here, we quantified fragmentation due to linear infrastructure by studying forest structural connectivity. We compared the existing forest patch characteristics with a scenario that excluded all linear infrastructure. We classified forest patches into three different fragmentation categories that combined information on patch size, inter patch distance and percentage perforations. Results show that power-transmission lines and roads were the most common infrastructure features within forests. We found a 6% increase in the number of forest patches due to the construction of linear infrastructure. Forest patches > 10,000 km^2 in size were severely affected and there was a 71.5 % reduction in the number of such patches. We found that 86 % of the existing forest patches are in the small (median patch size < 1 km^2) and isolated (a median distance of 155 m) category. The density of linear infrastructure inside protected areas was similar to density in non-protected forested areas. Our results highlight the need to minimize the effects of fragmentation in the future by considering re-routing or bundling of infrastructure. When infrastructure is unavoidable, there is a need to mitigate their potential impacts. The results of this study have been made publicly accessible (https://indiaunderconstruction.com) to provide information on 'where' to avoid future linear infrastructure development and to make informed decisions which can lead to optimally designed local management plans.

1. Introduction

Tropical forests are one of the most diverse ecosystems in the world. They are also one of the most threatened ecosystems undergoing rapid land use changes and fragmentation (Achard et al., 2002; Gibson et al., 2011; Hill et al., 2011; Laurance and Bierregaard, 1997; Mayaux et al., 2005; Miles et al., 2006; Ramachandran et al., 2018). One of the important factors contributing to fragmentation in tropical forests is infrastructure development (Geist and Lambin, 2002; Geneletti, 2004; Goosem, 1997, 2007; Laurance, 2015; Laurance et al., 2014; Reed et al., 1996). Infrastructure, especially linear structures such as roads, railway lines, power-transmission lines, canals, and pipelines create linear gaps which split a contiguous forested area into smaller units known as patches (Geneletti, 2004; Hawbaker et al., 2006; Mancebo Quintana et al., 2010; Miller et al., 1996)

Linear fragmentation leads to a reduction in habitat area and increased habitat isolation, which in turn affects biodiversity and wildlife movement across forests (Goosem, 2007; Karlson and Mörtberg, 2015;

Abbreviations: AP, amount of perforation; ENVIS, environmental information system; FC, fragmentation category; India-WRIS, water resources information system of India; IPD, inter-patch distance; LULC, land use/land cover; MoEFCC, Ministry of Environment Forest and Climate Change; NRSA, National Remote Sensing Agency; PA, protected area; PS, patch size

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Lovejoy et al., 1986). The problem is acute in tropical forests where certain animals tend to avoid forest clearings as narrow as 30 m (review in Laurance et al., 2009). Infrastructure act as barriers to faunal movement and affect habitat use and migration paths (Bhattacharya et al., 2002; Develey and Stouffer, 2001; Forman et al., 1997; Kociolek et al., 2011; Shepard et al., 2008; Strand, 2004). This barrier effect by linear structures may also reduce gene flow (Riley et al., 2006) and affect associated population sizes and densities (Benítez-López et al., 2010; Lesbarrères and Fahrig, 2012). Mortality of wildlife due to road kills and electrocution is well documented along roads, railways, and power-transmission lines (Coffin, 2007; Jaarsma, 2006; W. F. Laurance et al., 2009; Uddin, 2017). The patches resulting from linear gaps may be too small with limited resources and detrimental for the survival of some species, resulting in reduced diversity (Coffin, 2007; Fahrig, 2002; Girardet et al., 2013; Goosem, 2007; Mancebo Quintana et al., 2010; Opdam et al., 2001). Apart from the barrier effect and impacts on biodiversity, linear infrastructure can change soil properties, hydrologic cycles, and other ecosystem processes and functioning, and facilitate dispersal of invasive and pathogens into natural habitats (Forman and Alexander, 1998; Laurance et al., 2009).

India is one of the 17 'mega-diverse countries' in the world known for high endemism (Mittermeier et al., 2004). Most of the endemic species are restricted to subtropical and tropical forested tracts which constitute nearly 23 % of India's geographical area. In the recent past India's economy has witnessed a fast growth. Indian infrastructure network, especially roads, railway, and power-lines, have been greatly expanded and upgraded. For example, the increase in the length of highways (national and state highways) between 1980 and 2000 was 50 %, while this length was increased by nearly 40 % between 2001 and 2015 (https://data.gov.in/). In the process, many infrastructure projects were undertaken in pristine forested habitats and there have been nearly 7000 linear project proposals submitted to the Government of India for forest clearance between July 2014 and September 2017 (MoEFCC 2017).

Information on the distribution of forest patches and their connectivity is essential to account for biodiversity conservation in infrastructure development at a national level (Seiler and Eriksson, 1997). Recently, there has been growing interest in integrating conservation concerns in infrastructure developments in India (Dutta et al., 2018; WII, 2016). Although there is enough evidence on the impacts of linear infrastructure on forests, there is an urgent need to illustrate the extent of forest fragmentation due to linear infrastructure in India.

The main objective of this study was to understand the impact of infrastructure developments on forest structural connectivity in India. In this study, we quantified structural connectivity, which is defined as the spatial arrangement of forested habitats in a landscape, by analyzing forest patch characteristics. We quantified the impact of infrastructure development on structural connectivity by comparing existing forest patch characteristics that take into account the entire linear infrastructure, with a scenario that excluded linear intrusions within forested areas. We used patch indices – patch size, amount of perforation and inter-patch distance, to quantify fragmentation using GIS. Reduction in patch size and increase in the number of patches is directly linked to the splitting of a large forest habitat by linear structures (Goosem, 2007; Lovejoy et al., 1986; Mancebo Quintana et al., 2010), while an increase in inter-patch distance and perforation is a combination of the direct effect of linear infrastructure and associated changes in land use and land cover and increased human activity (Laurance et al., 2009). We performed cluster analysis using patch indices to identify large, intact patches that need to be preserved in future development action plans. We summarise our results at the national scale and for the existing protected area (PA) network. The results are also presented for two important conservation landscapes; the Western Ghats and Central India, which are rich in biodiversity and critical for survival of several threatened large mammals including tiger (*Panthera tigris*) and Asian elephant (*Elephas maximus*) (Baskaran et al., 1995; Baskaran, 2013; Sanderson et al., 2006). Both of these landscapes are also under severe development pressure from linear infrastructure projects. We present the most comprehensive map of structural connectivity and fragmentation for India which takes into account various infrastructure features.

2. Methods

2.1. Datasets

We used open access spatial datasets available in the public domain, updated up to 2015, for our analysis. We used datasets hosted and verified by government agencies, such as National Remote Sensing Agency (NRSA), Water Resources Information System of India (India-WRIS), Indian Rail Information System, National Highway Authority of India, and Ministry of Environment Forest and Climate Change (MoEFCC). We also made use of datasets from OpenStreet Maps (OSM) which were verified and updated up to 2015 using Google Maps.

2.1.1. Forest cover and infrastructure layers

The forest cover layer was derived from land use/land cover (LULC) map provided by the NRSA for the year 2014 – 15. We considered four major linear infrastructure features in this study; roads, canals, railways, and high tension power-lines. Apart from linear infrastructure, we used a reservoir and mines/quarry layer, which are known sources of forest cover loss and fragmentation. The source and details of these layers are provided in Supplementary Table 1.

2.1.2. Administrative and landscape boundaries

We obtained boundary files of the States and Union Territories,

Table 1
A summary of patch size (PS), inter-patch distance (IPD) and amount of perforation (AP) across the clusters and fragmentation categories (FC). FC have been generated for forest patches in the mainland India and islands were excluded from cluster analysis due to their large IPD values.

Cluster	Number of Patches	PS (km^2)	IPD (m)	AP (%)	Fragmentation Category (FC)
1	1	60,500.0	55.0	3.64	FC 1
2	5086	Median: 3.41 Range: 0.02–16,849.0	Median: 55.0 Range: 55.0–7,880.0	Median: 6.41 Range: 0.1–43.7	FC 1
3	302,482	Median: 0.05 Range: 0.009–412.0	Median: 155.0 Range: 55.0–2,709.0	Median: 0.00 Range: 0.0–4.86	FC 2
4	2339	Median: 0.04 Range: 0.009 – 11.0	Median: 5,903.0 Range: 4,338.0–56,656.0	Median: 0.00 Range: 0.0–4.8	FC3
5	42,448	Median: 0.03 Range: 0.009 – 27.0	Median: 1107.0 Range: 676.0–4,331.0	Median:0.00 Range: 0.0–2.14	FC3

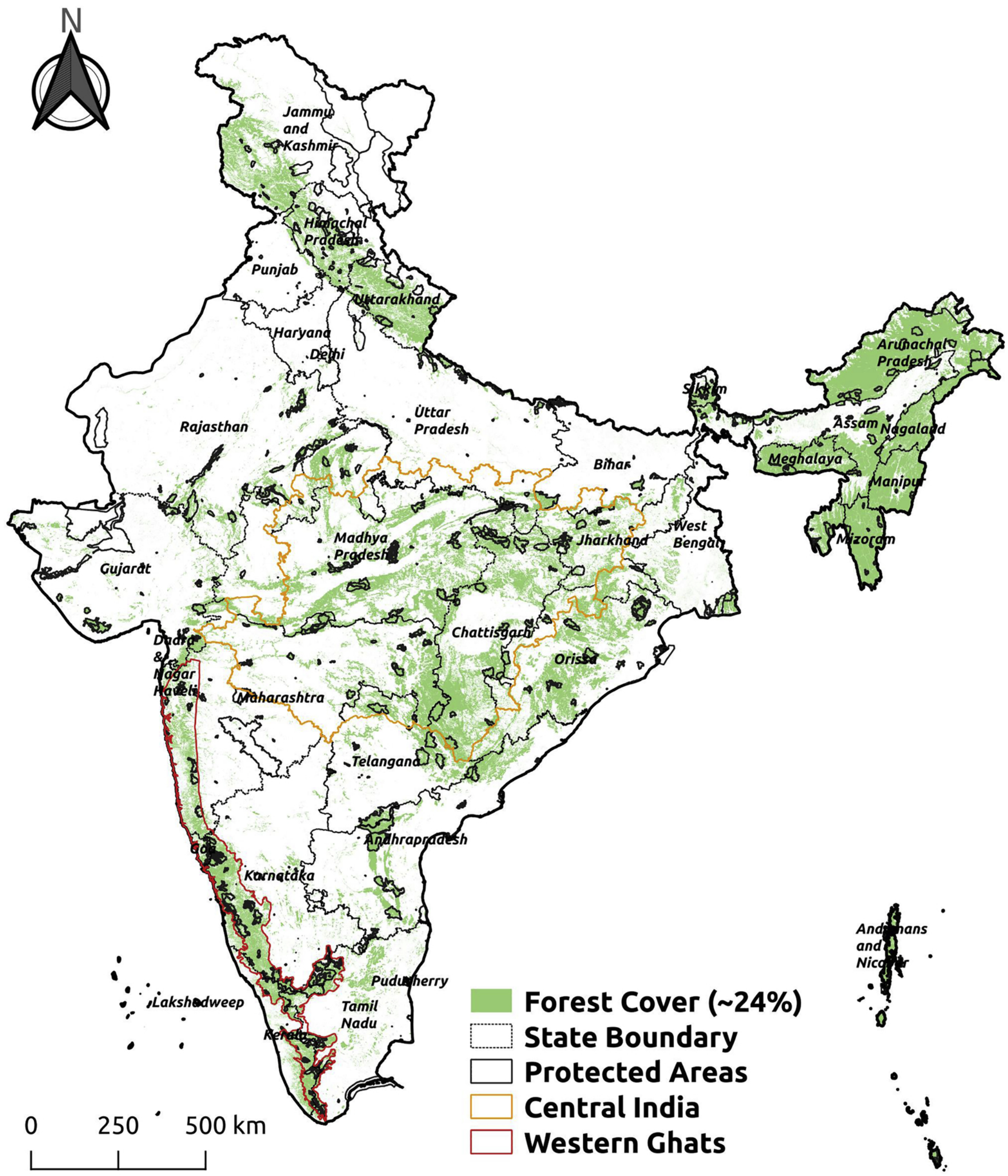

Fig. 1. Map showing administrative boundaries of India, protected areas and the two landscapes, the Western Ghats and Central India.

which are the main administrative units under the Indian federal system, from Survey of India (Fig. 1). There is no accurate PA layer available in the public domain. The widely used world database on protected areas is incomplete and inaccurate for India. Hence we collated PA boundaries across different government and published sources: PA layer for the Western Ghats was obtained from the dataset generated by Das et al., 2006. Boundaries of other PAs were digitized from the gazette notifications available with ENVIS PA database (ENVIS Centre on Wildlife & Protected Areas: http://www.wiienvis.nic.in/Database/Protected_Area_854.aspx) and from Eco-Sensitive Zones notifications available with the MoEFCC (http://envfor.nic.in/content/esz-notifications). This PA layer was further updated with input from researchers working in different landscapes in India.

We used the Western Ghats boundary as defined by Das et al., 2006. It demarcates an area of 120,000 km2of hill range running through a length of 1600 km from north to south along the west coast of India, covering six states, as the Western Ghats (Fig. 1). We delineated Central India boundary using agro-ecological regions and district boundaries. We used four agro-ecological regions, a) Deccan Plateau hot semi-arid ecoregion, b) Central Highlands hot sub-humid ecoregion, c) Eastern Plateau (Chattisgarh) hot sub-humid ecoregion, and d) Eastern Plateau (Chhota Nagpur) and Eastern Ghats hot sub-humid ecoregion (Sehgal et al., 1992). All the districts falling within these zones across nine states, Madhya Pradesh, Maharashtra, Chattisgarh, Jharkhand, Telangana, Rajasthan, Uttar Pradesh, Bihar, and Orissa, covering an area of 729,000 km2, were selected to delineate the boundary.

2.2. Preprocessing datasets

The LULC with 19 classes was re-sampled to 55 m using the nearest neighbour method and converted to a forest only layer by extracting the classes - Evergreen Forest, Deciduous Forest, Scrubland, and Littoral into one single "forest" class. Before extracting forest only class, we removed all stray pixels which resulted in a small isolated island like classes within a larger class, by merging them into the surrounding larger class using r.neighbors module in GRASS 7.2, with five neighborhood cells and a mode function. Some seasonal rivers inside forests were classified as "water-body" in the original LULC layer. As these were seasonal water bodies with a narrow width and known to allow movement of plants and animals across in the drier periods, we reassigned such pixels to the “forest” class. A river layer, obtained from the India-WRIS web-service, and surface water occurrence/seasonality layer obtained from global surface water explorer (Pekel et al., 2016) was used to facilitate this process.

We checked the topology of all vector layers (roads, railways, power-lines, mines, and reservoirs and dams) and errors such as overlaps, gaps and duplicate geometries were cleaned and the topology was fixed. Further, missing attribute values were updated. The road layer was restricted to major roads - national highways, state highways, and district roads, as other roads such as rural and urban roads were not captured effectively by the available road database. This layer was further updated by digitising missing roads using Google Earth scenes, available for the years 2014 and 2015. The railway line layer was updated and refined using the Indian Rail Atlas (https://indiarailinfo.com/atlas). The raster layer of canals and reservoirs was converted into vector layers. The quarry/mines layer was further updated by digitising open cast mines from Google Earth scenes for the Western Ghats and Central India available for 2014 − 15.

We used the r.clump module in GRASS 7.2 to identify physically discrete forest patches and converted the resulting raster layer into a vector polygon layer. The original LULC classification does not adequately represent linear infrastructure within forested areas; ideally, these features should have been classified as built-up (roads and railway line) or as water bodies (canals). To address this under-representation, we used infrastructure vector layers obtained from different sources and added a buffer of 27.5 m on either side of all linear features to match the spatial resolution of the LULC layer. We then conducted a vector difference operation and deducted all infrastructure features, linear as well as reservoir and mines, from the forest patch layer. We further removed patches which were less than 3 pixels in size (< 9000 m^2) from the resulting layer. This was our final layer which showed all distinct forest patches in India accounting for all infrastructure (Fig. 1). At the end of this exercise, we had two forest cover layers; one representing the forest patches without linear intrusions (simulated forest area) and one with all linear infrastructure included (henceforth existing forest area).

2.3. Analysis

We derived three different patch indices for the existing forest cover to quantify the structural connectivity:

Patch Size (PS): This is a simple measure of the size of the patch obtained by measuring the geometrical area of each individual patch. The area was expressed in m^2. Reduction in patch size is directly linked to the splitting of a larger forest habitat into smaller parts by linear structures (Goosem, 2007; Lovejoy et al., 1986; Mancebo Quintana et al., 2010). There is also an association between patch size and its use by animals (Uezu et al., 2005; Webb, 2013). Hence we chose this index for quantifying structural connectivity.

Amount of Perforation (AP): This is a measure of gaps or holes in a forest patch, which can be created by reservoirs, mines, settlements, agriculture/non-forest plantations, or changes in LULC associated with infrastructure developments, expressed as a percentage of the total patch size.

Inter-Patch Distance (IPD): This is an index of isolation of a forest patch in space from the nearest forest patch. IPD was defined as the nearest neighbor distance (m) for each forest patch. Patch shrinkage by linear intrusions could lead to an increase in distance between patches. If such distances are very large it could result in the complete isolation of a patch from the other and thus impact movement patterns and colonization of animals and plants across patches and landscapes (Schowalter, 2016; Webb, 2013). Hence we used this index in combination with PS and AP to quantify the impact of linear infrastructure on structural connectivity.

Patch size and the number of patches were compared between existing forest area and simulated forest area layers to evaluate the impact of infrastructure development on forest structural connectivity.

We performed agglomerative hierarchical cluster analysis on patch indices to identify naturally distinct clusters in our dataset. We used Ward’s method of agglomeration, which produces clusters of more equal size by keeping distances within the clusters as small as possible (Ward, 1963). We identified five unique groups using a dendrogram on the cluster solutions that we had obtained (Supplementary Fig. 1). These five groups were further classified into three fragmentation categories (FC) based on the patch characteristics (Table 1). FC ranged from small and distant patches to large and intact patches. This formed the basis for quantifying fragmentation and recommending planning priorities for infrastructure developments in the study region. We did not include island landscapes such as Andaman and Nicobar, and Lakshadweep Islands in the cluster analysis due to the large IPD values of forested patches. Cluster analysis was performed using R statistical software (R Core Team, 2018) and the hclust function available with R library fastcluster (Müllner, 2013).

We used infrastructure information and patch indices to characterize fragmentation in existing PAs and in Central India and the Western Ghats landscapes.

3. Results

We found an increase in the number of forest patches and a reduction in the number of large patches ($> 10{,}000$ km^2) due to linear infrastructure in India. High tension power-transmission lines and major roads were the most common linear intrusions within forests, and 70 % of the assessed PAs had some amount of linear infrastructure passing through them. Forest patches in Central India were more isolated than patches in the Western Ghats landscape.

3.1. Infrastructure and patch indices at the national level

We found an increase in the number of forest patches as a result of infrastructure construction in India. The total existing forest area of 783,300 km^2, 23.83 % of India’s landmass, is distributed across 352,674 forest patches of varying sizes. High tension power-transmission lines and major roads were the most common linear intrusions within forests with lengths of 59,500 km (density = 0.08 km/km^2) and 46,700 km (density = 0.06 km/km^2), respectively. The length of railway lines and canals passing through forests were 7400 km (density = 0.01 km/km^2) and 6100 km (density = 0.008 km/km^2) respectively. A comparison of the two forest layers suggested a 6% increase in the number of forest patches (patches without infrastructure = 331,240, patches with infrastructure = 352,674).

We found that approximately 18,250 large forest habitats under the simulated scenario were split into two or more smaller patches by linear intrusions across the country. Larger forest habitats faced greater fragmentation and were split into multiple smaller patches by linear infrastructure intrusions (Fig. 2a). The highest fragmentation due to linear intrusions was observed in Central India, where an intact forest habitat of size 162,000 km^2 was split into 5200 smaller patches with a mean patch size of 30 km^{2}and the largest patch being 16,850 km^{2}in size.

Reduction in size was observed in forest habitats that were impacted by linear intrusions. Eighty-one percent of forest habitats in the simulated scenario were reduced by half or more of their original size due to linear infrastructure (Fig. 2b). A comparison of median patch area suggested that forest patches of size > 10 km^2 were more vulnerable to size reduction with greater than 50 percent reduction in the patch size observed under simulated scenario (Fig. 2c). The largest patch size was 60,500 km^2 observed in the North Eastern part of the country, spread

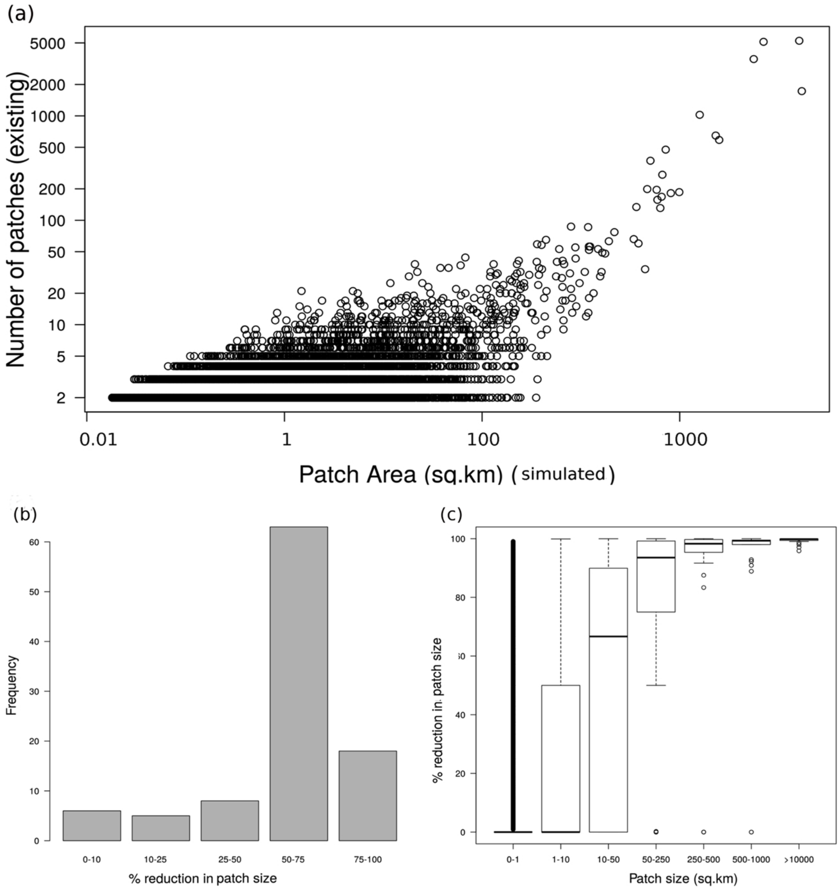

Fig. 2. (a) The log plot showing the relationship between number of forest fragments and the initial stage patch size (simulated scenario), which suggests an increase in number of fragments with an increase in patch size, (b) A greater reduction in size was observed in intact forest patches. 81 % of these patches were reduced by half or more of their size. (c) Box and whisker plot suggests that intact forest patches of size > 1 km2 were more vulnerable to fragmentation with > 50 % reduction in original size.

across the states of Arunachal Pradesh, Nagaland, and Manipur. This same patch was part of a larger patch of size 172,820 km^2 covering all seven north-eastern states in the simulated scenario, which was split into 1656 smaller patches with a mean patch size of 100 km^2 (Fig. 3 a& b). Furthermore, there was a 71.5 % reduction in the number of large patches (> 10,000 km^2) due to linear infrastructure.

Most of the forest patches (> 94 %), were less than 1 km^2 in size. However, they only accounted for approximately 4% of the total forested area in the country under both existing and simulated forest cover conditions. The distribution of existing forested areas across different patch size classes suggested that around 68 % of the forest area is comprised of forest patches of size between 250 and 10,000 km^2 (Fig. 3c). This forest area distribution across patch sizes changes drastically in absence of intrusions; forest patches of size > 10,000 km^2 alone covered nearly 67 % of the forested area in the simulated scenario (Fig. 3d).

The results for perforation analysis suggested that more than 98 % of forest patches had less than 5% perforation (Fig. 4a). There were only 91 forest patches which had more than 30 % perforation. The maximum perforation observed was 43.7 %, calculated for a patch of size 280 km^2 in Himachal Pradesh. A comparison of patch size to the amount of perforation suggested that the perforation was higher for patch size class 1,000–10,000 km^2 (median 8.03 %, Fig. 4b). The largest patch without any perforations was 77 km^2 observed in the state of Gujarat.

Around 92 % of forest patches had an IPD less than 1 km with 33 % having a distance less than 100 m (Fig. 4 c&d).

3.2. Fragmentation category (FC)

We found 5087 large, intact forest patches in FC 1 across India, which together formed 77 % of the total forested area in India. Eighty six percent of the total numbers of forest patches were in FC 2 (Table 1, Fig. 5).

3.3. Status of existing Protected Area (PA) Network

There are 769 PAs in India (ENVIS Centre on Wildlife & Protected Areas: http://www.wiienvis.nic.in/Database/Protected_Area_854.aspx). We were able to characterize fragmentation for 450 of the PAs which predominantly had forest cover. The rest of the PAs were primarily grasslands, water-bodies, snow-clad mountains, or marine protected areas and therefore were not assessed. Seventy percent of the assessed PAs had some amount of linear infrastructure passing through them. High tension power-transmission lines and major roads were the most common linear intrusions inside PAs with total lengths of 12,000 km (density = 0.06 km/km^2) and 10,000 km (density = 0.05 km/km^2) respectively. Canals and railways had lengths of 2800 km (density = 0.02 km/km^2) and 1270 km (density = 0.007 km/km^2), respectively, inside PAs. The densities of high tension power-transmission lines, major roads, railway lines, and canals were 0.08, 0.06, 0.01, and 0.008 respectively across all forested areas in India.

We found around 13,088 forest patches within the PA network. The average patch size within PAs was 30.80 km^2. We found that the majority of the forest patches within PAs, 70 %, were part of FC 1, which includes large and relatively intact forest patches.

3.4. A comparison between the Western Ghats and Central India

The existing forest area in Central India and the Western Ghats landscapes were 35 % (238,000 km^2) and 68 % (79,900 km^2), respectively. Nearly 25 % of the forested area in the Western Ghats was inside the PA network, while only 11.34 % was within the PA network in

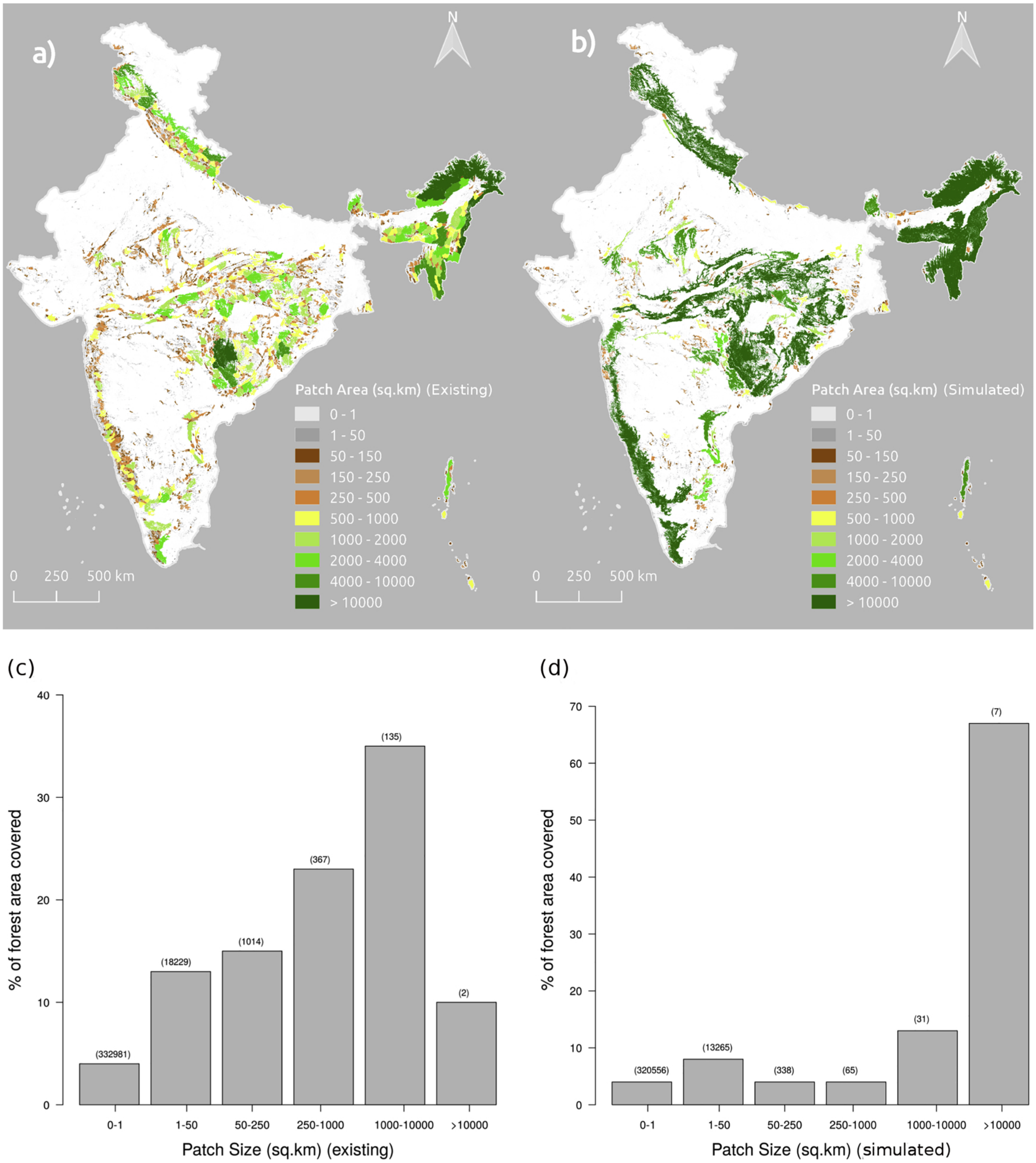

Fig. 3. Spatial distribution of forest patches and their size: (a) Depicts the patch size distribution as influenced by infrastructure; (b) Depicts patch size distribution in absence of infrastructure intrusion. A comparison of both figures suggests higher numbers of large intact patches in the absence of infrastructure intrusions across India. Distribution of patch size and % of total forested area covered under different patch size: (c) patch size distribution as influenced by infrastructure. Around 58 % of total forested area is composed of patches of size 250-10,000 km^2; (d) Patch size distribution in absence of infrastructure intrusions. In absence of infrastructure intrusions, around 67 % of forested area is covered by only 7 large patches of size > 10,000 km2.

Central India. The density of roads was 0.12 km/km^2 and 0.22 km/km^2 inside Central India and the Western Ghats respectively. We found 69,458 distinct patches in Central India and 20,284 patches in the Western Ghats. The mean patch size in the Western Ghats was 3.94 km^2, whereas the mean patch size in Central India was 3.42 km^2. Comparison of the distribution of forest areas across patch sizes suggests that nearly 300 patches of size greater than 1000 km^{2}constituted ~42 % of the forest area in Central India landscape, whereas in the Western Ghats landscape 14 large patches (PS > 1000 km^2) formed ~29 % of the forest area (Fig. 6 a&b). The largest patch size was 16,850 km^2 and 2940 km^2 in Central India and the Western Ghats respectively. Comparison of the median AP between Central India and the Western Ghats landscapes suggested an increase in AP with an increase in PS. Median AP for larger patches of size > 250 km^2 was higher in Central India than in the Western Ghats landscape (Fig. 6 c&d). Forests in Central India were more isolated than the Western Ghats with maximum and mean IPD in Central India being 28.4 km and 340 m respectively, while the maximum and mean IPD were 4.6 km and 170 m respectively for the Western Ghats. Similarly, nearly 62 % of patches in the Western Ghats landscape had IPD of 100 m or less, while only 48 % of patches in Central India had IPD of 100 m or less. There were 1240 and 598 large, intact forest patches (FC 1) in Central India and the Western Ghats respectively.

4. Discussion

Infrastructure development is the main cause for the fragmentation and loss of connectivity in tropical forests (Geneletti, 2004). In this

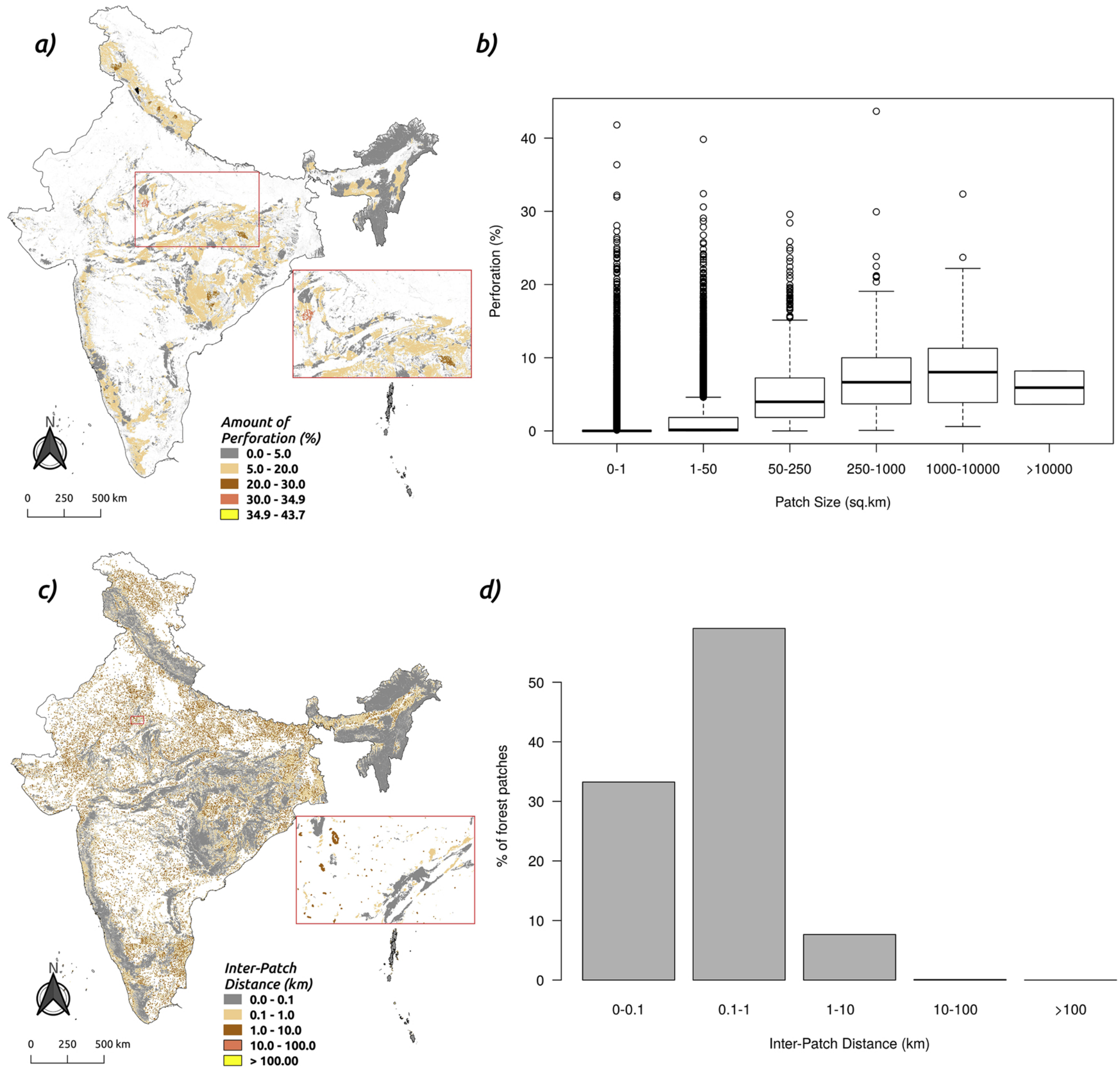

Fig. 4. (a) Map showing the amount of perforation across forest patches. (b) The median for amount of perforation is higher in the patch size class 1000-10,000 km2. (c & d). Majority of patches had less than 1 km inter-patch distance, with 33 % of patches having a distance of less than 100 m.

study, we quantified the effect of linear infrastructure on forest structural connectivity by using patch characteristics in India. We found an increase in the number of forest patches as a result of linear infrastructure. Linear infrastructure also resulted in a reduction in the size of the forested habitats.

Power-lines and roads were the most common linear intrusions observed within forested habitats. The density of roads within forested habitats (0.6 km/km2) in India is comparable to average road densities reported for some of the developed countries such as USA (0.75 km/km2, Forman, 2003) and higher than that reported for developed countries such as New Zealand (0.35 km/km2) and Navarra in Spain (0.45 km/km2, Serrano et al., 2002), and for developing countries such as China (0.43 km/km2) and Brazil (0.20 km/km2) (https://knoema.com/atlas/ranks/Road-density), which have an economic development similar to India. Our estimates are conservative as we have considered only major roads (national and state highways, and district roads) in this analysis. As there has been an increase of 69 % in the length of rural roads between 2000 and 2015 (https://data.gov.in/), the actual density and fragmentation by roads would be much higher than reported here when rural and other roads are included in the analysis. Although these rural roads might not be a complete barrier to wildlife movement, they may result in increased mortality, low patch quality, and a higher edge effect for species sensitive to habitat change. With proposed centrally-sponsored schemes like Bharatmala Pariyojana– a road and highway development project (National portal of India 2018, https://www.india.gov.in/spotlight/bharatmala-pariyojana-stepping-stone-towards-new-india), and industrial corridor project along the existing highways (Makeinindia 2018, http://www.makeinindia.com/live-projects-industrial-corridor), the density of roads through forests is likely to increase in future. This can lead to an increase in fragmentation as fragmentation is closely associated with an increase in road density (Hawbaker et al., 2006). Also, there is potential for a future increase in perforation and inter-patch distance due to the diversion of forest land to non-forest activities.

Up-gradation of road lanes will potentially increase road width and this can strongly hinder animal movements due to heavier traffic volume and speeds. Laurance and Gomez (2005) reported the inability of translocated male Amazonian understory birds to cross clearings of a width of 250 m. Similarly, tigers, snakes, turtles, bumblebees and several other vertebrates and invertebrates were found to demonstrate a strong avoidance of roads and railway lines (Bhattacharya et al., 2002; Kerley et al., 2002; W. F. Laurance et al., 2017; Shepard et al., 2008). Although the amount of forest land diverted to linear infrastructure is small, the effect of infrastructure spreads far beyond the exact location of these structures. A meta-analysis on the effects of infrastructure proximity on mammal and bird populations suggest a decline in

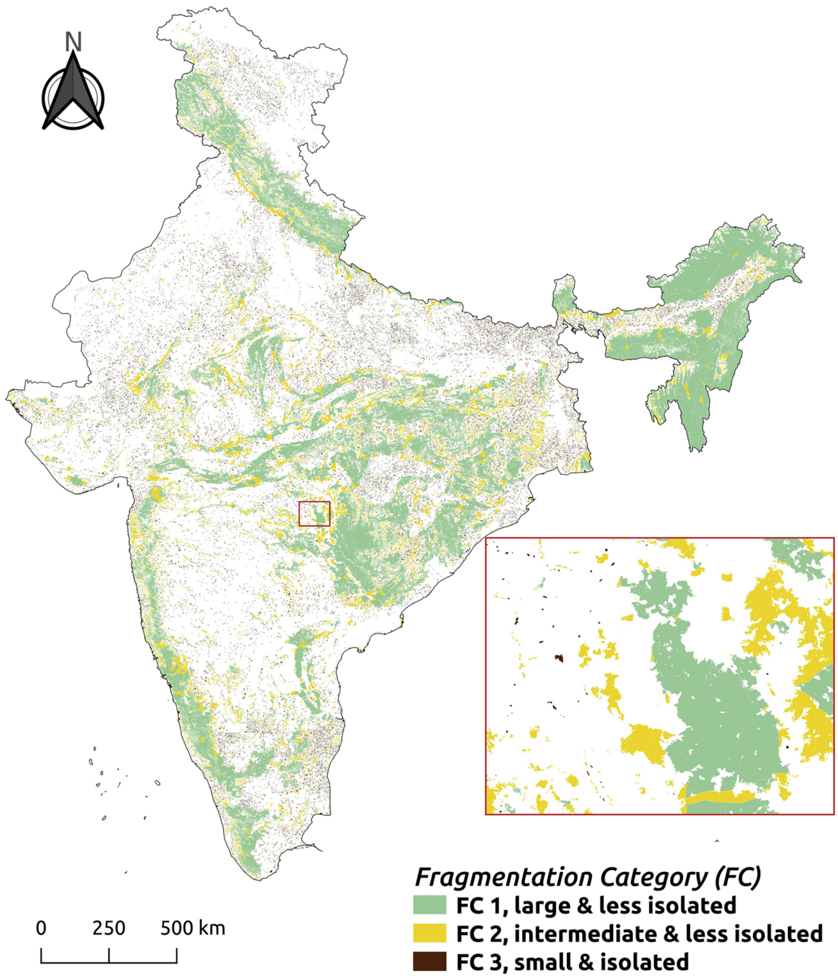

Fig. 5. Large, intact forest patches (FC 1) formed 75 % of total forested area in India.

abundances of birds and mammals within 2.6 km and 17 km from infrastructure, respectively (Benítez-López et al., 2010). Although recent meta-analysis studies suggest a positive effect of human paths on overall plant species richness and diversity (Root-Bernstein and Svenning, 2018), the richness and abundance of native plant species have been found to decline over distances up to 1 km from roads (Gelbard and Harrison, 2003). Hence there is a need to integrate conservation concerns in infrastructure development projects and our data could act as a baseline data for planning and rerouting infrastructure projects to minimize fragmentation.

We found 352,674 forest patches in India, similar to that reported by Reddy et al. (2013) (370,386). Although this is a large number, nearly 60 % of India's existing forest cover is represented by less than 1% of these patches. Fragmentation categories also revealed that nearly 5000 large patches (FC 1) together constituted 77 % of India's forested area. The IPD for these large patches was also very low (median- 55 m). This suggests that, in spite of ongoing degradation, with the proper management plan and mitigation strategies, connectivity between these large patches could be maintained and restored with minimal cost and resources. Identifying the critical points of animal crossing across these patches and providing effective structures across these linear intrusions would greatly help in restoring connectivity across forests (W. F. Laurance et al., 2009; Lesbarrères and Fahrig, 2012).

There was a 70 % reduction in the number of patches which are larger than 10,000 km2 in size compared to a scenario that excluded all linear infrastructure. Furthermore, forest habitats of size greater than 10 km2 were found to be more vulnerable to size reduction. We found that the mean patch size was only 2.2 km2 with more than 90 % of patches being smaller than 1 km2 in size. Studies in South Ecuador also reported a smaller mean patch size, which decreased from 15.1 km2 in 1976 to only 1.4 km2 (Tapia-armijos et al., 2015). Smaller patches sustain fewer species than larger or contiguous habitats and the extinction threat to a species increases in smaller fragments (Estrada-Villegas et al., 2010; Gibson et al., 2011; Gibson et al., 2013; Melo et al., 2010). Recent studies have suggested that smaller PAs are disproportionately important for connectivity (Dutta et al., 2016) and small isolated PAs have elevated the risk of tiger extinction (Thatte et al., 2018). Large patches could help to increase the probability of long-term persistence of large mammals by sustaining meta-populations (Wikramanayake et al., 2004). Studies also suggest that the size of forest habitats required for conserving genetic diversity could be 15 folds larger than those needed to safeguard species numbers (Struebig, 2011). Hence, protection of identified larger patches and restoring connectivity should be a conservation priority.

The reduced habitat size and increased forest edges may lead to an escalation of human-wildlife conflict (Fredriksson and Fredrikkson, 2005; Gurung et al., 2008; Michalski et al., 2006). The PA network in India covers only 5% of the total landscape (Rangarajan and Shahabuddin, 2006), but has played an important role in conserving the habitat of several species in India (Das et al., 2006; Wikramanayake et al., 2004). However, 70 % of the assessed PAs were part of large and relatively intact forest habitats, pointing to their role in decreasing forest degradation in India. Global studies also show that PAs have significantly lower rates of forest clearance and have played a major role in conserving tropical biodiversity (Bruner et al., 2001; Nagendra, 2008). Declaring some of the identified larger patches as PAs could be

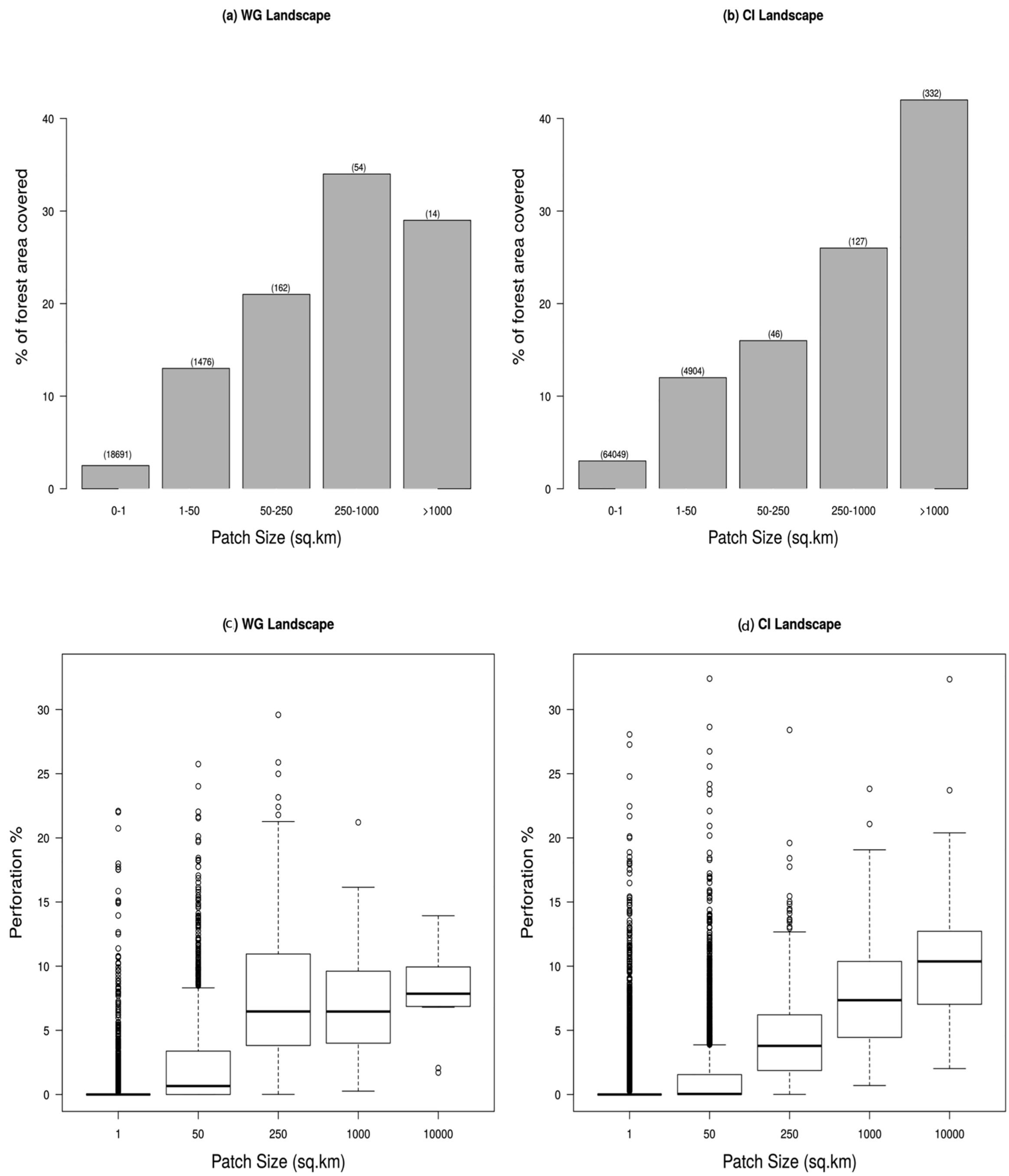

Fig. 6. (a & b) A comparison of distribution of forest cover across different patch sizes suggested that in the Central Indian landscape ~42 % of total forest cover is comprised of patches of size > 1000 km^2, whereas only 29 % of forest cover in the Western Ghats landscape is comprised of patches of size > 1000 km^2; (c & d). Median amount of perforation for larger patches of size > 250 km2 was higher in Central India than in the Western Ghats landscape.

an effective way of ceasing fragmentation and maintaining connectivity.

The Western Ghats and Central India are two important conservation landscapes critical for the survival of several threatened mammals including tiger *Panthera tigris*, Asian elephant *Elephas maximus*, leopard *Panthera pardus*, dhole *Cuon alpinus*, gaur *Bos gaurus*, sambar *Rusa unicolor*, lion-tailed macaque *Macaca silenus* etc. Results suggest that overall Central India has a greater proportion of forest area (42 %) comprised of larger patches (> 1000 km2), while only 29 % of forest area in the Western Ghats was contributed by patches larger than 1000 km2 in size. There were fewer major roads in Central India compared to the Western Ghats, and this might be a reason for more number of larger patches in Central India compared to the Western Ghats. However, inter-patch distance and perforation were higher for Central India when compared to the Western Ghats, which is an indication of poor quality of the existing forests. We suggest that the priority in Central India shall be to restore connectivity between large patches and minimize forest diversion for non-forestry activities such as mining. The integrity of smaller intervening patches shall also be considered while planning infrastructure as small patches have been found to facilitate movement of dispersing individuals between larger patches (Thatte et al., 2018). Based on the fragmentation indices for the Western Ghats, we suggest that the priority in this landscape should be to avoid further fragmentation of patches and explore options of establishing infrastructure along the existing features. In both of the landscapes, the majority of the forested habitat was outside the PA network.

Some of these forest patches outside PAs have been identified as crucial corridors and critical links for biodiversity conservation (Das et al., 2006; Joshi et al., 2013; Sharma et al., 2013; Thatte et al., 2018).

The forests in the hill ranges of the Western Ghats run parallel to the west coast of India. There are opportunities to establish linear infrastructure projects that connect north-south parts of this landscape, by aligning them along the coast or on the leeward side of the hill range without fragmenting the forest patches. However, the establishment of an east-west linear infrastructure project is feasible only along the natural breaks in the hills or such projects will necessarily result in some amount forest fragmentation. Furthermore, the costs associated with establishing E–W connecting infrastructures through the hilly terrain in the Western Ghats are very high and hence, the options of bundling several linear projects together along the natural breaks could be explored in this landscape. Unlike the Western Ghats, Central India landscape is in the heart of the country and crucial for establishing North-South and East-West linear infrastructure network. In the current context, where there is limited forest cover, we recommend that infrastructure projects should not be established through the existing forests and when inevitable, proper mitigation strategies to avoid negative impacts on forest connectivity shall be incorporated in the project development plans. A more rational development planning would be to connect larger numbers of villages or people while safeguarding forests rather than to establish the shortest routes that would destroy forests, biodiversity, and ecosystem services.

5. Conclusion

India is one of the fastest growing economies in the world. Its infrastructure network is undergoing great expansion and up-gradation. It is essential to integrate biodiversity conservation into this infrastructure development to achieve sustainable development in India. We found that States in the north-east had the highest forest cover and least infrastructure (Supplementary Table 3). Providing more infrastructure facilities in these areas is an identified economic priority for the Indian government. In this context, there is much that can be learned from a careful study of the impact of past infrastructure development in regions of India such as the Western Ghats and Central India. For example, there has been a substantial number of forest clearance applications for linear projects submitted to the MoEFCC in these states (Supplementary Table 3, MoEFCC 2017). Hence, conservation priority should be towards identifying forest habitats that would be affected by linear intrusions and developing effective mitigation strategies to preserve connectivity across the habitats. Several large-scale projects like river-interlinking (National Water Development Agency 2014), Bharatmala Pariyojana (National portal of India 2018), along with other linear projects could potentially increase fragmentation and affect connectivity across landscapes. The increasing trend of fragmentation would severely affect biodiversity by encouraging the spread of invasive species along the edges (Bustamante et al., 2003). Linear infrastructure can act as barriers to animal movement which in turn has negative demographic and genetic consequences that can result in local extinctions (Shepard et al., 2008). Fragmentation due to infrastructure developments could be minimized if these structures could be rerouted, bundled, or effective mitigation strategies are adopted. Data driven modeling approaches could be used to quantify the potential effects of these structures on fragmentation and connectivity.

Our study and its results provide information to guide 'where' and 'how' future infrastructure development activities could be undertaken with the optimal balancing of development and biodiversity conservation. Forest patches in fragmentation category 1 are large and relatively intact, and hence, future development plans should avoid routing structures through these patches. We are sharing this spatial data through a web-portal for the public to use (https://indiaunderconstruction.com/). Access to this data will enable local stakeholders in infrastructure projects to make informed decisions leading to develop optimal local management plans for them. Although we address only the issue of fragmentation within forests in this study, the techniques we have developed and presented here can be usefully applied to mitigate fragmentation problems in other fragile ecosystems such as tropical grasslands and savannas. Infrastructure expansion comparable to that in India is also rapidly occurring in many tropical countries (Venter et al., 2016) driven by the societal need for economic development. However, we believe knowledge of current and future impacts of such infrastructure development on biodiversity can assist developing societies to simultaneously align such development with conservation objectives, thus potentially presenting a win-win scenario.

CRediT authorship contribution statement

Rajat Nayak: Methodology, Data curation, Formal analysis, Writing - original draft. **Krithi K. Karanth:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing. **Trishna Dutta:** Data curation, Formal analysis, Writing - review & editing. **Ruth Defries:** Conceptualization, Funding acquisition, Writing - review & editing. **K. Ullas Karanth:** Conceptualization, Funding acquisition, Writing - review & editing. **Srinivas Vaidyanathan:** Conceptualization, Funding acquisition, Supervision, Methodology, Data curation, Formal analysis, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104619.

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