



Assessing the extent and impacts of linear infrastructure on Sri Lanka's natural and protected areas: Implications for future development planning

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Abstract Linear infrastructure (LI) has varying effects on landscapes depending on different ecosystems' sensitivity and threat levels. Economically developing tropical countries are particularly at risk from LI. Therefore, understanding a country's current LI network and planning future developments to avoid further fragmentation and disturbance is crucial. This study aimed to assess the extent of Sri Lanka's LI network (i.e., roads, railroads, and powerlines), given that it is both a biodiversity hotspot and an economically developing country in the tropics. First, we calculated the average normalized difference vegetation index (NDVI) and normalized difference built-up index (NDBI) indices and examined their spatial autocorrelation per divisional secretariat division. Then a multivariate cluster analysis was used to determine clusters of natural and protected areas that may receive similar impacts from different LI and their combinations. Results indicated that roads are

the most widespread LI type in Sri Lanka, followed by powerlines and railroads. Over 80% of Sri Lanka's total land area falls within 1 km of either a national or a provincial/local road. Areas with high NDVI were primarily manmade habitats, with less than 20% contribution from protected areas. Over 50% of the total protected area of Sri Lanka is being impacted by all three types of LI. Powerlines were the most common LI type in protected areas in proportion to their total network lengths. To minimize environmental impact while achieving development goals, future LI development activities should use a landscape approach to identify development needs and strategies informed by these findings.

Keywords Biodiversity hotspot · Economically developing country · Habitat fragmentation · Spatial analysis

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Introduction

Economically developing tropical countries face a higher risk of experiencing negative impacts from linear infrastructure (LI) due to their growing economy (Alamgir et al., 2017; Balmford et al., 2016; Dulac, 2013) and the unique biodiversity found in these regions. Recent projections suggest that nearly 90% of the 25 million km of roads projected to be built worldwide by 2050 will be in tropical regions (Dulac, 2013), highlighting the urgency of better planning

and decision-making in LI development. As these LI development activities receive significant financial investments from international and national funders (Alexander, 2014), failures in such projects due to inadequate planning may result in severe ecological and economic losses. Therefore, it is essential to understand the current extent of LI and its potential impact on habitats to optimize future LI projects, minimize adverse effects, and avoid further losses (Laurance et al., 2014).

Sri Lanka is a valuable case study for documenting the baseline information on LI networks and their impact on habitats for two primary reasons. First, the country plays a crucial role in the global biota being part of a biodiversity hotspot (Myers et al., 2000) due to its unique faunal and floral species. Despite its small size (65,000 km²), Sri Lanka hosts an impressive number of species (3087 angiosperm species and 778 vertebrate species), including many endemics (27.9% angiosperms and 40.9% vertebrates) (Ministry of Environment (MoE), 2012; Sri Lanka Biodiversity Secretariat, et.al., 2020), making it a significant contributor to the planet's biodiversity. Second, Sri Lanka is currently in a phase of rapid development to achieve several socio-economic goals by 2050 (NPPD-SL, 2019). To meet the country's growing development demands, significant improvements and expansions are planned for its road, railroad, and power transmission networks (CEB-Transmission Division, 2021; Georget, 2022; Road Development Authority, 2019). For example, the country's future energy supply projections anticipate a doubling of energy production by 2040 compared to 2022 (CEB-Transmission division, 2021), and over 600 bridges in the road sector are identified as needing to be either reconstructed or widened (Road Development Authority, 2019). The proposed expansions in energy and transportation sectors strongly suggest that Sri Lanka's LI networks are poised for significant growth.

The ongoing LI developments in Sri Lanka are being constructed atop an already well-established LI network. In particular, Sri Lanka has one of the densest road networks in South Asia (Road Development Authority, 2019), which has already had a significant impact on the country's critical habitats. Additionally, the country's island status amplifies its vulnerability to climate change impacts such as droughts, landslides, and floods (Eckstein et al., 2021), potentially requiring more frequent repairs in the LI network.

Most large-scale LI projects in Sri Lanka are financed through international loans, and any failure in such projects may result in significant economic losses, along with irreversible damage to its unique biota. Therefore, it is crucial to identify already affected natural areas and plan future LI development activities to avoid further disturbance to critical ecosystems. Furthermore, information on the status and potential impact of major LI networks on natural habitats can help Sri Lanka meet its sustainable development goals while achieving biodiversity conservation targets.

The impact on natural habitats could be minimized if future infrastructure developments are targeted to be built on existing networks, avoiding areas that should be kept intact and concentrating on sites with more development potential and benefits (Laurance et al., 2014). To achieve this, it is crucial to understand the current impact of linear development on natural ecosystems (Ibisch et al., 2017; Laurance et al., 2014; Laurance & Balmford, 2013). Therefore, this study aimed to assess the extent of the existing road, railroad, and powerline networks, which are the most common types of LI in Sri Lanka, and to determine their impact on natural areas.

Despite the importance of LI networks on the development of Sri Lanka, no comprehensive island-wide studies have focused on the spatial patterns of impacts of LI networks on natural habitats. Nonetheless, several independent studies have provided insights into land use change at both island-wide and regional scales (Edirisooriya, et al., 2021; Rathnayake, et al., 2020; Saparamadu, et al., 2018; Zahir et al., 2021), along with recommendations to enhance the structural integrity and transportation efficiency of the road network (Abesinghe & Jayatilake, 2020; Chandimal & Wijesekera, 2008; Pasindu, et al., 2018). For example, Rathnayake et al. (2020) present a country-wide land use land cover (LULC) change map for Sri Lanka over 25 years using Landsat time-series imagery from 1993 to 2018, while Saparamadu et al. (2018) report on land use change and related environmental characteristics such as land surface temperature (LST), surface water quality, and soil characteristics in Colombo, the commercial capital of the country. Studies that focused on enhancing the structural and functional performance of the road network have investigated the effects of climate change on roads (Abesinghe & Jayatilake, 2020) and

proposed strategies to improve road safety, decrease travel time, and increase efficiency (Chandimal & Wijesekera, 2008; Pasindu et al., 2018).

In this context, we aimed to use biophysical parameters of land surface, normalized difference vegetation index (NDVI), and normalized difference built-up index (NDBI) to assess the existing land use profile. The two indices have proven to be excellent indicators to measure the level of greenness and intensity of development (Macarof & Statescu, 2017; Malik, et al., 2019; Roy & Yuan, 2007). By identifying the land use profile, we can pinpoint critical areas that need attention when planning development activities at the local level. Additionally, we focused on identifying natural and protected areas in Sri Lanka that have already been impacted by LI. The study’s

results can provide valuable information for planning LI in Sri Lanka to accommodate future demands while causing the least possible damage to the natural environment. Moreover, this information can help to formulate defragmentation strategies to undo fragmentation that has already taken place.

Study area

Sri Lanka is located between 5° 55’–9° 51’ N latitude and 79° 52’–81° 51’ longitude in the Indian Ocean (Fig. 1). Its climate is characterized by two main seasons—the Maha season, associated with the northeast monsoon (September–March), and the Yala season, associated with the southwest monsoon (May–August) (DWC, 2008). Daily maximum temperatures remain

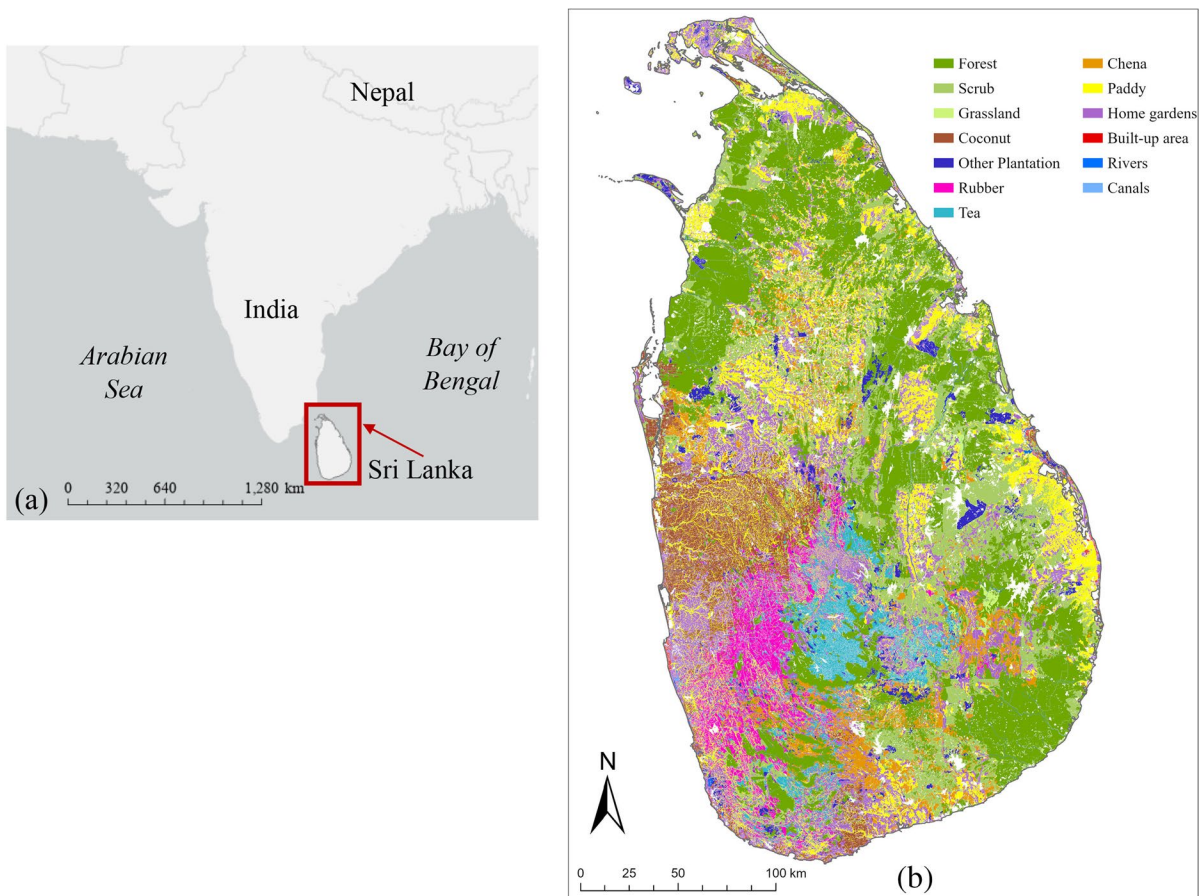
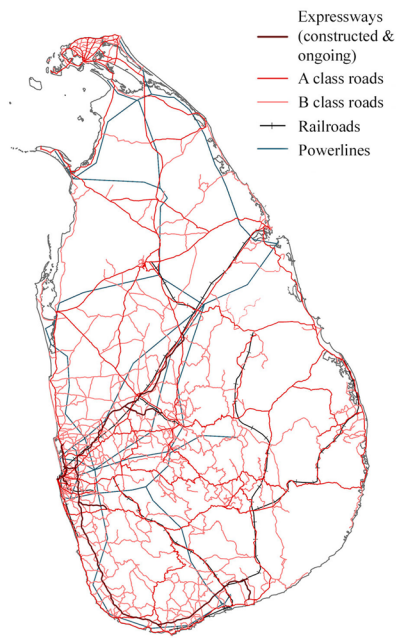
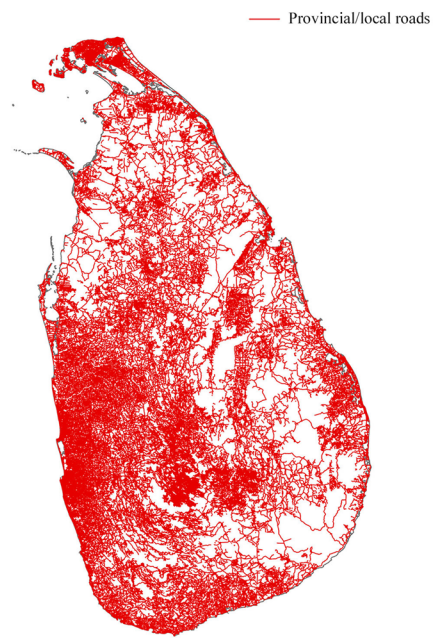


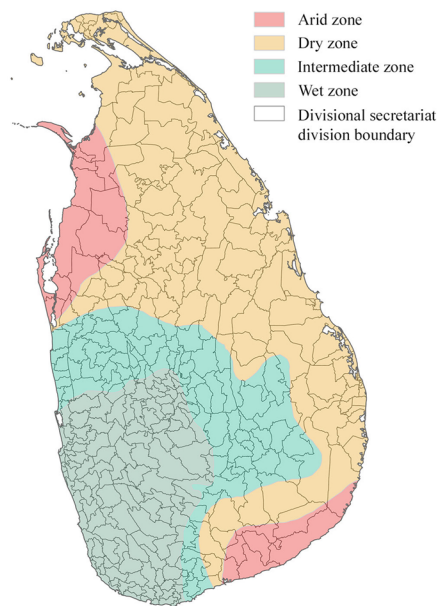
Fig. 1 a Location of Sri Lanka in South Asia and b land use and land cover of Sri Lanka, 2010 (source: Survey Department of Sri Lanka)



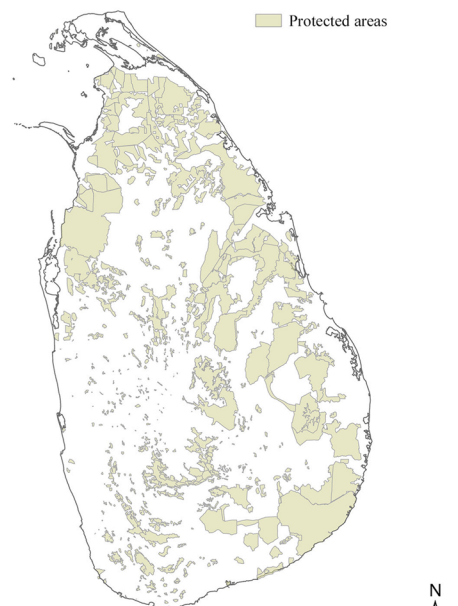
(a)



(b)



(c)



(d)

◀**Fig. 2** LI network of Sri Lanka. **a** National roads (class A, B, and expressways), railroads, and powerlines networks (source: the Road Development Authority of Sri Lanka); **b** all roads (national roads and provincial roads), railroads, and powerlines (source: the National Physical Planning Department of Sri Lanka); **c** the map of climatic zones and the divisional secretaries of Sri Lanka, and **d** the national protected area network (source: (UNEP-WCMC and IUCN, 2022))

around 31°C throughout the year, while altitude plays a critical role in temperature variations within the country. The south–central mountain ranges experience considerably lower temperatures. Furthermore, Sri Lanka’s precipitation regime is classified into three zones, namely wet, intermediate, and dry (Gunatilleke, et al., 2008).

Sri Lanka, despite its small size, boasts a rich diversity of ecosystems owing to its topography, climatic heterogeneity, and coastal influence. These ecosystems can be broadly classified into four categories: (i) coastal or marine ecosystems, (ii) natural forests, (iii) natural and semi-natural grasslands, and (iv) inland wetlands. Additionally, there are human-made ecosystems such as agroecosystems, including home gardens, cash-crop fields, and plantations that bear a resemblance to natural forests (Gunatilleke et al., 2008). Due to its unique and abundant biodiversity and the challenges it faces, Sri Lanka is recognized as one of the world’s 34 biodiversity hotspots, along with the Western Ghats of India (Myers et al., 2000).

Datasets

The sections below include brief descriptions of the various datasets used in the present study:

Satellite data

We obtained eight Collection-1 Level-1 Landsat satellite images with 30 m spatial resolution from www.earthexplorer.usgs.gov (USGS, 2022) for Sri Lanka, all acquired in January–February 2022 with low cloud cover (<20%). To create a single image for analysis, we merged the downloaded images using the mosaic function in ArcGIS Pro.

Sri Lanka geospatial data

LI network

We analyzed three major types of LI: roads, railroads, and 220 kV powerlines. The road network of Sri

Lanka is comprised of two components, the national and provincial road networks. The national road network comprises class A roads, class B roads, and expressways. Class A roads are main long-distance routes connecting major provincial cities, while class B roads distribute traffic between residential, industrial, and town areas, linking them to class A roads. Expressways are toll roads with controlled access, with speed limits ranging from 80 to 110 km/h (50 to 68 mph). The provincial road network includes jeep tracks and other local roads. This provincial road network is highly extensive and experiences varying levels of traffic. In comparison, the railroad and 220 kV powerline networks in Sri Lanka are not as extensive as the road network. We obtained LI network data from the National Physical Planning Department (NPPD) and the Road Development Authority (RDA) of Sri Lanka and combined them to produce four LI network layers, i.e., national roads, all roads (national and provincial roads), railroads, and powerlines (Fig. 2a, b).

Climatic zones

Sri Lanka’s rainfall patterns have created four distinct climatic zones: wet, intermediate, dry, and arid zones (Alahacoon & Edirisinghe, 2021; Gunatilleke et al., 2008). We digitized the climatic zone maps from Alahacoon & Edirisinghe (2021), which included all four climatic zones (Fig. 2c). For our analysis, we combined the dry and arid zones into a single category. The consideration of Sri Lanka’s climatic zones is essential due to the resulting variations in ecosystems that support diverse and unique fauna and flora within each zone (Gunatilleke et al., 2008). These ecosystems exhibit varying levels of sensitivity to human activities and may respond differently to the same developmental interventions. Therefore, assessing the level of impact in each climatic zone is crucial for obtaining a comprehensive understanding of the potential threats to ecosystems.

LULC data

We obtained provincial-level LULC data from the Survey Department of Sri Lanka for all nine provinces for the year 2010. We checked the topology of all datasets in the form of overlaps, gaps, and various LULC types. These provincial-level layers were then

merged to produce a final LULC layer for the entire island. This final LULC layer had 13 categories: forest, scrub, grassland, coconut, other plantation, rubber, tea, chena, paddy, home gardens, built-up area, rivers, and canals (Fig. 1). Given the focus of our study on the impacts of land use change on natural habitats, we grouped the LULC categories of forests, nature reserves, scrublands, and grasslands into a single category labeled as natural habitats. This coverage of natural habitats in Sri Lanka includes but is not limited to the country's protected areas. Therefore, natural habitats and protected areas were considered separate variables for our analysis. We obtained spatial data on protected areas of Sri Lanka from the www.protectedplanet.net/country/LKA (UNEP-WCMC and IUCN, 2022) (Fig. 2d).

Methods

Baseline spatial statistical analysis

Initially, to establish the baseline information on the extent of each LI type, we performed calculations using the statistics function on the attribute tables of the geospatial data for each LI type. Then, using the intersect tool in ArcGIS Pro, the percentage length of each LI type that overlaps with the natural and protected area network was calculated. Since the road network was the most extensive LI network in Sri Lanka, additional analyses were performed on the road network. First, spatial patterns in road density were identified using the line density tool in ArcGIS Pro. The line density tool calculates a magnitude-per-unit area from polyline features within a radius around each cell (Esri, 2022b). Road layers were converted into a projected coordinate system to have the line density values in kilometers per square kilometer. Then, the tool's default settings return a raster layer with a line density value assigned to each cell. This analysis was performed for both road layers, i.e., national roads and all road layers.

Then, using a buffer zone surrounding the road network, we assessed the extent of land area influenced by roads. Previous studies on road effect zones have indicated a range of 100 to 5 km from the road (Benítez-López et al., 2010; Forman & Deblinger, 2000; Reijnen et al., 1995). Larger road effect zones, often spanning several kilometers, primarily consider

the impact on large mammals and environmental pollutants (Benítez-López et al., 2010; Forman & Deblinger, 2000). However, given the uneven distribution of biodiversity and variations in traffic volume across different roads in Sri Lanka, we opted for a standardized 1-km buffer to define the ecologically affected land area for each road.

Satellite image analysis (NDVI and NDBI)

To examine the patterns and relationship between vegetation and development in Sri Lanka, we calculated two ratio measures, NDVI and NDBI. NDVI calculates the normalized difference in reflectance between the near-infrared (NIR) and red bands of the electromagnetic spectrum (Kshetri, 2018), represented by the equation below:

$$\text{NDVI} = \left(\frac{\text{NIR} - \text{red}}{\text{NIR} + \text{red}} \right) \quad (1)$$

This index ranges between -1.0 and 1.0 , representing vegetation density and vigor. Areas with dense and green vegetation will produce values towards the positive end of the spectrum. In contrast, water, snow, and sparse vegetation will produce either negative or moderate values. This index is widely used in vegetation and land degradation studies for various applications, including agroecosystem resilience, land cover change, desertification, and vegetation burning (Roy & Yuan, 2007; Yengoh et al., 2014).

The built-up areas and bare soil reflect more shortwave-infrared (SWIR) than NIR. Therefore, the NDBI index is widely used to monitor urbanization, map urban built-up areas, and identify desertification (Zhao & Chen, 2005). NDBI is calculated using the following equation:

$$\text{NDBI} = \frac{(\text{SWIR} - \text{NIR})}{(\text{SWIR} + \text{NIR})} \quad (2)$$

It is used to emphasize manufactured built-up areas (He et al., 2010; Malik et al., 2019; Zhao & Chen, 2005). NDBI index values range between -1.0 and 1.0 , with negative values representing water bodies and higher values representing built-up areas. NDBI values for vegetation are low. Therefore, higher NDBI values represent a greater proportion of the built-up area.

Next, the average NDVI and NDBI values were calculated for each Divisional Secretariat Division (DSD), which is the second smallest administrative unit in Sri Lanka (Fig. 2c). The analysis was done at the DSD scale because about 90% of the road network in Sri Lanka is administered by provincial and local authorities such as provincial, municipal, and urban councils, except for the national road network. Furthermore, demographic information is also collected at the DSD level. In addition, development needs are often identified, planned, and executed within the country at DSD scale. Therefore, for the scope of this study, DSD level appeared to be the most appropriate scale to report results.

Geostatistical analysis

We conducted spatial autocorrelation (Getis Ord, G_i^*) to determine spatial clustering of average NDVI and NDBI values at the DSD level. The Getis-Ord G_i^* is a neighborhood-based statistic that identifies hot and cold spots by considering each NDVI/NDBI average per DSD within the context of all NDVI/NDBI averages in the neighborhood and determining whether and how the local pattern of NDVI/NDBI average in the neighborhood is statistically different from the global pattern of NDVI/NDBI average across all DSDs. The G_i^* statistics is a z-score, with statistically significant high G_i^* values representative of clustering or the presence of hot spots while cold spots represented by clusters of statistically significantly lower scores (Scott et al., 2016). Consequently, hotspots and cold spots indicate higher or lower vegetation cover or built-up areas, respectively, for NDVI and NDBI.

Finally, we conducted a multivariate clustering analysis to identify groups of natural habitats and protected areas similarly affected by LI. For this analysis, all data layers on all three LI types, natural habitats, and protected area network were used. First, the nearest distance from a given polygon to each LI type (i.e., roads, railroads, and powerlines) was calculated. Then, a multivariate clustering analysis was performed to identify natural groupings (Tullis-Joyce & Roy, 2021) based on the nearest distance to the three LI types and the area of a given natural habitat or protected area polygon. The Multivariate Clustering tool in ArcGIS Pro constructs nonspatial clusters. This tool uses either the K means or K medoids algorithm to partition features into clusters. To establish the suitability of a given number of clusters, we used summary statistics by clusters for the grouping output. Each cluster contains polygons affected similarly by the three different LI and their combinations. All the above analyses were conducted using ArcGIS Pro 3.0. (Esri, 2022a) and JMP statistics software (SAS Institute Inc., 2019).

Results

Baseline spatial statistics

Roads are the most pervasive LI type in Sri Lanka, followed by powerlines and railroads (Table 1). However, in comparison to the network’s total length, powerlines were the most extensively spread LI type in protected areas and natural habitats (21.43% and 27.47% of the network are within protected areas and natural habitats, respectively), followed by railroads (14.43%—protected areas

Table 1 The extent of linear infrastructure network through protected and natural habitat areas of Sri Lanka. Percentages of total network length are indicated in parentheses. Geospatial data sources: from the Road Development Authority of Sri Lanka and the National Physical Planning Department of Sri Lanka

LI type	Total length (km)	Protected areas	Natural habitats
Roads (all categories)	92,342.35	11,026.04 (11.94)	4695.12 (5.08)
National roads	12,429.82	1011.09 (8.13)	1264.56 (10.17)
Class A	4186.35	398.60 (9.52)	441.03 (10.53)
Class B	7759.82	608.26 (7.84)	794.92 (10.24)
Expressways	483.65	2.12 (0.44)	23.16 (4.79)
Provincial roads (jeep tracks and local roads)	79,912.53	10,014.95 (12.53)	3430.56 (4.29)
Railroads	1391.02	200.75 (14.43)	299.46 (21.53)
Powerlines	1910.39	409.32 (21.43)	524.71 (27.47)

and 21.53%—natural habitats) and roads (11.94%—protected areas and 5.08%—natural habitats). The detailed analyses of the road network revealed that the road density in Sri Lanka ranges between 0.01–1.16 km/km² and 0.01–8.99 km/km² for national and all road networks, respectively. Even though the national road network had a comparatively lower road density across the island, it showed a greater number of distinct high road–density spots than for the all road layers. The main high road–density areas that were discovered in this study include Colombo, Gampaha, Kandy, and Jaffna. All roads layer showed similar patterns but with greater road density values. For this layer with provincial/local roads, the highest road density was reported in the northern part of the country, for Jaffna and Kilinochchi. Notably, the high road–density areas were wider for provincial/local roads than for the national roads (Fig. 3).

Over 80% of the total land area of Sri Lanka falls within 1 km of either a national or a provincial/local road. Considering only the national road network, about 30% of the total land falls within a 1-km distance of a road. The percentage of natural habitats and protected areas within a 1-km buffer of any road is 64.96% and 56.01%, respectively, whereas the proportions for the same habitat categories are 13.55% and 10.29%, respectively, for the national road network. Figure 4 shows the segments of each LI type that traverse either a natural habitat or a protected area.

Spatial patterns of LI network, NDVI, and NDBI

The results of spatial autocorrelation analysis identified several hotspots and coldspots comprising multiple DSDs with significantly high and low averages for NDVI and NDBI indices (Fig. 5). Of the total 331

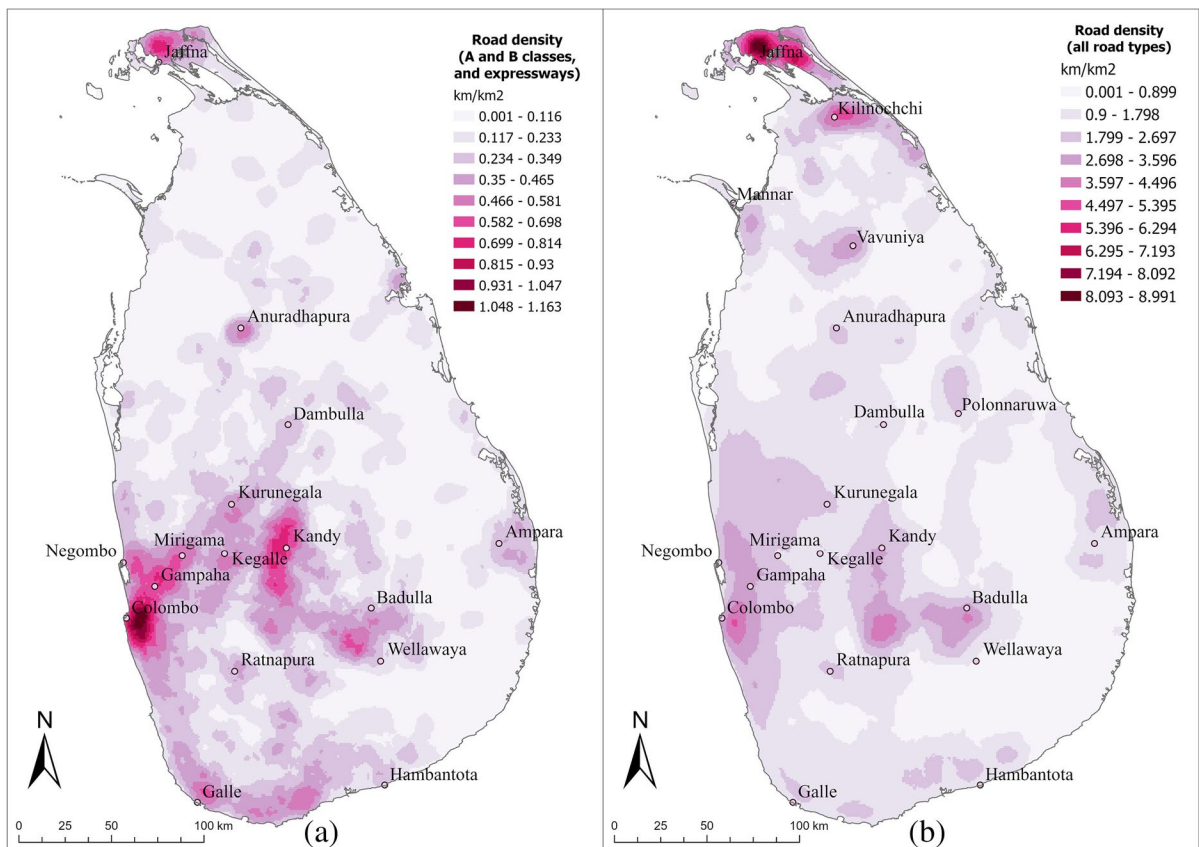


Fig. 3 Results of line density analysis for **a** national road network (class A, B, and expressways) and **b** all roads network (class A, B, expressways, and provincial roads)

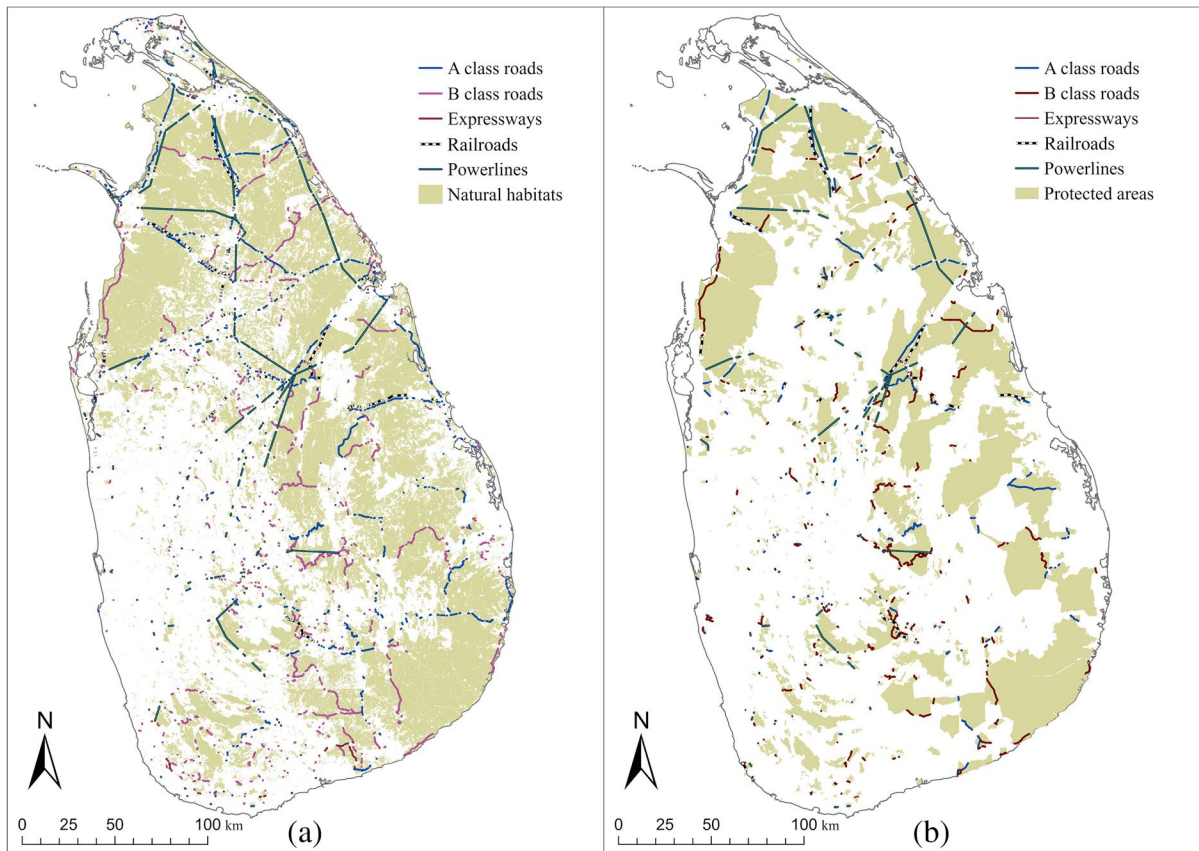


Fig. 4 Areas of overlap between linear infrastructure and **a** natural habitats, and **b** protected areas of Sri Lanka

DSD units, 99 were included in the NDVI hotspots, while 73 were included in the coldspots. These values for NDBI hotspots coldspots layer were 88 and 98 DSDs, respectively. Over 80% of hotspots and coldspots for NDVI overlapped correspondingly with coldspots and hotspots of NDBI. Average NDVI and NDBI values at the DSD level showed a significant negative correlation ($R^2 = 0.82, p = 0.000$), further suggesting a general trend of having lower average NDVI in DSDs with high built-up areas.

In addition, it was revealed that the overlap of the protected area network with NDVI hotspots was less than 20%. Home gardens and tea and rubber plantations were the primary land use types that were found within areas with significantly high vegetation reflectance. Nearly 90% of the DSDs that formed NDVI hotspots are within the wet and intermediate zones. Regarding NDBI hotspots, it was revealed that they also overlapped with high road-density areas within the country. Two regions, one in the western province

where the country’s capital is located, and the other in the northern province, were highlighted as the most distinct overlaps. Of all the climatic zones, the country’s wet zone had the overall highest NDVI and road densities.

Clustering of habitats impacted by LI

Multivariate cluster analysis identified four clusters for each vector layer that covered all natural habitats and protected areas. Based on summary statistics for each cluster (mean, minimum, and maximum of nearest distance to each LI type), each group was labeled by the LI type/s most closely located to polygons in each vector layer (Table 2; Fig. 6). The overall analyses revealed five distinct categories. Three of these categories were common among cluster results for both natural habitats and protected areas, i.e., polygons affected by (1) all LI types, (2) roads and railroads, and (3) roads and powerlines. In addition to the

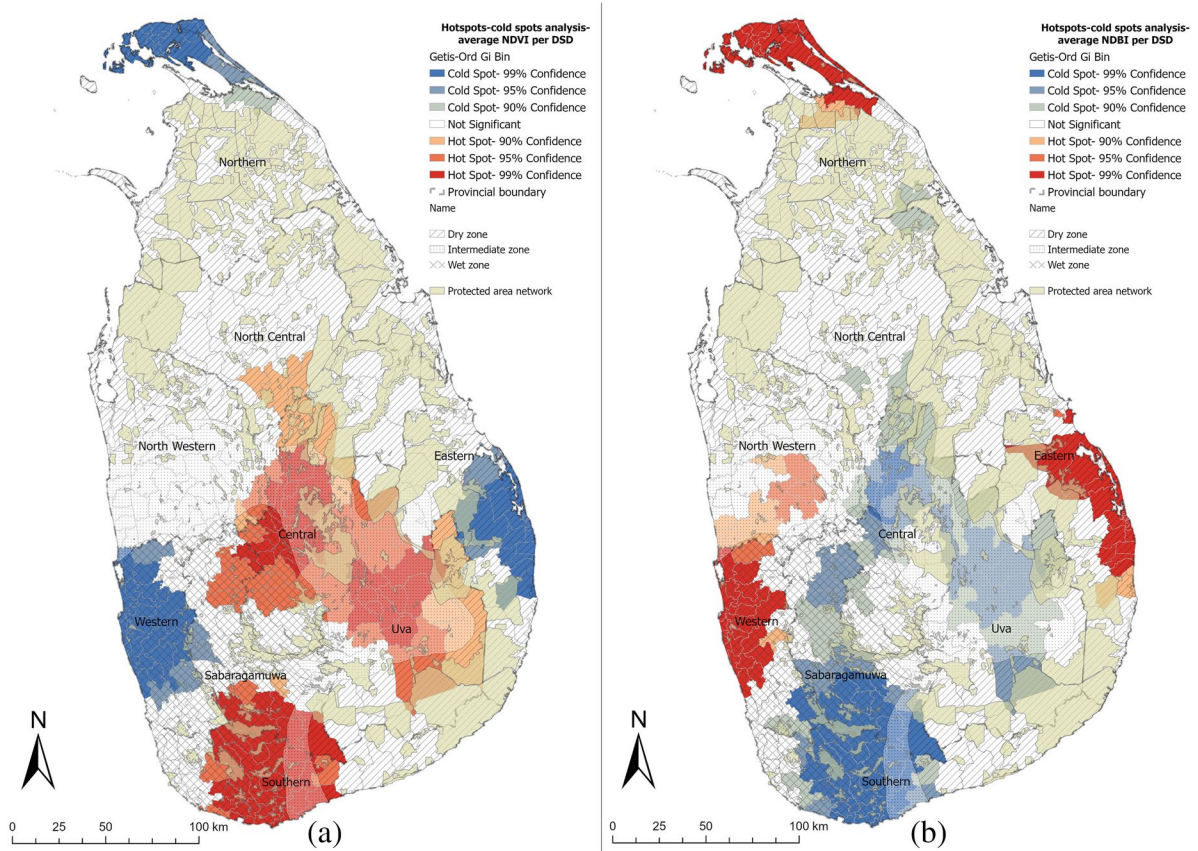


Fig. 5 Results of spatial autocorrelation analysis for **a** normalized difference vegetation index (NDVI) and **b** normalized difference built-up index (NDBI) averages per Divisional Secretariate Division

Table 2 Descriptive statistics on the area of polygons in non-spatial clusters resulting from the multivariate cluster analysis. These clusters comprise protected and natural habitat area polygons that are similarly affected by different types or combinations of linear infrastructure (LI). The clustering of polygons

is based on the nearest distance to a specific LI type and the area of each polygon. All polygons within a particular category are impacted similarly (due to their close proximity) by the LI types specified in their category name

Category	Total (km ²)	Mean (km ²)	Minimum (km ²)	Maximum (km ²)	% of total protected/natural area
Natural habitats					
All LI	17,063.01	1.43	0.000	343.96	59.00
Roads/railroads	5994.39	2.15	0.000	609.18	20.73
Roads/powerlines	3400.51	1.04	0.001	306.04	11.76
Powerlines/railroads	2462.44	1.00	8.69	168.97	8.51
Protected areas					
All LI	11,561.83	27.07	0.001	1312.81	51.57
Roads/railroads	5760.87	71.12	0.06	1428.01	25.70
Roads/powerlines	4954.16	52.15	0.03	518.49	22.10
Powerlines	141.64	10.12	0.09	54.22	0.63

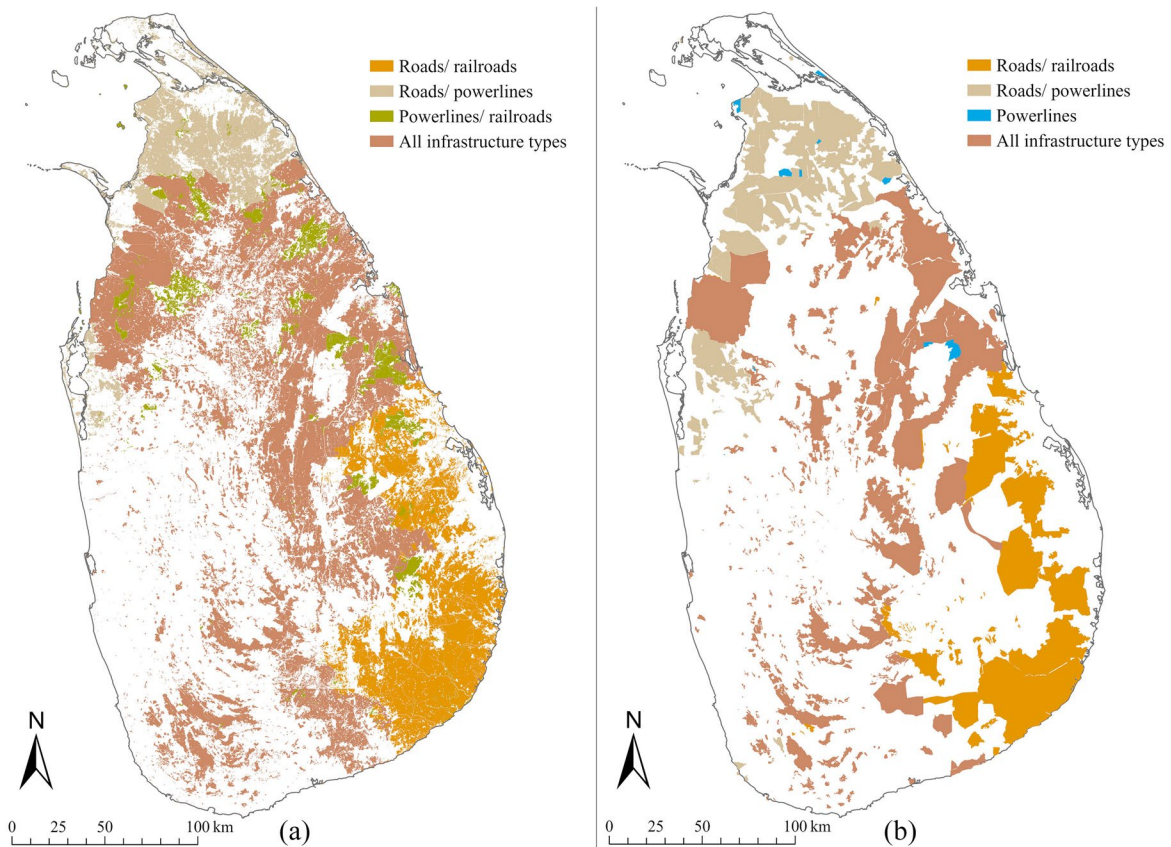


Fig. 6 Clusters identified by multivariate cluster analysis for **a** natural habitats and **b** protected areas

above three categories, natural habitats and protected areas had a fourth cluster that was not shared between the two sets of clusters, i.e., polygons close to powerlines only, and powerlines and railroads, for protected areas and natural habitats, respectively. Over 50% of the natural habitats and protected areas got selected as being affected by all three LI types (Table 2). Among the three types of LI, roads were found in three out of the five clusters, indicating their prevalence as the primary LI type in proximity to natural habitats and protected area networks.

Discussion

The objective of this study was to provide an extensive understanding of the current status of roads, railroads, and powerline networks in Sri Lanka and their impact on the natural habitat. The study found that roads are the most widespread LI type in Sri Lanka.

However, powerlines were the most common linear intrusion in forested areas concerning the total length of the network. This finding supports the commonly held belief in Sri Lanka that powerlines are mostly installed over wilderness areas to avoid human settlements and minimize potential human exposure to electromagnetic fields (Hewavithana, 2022).

Different types of LI have varying impacts on the environment. Roads and railroads can contribute to animal-vehicle collisions, impede animal movement, facilitate the spread of invasive species, alter predator-prey interactions, and cause environmental pollution from moving vehicles (Forman & Alexander, 1998; Forman et al., 2003; van der Ree, et al., 2015). On the other hand, powerlines, although not involving any moving objects, can be equally harmful during both the construction and operational phases (Bagli et al., 2011). For instance, the fragmentation effects created by clearing the habitat for accessing and establishing the powerline corridor may last as

long as the powerline is in place (Biasotto & Kindel, 2018). Furthermore, powerlines can act as a physical barrier for individuals, leading to bird collisions and electrocution (Pruett et al., 2009; Raab et al., 2011).

Our study revealed that over 80% of the total land area of Sri Lanka is accessible to humans within 1 km of either a national or a provincial/local road. Using only the national road network, the amount of accessible land is about 30% of the island. Similar analyses have reported that nearly 80% of the land in the conterminous United States is within 1 km of a road of any type (Riitters & Wickham, 2003), while 50% of the European continent is estimated to be within 1.5 km of either a paved road or a railroad (Torres et al., 2016). It is alarming that Sri Lanka, an island nation with an emerging economy, has reached comparable road densities to that in large and economically developed countries. Therefore, our study recommends avoiding the construction of new roads that would contribute to further fragmentation and instead suggests exploring options for establishing infrastructure along existing features to mitigate the environmental impact of LI development. This approach is in line with recent research advocating for the integration of transportation and conservation planning to promote sustainable development (Nayak et al., 2020).

Our findings highlighted the importance of re-evaluating national conservation targets and making plans for development and conservation accordingly. For example, results from the NDVI, NDBI, and line density analyses collectively demonstrated that the country's wet and intermediate zones harbor healthy vegetation but also, at the same time, are experiencing a higher level of anthropogenic impacts. For Sri Lanka, the country's richest biodiversity is found in the wet and intermediate zones (Gunatilleke et al., 2008). In addition, the wet and intermediate zones of the country had a greater number of high road-density sites than the dry zone. However, it was also noted that this healthy vegetation is present mainly in home gardens and plantations. Studies that have been conducted on the use of Sri Lankan home gardens in maintaining the agricultural and environmental sustainability of the country have revealed that even though such land uses are important for biodiversity conservation they should not be considered as a replacement for natural habitats (Pushpakumara et al., 2012). Therefore, we recommend including more natural land units from the wet and intermediate zones of

the country in the national protected area network. A higher level of protection for these critical habitats would ensure that they are not affected by LI development due to a lack of protection. In addition, for areas with highly fragmented natural forests, attempting to connect these forest patches via home gardens would help reduce the impact of fragmentation.

As outlined in the national physical plan for Sri Lanka, the country's dry zone will also receive unprecedented development by 2050, including several large-scale LI projects (National Physical Planning Department, 2019). Consequently, it is essential to actively prioritize habitat connectivity and the mitigation of LI's impact on the natural environment within the dry zone. This approach aligns with research indicating the need to effectively separate busy roads from nature reserves, ensuring that upcoming transportation systems facilitate not only safe human mobility but also ecological flows and biodiversity preservation (Forman & Deblinger, 2000). Furthermore, the dry zone in Sri Lanka serves as a habitat for many of the large faunal species found in the country, such as the Asian elephant (*Elephas maximus*), leopard (*Panthera pardus kotiya*), and sloth bear (*Melursus ursinus inornatus*). Fahrig & Rytwinski (2009) review underscores that species with large home ranges and low reproductive rates are often adversely impacted by roads, an observation mirrored by Poessel et al.'s (2014) consistent findings that bobcats avoid roaded areas in their home-range selection. Therefore, we recommend devoting special attention to maintaining habitat connectivity within Sri Lanka's dry zone when choosing sites for LI placement and upgrades, ensuring the region's ecological sustainability.

Results from the multivariate cluster analysis conducted in this study provide a bird's eye view of the impact of LI on Sri Lanka's natural habitats and protected area network. These results offer valuable insights for planners to inform future LI development decisions. By identifying areas with high LI impact, planners can avoid those locations and instead focus on utilizing existing LI to minimize the need for new constructions. One approach to achieve this is through the implementation of "traffic calming" strategies, which involve redirecting traffic from rural areas to trunk roads. This may involve downgrading or closing some existing roads, while upgrading others to achieve the desired traffic reduction (Coffin et al.,

2021; Jaarsma & Willems, 2002). Given that Sri Lanka is an island nation with limited land resources, such considerate measures are imperative to mitigate the diminishing land availability caused by rapid development.

Furthermore, this information is crucial for conducting comprehensive environmental impact assessments of LI projects. Traditional environmental impact assessments have often been criticized for their narrow focus on direct impacts and the presence of specific species (Söderman, 2006; Thompson et al., 1997). Therefore, we strongly recommend adopting a “big picture scenario” approach when proposing new LI developments, considering the cumulative impact on the environment. This holistic perspective will ensure that environmental impact assessments adequately address the broader ecological consequences of LI projects.

Conducting studies on the impact of LI on natural habitats and protected areas requires reliable and up-to-date data. The support of LI development and conservation agencies is essential to ensure that such data is readily available. By receiving strong support from these agencies, studies could produce more precise results. Additionally, to make these research efforts more useful for local decision-making, it is crucial to emphasize the importance of data sharing and local collaborations. These measures could facilitate the implementation of effective conservation and development policies, leading to sustainable growth in countries like Sri Lanka.

Conclusions In conclusion, our study highlights the significant impact of LI on biodiversity hotspots like Sri Lanka and emphasizes the necessity for a landscape approach to mitigate its environmental impact while simultaneously achieving development goals. The methodology used in this study can serve as a guideline for initial assessments of high impact areas to inform future infrastructure planning and habitat defragmentation efforts. The dominance of roads in Sri Lanka’s LI network is a cause for concern, with over 80% of the land falling within 1km of either a national or provincial/local road. Furthermore, the finding that powerlines are the most common type of LI within protected areas in proportion to their total length underscores the need for increased awareness and monitoring of their spread. Overall, the study emphasizes the importance of sustainable

development practices to safeguard the ecological health of tropical ecosystems.

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Author contribution Dishane K Hewavithana: conceptualization, data curation, writing—original draft preparation, formal analysis. Devaka K. Weerakoon: conceptualization, writing—review and editing, validation. Shouraseni S. Roy: conceptualization, supervision, methodology, writing—review and editing, visualization.

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Data availability We utilized publicly available satellite images with the source link provided in the methods section. The LI network geospatial data and land use land cover data were obtained from the Road Development Authority and the National Physical Planning Department of Sri Lanka, respectively, with their permission for educational purposes. As a result, these data are subject to availability restrictions and are not publicly accessible. However, upon reasonable request and with the approval of the respective authorities, the data can be obtained from the authors. The published article includes all the other data generated or analyzed during this study.

Declarations

Competing interests The authors declare no competing interests.

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