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Spatio-temporal Analysis of Land Use/Land Cover Changes in Urban Forest Ecosystem

A Case Study of Delhi Ridge Forest

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Abstract: Urban green spaces play a substantial role in alleviation of multiple environmental challenges caused by intensified urbanization. However, urban forests themselves are prone to degradation from unsustainable human activities. The forests of Delhi Ridge provide myriad of essential ecosystem services to the citizens of Delhi, though it is under immense anthropogenic pressure. This study is carried out for identifying the overall land use/land cover dynamics in the four different parts of Delhi Ridge in light of rampant urbanization in the area. Variations were estimated for the period of three decades (1989-2020) with the intervening gap of 5 years and Landsat data has been analyzed for this period. All the four parts of Delhi Ridge exhibit overall increase in the green cover with maximum percentage change in area in moderately dense forest class has been observed in Central Ridge (494.31%). On the contrary, there is also an increase in built-up area at the boundaries and also within the Ridge forest depicting severe human interference with maximum percentage change in built-up observed in Southern Ridge (339.28%). The present study provides baseline information on the spatio-temporal changes observed in the Delhi Ridge forest and also highlights the impact of urbanization. Such findings hold substantial implications in framing rational urban policies for ensuring long-term conservation of the fragile habitat of Delhi Ridge forest.

1. INTRODUCTION

Urbanization has become a global trend sustaining large human populations (Cohen, 2006). With enhanced industrialization and booming employment opportunities, urban centers have seen an unprecedented influx of populations from rural areas (Avtar, Tripathi et al., 2019). Proliferation in the urbanization phenomenon has put pressure on natural ecosystems within and periphery of the urban centers (Mundia and Murayama, 2010). Besides this, urban areas are prone to myriad of environmental problems ranging



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from air, water soil and noise pollution, urban heat island effect, greenhouse gas emission to land degradation, ground water depletion etc. ([Livesley, McPherson et al., 2016](#); [Uttara, Bhuvandas et al., 2012](#)).

Planners, policymakers and conservationists across the globe stress on the need for the inclusion of urban green spaces in integrated sustainable development models and action plans ([Sturiale and Scuderi, 2019](#); [Vargas-Hernández, Pallagst et al., 2018](#)). Urban forests play a pivotal role in sustaining biodiversity, groundwater recharge, pollution mitigation, carbon sequestration, recreational & aesthetic benefits along with providing other ecosystem services in urban landscapes ([Heidt and Neef, 2008](#); [Hirokawa, 2011](#)). Alike the global perspectives, Indian cities are also increasingly realizing the importance of urban greens in maintaining the environmental balance ([Ramaiah and Avtar, 2019](#)). However, the growing human population and developmental activities have transgressed into these urban forests causing their degradation and fragmentation, altering the overall habitat quality and the tendency of ecosystems to produce various goods and services ([Haddad, Brudvig et al., 2015](#); [Matthews, 2014](#)). An analytical examination of these anthropogenic drivers of change is thus crucial to find out the magnitude of degradation of natural ecosystems ([Das and Das, 2019](#)).

Forest ecosystems are quite dynamic in nature with large-scale variations in productivity and soil dynamics based on temperature, precipitation, etc. Tropical forests are a storehouse of biodiversity and provide habitat for a myriad of wildlife, however, they are negatively impacted by urbanization effects. Land use/land cover (LULC) analysis is one of the essential methods to determine and document the on-ground variations in vegetation cover and anthropogenic activities over a period of time ([Smith, 2003](#); [Thakur, Patel et al., 2020](#)). Advancements in GIS and related technologies have proved quite effective in real-time monitoring of changes and disturbances over a large area ([Rawat and Kumar, 2015](#)).

Several studies examined the variations in land use/land cover brought by rapid urbanization ([Al-Rashid, Nadeem et al., 2021](#); [Alzamili, El-Mewafi et al., 2015](#); [Ha, Tuohy et al., 2020](#); [Han, H. and Lin, 2017](#); [Mbereggo and Li, 2017](#); [Yilmaz and Terzi, 2020](#)). LULC studies are effective in providing valuable data needed for the assessment of qualitative and quantitative changes brought by human activities that have an adverse bearing on the forest ecosystems and biodiversity ([Cheng, Chen et al., 2019](#); [Kumne and Samanta, 2019](#); [Sharma, Chaudhry et al., 2017](#); [Srivastava, Singh et al., 2020](#)). [Hadagha, Farhi et al. \(2021\)](#) investigated the impact of urbanization on palm groves and desert oasis ecosystems while [Phan, Trung et al. \(2021\)](#) reported a tenfold increase in urban areas across Vietnam which came at the expense of the productive agricultural ecosystem. Some researchers have also used GIS as a tool to quantify the negative impact of urbanization on ecosystem services such as carbon sequestration ([Han, Y., Kang et al., 2018](#)), impact on land surface temperature ([Hussain and Karuppanan, 2021](#)) and habitat quality ([He, Huang et al., 2017](#)). Therefore, critical analysis of trends and status of urban ecosystems can help in shaping management framework and formulation of sustainable urban policies ([Aksoy, Dabanli et al., 2022](#)).

In India, the assessment of the impact of urbanization on land use/land cover dynamics has attracted substantial interest from researchers ([Bhat, ul Shafiq et al., 2017](#); [Pawe and Saikia, 2018](#); [Prabu and Dar, 2018](#)). [Ahmad, Goparaju et al. \(2017\)](#) carried out LULC analysis of Ranchi city, India using Markov chain predictive model which predicted that there will be 43% more urban expansion for the city in 2028 as when compared to the year 2015.

[Paul, Saxena et al. \(2021\)](#) studied the urban expansion in peripheral regions of the Delhi region to find that an annual urban expansion rate of 38.64% has largely occurred in the scrubland of these areas. On the other hand, very few studies are available that quantify the impact of urbanization on urban green spaces ([Dinda, Chatterjee et al., 2021](#); [Rao and Puntambekar, 2014](#)).

The capital of India- Delhi has seen a high rate of urbanization due to an increase in population pressure. The population of Delhi rose by 21.20% in between 2001 and 2011 ([Economic Survey of Delhi, 2018-19](#)). Delhi Ridge forest is an important natural ecosystem of the city. However, the forest of Delhi Ridge is under multiple pressures that include rapid urbanization, biological invasion by invasive species, conversion of forests into parks and introduction of non-native ornamental species, building of infrastructure-roads, metro rail line etc., dumping of construction waste, illegal encroachments etc. From the above perspective, it is essential to determine how the Delhi Ridge forest ecosystem is changing so that the findings can be integrated with decision-making and sustainable urban planning. The main objectives of this study are:

- To analyze the spatio-temporal changes in vegetation pattern of the Delhi Ridge.
- To determine drivers of change and also how expanding urbanization has impacted the region.

The present study is aimed to analyze key changes in Delhi Ridge from 1989 onwards when large-scale industrialization and infrastructure building were given administrative and policy push in the city. The supervised classification of satellite imageries is used to determine the changes in vegetation structure and also to recognize the key factors and driving forces that are causing LULC changes within and in periphery regions of Delhi Ridge forest. Moreover, the relation between classes is interpreted especially with built-up for deriving a general overview. The key findings of this study will have positive implications on the long-term management of the Delhi Ridge forests especially in minimizing the impact of urbanization through policy interventions.

2. STUDY AREA

Delhi, the capital city of India, is one of the fastest growing urban conglomerations in the world with a population of nearly 20 million. The city lies in the subtropical zone with a semi-arid climate, having a short cold season and a long dry, hot season with moderately low annual rainfall (711cms) occurring predominantly in Monsoons which last from July to September.

Delhi has a rich historical legacy and has two distinct natural ecosystems- River Yamuna and Delhi Ridge. Delhi Ridge (*Figure 1*) is an extension of Aravalli Mountain Range- one of the ancient mountain chains of the world with an age of 1.5 billion years old. With its total length of 35 Kms, Delhi Ridge lies between 28° 12' and 28° 53' North and 76° 50' and 77° 23' East spanning from the Bhatti Mines area located in southeast Delhi to the Wazirabad area in Northeast Delhi. The geology of the region mainly comprises of quartzite stone, arkosic grit and micaceous schist ([Sharma, Chaudhry et al., 2017](#)).

Delhi Ridge was once more or less contiguous from Southeast to Northeast but because of the burgeoning population (*Table 1*) and enhanced urbanization, Ridge at present is divided into four distinct fragments-

Northern Ridge (87 hectares), Central Ridge (864 hectares), South Central Ridge (626 hectares) and Southern Ridge (6200 hectares). Most of the Ridge falls under the category of the reserved forest, however, it is managed by multiple Government agencies including Forest Department, Delhi Development Authority (DDA), Municipal Corporation of Delhi (MCD), Army etc. The major part of Southern Ridge is protected through Asola Bhatti Wildlife Sanctuary which was carved out in the year 1986. Some parts of Southern Ridge were mined for extracting feldspar and red morrum used in building construction, however, this detrimental practice has now been stopped completely.

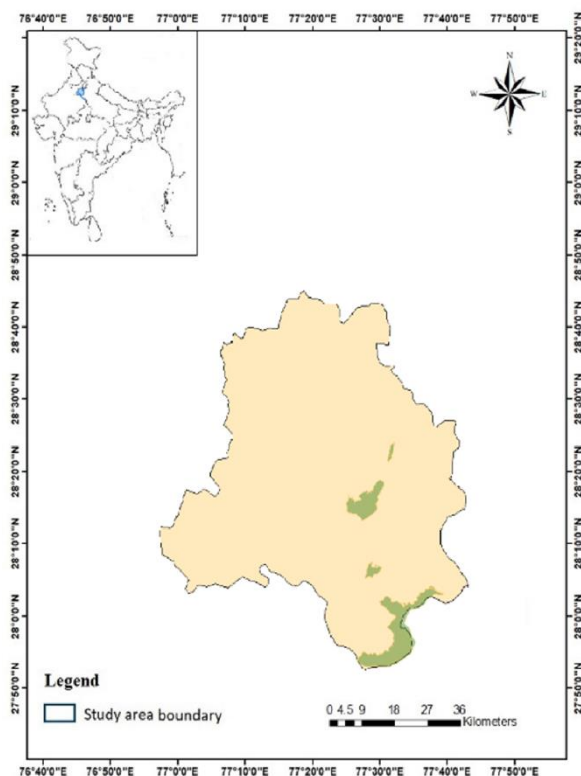


Figure 1. Map of India and Delhi showing location of four segments of Delhi Ridge

The main vegetation of Delhi Ridge is a tropical dry thorn forest with the predominance of *Acacia* sp. and other thorny species ([Champion and Seth, 1968](#)). The dominant native tree species of this area are *Acacia catechu*, *Acacia modesta*, *Acacia leucophloea*, *Acacia senegal*, *Diospyros montana*, *Balanites aegyptiaca*, *Wrightia tinctoria*, *Butea monosperma*, *Prosopis cineraria*, *Salvadora persica* and *Ehretia laevis*. One of the characteristic tree species of Aravalli forest -*Anogeissus pendula*, known to form pure patches in rocky cliffs, was once abundant throughout the Delhi Ridge but now this species is in retreat and only a few patches of *Anogeissus* forest can be found in the southern part of Delhi Ridge. The main shrub species present in the Ridge are *Adhatoda vasica*, *Capparis sepriaria*, *Maytenus senegalensis*, *Carissa spinarum*, *Zizyphus nummularia* and *Grewia tenax*.

Table 1. Decadal Population growth and % growth (1981-2011)

Year	Population (in millions)	Growth in Percentage
1981	6.220	53.00
1991	9.421	51.45
2001	13.851	47.02
2011	16.788	21.20

Most of the Ridge forest is an open type with a predominance of grasses and herbs during the rainy season. However, an invasive tree species called *Prosopis juliflora* from South America, has come to dominate the entire vegetation of Delhi Ridge. At present, all the four parts of Ridge are infested with *Prosopis juliflora* (Sharma and Chaudhry, 2018; Sinha, 2014). Several studies have reported that *Prosopis juliflora* depict allelopathic effect, affecting the growth and establishment of native species in invaded areas (El-Shabasy, 2017; Mahdhi, Tounekti et al., 2018). Another tree species from South America called *Leucaena leucocephala* is spreading fast in parts of Delhi Ridge. A global invasive shrub – *Lantana camara*, has also formed dense thickets in the area. Entire Northern Ridge and parts of South-Central and Southern Ridge which fall under the jurisdiction of Delhi Development Authority are now being developed as Kamla Nehru Biodiversity Park, Aravalli Biodiversity Park, Neela Hauz Biodiversity Park Tuglakabad Biodiversity Park and Tilpath Valley Biodiversity Park (Delhi Biodiversity Foundation D.D.A., 2021). Here invasive *Prosopis juliflora* is removed and native flora of Ridge is being re-introduced for ecological restoration of the area. Active plantation of native tree species is also undertaken by Forest Department, especially in Southern Ridge. (Delhi State Action Plan on Climate Change, 2019; Sharma and Chaudhry, 2018; The Indian Express, 2017a).

3. MATERIALS AND METHODS

For studying the dynamics of changes in the vegetation of urban green spaces and expansion of the built-up, a study of LULC changes is required through satellite images. The methodological framework of this study encompasses two main parts. The first part monitors the forest cover area through spatiotemporal analysis using remote sensing and GIS. This involves data collection, image pre-processing, image classification, accuracy assessment followed by map generation and change detection. The second part discusses the relationship between LULC classes and drivers of changes in forest cover. The detailed overview of the research flow is represented in Figure 2.

Satellite data of Landsat MMS, Landsat TM, Landsat ETM+ and Landsat OLI have been used to estimate the status of forest cover after every 5 years i.e., 1990,1995,2000,2005,2010,2015 and 2020. The main criteria behind this are to derive and analyze the changes in the vegetation pattern that may occur in an urban forest located amidst high human pressure. The spatial resolution of Landsat data is 30m*30m and has path 146/row 40. These satellite images are freely available and have been downloaded from USGS website (<http://earthexplorer.usgs.gov/>) for the month of October-November to determine spatiotemporal variations in forest coverage.

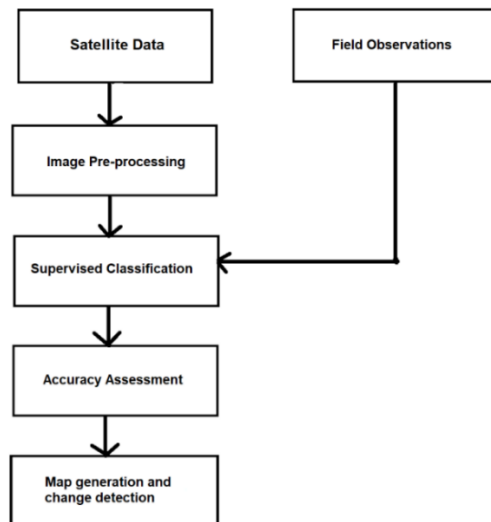


Figure 2. Flow chart of methodology used in LULC analysis of Delhi Ridge Forest

Topographic maps of the study area were obtained from the Geological survey of India of scale 1:50000. These maps were georeferenced to the Universal Transverse Mercator (UTM) coordinate system and digitized to create a shapefile, which was further used for sub-setting the area of interest (AOI) from the image. Some part of surrounding areas was also included in the study to determine the magnitude of changes caused by human interference. Pre-processing of images includes creating a standard False colour composite (FCC) by over-layering the proper band combinations and image enhancement to increase the quality of images (Bera, Saha et al., 2020).

Satellite image classification is required to classify the image into several categories (Dinda, Chatterjee et al., 2021). In this study, pixel-based supervised classification was applied to classify the images into seven different land use land cover classes/land type classes namely- Moderate dense forest, open forest, scrub, build up & human settlement, water bodies and open area. A new class-mining affected area was used exclusively for LULC analysis of Southern Ridge as the area was subjected to mining. The advantage of using supervised classification with a maximum likelihood classification algorithm is that it is more accurate as it considers several training sites for each land type category (Rahman and Sumantyo, 2010). The field observations bring out important reference data for recognizing land types. The description of classes is given in Table 2. The output of this was used to generate land use land cover maps of all the four parts of Delhi Ridge and to determine the class-wise area from the images. After classifying the maps, the Raster Calculator tool was used to compute class-wise areas.

Table 2. Description of classes used in LULC Analysis

Class name	Description of class
Moderately Dense Forest	Forest with tree canopy density above 40 percent but less than 70 percent
Open Forest	Forest with tree canopy density between 10 and 40 percent
Scrub	Area with sparse vegetation and less than 10 percent tree canopy density
Built-Up and Human Settlement Water Bodies	Urban Areas, Rural Areas, Farmhouses Natural & Artificial ponds/lakes
Open Area	Area with very low or no vegetation, rocky outcrops, barren land, abandoned land, stone processing areas etc.
Mining affected area	Mining Activities, Stone Quarries

To compute the rate of change in the forest coverage after every five years, a comparative analysis was done on the classified images that illustrate the net transformation taken place over time. The LULC maps of four ridges are shown in *Figure 3 to 6*. The mean overall accuracy and kappa analysis came out to be in the range of 0.84 to 0.90 respectively. The study was also supplemented with correlation analysis between the area obtained for various LULC classes to derive the positive and negative relationship between them.

4. RESULTS

The variations observed in vegetation pattern are analyzed and the driving forces that result in LULC changes in Delhi Ridge forest have been identified through spatio-temporal analysis. Several changes have been observed in all the four parts of Delhi Ridge over the period of three decades (1989-2020). The spatial extent of the moderately dense forest has shown an incremental trend in all the four areas with the maximum percentage change in the area being observed in Central Ridge (494.31%). The ongoing and past plantation activities combined with protection of this region from illegal cutting through fencing, boundary walls and enhanced patrolling by various land-owning agencies namely- Forest Department, Delhi Development Authority (DDA), Municipal Corporation of Delhi (MCD), Delhi Biodiversity Foundation etc., has been instrumental in increasing the forest cover. However, the dominant tree species in all the four regions of Delhi Ridge is *Prosopis juliflora* which is an invasive alien species in this region and forms a majority of the vegetation cover ([Sharma, Chaudhry et al., 2017](#); [Sinha, 2014](#)). On the flip-side, a decreasing trend was observed for open forest and scrub forest in these three decades. A similar trend is observed in the case of the built-up area indicating a steady increase in human-induced activities in and around the Delhi Ridge area.

4.1 Northern Ridge

In 1989 (*Figure 3, Figure 4 and Table 3*), scrub and open forest predominates the forest cover in the Northern Ridge covering 29.50% and

31.81% of the total area respectively while area under moderately dense forest was 21.72%. By 1995, there is slight decrease in scrub and open forest and moderately dense forest increased upto 25.26%. From year 2000, there is steady increase in moderately dense forest. In 2020, moderately dense forest has covered 57.35% of the total area. On the other hand, open forest and scrub has decreased from 1989 to 2020 especially scrub which has come down to occupy 5.74% in 2020. The area under open forest has also shown continuous decline with 31.81% in 1989 to 18.34% in 2020.

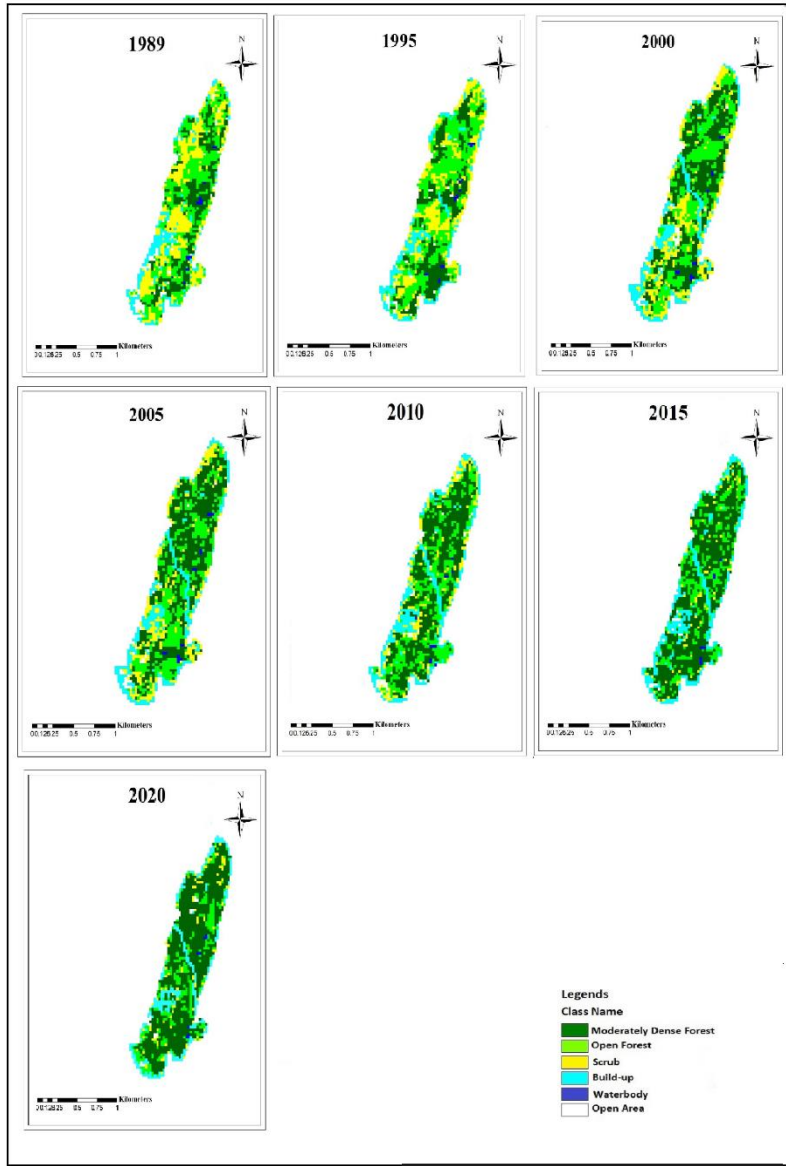


Figure 3. LULC Variations in Northern Ridge

The area under built-up has increased steadily from 12.01% in 1989 to 16.41% in 2020. The area is crisscrossed by several roads now. Our study has also shown that there is decrease in water bodies from 0.91% to 0.48% in 2015 although it has remained steady from there till 2020. The similar trends can be observed in the case of open area.

As mentioned earlier, Northern Ridge is the smallest among all parts of Delhi Ridge and also surrounded by dense human habitation. It has been found that some parts of the area had been converted into park with walking path and other amenities for visitors in the past. However, in 2015, Northern

Ridge has been designated as a Biodiversity Park and now the focus is to ecologically restore this area through native plants and also to ensure rain water harvesting and regeneration of aquifers ([Delhi Biodiversity Foundation D.D.A., 2021](#)).

Table 3. Changes in LULC classes year wise in % for Northern Ridge

Class	Year						
	1989	1995	2000	2005	2010	2015	2020
Moderately Dense Forest	21.727	25.268	35.247	40.075	42.543	52.629	57.350
Open Forest	31.813	30.579	27.521	26.824	26.395	23.176	18.348
Scrub	29.506	28.916	19.742	15.612	11.856	5.526	5.740
Built-Up	12.017	12.232	15.075	15.075	16.899	16.524	16.416
Water Body	0.912	0.912	0.751	0.805	0.590	0.483	0.483
Open Area	4.024	2.092	1.663	1.609	1.717	1.663	1.663
Total Area (Sq. Kms.)	1.67						

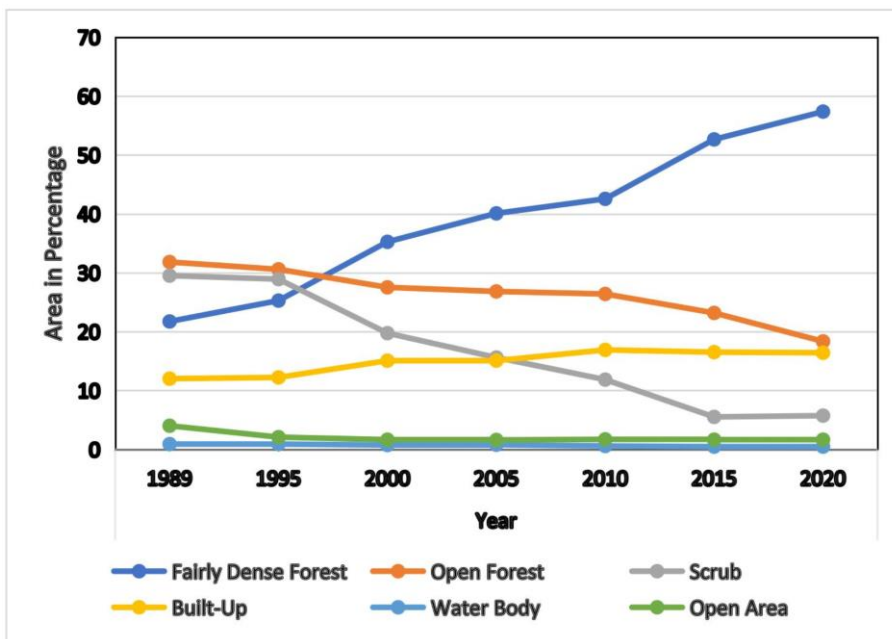


Figure 4. Graph showing changes in area (in percentage) for various LULC classes for Northern Ridge

4.2 Central Ridge

Figure 5, Figure 6 and Table 4 shows the land-use changes observed in the Central Ridge area. As observed in Northern Ridge, scrub and open forest was seen as the dominant form of vegetation in the Central Ridge in the year 1989 with each covering 40.04% and 37.47% respectively. A rapid decline in the area under the scrub category was observed which was found to be 39.17%, 23.55, 18.54%, 17.31%, 16.40% and 11.16% for the years 1995, 2000, 2005, 2010, 2015 and 2020 respectively. At the same time, a rapid increase in moderately dense forest was observed which incremented from just 10.64% in 1995 to 26.39% in the year 2000. By the year 2020, the

area under moderately dense forest has covered 50.26% of the total area. The area under the open forest category registered a consistent decline from 1989 to 2020.

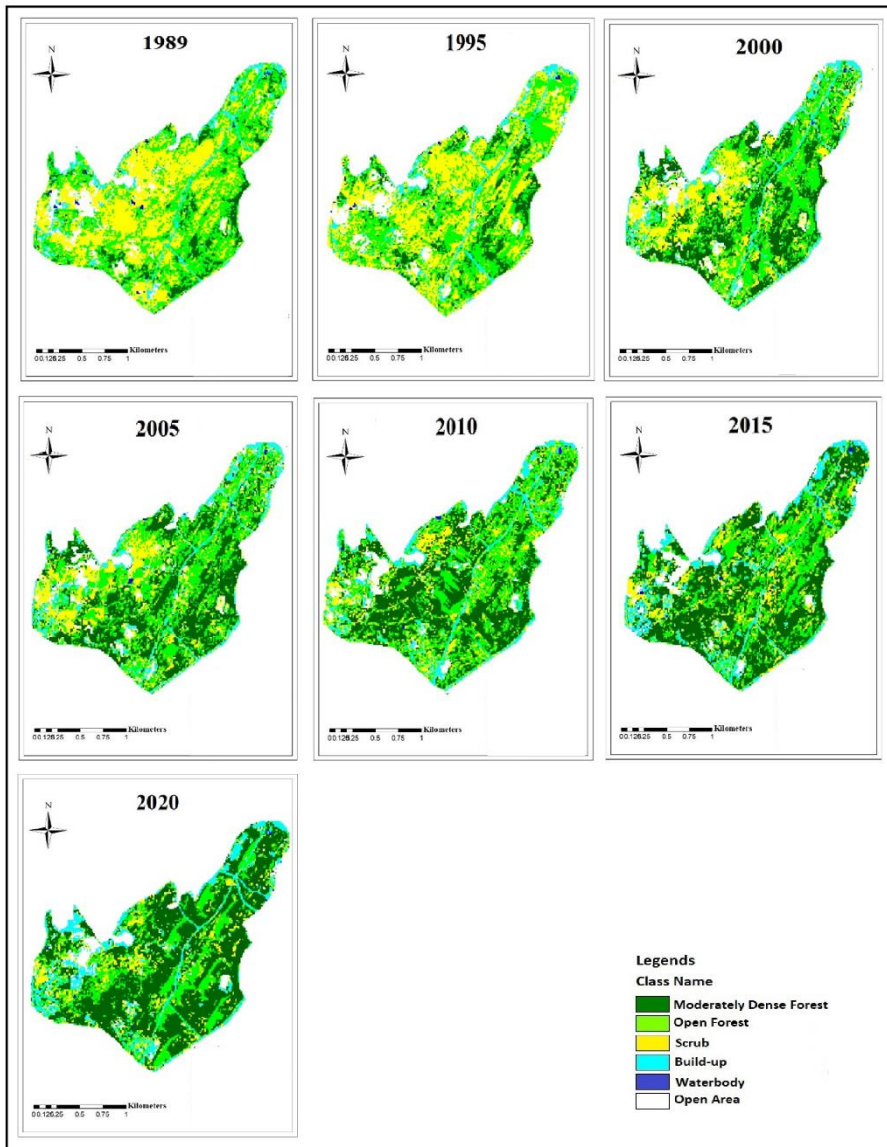


Figure 5. LULC Variations in Central Ridge

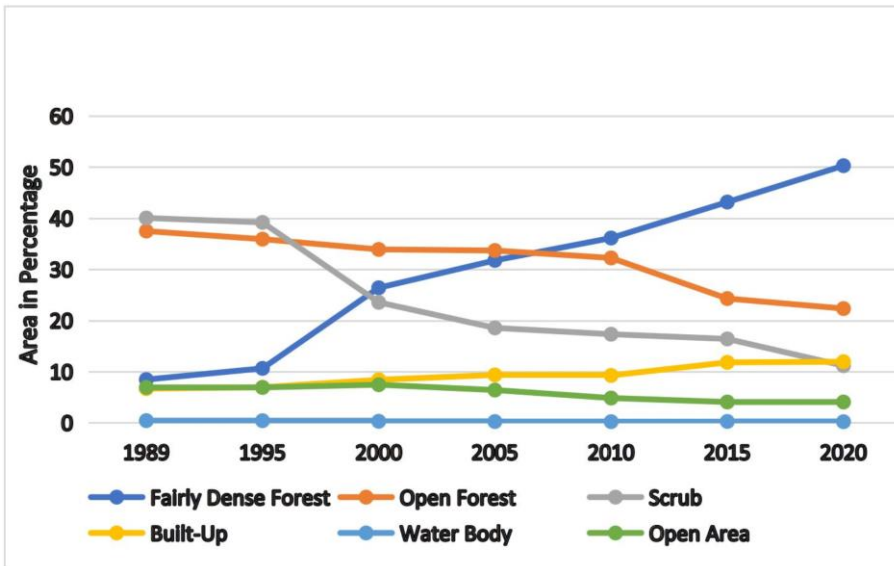


Figure 6. Graph showing changes in area (in %) for various LULC classes for Central Ridge

Table 4. Changes in LULC classes year wise in % for Central Ridge

Class	Year						
	1989	1995	2000	2005	2010	2015	2020
Moderately Dense Forest	8.458	10.645	26.397	31.750	36.125	43.156	50.266
Open Forest	37.478	35.901	33.893	33.686	32.226	24.294	22.336
Scrub	40.040	39.179	23.550	18.549	17.318	16.401	11.165
Built-Up	6.679	6.947	8.413	9.364	9.263	11.814	11.948
Water Body	0.425	0.414	0.296	0.246	0.224	0.269	0.218
Open Area	6.920	6.914	7.451	6.405	4.844	4.067	4.067
Total Area (Sq. Kms.)	16.08						

The area under waterbody decreased from 0.42% to 0.21% while open area also declined from 6.92% to 4.06%. In the case of built-up and human settlements, a proportional increase can be seen with major turnaround from 2010 onwards. A network of major arterial roads has fragmented the entire forest habitat of Central Ridge. Plans are in place now to remove invasive *Prosopis juliflora* in phase wise manner and replace it with native vegetation.

4.3 South-Central Ridge

The LULC analysis (Figure 7, Figure 8 and Table 5) of South-Central Ridge has revealed pattern as was observed in Northern and Central Ridge areas. There is a continuous increase in moderately dense forest which was only 13.12% in 1989 and rose to 14.10% in 1995, 22.61% in 2000, 24.17% in 2005, 28.46% in 2010, 38.28% in 2015 and finally 42.90% in 2020. Area under open forest category has initially registered an increase from 36.51% in 1989 to 40.03% in 1995, 45.68% in 2000 and 46.12% in 2005. From 2010 onwards it started shrinking and stood at 26.74% in 2020. Scrub area has witnessed a steeper decline from 35.45% in 1989 to 12.23% in 2020. There is almost 3 times increase in the area under built-up and human settlements

which changed from 5.26% in 1989 to 15.26% in 2020. Open area class in this segment was represented by 7.32% area in 1989 which declined to a minimal 0.61% in 2020. The noticeable change was observed in the area under water bodies which initially shrunk from 2.31% in 1989 to 1.38% in 2010 but again increased to 2.23% in 2020. This has been probably due to active water management and harvesting practices introduced in this area by Delhi Development Authority (DDA) and a part of this area has been managed as Neela Hauz Biodiversity Park.

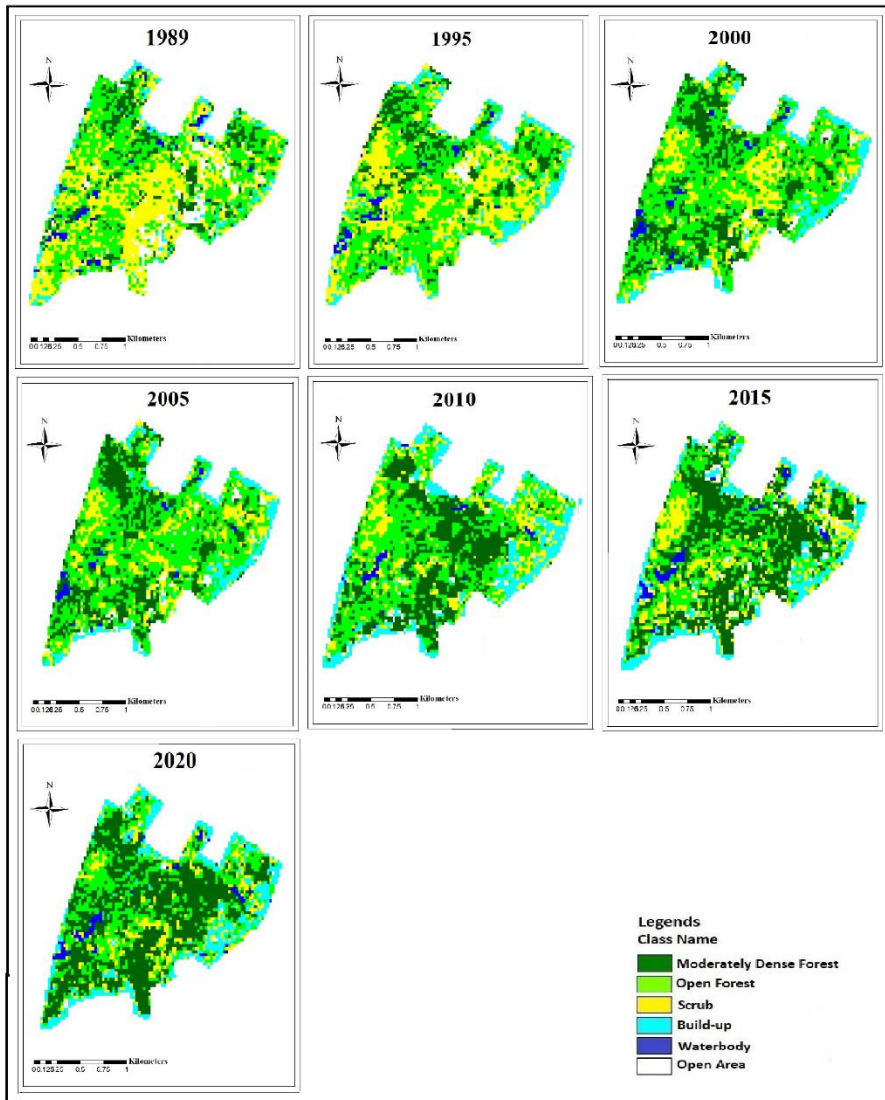


Figure 7. LULC Variations in South-Central Ridge

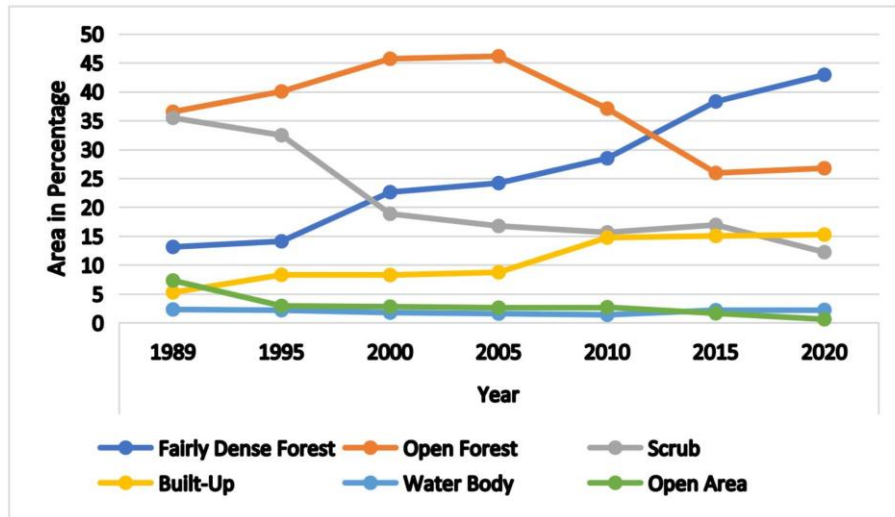


Figure 8. Graph showing changes in area (in percentage) for various LULC classes for South-Central Ridge

Table 5. Changes in LULC classes year wise in % for South-Central Ridge

Class	Year						
	1989	1995	2000	2005	2010	2015	2020
Moderately Dense Forest	13.129	14.106	22.610	24.178	28.469	38.284	42.909
Open Forest	36.511	40.031	45.683	46.120	37.050	25.925	26.747
Scrub	35.457	32.451	18.859	16.752	15.647	16.932	12.230
Built-Up	5.267	8.299	8.273	8.736	14.748	15.031	15.262
Water Body	2.312	2.184	1.773	1.593	1.387	2.184	2.235
Open Area	7.323	2.929	2.801	2.621	2.698	1.644	0.617
Total Area (Sq. Kms.)	3.50						

4.4 Southern Ridge

Figure 9, Figure 10 and Table 6 shows area under each class for Southern Ridge for each period of analysis and magnitude of change. Drastic changes were observed in the forest cover of the region. In 1989, LULC analysis depicts the predominance of scrub and open area in the region, covering 68.43% of the total area. Although, mining was banned in the area in 1986 but our study has shown that the area affected by mining in 1989 was 0.97% of the total area. The area under open forest and moderately dense forest in 1989 was 22.20% and 3.43% respectively. By 1995, the moderately dense forest category rose to 6.05%, open forest reported an increment and stood at 27.03% while a decrease has been observed in the scrub category (44.77%). By the year 2000, active plantation of the Bhatti Mines area has been initiated by the Forest Department in association with Eco-Task Force.

However, that year the percentage of area in moderately dense forest, open forest and scrub was 7.52%, 25.82% and 43.45% respectively. From 2005 onwards, a steady increase in both moderately dense forest and open forest has been observed until 2015, whereafter a slight decrease in the moderately dense forest category has been observed in the year 2020. At the

same time, a fall has been observed in the area under the scrub category till 2015 and a slight increase thereafter till 2020. A probable reason behind this can be removal of invasive plants such as *Prosopis juliflora* and *Lantana camara* and their replacement with the plantation of native tree species by the Forest Department ([The Indian Express, 2017b](#)).

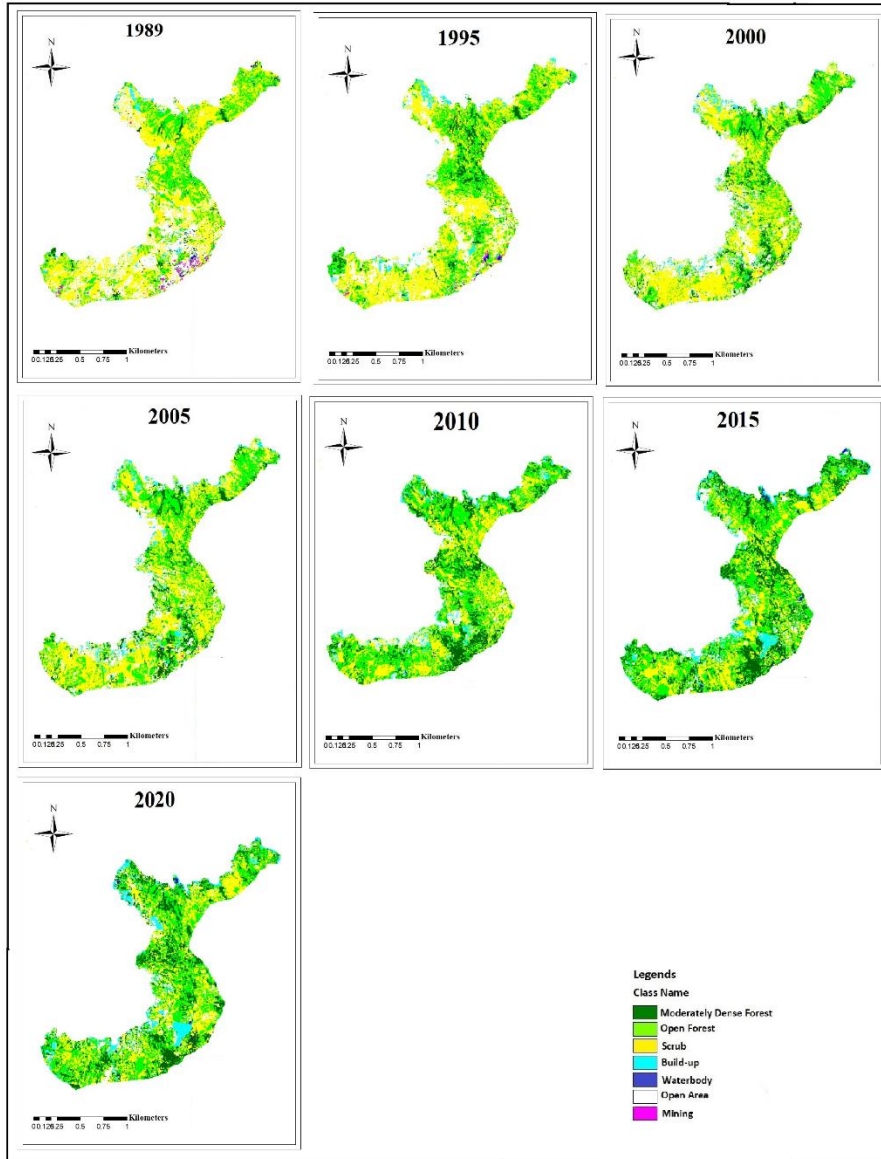


Figure 9. LULC Variations in Southern Ridge

As seen in other parts of Delhi Ridge, a continuous increase in built-up area from meagre 1.50% in 1989 to 6.60% in 2020 has been noticed. It must be mentioned that over the years, parts of agricultural land/fallow land/common land including pastures of surrounding villages of Southern Ridge like Asola, Bhatti and Maidangarhi have seen conversion into farmhouses and rampant encroachment cases have also been reported. The open area has witnessed a continuous decline while the area affected by mining has substantially reduced till the year 2000 and nullified thereafter because of active plantation undertaken by the Forest Department and invasion by *Prosopis juliflora*. The area under water bodies has seen a slight increase from 0.43% in 1989 to 0.49% in 2015 because of active rain water harvesting and water management techniques adopted by the Forest

Department. On the other hand, it has seen a slight dip in the year 2020 (0.43%).

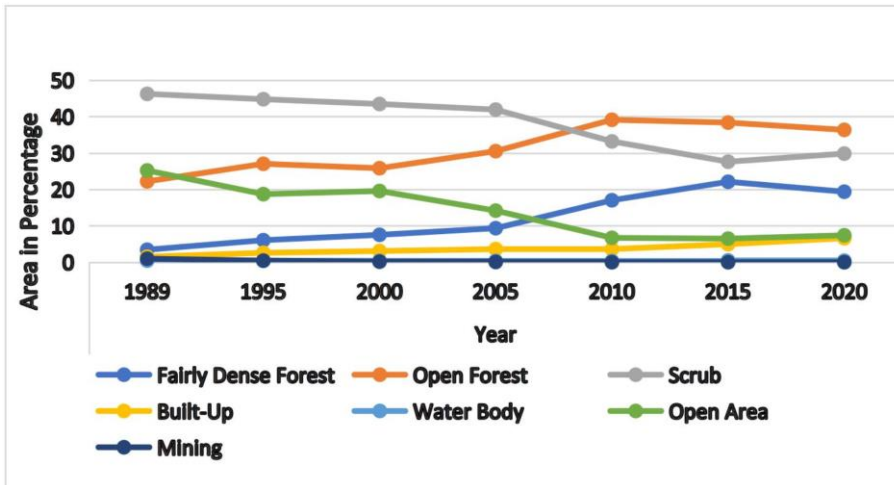


Figure 10. Graph showing changes in area (in percentage) for various LULC classes for Southern Ridge

Table 6. Changes in LULC classes year wise in % for Southern Ridge

Class	Year						
	1989	1995	2000	2005	2010	2015	2020
Moderately Dense Forest	3.436	6.054	7.527	9.352	17.024	22.101	19.367
Open Forest	22.200	27.033	25.822	30.505	39.129	38.353	36.352
Scrub	46.237	44.774	43.458	41.919	33.193	27.602	29.837
Built-Up	1.504	2.591	3.085	3.606	3.610	4.965	6.608
Water Body	0.436	0.403	0.380	0.374	0.343	0.496	0.430
Open Area	25.209	18.700	19.568	14.173	6.701	6.482	7.406
Mining	0.977	0.444	0.159	0.072	0.000	0.000	0.000
Total Area (Sq. Kms.)	43.55						

Correlation analysis has been carried out to understand the relationship between LULC classes (Table 6 Table 7). In case of Northern Ridge it has been observed that strong negative relationship exists between moderately dense forest and open forest ($r = -0.968$) and moderately dense forest & scrub categories ($r = -0.985$), indicating that with increase in area under moderately dense forest the area under rest two classes has decreased. Similar result has been observed for Central Ridge and South-Central Ridge too except Southern Ridge where relationship between moderately dense forest & open forest were observed to be strongly positively correlated ($r = 0.952$). In case of built-up, strong negative relationship was found between scrub & built-up and open area & built-up classes for all the four parts of Ridge, indicating the probability that the built-up has increased largely at the expanse of scrub and open area. Negative relationship was also observed between open forest & built-up classes in case of Northern Ridge ($r = -0.800$), Central Ridge ($r = -0.964$) and South-Central Ridge ($r = -0.690$).

Table 7. Coefficient of Correlation (r) values for various LULC classes

Part of Ridge	Moderately Dense Forest & Open Forest	Moderately Dense Forest & Scrub	Open Forest & Scrub	Open Forest & Built-up	Scrub & Built-up	Open Area & Built-up	Moderately Dense Forest & Open Area
Northern Ridge	-0.968	-0.985	0.915	-0.800	-0.944	-0.734	-0.680
Central Ridge	-0.907	-0.975	0.796	-0.96	-0.907	-0.873	-0.841
South-Central Ridge	-0.699	-0.852	0.240	-0.690	-0.777	-0.774	-0.780
Southern Ridge	0.9520	-0.996	-0.934	0.767	-0.857	-0.8280	-0.956

5. DISCUSSION & CONCLUSION

All major urban development plans uphold the significance of the protection and conservation of urban green spaces to ensure sustainable development ([Sathyakumar, Ramsankaran et al., 2020](#)). Assessing the changes occurring within urban green spaces is a prerequisite to ensuring effective, long-term management of these areas ([Kolcsár, Csikós et al., 2021](#)). The present study has provided baseline information on the spatio-temporal changes observed in the vegetation of Delhi Ridge forest in the last three decades and has also highlighted the impact caused by urbanization in the region. Although the previous studies only focussed on a part of Delhi Ridge ([Sharma, Chaudhry et al., 2017](#)), this study has undertaken the spatio-temporal analysis of all the four segments of Delhi Ridge.

The results of the study confirm that Delhi Ridge has undergone dramatic transformations in terms of vegetation cover with changes occurring in quick succession in these decades. There is an increase in vegetation density in all the four parts of the Ridge with a simultaneous decrease in scrub and open area. Maximum percentage change in area in case of moderately dense forest class has been observed in Central Ridge (494.31%) followed closely by Southern Ridge (463.61%), South-Central Ridge (222.89%) and Northern Ridge (118.60%) from the period of 1989 to 2020. The efforts of greening agencies are reflected in overall increase in green cover across Delhi including the Delhi Ridge ([Imam and Banerjee, 2016](#)).

An increase in the human population through migration can directly impact the land use/land cover of the region ([Nelson, Sander et al., 2010](#)), and the same holds for Delhi as well. A continuous increase in built-up and human settlements in surrounding areas and within the limits of Ridge is of concern and have far-reaching implications as it increases habitat fragmentation and thus affects the movement of wildlife and the overall tendency of forest to sustain biodiversity ([Liu, He et al., 2016](#)). Maximum percentage change in area in case of the built-up class has been observed in Southern Ridge (339.28%) followed by South-Central Ridge (189.75%), Central Ridge (78.89%) and Northern Ridge (34%) from the period of 1989 to 2020. It has been observed that most of the built-up area observed in and around Delhi Ridge has come at the expense of scrub and open area. Some previous studies carried out in Delhi/National Capital Region also confirm that scrubland, barren land and open spaces are major land-use types that get

converted into built-up as urbanization progressed ([Naikoo, Rihan et al., 2020](#); [Paul, Saxena et al., 2021](#)).

We have carried out field visits in all the four segments of Delhi Ridge along with thorough research of published material to ensure accuracy in the results. However, our study is based on publicly available data having a resolution of 30 metres which doesn't take into account of some under canopy changes occurring in the region. Nevertheless, the study findings will be instrumental in designing a rational, region-specific policy framework which can be applied in the management of other important green infrastructures as well that is located in Delhi, given the fact that the city is already experiencing high population growth, land scarcity, massive consumption of resources, and high air pollution levels along with enhanced risk from climate change. The key management steps that can be immediately ensured include checking and removal of illegal encroachment along the boundaries of the Ridge, implementation of nature-based solutions such as ecological restoration in Ridge management rather than ornamental interventions which can drastically alter the habitat of the Ridge, incorporating prediction based modelling approaches in the development of regional and subregional masterplans so that future impact of urbanization on Delhi Ridge area can be quantified and preventive measures can be ensured beforehand. Moreover, there is an urgent need for the formulation of a separate action plan for each segment of Delhi Ridge taking into account patterns of urbanization in the neighbourhood region to ensure integrated management. It is recommended that comprehensive investigative research work mapping the impact of urbanization on the ecosystem services supply from the Delhi Ridge must be undertaken. The results of our study can provide suitable base for such assessments in the future.

AUTHOR CONTRIBUTIONS

Conceptualization, B.C. and Y.S.C.K.; methodology, B.C. and B.S.; investigation, B.C. and B.S.; data curation, B.C. and B.S.; writing—original draft preparation, B.C.; writing—review and editing, B.C. and B.S.; supervision, Y.S.C.K. All authors have read and agreed to the published version of the manuscript.

ETHICS DECLARATION

The authors declare that they have no conflicts of interest regarding the publication of the paper.

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