



SPATIO-TEMPORAL DYNAMICS OF LAND USE CHANGE AND ECOSYSTEM SERVICES IN THE NATIONAL CAPITAL REGION, INDIA (1991–2011)

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Abstract

The rapid pace of urbanization in India's National Capital Region (NCR) over the past three decades has triggered substantial transformations in land use and land cover (LULC), posing challenges to ecological integrity, food security, and sustainable regional development. This study investigates the spatial and temporal patterns of LULC change across NCR between 1991 and 2011 and evaluates their implications for agricultural provisioning ecosystem services. The research aims to quantify land transitions using multi-temporal satellite imagery and assess the associated decline in crop productivity using a spatial modeling approach. Landsat imagery for the years 1991, 2001, and 2011 was processed and classified using supervised methods with the maximum likelihood algorithm. Changes in LULC categories were analyzed at the sub-regional level to capture the heterogeneity of urban growth and its ecological consequences. In addition, the InVEST Crop Production Model was applied to estimate spatial patterns of agricultural output between 2002 and 2012 using MODIS-derived crop phenology and Fourier-based time-series analysis. The results indicate that built-up area across NCR more than doubled during the study period, expanding from 1,606.5 km² to 3,279.7 km². This expansion came largely at the expense of agricultural land, which declined by over 2,200 km². High-yield crop zones, once concentrated in peri-urban districts such as Meerut, Baghpat, and Ghaziabad, diminished significantly by 2012. The findings highlight a clear trade-off between urban expansion and provisioning services, especially in ecologically and socio-economically sensitive transition zones. The study underscores the need for ecosystem-informed spatial planning and policies that protect peri-urban agricultural landscapes. Tools such as InVEST can support proactive land governance by quantifying trade-offs and guiding evidence-based decision-making. This research contributes to a growing body of work on urban-rural land dynamics and provides a replicable framework for assessing ecosystem service losses in megaregions of the Global South.

Keywords: Land use change; Ecosystem services; Remote sensing; Crop modeling; Urbanization; NCR; InVEST

1. Introduction

Recently research on linking land use change and ecosystem services has grown rapidly (Qui et al 2013; Costanza et al 2014; Seto 2016 etc), but understanding their relationship with society has always challenging. Land use change is one of the most pervasive anthropogenic forces transforming ecosystems, reshaping landscapes, and influencing the sustainability of human-environment systems.

Driven by rapid urbanization, industrial expansion, and demographic shifts, changes in land use and land cover (LULC) are tightly coupled with socio-economic transitions and have far-reaching implications for ecosystem services (ES), food security, and human well-being (Costanza et al., 2014; Millennium Ecosystem Assessment, 2005). These dynamics are especially visible in the urban-rural interface of developing economies, where fragmented institutional governance often lags behind the pace of spatial transformation.

Alteration in land use is likely to be major driver of changes in the distribution of ecosystem services before 2050 (MA 2005). In India, urbanization will probably be the main cause of land use change. This increase in urbanization will result in spatial shifts in both supplies of ecosystem services and beneficiaries of those services. Several studies in recent years have forecasted global urban expansion and examined its potential impacts on biodiversity and ecosystem services (Mace et al. 2012; Guneralp et al. 2013; Nagendra et al 2014). Urbanization impacts biodiversity both directly through physical expansion over land, and indirectly due to land use and human behaviours within urban areas. Urban expansion has the effect of decreasing, fragmenting, and isolating natural patches by altering the size, shape, and interconnectivity of the natural landscape (Ricketts 2001; Alberti 2005). The urban growth affects the ecosystem not only in the core city but also in the periphery of the city. It is evident in many areas with the process of urbanization that urban growth significantly determines land use and land cover changes. There is interaction between biological and non-biological components in an urban environment. This interaction in an urban environment is termed as 'urban ecosystem.' There is now a growing understanding that human processes and culture are fundamental for sustainable management of ecosystems, and in urban planning it is becoming increasingly evident that urban management needs to operate at an ecosystem scale rather than within the traditional boundaries of the city (Breuste 2007; Breuste et al. 2013).

LULC change is both a cause and a consequence of urbanization. While urban development fosters economic growth and improved living standards, it also exerts pressure on natural landscapes and resources. Unplanned urban expansion leads to land degradation, ecosystem fragmentation, and loss of agricultural land, thereby reducing the provisioning capacity of ecosystems (Newman & Kenworthy, 1999; Millennium Ecosystem Assessment, 2005). According to the 2011 Census, urbanization in India has increased faster than expected. For the first time since independence, the absolute increase in the urban population was higher than that in the rural population with 31.16 percent of its population or 377 million people now living in cities, an increase from 27.81 per cent in 2001. This growth has been particularly intense in the National Capital Region (NCR), a trans-boundary metropolitan region encompassing Delhi and parts of Haryana, Uttar Pradesh, and Rajasthan. As NCR urbanizes, peri-urban landscapes are being rapidly converted to built-up areas, disrupting local ecological processes, reducing agricultural land, and generating new spatial configurations of environmental risk and socio-economic inequality (Narain, 2009; Nagendra et al., 2014). The trade-offs inherent in this transformation pose critical questions for land use policy, urban planning, and sustainable development.

While the impacts of urbanization on land cover and biodiversity have been widely studied (Alberti, 2005; Guneralp & Seto, 2013), there remains a distinct need for integrated assessments that link spatial land transformations to ecosystem service losses, particularly in high-growth urban regions like NCR. Moreover, there is a scarcity of empirical research using long-term, multi-temporal satellite data combined with spatial modeling of provisioning services to inform land governance.

This study aims to assess the spatial and temporal dynamics of land use and land cover change in India's National Capital Region between 1991 and 2011, and to evaluate its impacts on ecosystem provisioning services, particularly agricultural productivity. The research employs remote sensing based LULC classification and the InVEST crop production model to link land change trajectories with ecological outcomes.

The core objectives are:

- To map LULC change in NCR over two decades using Landsat imagery and GIS.
- To analyze the implications of these changes for crop productivity and yield.
- To assess trade-offs in land use transitions in terms of ecosystem service loss.

This study presents a novel integration of satellite-based land use mapping with ecosystem service modeling using the InVEST tool in the NCR, a region of geopolitical, economic, and ecological significance. While prior research has often addressed LULC or ES independently, this paper bridges the two by combining empirical land change data with biophysical modeling to evaluate the impact of urbanization on ecosystem functionality. Furthermore, the district-level disaggregation provides granular insights into spatial inequalities and trade-offs in land use, contributing valuable evidence for sustainable urban and regional planning in developing megaregions.

2. Study Area

The study focuses on the National Capital Region (NCR) of India, a unique and dynamic urban agglomeration that encompasses the National Capital Territory (NCT) of Delhi and parts of three adjoining states-Haryana, Uttar Pradesh, and Rajasthan. The region spans 24 administrative districts and serves as both a political hub and one of the most rapidly urbanizing zones in South Asia.

The NCR was conceptualized under the National Capital Region Planning Board (NCRPB) Act, 1985, with the aim of decentralizing economic activity and mitigating population pressure on Delhi. According to Census 2011, the region is home to over 46 million people, with NCT-Delhi alone hosting 16.7 million, ranking it among the world's largest urban agglomerations. The UN's World Urbanization Prospects (2011) ranks Delhi second only to Tokyo in terms of population size.

The region is defined by dense urban cores, peri-urban expansion zones, and agrarian hinterlands, creating a complex mosaic of land use categories. Delhi's expansion is predominantly radial, supported by a robust transport network including National Highways 2, 8, and 24, linking it to major cities like Jaipur, Kanpur, and Mumbai. These corridors pass through rapidly urbanizing districts such as Gurgaon, Faridabad, Ghaziabad, and Gautam Budh Nagar, which have become epicenters of real estate and industrial development.

The NCR is characterized by heterogeneous topography and land use practices, including, dense residential and commercial zones in NCT-Delhi, mixed agricultural and industrial landscapes in Haryana and Uttar Pradesh sub-regions, and semi-arid agricultural terrain in the Rajasthan sub-region (primarily Alwar district). The NCR offers a representative case study for examining LULC change and its implications for ecosystem services in a megaregion context. Its administrative complexity, economic significance, and ecological vulnerability make it an ideal setting to explore how spatial land transformations affect provisioning services over time. Furthermore, the diversity of land cover classes across the sub-regions provides analytical depth for spatially differentiated modeling of land transitions and their socio-ecological consequences.



Fig. 1 Administrative divisions of Study Area

3. Materials and Methods

This study employs a two-tiered methodological approach to analyze land use and land cover (LULC) changes in the National Capital Region (NCR) of India and their impacts on ecosystem services. The approach includes:

- (i) multi-temporal classification and analysis of satellite imagery, and
- (ii) crop production modeling using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool to assess changes in provisioning services over time.

3.1 Land Use and Land Cover (LULC) Classification

Data Source and Preprocessing:

Landsat satellite images were utilized for three time periods: 1991, 2001, and 2011. The imagery was sourced from the United States Geological Survey (USGS) repository. Details of the datasets used are provided in Table 1.

Table 1 Dataset used

S. No.	Satellite	Sensor	Path/Row	Acquiring month
1.	Landsat-5	TM	146/40	Jan-Feb 1991
2.	Landsat-5	TM	146/40	Feb-March 2001
3.	Landsat-7	ETM+	146/40	Feb-March 2011

Image Classification:

The images were processed and classified using Erdas Imagine 14.0 and ArcGIS 10.2 software. A supervised classification approach was applied using the Maximum Likelihood Classifier (MLC) algorithm, based on training samples derived from reference data, ancillary ground information, and visual interpretation. Eight LULC categories were identified that includes built-up area, agricultural land, dense vegetation, open vegetation, fallow land, scrub land, water bodies, and waste/barren land.

The classified maps were validated using reference points, field surveys, and high-resolution ancillary datasets. Classification accuracy and Kappa statistics were computed to ensure reliability.

3.2 Crop Production Modeling Using InVEST

To assess the impact of LULC change on agricultural provisioning services, the InVEST Crop Production Percentile Model was employed. This tool estimates both crop yield (tons/hectare) and total production (tons per pixel) across spatial units.

i. Crop Mapping and Phenology

The crop calendar was derived by integrating MODIS Enhanced Vegetation Index (EVI) data (MOD13Q1 16-day composite, 250m resolution) with regional phenological data. The time series covered Julian Day 129 (May 2011) to JD 113 (April 2012), comprising 23 layers representing seasonal crop cycles.

ii. Temporal Smoothing

To address noise caused by cloud cover and atmospheric interference, the Savitzky–Golay filter was applied. This temporal filter improves signal fidelity by fitting a second-degree polynomial to each data point over a moving window (Chen et al., 2004). The smoothed time series enabled clearer detection of crop phenology (Sakamoto et al., 2005).

iii. Fourier Analysis

Following smoothing, Discrete Fourier Transform (DFT) was used to extract amplitude and phase terms indicative of vegetation intensity and peak timing for each pixel. The strength of the signal processing of fourier analysis was harnessed by several authors to analyze the vegetation phenology using only the amplitude and phase term of the most important periodic component (Azzali & Menenti, 2000; Canisius, Turrall, & Molden, 2007; Galford et al., 2008; Jakubauskas, Legates, & Kastens, 2002; Menenti, Azzali, Verhoef, & Van Swol, 1993; Mingwei et al., 2008; Son, Chen, & Cru, 2012). These metrics were used to characterize dominant cropping patterns and their spatial shifts over time.

iv. Classification and Validation

The phase and amplitude term derived from Fourier analysis were linked with information of crop type (Jakubauskas, Legates, & Kastens, 2001). Fourier-derived features were clustered using ISODATA unsupervised classification, initiated with 50 clusters and reduced to six dominant crop systems based on similarity and regional relevance. Area estimates for each crop class were validated against Ministry of Agriculture statistics.

3.3 Integration and Analysis

The final output included: LULC classification maps for 1991, 2001, and 2011; Crop yield and production maps for 2002-03, 2004-05, and 2011-12. These outputs were spatially analyzed to assess temporal changes in land use classes, decline in agricultural extent and productivity, and impacts on food provisioning ecosystem services. The results informed a policy-oriented discussion on land transitions, ecosystem degradation, and sustainability planning.

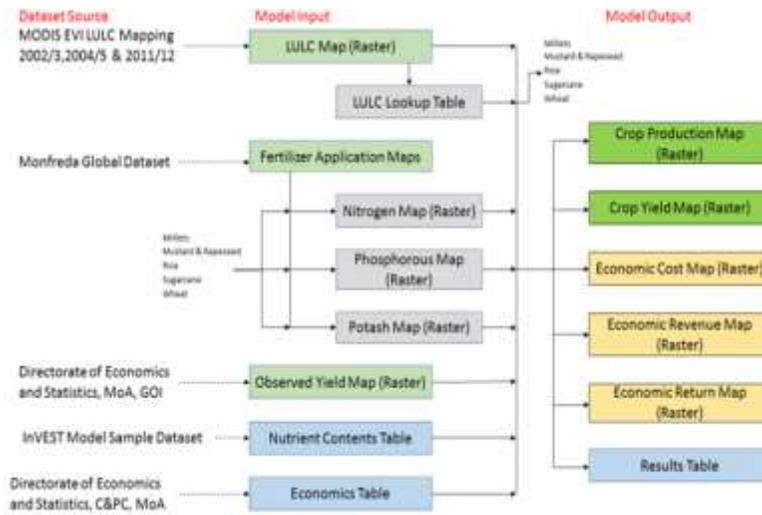


Fig. 2 Flow diagram of crop production model

4. Results and Discussion

4.1 Regional Patterns of Land Use and Land Cover Change (1991–2011)

The spatial and temporal analysis of land use and land cover (LULC) across the National Capital Region (NCR) reveals a vivid transformation between 1991 and 2011. Built-up land witnessed a steep rise, doubling from 1,606.5 km² in 1991 to 3,279.7 km² in 2011, largely due to infrastructural development, real estate expansion, and population influx into Delhi’s surrounding districts. In contrast, agricultural land declined from 23,008.9 km² to 20,739.5 km², a net reduction of 6.6% over two decades, signaling a structural shift away from rural land use (Table 2). Dense vegetation increased modestly from 652.3 km² to 717.8 km², likely because of afforestation programs or peri-urban greening initiatives. Fallow land, once 9.3% of NCR’s total area, declined to 6.2% in 2011, while water bodies showed a minor increase from 182.9 km² to 252.2 km². These trends are visualized in the LULC maps (Fig. 6), with specific transitions detailed in Figures 4 and 5. The results confirm that urban expansion, especially in the periphery of NCT-Delhi, has led to a substantial reconfiguration of land uses with far-reaching implications for ecosystem services.

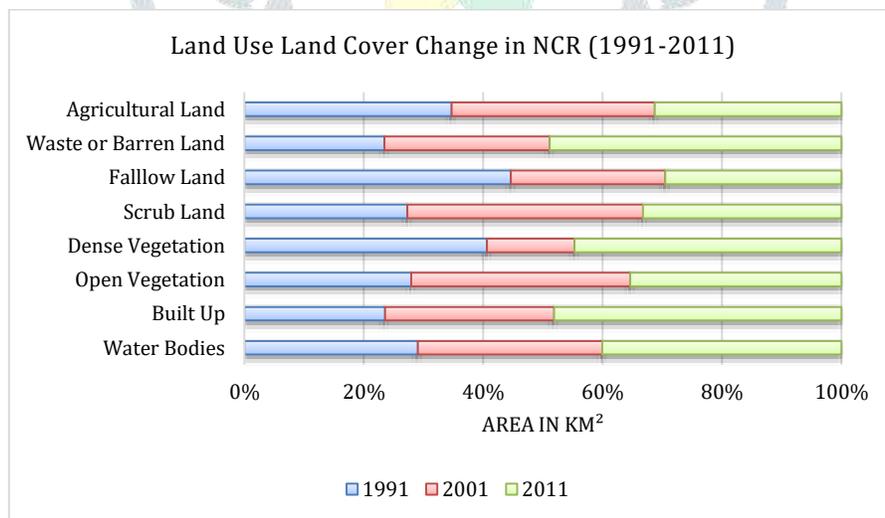


Fig. 3 Land use land cover change in NCR (1991-2011)

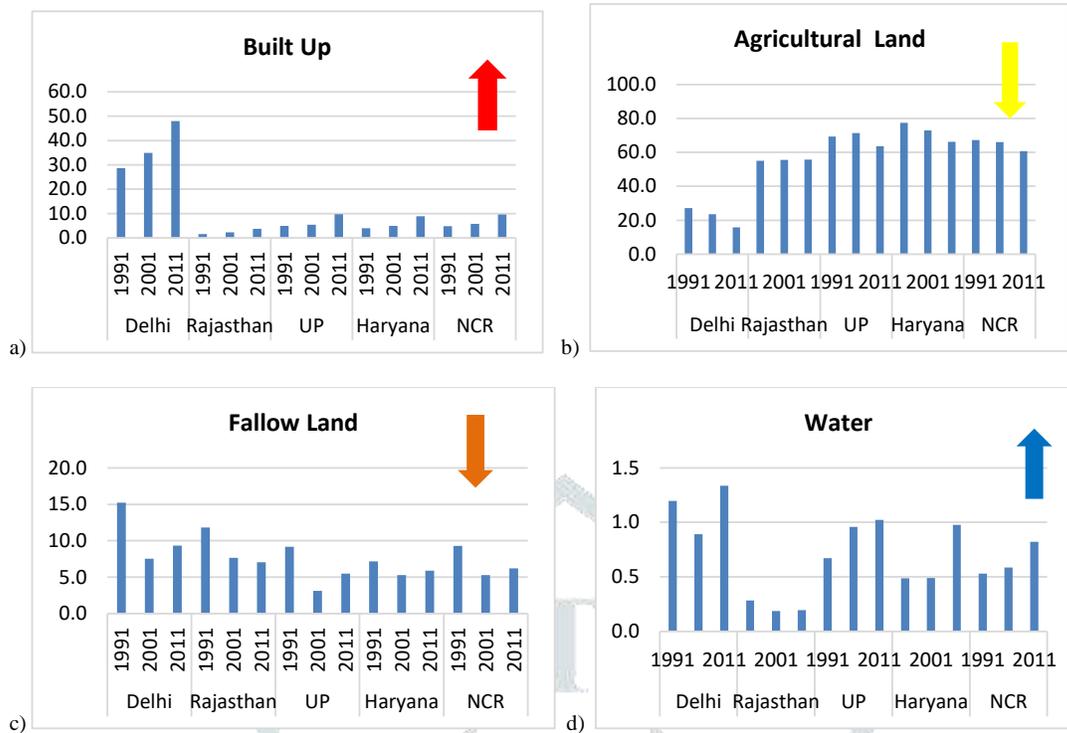


Fig. 4 Trade off among different types of LULC, a) Built-up b) agricultural land c) Fallow land d) water bodies.

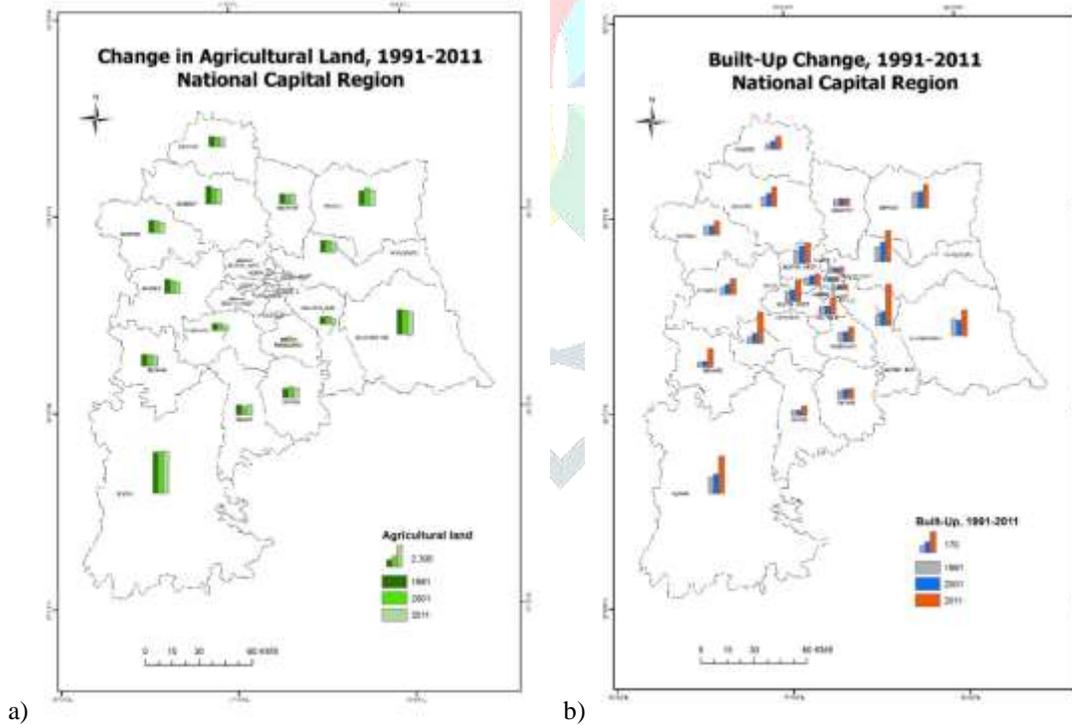


Fig 5. a) change in agricultural land (1991-2011) & b) change in built-up area (1991-2011) in NCR

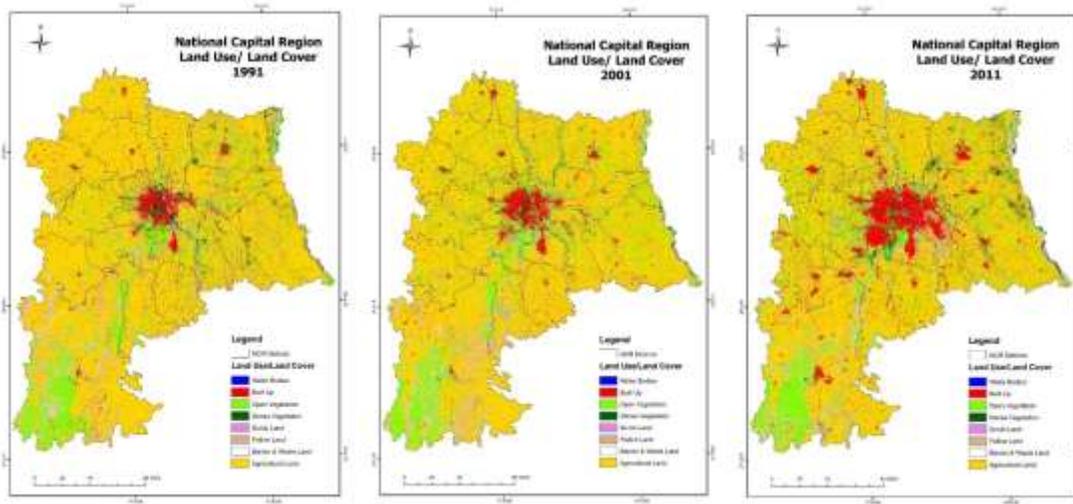


Figure 6. Classified Land use/ Land cover map of NCR 1991-2011

4.2 Sub-Regional Differentiation of LULC Transitions

To assess the influence of urbanization on land use and land cover (LULC) change across the National Capital Region (NCR), it is essential to examine spatial transformations over time in comparison with adjacent regions. The NCR comprises 24 districts spread across four administrative territories: the National Capital Territory (NCT) of Delhi, Haryana, Uttar Pradesh, and Rajasthan. The NCT of Delhi consists of nine districts, including North West Delhi, North Delhi, North East Delhi, West Delhi, East Delhi, South Delhi, South West Delhi, Central Delhi, and New Delhi. The Haryana sub-region includes Panipat, Sonapat, Jhajjar, Rohtak, Rewari, Gurgaon, Mewat, Faridabad, and Palwal. In Uttar Pradesh, the NCR includes the districts of Ghaziabad, Gautam Budh Nagar, Meerut, Baghpat, and Bulandshahr. Rajasthan is represented in the NCR by the district of Alwar.

Among these, the districts of Ghaziabad, Faridabad, Gurgaon, and Gautam Budh Nagar have emerged as the most rapidly urbanizing zones, characterized by intense real estate development, population influx, and infrastructure expansion. These areas, due to their proximity to Delhi and connectivity through major transport corridors, have experienced the most significant land use shifts from agricultural and open lands to built-up urban forms. Comparative analysis across all districts provides critical insight into how urbanization-driven dynamics differ spatially within the NCR and how they collectively contribute to regional ecological transformation.

NCT-Delhi

Delhi, along with its surrounding satellite cities, has evolved into a major urban agglomeration characterized by a high concentration of public and private sector enterprises, industrial hubs, extensive infrastructure, and large residential colonies. This convergence of economic and institutional activities has positioned Delhi as a prominent opportunity hub, attracting a diverse working population from across India. Over the past century, the city has experienced unprecedented demographic expansion. According to Census data, Delhi's population surged from 0.46 million in 1901 to 16.7 million in 2011 (Census of India, 2011), reflecting its rapid urbanization and economic magnetism.

Land use and land cover (Fig. 7a) reveal that Delhi's built-up area expanded significantly from 430.5 km² in 1991 to 722.3 km² in 2011. This spatial growth came at the expense of agricultural land, which declined from 409.2 km² to 236.9 km² over the same period. The relentless demand for housing, commercial space, and public infrastructure has contributed to this marked conversion of land, raising critical concerns about urban sustainability. Environmental consequences associated with this transformation are becoming increasingly visible. Rapid urbanization has contributed to worsening air and water pollution, traffic congestion, groundwater depletion, and the intensification of the urban heat island effect. While some categories of land cover remained relatively stable, dense vegetation showed a slight decrease from 67.6 km² in 2001 to 64.3 km² in 2011. Conversely, waste land area grew steadily from 7.4 km² in 1991 to 16 km² in 2011 suggesting land degradation and the proliferation of unused or marginal lands due to unplanned development.

Haryana Sub-Region

In the Haryana sub-region of the National Capital Region (NCR), agriculture remains the dominant land use category, accounting for approximately 66.5% of the total area in 2011. This is followed by open vegetation (14.7%), built-up areas (8.9%), fallow land (5.8%), dense vegetation (0.9%), and water bodies (0.8%). However, a detailed temporal analysis of land use change from 1991 to 2011 reveals significant spatial transformations. Notably, the share of open vegetation increased by nearly 6.3%, rising from 8.4% in 1991 to 14.7% in 2011 (Fig. 7b). This shift may reflect processes of land fragmentation, abandoned agricultural plots, or reversion to natural cover in peri-urban areas.

The most notable urban transformation is observed in the expansion of built-up land, which grew from 3.9% in 1991 to 4.9% in 2001, and further to 8.9% in 2011 a net increase of 5% over two decades. This expansion aligns with the growth of urban settlements and infrastructure, particularly in districts such as Faridabad, Gurgaon, and Sonipat, which are closely integrated with Delhi's economic zone. Conversely, agricultural land saw a substantial decline of 11.2%, dropping from 77.7% in 1991 to 66.5% in 2011. This reduction highlights the increasing conversion of fertile farmland into urban and peri-urban uses, a trend driven by real estate pressures and rural-to-urban migration. Fallow land also declined slightly by 1.3% over the study period, while dense vegetation and water bodies experienced marginal gains of 0.17% and 0.35%, respectively. These changes reflect the dual forces of urbanization and ecological transformation underway in Haryana's NCR districts. While built-up growth supports economic expansion, the simultaneous loss of agricultural land raises concerns over long-term food security and ecological sustainability in the region.

Uttar Pradesh Sub-Region

The Uttar Pradesh sub-region of the National Capital Region (NCR) comprises five districts: Ghaziabad, Gautam Budh Nagar, Meerut, Baghpat, and Bulandshahr. As of 2011, the dominant land use type in this sub-region was agricultural land, accounting for 63.6% of the total area. This was followed by open vegetation (12.9%), built-up areas (9.6%), fallow land (5.4%), dense vegetation (4.4%), scrub land (1.6%), waste/barren land (0.9%), and water bodies (1%) (Fig. 7c).

Temporal analysis of land use change between 1991 and 2011 reveals a notable increase in built-up land, which rose by 4.8%, indicating rapid urban growth in key urban centers such as Ghaziabad and Gautam Budh Nagar. These districts have become prominent urban corridors due to their proximity to Delhi and extensive infrastructure development, including expressways, metro lines, and industrial hubs. Simultaneously, agricultural land declined from 69.3% in 1991 to 63.6% in 2011, reflecting a net loss of 5.7%. This reduction signifies increasing pressure on arable land due to real estate development and urban expansion. Other land use categories such as open vegetation, dense vegetation, and scrub land showed marginal gains of 1.2%, 0.9%, and 1.4%, respectively, possibly due to either natural vegetation regeneration in unused plots or landscape restructuring in peri-urban areas. Water bodies and waste land also increased slightly by 0.3% and 0.5%, respectively.

Rajasthan Sub-Region

The Rajasthan sub-region of the National Capital Region (NCR) is represented solely by Alwar district, which exhibits a land use pattern distinct from the more rapidly urbanizing zones of the NCR. As of 2011, agricultural land constituted the predominant land use category, accounting for 55.7% of the total area. This was followed by open vegetation (22.6%), scrub land (10%), fallow land (7%), built-up area (3.6%), and a very limited extent of water bodies (0.1%).

A temporal analysis of land use change from 1991 to 2011 (Fig. 7d) reveals a relatively stable land system compared to the rest of the NCR. Built-up land increased moderately by 2%, reflecting a slow pace of urbanization. Interestingly, agricultural land experienced a marginal increase of 0.42%, rising from 55.3% in 1991 to 55.72% in 2011. This contrasts with the declining agricultural trends observed in other sub-regions and may be attributed to stable demographic pressures and limited industrial expansion in Alwar. In contrast, the analysis indicates a decline in several land cover types. Fallow land decreased significantly by 4.8%, possibly reflecting either land reclamation or conversion into permanent agricultural or vegetative use. Scrub land, dense vegetation, and waste land experienced slight reductions of 0.13%, 0.01%, and 0.1%, respectively. The area under water bodies also declined slightly, which may suggest challenges related to water resource management or seasonal desiccation. Overall, the Rajasthan sub-region displays relatively low-intensity urban transformation and a stable agricultural base, distinguishing it from the more dynamic patterns observed in the Delhi, Haryana, and Uttar Pradesh sub-regions.

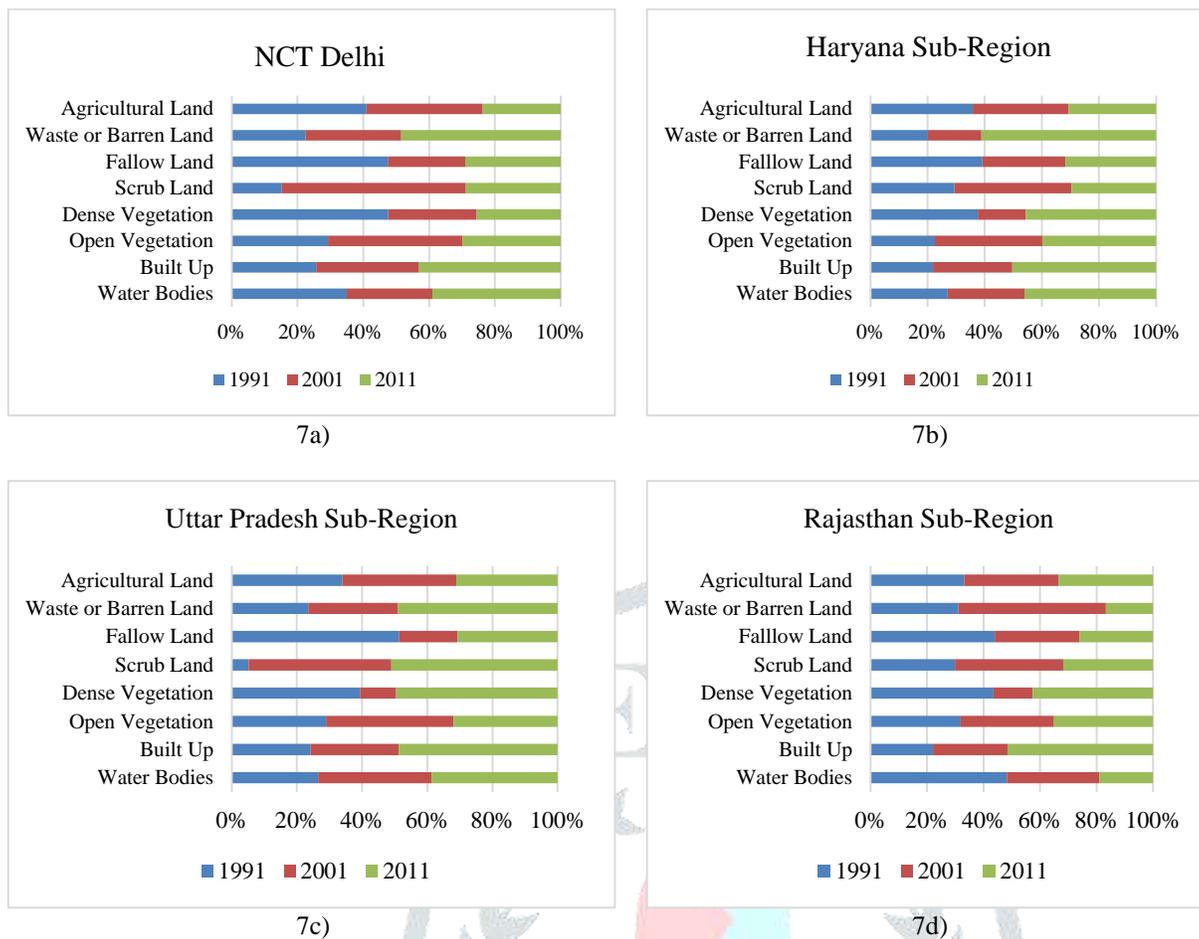


Fig. 7 Land use land cover change in Sub-Regions of NCR (1991-2011): a) NCT-Delhi; b) Haryana Sub-Region; c) U.P. Sub-Region; d) Rajasthan Sub-Region

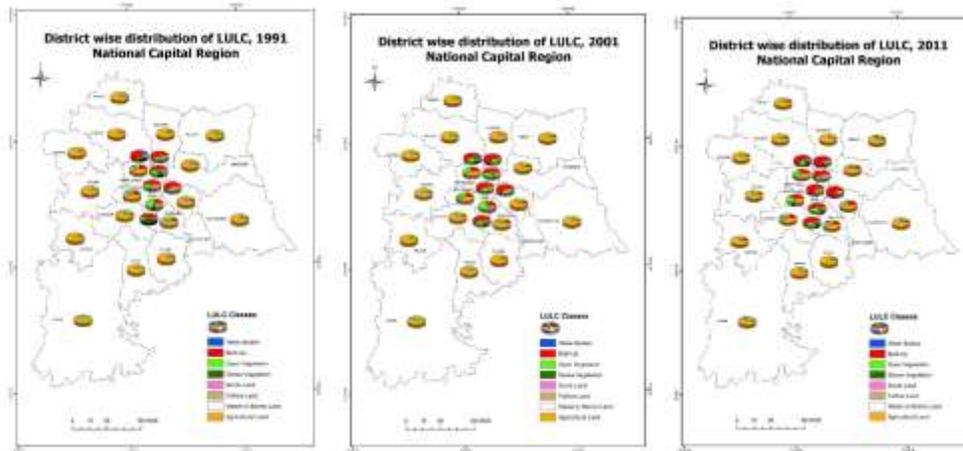


Fig. 8 District-wise spatial distribution of land use land cover change 1991, 2001 & 2011

4.3 Decline in Crop Production and Spatial Patterns of Yield (2002–2012)

The decline in agricultural productivity across NCR is evident from the spatial crop production maps derived using the InVEST model. Between 2002–03 and 2011–12, there was a notable shrinkage in areas producing more than 275 tons per pixel. In 2002–03, such zones were concentrated in districts like Meerut, Baghpat, Ghaziabad, and Bulandshahr. However, by 2011–12, these high-productivity areas had contracted significantly (Fig. 9a, 9b, 9c). Mid-range productivity zones (25–275 tons per pixel), which had covered large parts of Faridabad, Panipat, and Rohtak, were also reduced in extent. The most prominent changes were seen around urban-fringe zones, where

farmland was either left fallow or converted into residential or commercial uses. These production losses reflect a combination of factors, including declining arable land, fragmentation of farm plots, urban pollution, and increased pressure on groundwater.

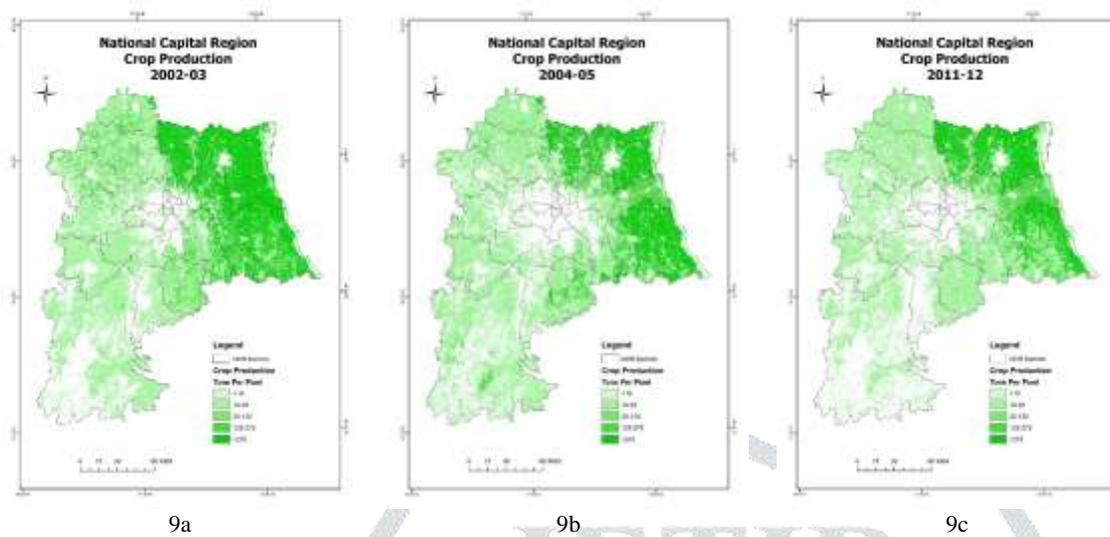


Fig. 9 Crop Production map of NCR: a) 2002-03 b) 2004-05 & c) 2011-12

Yield maps (Fig. 10) further reveal that high-yield areas (>50 tons/ha) persisted in parts of western Uttar Pradesh but contracted over time. Meerut, Baghpat, and Bulandshahr retained relatively high yields in 2002–03, but by 2011–12, their productive zones were significantly reduced. The reduction in crop yields is likely associated not only with land conversion but also with indirect impacts such as dust deposition on crops, increased urban heat effects, reduced irrigation efficiency, and growing input costs. These findings emphasize that land use change has impaired the provisioning capacity of the landscape, reducing the agricultural output that sustains both rural livelihoods and urban food demand.

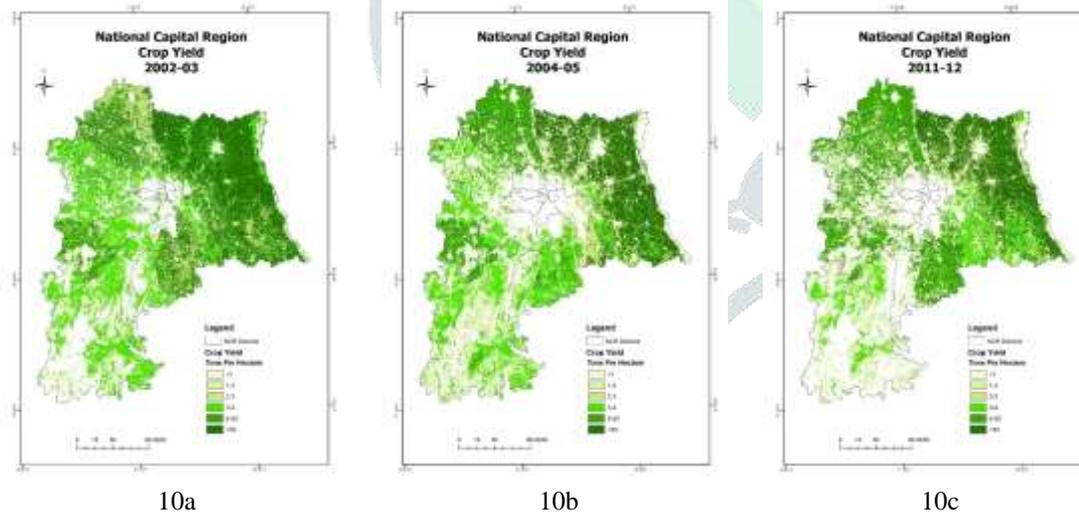


Fig. 10 Crop Yield map of NCR: a) 2002-03, b) 2004-05 & c) 2011-12

4.4 Ecosystem Services Loss and Socio-Ecological Trade-Offs

The cumulative evidence from LULC mapping and crop yield modeling points toward a significant degradation of provisioning ecosystem services. As agricultural lands give way to built-up environments, the ability of ecosystems to provide food diminishes. This loss is particularly critical in peri-urban areas, where food provisioning is directly linked to the ecological and economic security of both urban and rural populations. The decline in crop production also affects food affordability and availability, exacerbating vulnerabilities among low-income groups. Moreover, the urban-centric development has resulted in spatial inequalities, where fringe

communities lose productive land and are pushed into insecure labor markets. From an ecological standpoint, land transformation has reduced natural vegetation cover, altered hydrological flows, and increased soil erosion risks. These landscape-level changes reflect a growing disconnect between urbanization and environmental sustainability (Nagendra et al., 2011).

The ongoing shift in land use patterns, driven by industrialization and rapid urbanization, has led to significant environmental degradation, most notably through increasing levels of air, water, and soil pollution. These changes are closely linked to evolving socio-economic dynamics and have contributed to widespread ecological disruption. Air pollution has posed serious challenges, including the depletion of the ozone layer a critical atmospheric shield against harmful ultraviolet radiation. Recognition of the severity of this threat led to a coordinated global policy response through the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, widely regarded as one of the most successful international environmental agreements (UNEP, 2006). Concurrently, the rise in greenhouse gas emissions over the past century and a half has been tightly correlated with the expansion of energy-intensive industrial economies and land conversions that increase carbon footprints. These emissions are now a primary driver of anthropogenic climate change, which is exerting compounding pressures on biodiversity and ecosystem services across diverse landscapes.

The consequences of climate change for natural ecosystems are expected to be both widespread and severe. Vulnerable systems, such as coral reefs, mountain habitats, and polar regions, are already experiencing degradation, while species extinction rates are projected to rise globally as climatic thresholds are exceeded (Peters & Lovejoy, 1992; Schneider & Root, 2002). These ecological impacts are accompanied by serious socio-economic risks. Shifts in temperature and rainfall patterns directly affect agricultural productivity, which in turn jeopardizes food security. Projections from the International Food Policy Research Institute (IFPRI, 2009) estimate that by 2050, climate change could drive additional price increases of 32–37% for rice, 52–55% for maize, and 92–111% for wheat. These trends highlight the urgency of incorporating climate resilience, ecosystem preservation, and sustainable land governance into future land use planning frameworks.

4.5 Planning and Policy Implications

These results underscore the urgent need to integrate ecosystem service assessments into land governance and spatial planning processes. Urban expansion, if left unregulated, poses a direct threat to regional food security and ecological resilience. Policy instruments such as land use zoning, green buffer mandates, and ecological compensation schemes can help mitigate these impacts. Additionally, peri-urban agriculture should be incentivized through fiscal and policy support, ensuring that urban growth does not entirely displace productive land systems. Spatial tools like InVEST, when used in planning workflows, can guide decision-makers toward more balanced urban development strategies. In the context of NCR, where jurisdictional fragmentation and multi-state governance complicate land management, a coordinated regional planning framework is essential. Recognizing and quantifying the value of ecosystem services can shift policy focus from short-term land commodification toward long-term ecological sustainability.

5. Conclusion

This study set out to analyze the spatio-temporal dynamics of land use and land cover (LULC) change in the National Capital Region (NCR) of India between 1991 and 2011 and assess their implications for ecosystem services, with particular attention to agricultural productivity. Using multi-temporal Landsat imagery, supervised classification techniques, and the InVEST crop production model, the research provides a comprehensive evaluation of how urban expansion has reshaped the region's landscape and impacted key provisioning services.

The findings confirm a significant conversion of agricultural land to built-up uses, especially in the peri-urban belts surrounding Delhi, driven by population growth, infrastructural development, and market-led land dynamics. Built-up area doubled over two decades, while agricultural land declined by more than 2,200 km². This transformation was uneven across sub-regions, with the most rapid changes occurring in Ghaziabad, Faridabad, Gurgaon, and Gautam Budh Nagar. While some marginal gains in vegetation and water bodies were observed, they were insufficient to offset the scale of agricultural land loss. In parallel, crop production and yield declined across the NCR, with high-productivity zones shrinking significantly between 2002 and 2012. This decline was most pronounced in areas undergoing intense urbanization, suggesting a direct trade-off between land conversion and the ecosystem's ability to support food provisioning. The implications are profound not only for regional food security and rural livelihoods, but also for the ecological health of a rapidly urbanizing megaregion.

These outcomes underscore the need for integrated, spatially informed land use planning that recognizes and incorporates the value of ecosystem services. The findings highlight the importance of protecting peri-urban agricultural zones, regulating unplanned urban expansion, and adopting ecosystem-based approaches in regional planning. Moreover, spatial tools like InVEST should be institutionalized within planning agencies to evaluate land use trade-offs before major policy decisions are enacted.

Future research should explore additional ecosystem service categories such as regulating and cultural services and investigate how land governance structures across the NCR's multi-state framework influence spatial outcomes. Longitudinal studies incorporating predictive LULC models can further inform sustainable urban development strategies. Ultimately, this study contributes to a growing body of evidence advocating for a transition from land consumption-driven development to more ecologically balanced urbanization in India and other emerging economies.

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Appendix

Table 2 Land use change statistics in NCR from 1991 to 2011

LULC classes	1991	2001	2011	% change 1991-2011
	Area in km ² (% to total area of NCR)			
Water Bodies	182.9 (0.5)	194.4 (0.6)	252.2 (0.7)	0.2
Built Up	1606.5 (4.7)	1930.6 (5.7)	3279.7 (9.6)	4.9
Open Vegetation	4399.8(12.9)	5778.4 (16.9)	5569.0 (16.3)	3.4
Dense Vegetation	652.3 (1.9)	235.2 (0.7)	717.8 (2.1)	0.2
Scrub Land	998.1 (2.9)	1443.2 (4.2)	1215.6 (3.6)	0.7
Fallow Land	3177.6 (9.3)	1845.0 (5.4)	2102.8 (6.2)	-3.1
Waste/Barren Land	121.8 (0.4)	144.1(0.4)	254.2 (0.7)	0.3
Agricultural Land	23008.9 (67.4)	22577.1 (66.1)	20739.5 (60.8)	-6.6

Table 3 Land use statistics of NCT-Delhi Sub-Region from 1991-2011

LULC Classes	1991	2001	2011	change in % 1991-2011
	Area in %			
Water Bodies	1.2	0.9	1.3	0.1
Built Up	28.6	34.9	48.0	19.4
Open Vegetation	18.9	26.4	19.3	0.5
Dense Vegetation	7.9	4.5	4.3	-3.7
Scrub Land	0.5	1.7	0.9	0.4
Fallow Land	15.2	7.6	9.3	-5.9
Waste or Barren Land	0.5	0.6	1.1	0.6
Agricultural Land	27.2	23.5	15.8	-11.4

Table 4 Land use statistics of Haryana Sub-Region from 1991-2011

LULC Classes	1991	2001	2011	change in % 1991-2011
Water Bodies	0.49	0.49	0.83	0.35
Built Up	3.88	4.9	8.9	5.02
Open Vegetation	8.36	13.97	14.77	6.41
Dense Vegetation	0.79	0.35	0.96	0.17
Scrub Land	1.3	1.81	1.31	0.01
Fallow Land	7.16	5.31	5.81	-1.35
Waste or Barren Land	0.29	0.27	0.88	0.59
Agricultural Land	77.72	72.9	66.52	-11.21

Table 5 Land use statistics of U.P. Sub-Region from 1991-2011

LULC Classes	1991	2001	2011	change in % 1991-2011
Water Bodies	0.7	0.92	1.02	0.33
Built Up	4.81	5.43	9.7	4.89
Open Vegetation	11.72	15.84	12.96	1.23
Dense Vegetation	3.55	0.99	4.47	0.91
Scrub Land	0.17	1.42	1.66	1.48
Fallow Land	9.22	3.21	5.5	-3.72
Waste or Barren Land	0.47	0.55	0.98	0.51
Agricultural Land	69.36	71.66	63.63	-5.73

Table 6 Land use statistics of Rajasthan Sub-Region from 1991-2011

LULC Classes	1991	2001	2011	change in % 1991-2011
Water Bodies	0.28	0.19	0.11	-0.18
Built Up	1.57	1.88	3.66	2.09
Open Vegetation	20.65	21.43	22.66	2.01
Dense Vegetation	0.47	0.15	0.46	-0.01
Scrub Land	9.61	12.29	10.2	0.58
Fallow Land	11.83	8.03	7.01	-4.82
Waste or Barren Land	0.28	0.47	0.15	-0.13
Agricultural Land	55.3	55.57	55.72	0.42