Development of an Urban Spatial Scenario Design Model (USSDM) for Climate-Resilient Urban Planning in Lahore, Pakistan

Tooba Iftikhar[1,*], Tabassam Raza[1 2 3]
[1]*Department of City and Regional Planning, University of Engineering and Technology, Lahore, Punjab, Pakistan*
[2]*Graduate School of Business, Disaster Risk Management Unit, and Information and Communication Technologies, Philippine School of Business Administration, Manila, Philippines*
[3]*School of Urban and Regional Planning, University of the Philippines Diliman, Quezon City, Philippines*
[*]*Corresponding Author: <toobaiftikhar383@gmail.com>*

Abstract

Rapid urbanization and climate change present significant challenges for cities worldwide, with developing world cities facing heightened risks. Factors such as population growth, land use changes, environmental degradation, and increased vulnerability to climate-related hazards contribute to the vulnerability of these cities. This study addresses these challenges by projecting future development scenarios and evaluating their impacts on urban sustainability and resilience. We develop an Urban Spatial Scenario Design Model (USSDM) to integrate climate change resilience into urban planning, with a focus on future carbon stock changes and their implications for urban greening. The research utilizes the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to assess current and projected Carbon Storage and Sequestration (CSS) capacities. This involves analysing two development scenarios—Business as Usual (BAU) and Densification—over a 10-year period. The development process includes (a) data collection, (b) model design, (c) implementation in Geographic Information Systems (GIS), (d) scenario analysis, and (e) interpretation of results. highlight the need for advanced modelling tools and enhanced planning practices to better manage urban growth and environmental sustainability in Pakistan. This initiative not only aims to inform decision-makers but also to promote climate-resilient urban development in Pakistani cities, making it an essential component of their master plans for a sustainable and resilient future.

Keywords*: Land Use Changes, Urban Sustainability, Carbon Storage and Sequestration, Scenario Analysis, Advanced Modelling Tools*

1 Introduction

In past decades, many urban areas have seen significant expansion due to increased population and the global economy's transformation (Cohen, 2006), where the population growth in the Global South was nearly twice as fast as that in industrialized nations (Verma & Das, 2024). The number of people living in urban areas worldwide is expected to keep rising, reaching between 4.72 and 5.00 billion by 2030, representing the growth rate of 48.6% to 57.8% (Zhang, 2008). This urbanization, on one hand, is largely advantageous, contributing to improved living standards and over 90% of the global gross value added (Phelan et al., 2015). On the other hand, the very phenomenon has disrupted natural surface energy balances and water cycles, converting vegetated areas into heat-retaining impervious surfaces and reducing urban canopy coverage, which has led to increased surface temperatures (Nice et al., 2024).

Cities, as engines of economic growth, are more susceptible to the impacts of climate change (Kuittinen et al., 2016; Zhou et al., 2022), and they are already experiencing record-high summer temperatures globally (Yin et al., 2024). According to a United Nations report in 2023, the warming trend in Asia from 1991 to 2023 was nearly twice as fast as the trend from 1961 to 1990 and that significantly exceeded the numbers of earlier three decades (United Nations | Peace, Dignity and Equality on a Healthy Planet, 2024). Urban green spaces (UGS) are crucial in this regard as they help reduce the impacts of global warming (Korah et al., 2024). These are also vital for maintaining the Earth's carbon balance and mitigating greenhouse gas accumulation (Lahiji et al., 2020), but uncontrolled housing construction has resulted in a significant loss of UGS (Zarie et al., 2024a). As cities become more urbanized and densely populated, this trend not only contributes to the urban heat island (UHI) effect but also results in significant habitat loss and a decline in biodiversity (Home - Carbon Brief » Clear on Climate, 2024).

Urbanization not only harms the natural ecosystem but also disproportionately impacts vulnerable populations, thereby promoting socioeconomic inequalities (Chen, 2024). Rapid urbanization frequently results in the growth of informal settlements or slums (Samadkulov, 2024), where residents often face inadequate basic services and limited legal protection (Ono & Muya, 2024). It is estimated for Lahore that 75% of residential land development is done by informal/unplanned sector (Hussnain et al., 2016), often with minimal or no concern for urban greening. Urban land expansion is continually outpacing the growth of urban populations where major development happens in haphazard manner. The development of these settlements is a notable aspect of modern urbanization (Ulack, 1978), and this trend is projected to become more fast-paced in future.

Developing nations face the dual challenge of pursuing industrialization and progress while simultaneously working to mitigate climate change impacts (Avenyo & Tregenna, 2022; Zheng et al., 2022). An eye-opening piece of data shared by Dr Hanif was that Lahore is now the most vulnerable city in Pakistan, experiencing climate impacts for 150 days a year (Pakistan: From Global Warming To Global Boiling, 2024). This includes 75 extremely hot days (from May to September), 30 days of smog, 35 days of dense fog, and 10 days of urban flooding. As a result, the people of Lahore endure harsh conditions 40% of the year. Further he added that the UHI effect in Pakistan has significantly increased, by about 25%, due to the rise of concrete structures and the lack of green spaces. Therefore, simulating urban growth patterns is becoming crucial for ensuring long-term and sustainable development (Barredo et al., 2003).

To address this growing crisis, it is crucial to implement thoughtful land use strategies that prioritize green spaces and sustainable development. Sustainable urban development involves current generations actively reducing consumption and pollution to ensure that future generations can enjoy similar or improved living conditions (Chen, 2024). This study aims to project future development scenarios for Lahore and evaluate the most effective development patterns with a focus on urban greening. The manuscript is organized as follows: Section 2 reviews the past literature on the complexities of urbanization, the challenges of managing UGSs, the inadequacies of current urban planning practices in Pakistan, and the importance of advanced modelling tools for sustainable urban development. Section 3 outlines the study's scope and the methodology used. Section 4 presents the analysis and findings. Lastly, Section 5 provides conclusions, recommendations, and potential areas for further exploration.

2 Literature Review

Urbanization patterns vary greatly between regions, and there's even more variation in how quickly individual countries or cities within those regions are growing (Cohen, 2006). Despite the variety of changes, the spatial dimension has gained importance over the past decades. We have seen patterns of urban clustering that go beyond traditional boundaries. This highlights the increasing complexity of cities of today (Carlucci et al., 2020). In response to urbanization, several policies advocate for urban densification—such as creating compact city forms or densifying existing urban areas—to mitigate urban sprawl (Mohammed et al., 2021). European planning policies, in particular, emphasize "smart" growth by promoting high-density building development and a range of urban functions within walkable distances to create more compact cities (Koning et al., 2020).

Over the past three decades leading up to 2022, land growth and consumption have become uncontrolled and disorganized, especially in the marginal areas (Farhan et al., 2024). Mohajeri et al., 2019 concluded that while a densification strategy requires 3–6% more cooling in the short term, it results in a 12–15% reduction in cooling demand over the long term. Thus, evaluating the efficiency of various urban density and centralization patterns is crucial for creating liveable communities (Flores & Sosa, 2017). It is important to avoid both excessively dense and overly scattered or fragmented development. Newly designated zones for future development, which currently have no buildings, are overlooked as the focus is on densifying the existing building stock (Eggimann et al., 2021). The challenge for Lahore is to sustain the liveability of a denser urban environment as seen in the case of the cities developing world.

Lahore has undergone remarkable growth in recent decades (Fahad et al., 2021; Nasar-U-minallah et al., 2021), significantly advancing in infrastructure development due to its large population, the influence of major political parties, and growth in businesses and industries (Rana et al., 2017). S. Arshad et al., 2022 studied urban development in Lahore from 2003 to 2019 and found a 36% decline in urban vegetation as a result of urban sprawl. Nadeem et al., 2021 evaluated the feasibility of compact city development in Lahore. The analysis revealed that urban growth was driven by 70% natural population increase, 20% migration, and 10% expansion of city boundaries.

The shift of the population towards the suburbs, driven by more affordable land on the city's periphery, along with an inadequate public transport system, has led to a sharp rise in the number of privately owned vehicles (Imran Naqvi et al., 2023). This increase has significantly intensified urban traffic congestion and is a major contributor to the deterioration of Lahore's Air Quality Index (AQI), which currently averages175 $\mu g/m^3$ (Tariq et al., 2023). Lahore Master Plan 2050 allocates large parcels of land for single-family housing, a trend that could exacerbate the city's issues and then it will be far from realizing the net zero emission targets. For this, we need a better understanding or various urban land uses and their placement to control the overall thermal environment. Sustainable Development Goals (SDGs) and Green Building Standards should be taken into consideration given the rising temperatures and increasing pollution levels.

The PSS Core Strategy 2047 by The Urban Unit emphasizes ensuring universal access to water and sanitation for all urban residents and updating land use and zoning regulations to support a diverse range of housing types in major urban centres of Punjab (The Urban Unit, 2024). This also emphasizes that, alongside single-family homes, the focus should shift toward denser development patterns, supported by more effective land use planning. The key authorities responsible for municipal services and construction in Lahore include the Metropolitan Corporation of Lahore, the LDA, the Punjab Central Business District Development Authority, the Ravi Urban Development Authority, the Walled City Authority, and Lahore Cantonment Board. The situation earlier resulted in lack of implementation of the Master Plan 2020. Some areas of Lahore have high-rise buildings, while in others the construction of more than two storey is not allowed (LDA to Develop Commercialisation Policy, 2024).

In the wake of city densification, models serve multiple purposes in urban planning and policy design (Hamel et al., 2021). Firstly, they inform on-the-ground decisions by providing quantitative assessments with relatively low uncertainty. Secondly, they aid exploration by enhancing understanding of general trends and dynamics in complex systems, helping infer implications of different planning options (Hamilton et al., 2019). Lastly, they facilitate communication and learning by conveying key insights and fostering shared understanding among stakeholders. Using Remote Sensing (RS) and GIS techniques to model urban growth patterns provides insights into how urban areas expand spatially over time, aiding in the formulation of future sustainable development policies. In developing countries such as Pakistan, the effectiveness of modelling and environmental assessments is constrained by a shortage of high-quality data.

There are various parameters to determine the future land use pattern of the cities. The impact of urbanization is primarily influenced by the extent of land consumption and the intensity of its use (Chakraborty Anasuaand Omrani, 2022). Most studies use a raster-based Cellular Automata (CA) model for predicting future urban development, which represents entities as two-dimensional cells (rows and columns). To address the limitations of this approach, a vector-based CA model can be used for studying urban densification. This model selected for this research uses both raster and vector data formats, switching between them at various stages to enhance data presentation and accuracy. The Urban Spatial Scenario Design Model (USSDM) by Abo-El-Wafa et al., 2018 is recognized for its user-friendliness and simplicity, making it well-suited for use by urban planners in Pakistan. Based on the reviewed literature and the current research landscape in Pakistan, this model is ideal for its compatibility with available data and its accuracy. USSDM uses the input parameters mentioned in Table 1. Significance of these parameters for future urban development is confirmed from the literature and other models suggested in past.

Table 1. Input Parameters for USSDM Validated by Literature

Input Parameters	References	Concept/ Explanation
City Centre	(Hamidi & Ewing, 2014)	This study, conducted on 162 urbanized areas in the US in 2010, identified not only central business districts (CBDs) but also employment sub-centres, providing a more comprehensive understanding of urban centres.
	(Terzi & Serdar Kaya, 2024)	As the urban form becomes more complex and irregular in concentrated growth areas, the extent of sprawl also increases.
	(Giuliano & A. Small, 1999)	Agglomeration economies are heavily influenced by accessibility and proximity to areas of urban densification.
Road Proximity	(Garcia-López, 2019)	A 10% increase in highway length leads to a 1.1% rise in residential land area, a 2% increase in residential lots, and a 25-percentage point growth in undeveloped land around residential areas over 20 years, indicating that highways contribute to residential sprawl by promoting more fragmented and isolated development.
	(Zhao et al., 2024)	The relationship between urban sprawl and road network features provides valuable insights for the future growth of developing cities worldwide. By understanding road network density, it becomes possible to predict urban land expansion, avoid irregular growth patterns, and address issues related to inefficient land use.
	(Wu et al., 2017)	A new city expansion model is introduced in the study to analyse the interplay between population diffusion and road growth while exploring the complexities of population distribution and road network structure in urban expansion.
	(Cervero, 2003)	The research demonstrates that improvements in freeway infrastructure led to significant "induced growth," where real estate development becomes concentrated around upgraded roadways, and "induced investment," where increased traffic volumes from this development drive subsequent investments in further road enhancements.
Existing Land Uses	(Carrión-Flores & Irwin, 2004)	High productivity lands, typically fertile, well-drained, and close to water sources and urban areas, are often prioritized for urban development. Fragmented small farm units face higher management costs and difficulties accessing production inputs and financial services. Such fragmentation is often more pronounced near city boundaries where urban pressure is stronger.
	(Steurer & Bayr, 2020)	This paper examined how to measure key aspects of urban sprawl using land use data. Thus, land use data is crucial for detecting and forecasting changes in development patterns.
	(Abdrabo et al., 2021)	There are four types of land that can be infilled: non-arable lands, which are agricultural lands that have not been replanted; vacant lands, which are unoccupied plots available for development; agricultural pockets, which are agricultural lands located within or on the edges of urban clusters and surrounded by buildings; and yards, which are vacant lands used informally as dumps.
Neighbourhood	(Bhatia et al., 2024)	The study highlights the importance of neighbourhood assessment in urban growth prediction, as models incorporating neighbourhood effects demonstrated higher accuracy compared to those that did not.

(Moroke et al., 2019)	While sustainability is a central focus in urban development, it has been inadequately addressed, particularly spatial factors. The paper emphasizes the need for a comprehensive model to assess and integrate neighbourhood sustainability effectively.

USSDM has also uses slope as an input parameter. From a real estate perspective, construction on steep land is more expensive than on flat land. Therefore, it's an important factor needed to be taken into consideration (Ustaoglu & Williams, 2017). The global trend of urban land expansion shows a decrease in predominantly flat areas from 84.85% to 83.99%, with population growth and terrain being key drivers of the "slope-climbing" pattern in urban development (Shi et al., 2023). While this trend is not highly relevant for Lahore, it becomes significant when studying urban regions in mountainous areas.

Continuous urban expansion is a threat to UGS. These spaces play a major role in reducing the heat load caused by built-up areas (Sun et al., 2020). They significantly enhance the environmental quality of cities by improving shading, optimizing landscaping, and increasing evapotranspiration rates (Pauleit et al., 2017). Having such significance, these spaces have often been neglected and ignored as they failed to become a main aspect of our city planning and processes. Lahore has a minimal amount of green space, consisting mainly of a few city parks and limited agricultural land (Ahmad & Sarwar, 2023). Atmospheric factors, including rising land surface temperatures and intense storms with heavy rainfall over the past year, have impacted agriculture sector of the region (Ismail et al., 2023).

There are numerous challenges to both creating and protecting green spaces amid broader urban development (Practical Considerations and Challenges to Greenspace - Forest Research, 2024). One issue identified is the insufficient presence of UGS in densely populated urban areas and the elimination of existing green spaces during the densification of city areas (Haaland & van den Bosch, 2015). Maintaining UGS incurs costs. Consequently, where green spaces are perceived as deteriorating, there's a heightened risk of redevelopment rather than renovation (A. C. K. Lee et al., 2015). Thus, such green spaces have been converted to grey infrastructure to meet housing needs of the growing population.

Policies may advocate for sustainable development, but in most cases, actual development has not aligned with the recommendations of local planners and plans. Instead, it has often been driven primarily by the interests of developers and residents (Azhdari et al., 2022). Practitioners in Pakistan, including town planners, lack advanced skills and work in a stagnant system. All the research being done in Pakistan is limited to research papers and not being implemented in actual scenarios. No research has been conducted to analyse the impact of Ravi City development on the urbanization of Lahore. The assessment of densification potentials in relation to sustainability is generally lacking. The geographical location is only minimally considered when evaluating densification sites.

This study aims to project two different future development scenarios for Lahore and evaluate the most effective development pattern. While numerous international studies have explored the relationship between land use and land cover (LULC) and Carbon Storage and Sequestration (CSS) (Adelisardou et al., 2022), there is a lack of research at the national level. This study seeks to fill this gap by exploring the city's green assets. By doing this, it aims to make it easier to use advanced modelling tools in real-world urban planning. This research is crucial for making better decisions about managing urban land use in Pakistan. By implementing the modelling, it will give us valuable information about how to add the factors of sustainability and resilience in our rapidly urbanizing cities. Urban planners in Pakistan require skill enhancement and improved statistical and spatial tools to effectively compete with business-driven spatial planning.

The objectives of this study include:

- Examine the current urban expansion trends in Lahore and develop two alternative future scenarios for the predicted period.
- Assess both current and projected CSS capacities using InVEST.

- Explore the spatial distribution and dynamics of carbon storage and sequestration over time to enhance decision-making for ecosystem management.

3 Materials and Methods

3.1 Case Study Area

Lahore is situated in the north-east of Pakistan, in Punjab Province, between 31°15′—31°45′ N and 74°01′—74°39′ E (Figure 1). Ravi River flows on the north of the city. District Lahore has the area of 1772 km2 with a population of over 13 million, ranking it among the top megapolis of the world (Welcome to Lahore | Lahore, 2024). It's the provincial capital with 15 percent of the Punjab's total migrants migrating to Lahore as per the Labor Force Survey of 2014 (The Urban Unit, 2024). Lahore's expansion had been primarily directed towards the south and southeast due to the constraints posed by the River Ravi, and growth towards the east was limited by the proximity of the Indian border (Nadeem et al., 2021). With the planned development of Ravi City, Lahore is set to expand westward and north-westward along the River Ravi. This new urban city is located at the intersection of Lahore and Sheikhupura districts and is primarily designed to accommodate the future population of Lahore. Thus, the area of interest (AOI) for this study includes the entire Lahore district, along with the area under the Ravi Urban Development Authority (RUDA), covering a total land of 2002 km^2.

Reasons for choosing the study area are:

- Significant loss of highly productive land in the region.
- Worsening air quality in Lahore, highlighting the need for increased greenery.
- Limited use of advanced modelling tools in the region.
- Insufficient data on the location, distribution of carbon stocks, and land-use changes, with a lack of comprehensive studies.

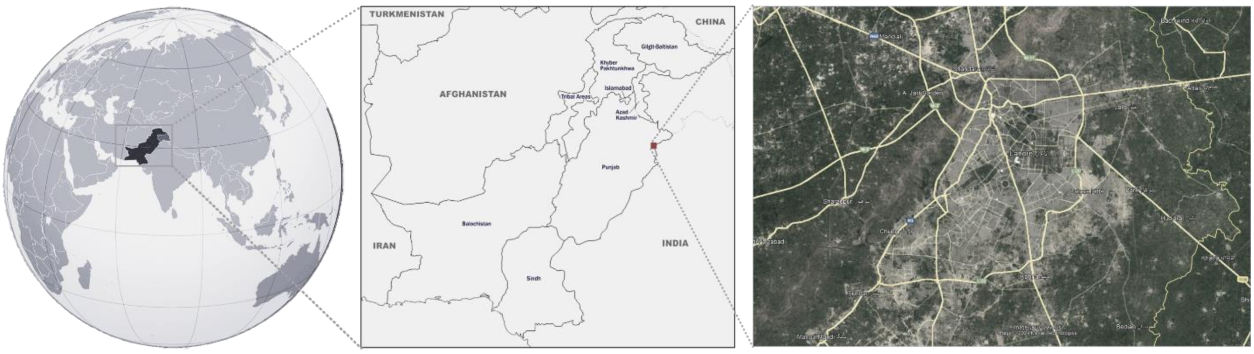

Figure 1. Location of Case Study Area

3.2 Data Collection and Tools

A range of analytical tools were utilized for the analysis, including the USSDM, Google Earth Engine (GEE), Google Colab, Maximum Likelihood Classification (MLC) algorithm by ArcGIS 10.8, and the CSS by Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. The final selection of the models was based on frequent citation in the literature and a thorough assessment of the quality and availability of data for AOI. Remote sensing (RS) technologies is a powerful method for examining urban issues, particularly for mapping urban and built-up land cover (Martinuzzi et al., 2007). The advantages of satellite data include its broad availability, often at no cost, through various national and international agencies. It can be collected effortlessly, even from the most remote locations. Additionally, satellite data ensures objectivity and allows for consistent comparisons across different regions and countries. Models used in this study predominantly leverages secondary data sources that are publicly accessible at no cost.

The data source used for identifying the current land uses in the AOI included RS imagery with a 30-meter spatial resolution from the Landsat 9 satellite, provided by the U.S. Geological Survey. The dataset is processed to Level 2 Surface Reflectance (L2SP) with Collection Number 02 and Collection Category T1 (Tier 1), acquired on June 25, 2024. The imagery features minimal cloud cover at 0.03% and image quality is rated as 9 for both the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The MLC algorithm, recognized as the most advanced image classification technique, was employed to categorize the LULC of AOI for year 2024. On-site visits were conducted to create a ground truth map using 500 ground control points (GCPs), representing various LULC categories for 2024. This data was employed for calibration and to apply necessary corrections. Accuracy assessment showed substantial values for user's accuracy (UA), overall accuracy (OA), and producer accuracy (PA), with the kappa coefficient approximating 86%.

Secondary data on the historical spatial growth of Lahore District, population density, demographic trends and related information were gathered from key sources such as the Integrated Master Plan for Lahore 2021, Punjab Spatial Strategy 2047, Lahore Master Plan 2050, publicly available documentations from Ravi Urban Development Authority (RUDA), Pakistan Bureau of Statistics reports, and journal articles on LULC analysis of Lahore etc. This study further employs district maps to measure carbon storage and sequestration across various land use types, aiming to evaluate the impacts of two future land use scenarios. We devised a comprehensive modelling approach to examine the spatial and temporal effects of LULC on carbon storage and sequestration value during the predicted scenarios period (2024–2034). Conceptual framework of the study is provided in Figure 2.

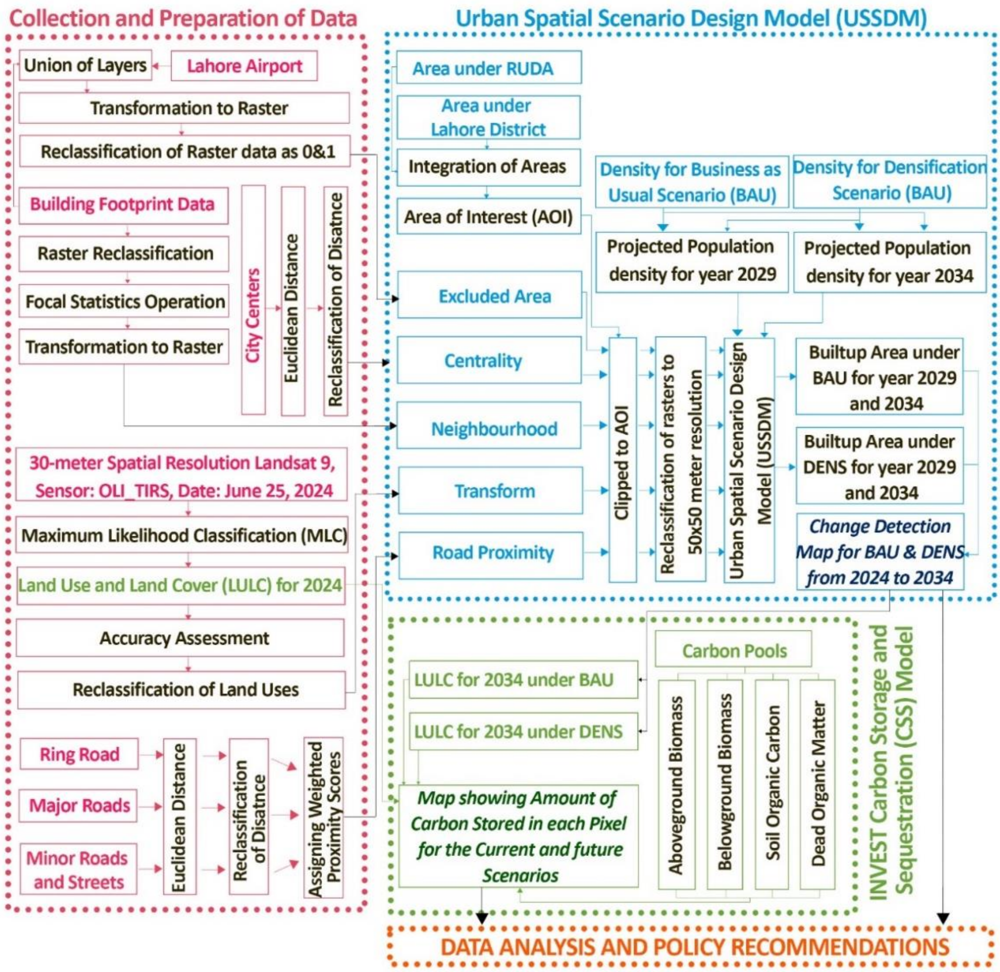

Figure 2. Conceptual Framework

3.3 Modelling Scenarios

For the analysis of future development trends, following two scenarios were taken into consideration as specified by Abo-El-Wafa et al., 2018:

- BAU (Business-As-Usual Scenario): In this scenario, urban development continues in its current trend, which primarily involves horizontal expansion. This means that more land is being covered with buildings, roads, and other infrastructure in the form of private housing schemes. This results in a significant loss of agricultural land and conversion of barren land into cement covered areas. The current population density of Lahore is 6,275 people per sq. km. However, after incorporating the area of Ravi City into the Lahore District, the new population density is estimated to be around 5,500 people per sq. km.
- Dens (Densification Scenario): In this scenario, the focus is mainly on vertical development which reduces the amount of land needed for expansion. The goal is to protect as much vegetation and natural features as possible while accommodating the growing population and urban needs. According to UN Habitat Report in 2014, population density in a sustainable neighbourhood should be at least 15,000 persons per sq. km (150 persons per hectare).

3.4 Carbon Sequestration and Storage (CSS)

InVEST, developed collaboratively by Stanford University, the University of Minnesota, the Nature Conservancy, and the World Wildlife Fund, is freely available for download from the Natural Capital Project website. The mathematical formulation of the investment in CSS model has been thoroughly detailed in various studies (Adelisardou et al., 2022; Babbar et al., 2021; Bosch et al., 2021; Carrasco-Valencia et al., 2024; Fadaei et al., 2020; Hamel et al., 2021; He et al., 2016; Kaur et al., 2022; Kohestani et al., 2024; Lahiji et al., 2020; Lim et al., 2024; Piyathilake et al., 2022). By integrating LULC maps with data on carbon stored in various carbon pools, this model calculates the net carbon sequestration in a land parcel over time.

LULC types were evaluated for the four IPCC carbon pools: aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter. It aligns with IPCC guidelines, which stress the importance of comprehensive greenhouse gas estimation and reporting by accounting for all land cover types (Mauya et al., 2019). The carbon values for aboveground and belowground biomass across various LULC types, including agricultural land, water bodies and built-up area, were estimated in accordance with the guidelines set forth by the IPCC (2006) as highly used in the past research (Fusco et al., 2019; Kohestani et al., 2024; Pechanec et al., 2018; Piyathilake et al., 2022). These values are given in Table 2.

Table 2. Estimated Carbon Values Across Various Land Use/Land Cover (LULC) Types

Land-use type	Ca	Cb	Cs	Cd
Agriculture	3	2	8	1.5
Unused land	0.1	1.9	0.8	0
Water	0	0	0	0
Urban	1	0.5	2	0

4 Results and Findings

Lahore mainly functions as a single-core city, with its main commercial hub in the centre and various smaller, informal centres scattered around the city (Nadeem et al., 2021). Subcentres with rapidly expanding industries and those located near airports tend to experience significant growth (Giuliano & A. Small, 1999). As metropolitan infrastructure improves, the benefits of clustering in central employment areas diminish because people can more easily access jobs and services from other locations, reducing the need for everyone to be located in the same central area (B. Lee, 2007). A significant level of spatial dispersion is evident in German cities due to a considerable amount of activity being situated in non-central areas (Krehl & Siedentop, 2019).

Gulberg is commonly recognized as the city's central business district (CBD), but Lahore’s urban fabric includes several significant markets and focal points scattered throughout. Key attractions are the Fortress Stadium, Emporium Mall, Anarkali Bazaar, Thokar Niaz Baig etc but these are merely the congestion points of the city with limited infrastructure. These areas serve as vital nodes in the urban network. The size of these centres has been carefully analysed based on consultations with town planners and experts from various development authorities in Lahore. This comprehensive approach ensures that the diverse functions and influences of these centres are well-represented and considered in future urban development strategies. The distance from each city centre was calculated and subsequently classified into four categories, as shown in the Figure 3.

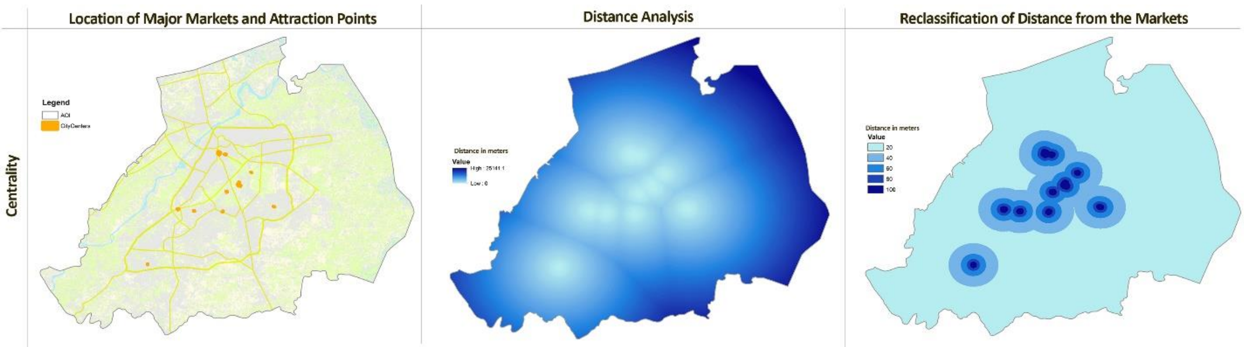

Figure 3. Subcentres of Lahore and Their Distance Analysis

Being close to major roads and highways is a constant and enduring factor that attracts commercial development. This means that as long as properties are near these transportation routes, they will continue to be appealing for commercial use (Yang et al., 2019). The road network was systematically classified into three hierarchical classes based on their importance: the ring road, which serves as an orbital road around the central business district; major roads having high traffic volumes; and minor roads and streets, which include all lower hierarchy roads (Figure 4). The analysis did not include major roads on the eastern side because development is restricted in that part of the district. Using the Euclidean distance tool, a proximity analysis was conducted, producing a raster file where grid values correspond to the distance to the nearest road.

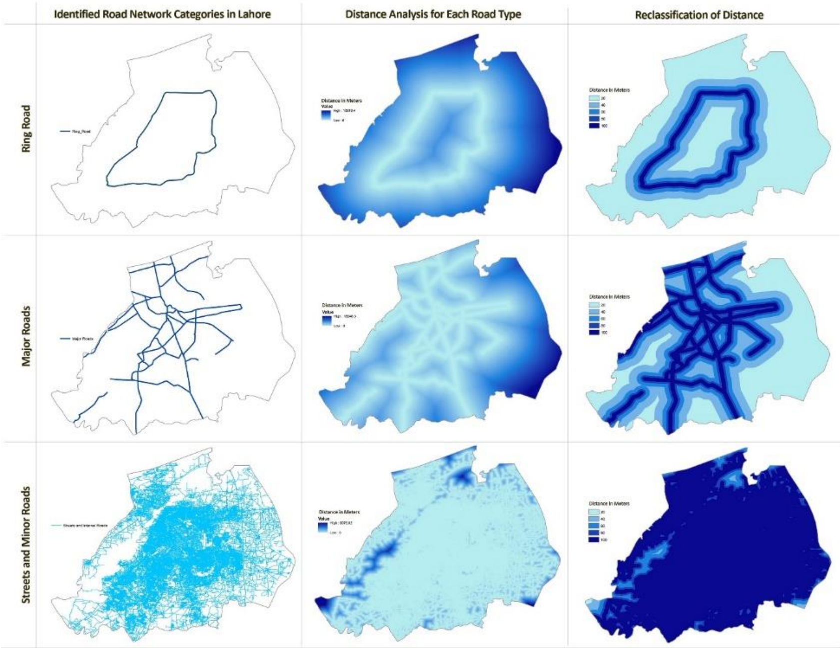

Figure 4. Identified Road Network Categories in Lahore and Their Distance Analysis

The analysis assigned weighted proximity scores based on the road class, with weights of 40% for the ring road, 35% for major roads, and 25% for minor roads and streets resulting in a raster illustrated in Figure 5.

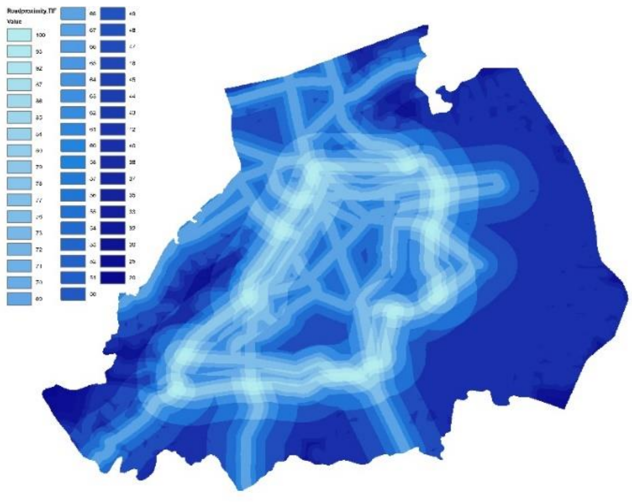
Figure 5. Road Proximity

The RS image of the study area for the year 2024 was categorized into four main LULC classes as given in Figure 6. The explanation of these classes along with their transformability score are provided in Table 3.

Table 3. Land Use/Land Cover (LULC) Classification and Transformability Scores for the Study Area (2024)

Land Cover	Description	Transformability Score
Built-up Area	Includes residential areas, public and private facilities, commercial centres, roads, and transportation infrastructure	0

Water Bodies	Comprises rivers, swamps, and drains	14
Vegetation	Covers both sparse and dense green areas, agricultural land, crops, and parks.	70
Barren Land	Represents bare soil and exposed ground	100

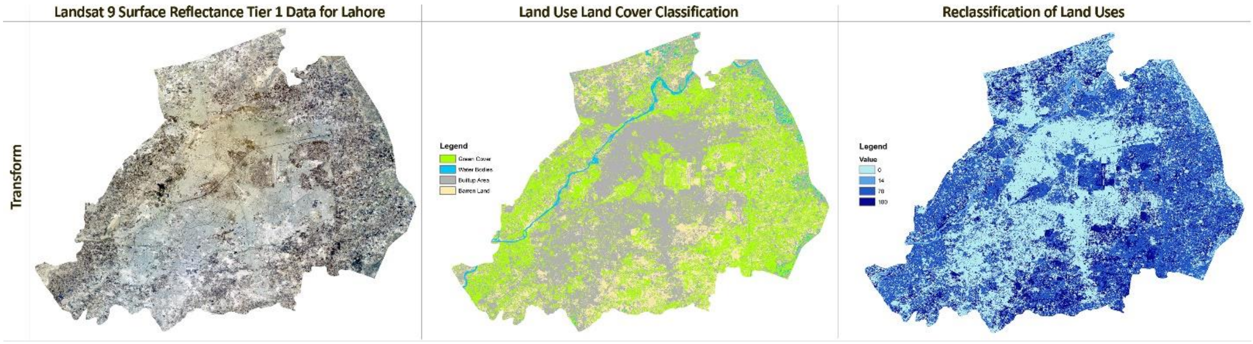

Figure 6. Land Use Land Cover (LULC) Classification for the Study Area (2024) and Its Reclassification

The excluded area was represented in a raster file, where cells with a value of 1 indicated built-up areas, and cells with a value of 0 represented other land use classes. Urban built-up areas were defined using building footprint data. This method utilizes GEE to filter and merge building polygons based on their confidence levels. It starts by defining a feature collection ('GOOGLE/Research/open-buildings/v3/polygons') and filtering it based on AOI. This dataset represents building footprints mapped by Google using satellite imagery and machine learning (Sirko et al., 2021). Buildings are classified into three categories based on confidence levels: low (0.65-0.7), medium (0.7-0.75), and high (>= 0.75). The collection is exported as a shapefile and later rasterized and reclassified for analysis as provided in fig ... Neighbourhood parameter explain that the residential location decisions are heavily influenced by the immediate quality of the local environment which is better in suburbs (Yang et al., 2019). Future development will be closely placed near existing neighbourhood. So, this raster file served as a valuable input parameter given in Figure 7.

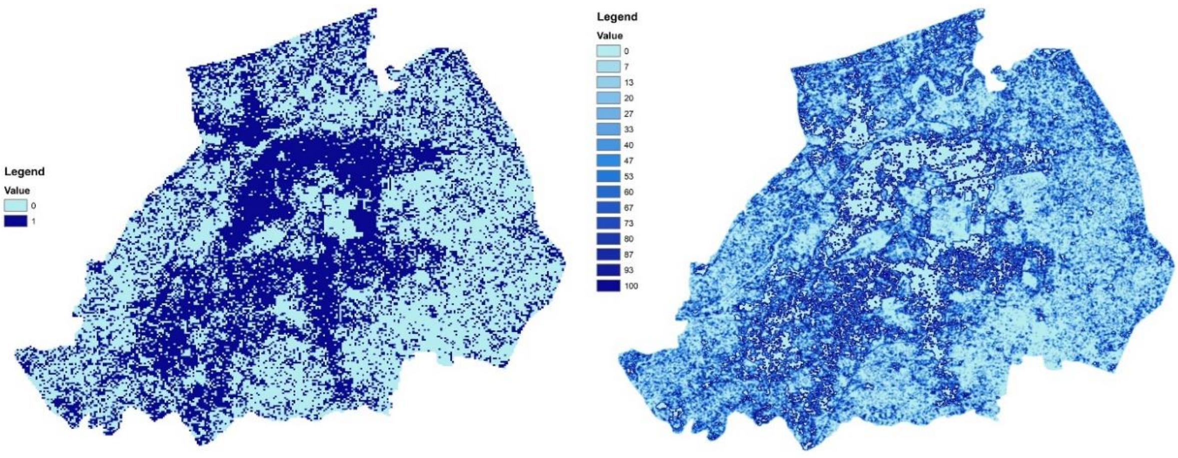

Figure 7. Reclassified Raster Images of Excluded Area (Left) and Neighbourhood (Right)

For the inputs of USSDM, we needed to estimate the future population and determine the number of raster cells required to accommodate projected development. This involved calculating the spatial demand for future urban expansion based on population forecasts which is given in Table 4.

Table 4. Estimation of Future Population and Raster Cell Requirements for Projected Urban Expansion

Year	Population	Increment	Area Required for Future Population (sq. km)		Required Cells	
			BAU	DENS	BAU	DENS
2024	13,676,179	2,556,194				
2029	15,854,440	2,178,261	392.22	145.22	156890	58087
2034	18,379,641	2,525,201	454.70	168.35	181878	67339

LULC analysis conducted by Farhan et al., 2024 was utilized to predict future land use patterns, as illustrated in the Figure 8. The results indicate a significant increase in built-up areas, accompanied by a sharp decline in UGSs and this situation aligns perfectly with our BAU scenario.

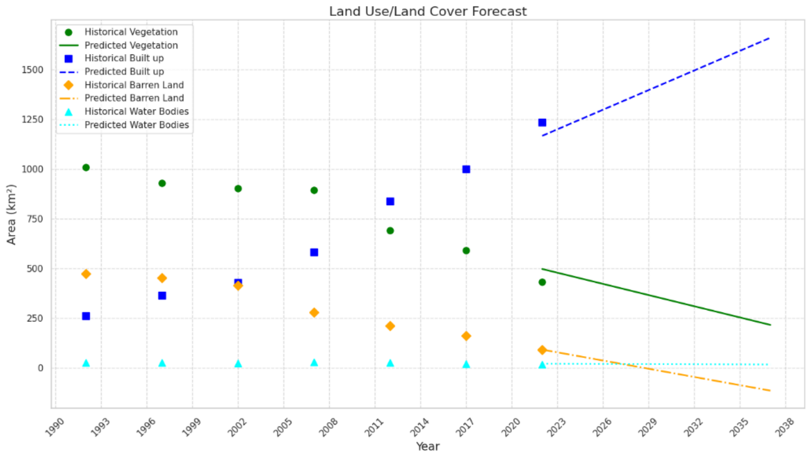

Figure 8. Predicted Future Land Use Patterns Until 2038 Based on Past LULC Analysis

By 2029, the BAU scenario predicts the conversion of 669 sq. km into built-up areas, while the DENS scenario reduces this expansion to 400 sq. km. By 2034, if the BAU pattern continues, 92.1% of the district will be urbanized. However, under the DENS scenario, only 71.4% of the area will be built up, preserving the remaining land as natural cover. Literature indicates that increased population density can sometimes harm local environments, even though densification may achieve per capita sustainability gains (Eggimann et al., 2021). Densification is a complex process that impacts various qualities that cities should possess. It requires huge infrastructure investments and significant upgradation of civic infrastructure. Table 4 compares two urban development scenarios over a 10-year period, focusing on settlement and non-settlement areas. The data is better explained by Figure 9.

Table 5. Comparison of Urban Development Scenarios from 2024 to 2039

Year	BAU		DENS	
	Area in sq. km	Increment	Area in sq. km	Increment
Non-settlement Areas	123		Non-settlement Areas	123
Settlement Area 2024	670	670	Settlement Area 2024	670
Settlement Area 2029	669	1339.03	Settlement Area 2029	669
Settlement Area 2034	505	1843.86	Settlement Area 2034	505

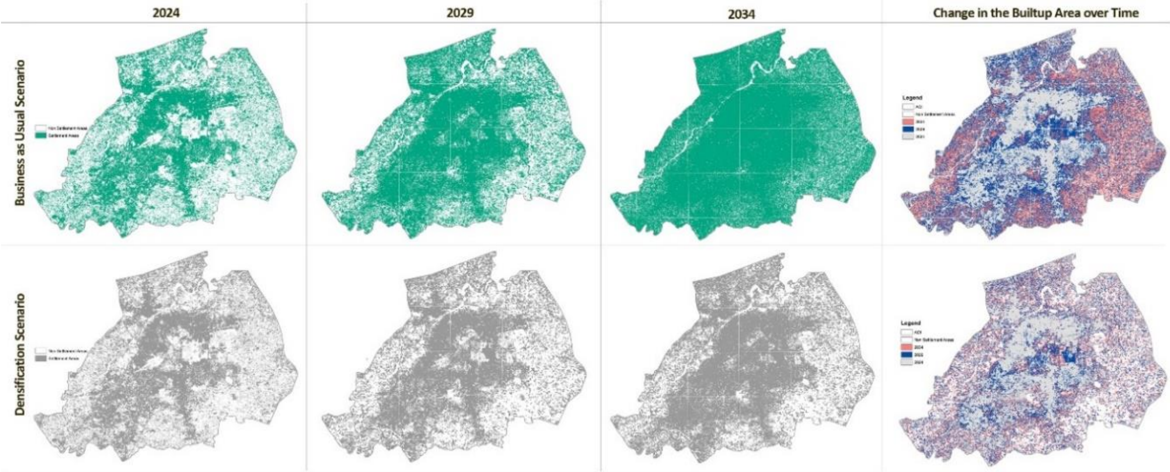

Figure 9. Increase in the Built-up Area under BAU and DENS scenario from 2024 to 2039

Further analysis of the figure highlighted the impact of urban expansion on retained vegetation. The findings indicate that Lahore’s urban growth has primarily led to the loss of fertile agricultural land, vegetation, and cultivation areas. In the DENS scenario, natural land cover, especially vegetation and water bodies, is retained more effectively compared to the BAU scenario. Although water bodies are largely preserved in both scenarios, the BAU approach results in a significant reduction in vegetation cover, whereas the DENS scenario maintains more vegetation. Additionally, the DENS scenario shows less conversion of barren land as given in Table 6. Overall, the DENS scenario represents a more sustainable urban expansion strategy, emphasizing reduced environmental degradation and better preservation of natural land features as illustrated by Figure 10.

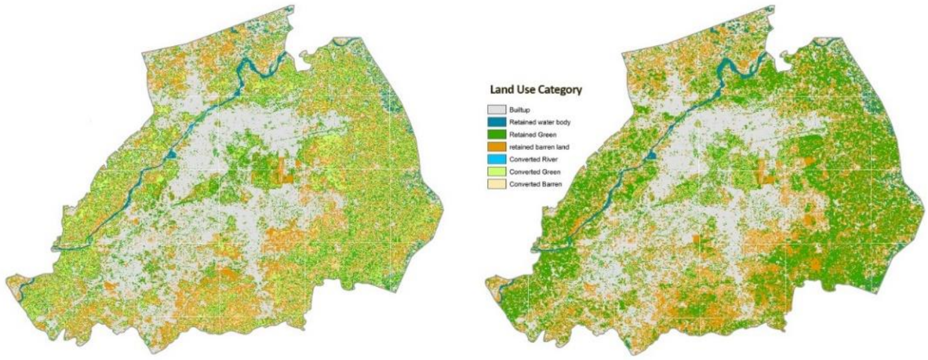

Figure 10. Loss of Agricultural and Barren Land over time in BAU (Left) and DENS (Right)

Table 6. Comparison of Land Use Changes from 2024 to 2039 Under Business as Usual and Densification Scenarios

	Business as Usual Scenario		Densification Scenario	
Type	Area in sq. Km	%age	Area in sq. Km	%age
Retained Water Bodies	37	1.85	40	2.00
Retained Vegetation Cover	364	18.39	580	29.34
Retained Barren Land	442	22.37	537	27.15
Lost Water Bodies	3	0.16	0	0.01
Vegetation Loss	289	14.63	73	3.67
Barren Land Conversion	85	4.28	74	3.76

The transition matrix given in Figure 11 shows the changes in LULC between 2024 and 2034. It reveals how much area has been converted from one land use type to another and it indicates which areas have remained unchanged. DENS scenario will improve the compactness score of Lahore. Expansion characterized by low densities, segregated land uses, commercial strips, and poorly connected streets will decrease compactness scores, while expansion with moderate to high densities, integrated land uses, activity centres, and interconnected streets, as well as growth through infill and redevelopment, will improve the compactness scores as highlighted by Hamidi & Ewing, 2014.

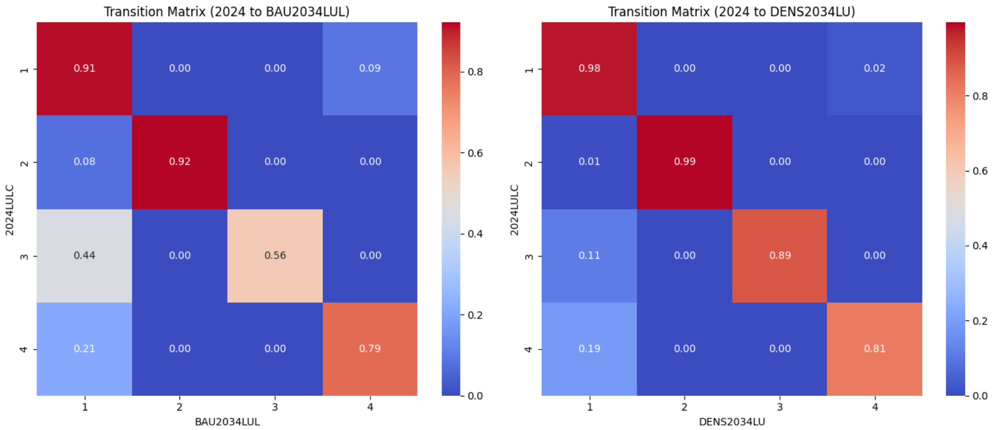

Figure 11. Transition Matrix of Land Use/Land Cover (LULC) Changes from 2024 to 2034

Contemporary urban planning faces the challenging task of ensuring that densification contributes to the preservation and creation of high-quality living spaces. Conflicts may arise between stakeholders, such as developers and environmental groups, due to differing interests and priorities (Chen, 2024). City centers need further enhancement in terms of its social infrastructure. For the DENS scenario, a city requires a well-integrated mass transit system. A well-functioning mass transit system typically caters to at least 20% of a city's daily ridership, but Lahore's current figure is notably lower. The Metro Bus system's focus has been primarily on hard infrastructure, neglecting key elements like area development, social and cultural value, and human-centered design (Anwar et al., 2024).

The USSDM approach was applied to Addis Ababa and Dar es Salaam in the past literature to evaluate urban growth under different scenarios. In Addis Ababa, In Addis Ababa, the DENS scenario would save 5,441 hectares of land compared to the BAU scenario, reducing the impact on farmland and flood-prone areas. In Dar es Salaam, higher population density scenarios could cut settlement expansion by up to 5,000 hectares, mitigating farmland loss and flood risk. Both studies emphasize the benefits of strategic, dense development and green infrastructure to balance urban growth and environmental preservation. For Lahore, the DENS scenario saved 41,460 hectares of land.

Instead of allowing unrestricted development on all available peripheral land, strict policies should be implemented to ensure land conservation for future growth. Forest cover is significantly limited relative to the region's greenhouse gas (GHG) emissions. In addition, human activities and overgrazing have resulted in diminished biomass carbon in degraded rangelands. This has led to a decline in the regeneration and growth of herbaceous plants, while the unchecked proliferation of shrubs has suppressed tree growth. In urban planning, determining the location of green spaces is crucial for planners and urban ecologists, as it plays a key role in promoting sustainability and ensuring environmental justice (Rehman et al., 2023). With rising urbanization and uncontrolled city development over the past decade, designing public UGS as nature-based solutions has become essential. Alongside increasing city density, there should also be a focus on vertical greening to enhance urban environments (Zarie et al., 2024b).

The current total carbon stock of the AOI is 22,860.052 metric tons. Our analysis reveals that agriculture and urban expansion have significantly decreased carbon storage due to rapid urbanization. If the historical trend persists, the BAU scenario will lead to substantial carbon loss in the AOI by 2034. Specifically, in the BAU scenario, the stock decreases from 22,860.052 to 12,643.789, resulting in a loss of 10,216.263 metric tons. In contrast, the DENS scenario shows a decrease to 20,074.8 metric tons, leading to a smaller loss of 2,785.252 metric tons. This suggests that the DENS scenario preserves more carbon stock compared to the BAU scenario.

Land Uses	2024 (Metric ton)	BAU2034 (Metric ton)	DENS2034 (Metric ton)
Built-up	76.376905	109.28541	86.183639
River	0	0	0
Green	22738.417	12501.771	19949.863
Barren Land	45.257799	32.732279	38.752559
Total	22860.052	12643.789	20074.8

5 Discussion and Conclusion

5.1 Scope for Future Research

Densification efforts must also consider cultural factors. Residents of Lahore oppose high-rise living and prefer owning their own land, which may lead to challenges in the future. The government needs to work on changing public attitudes and should focus on new housing development plans that include apartments. However, previous government schemes in Pakistan have struggled. Involvement of the private sector is crucial, and bylaws for private housing schemes should be revised with strict implementation and monitoring. Studies can further seek to identify the zoning patterns within the densification scenario. Obtaining comprehensive and reliable data for research from public institutions and authorities in Lahore is often challenging. Further, detailed building-related information is essential for conducting high-resolution densification analysis.

For a more rigorous planning application, additional factors such as land uses, building conditions, historical buildings, slum areas, maximum allowable heights, building footprints, natural and man-made risk areas, road widths, building heights, land values, industrial centres and public transport routes should be integrated. The utilized methodology could be improved by incorporating these additional indicators and data points over time. Selection of these indicators can be informed by current policy programs to evaluate their success or failure. Furthermore, integrating other development sectors such as socioeconomic factors and environmental aspects into this multi-scale approach would provide a more comprehensive perspective for achieving sustainable and balanced development. Predicting future LULC dynamics is a complex task, involving multiple factors such as economic and social conditions, ecological constraints, and the diverse perspectives of stakeholders in planning for the future that is beyond the scope of this research.

Similar study can also be conducted on a much larger scale using Colour Infrared Aerial (CIR) photographs, as demonstrated by the research of (Banzhaf et al., 2007). Such study will be focused on regional development. Where this study was focused on identifying potential new areas for development, future studies should focus on developing geospatial models with irregular spatial tessellations to represent mid- and high-rise buildings in 3D similar to the model proposed by Koziatek et al., 2016 for the City of Surrey, Vancouver, integrates GIS, fuzzy multi-criteria evaluation, and 3D procedural modelling. Pakistan should advance spatial research into three dimensions to improve research outcomes and enhance planning practices in the country.

5.2 Concluding Remarks

Gaining insights into the quantifiable benefits of natural infrastructure, including their distribution and recipients, empowers local governments to make informed investment decisions. Additionally, it provides valuable guidance for private sector entities, non-governmental organizations, civil society groups, and researchers to integrate scientific and technological innovations into on-the-ground projects. The protection and management of habitats can be improved by creating dedicated protected areas and implementing and enforcing appropriate laws and policies. Public awareness of biodiversity conservation should be increased through education and outreach, enhancing understanding and support for protected area policies and regulations. Additionally, encouraging public involvement in the management and oversight of these areas is crucial. Urban forests can also be developed to support these conservation efforts.

Analysing and mapping changes in land use over time, particularly in eco-fragile regions, is crucial for understanding environmental impacts and guiding sustainable management. Instead of engaging in comprehensive planning, planning departments are currently focused on significantly expanding the existing infrastructure. Urban planners should prioritize developing solutions that can be effectively adapted to a range of different scenarios including densification. Newly designated zones for future development, which currently have no buildings, are overlooked as the current policy focus is on densifying the existing building stock (as observed in the commercialization policy of LDA). Additionally, Lahore still requires focused efforts to enhance its sanitation infrastructure (Rana et al., 2017). If Lahore will be going toward a more compact development, then it'll be about putting more pressure on civic infrastructure of the city where the sewers are already chocked. Therefore, a balanced approach that integrates both infrastructure enhancement and strategic land use planning is essential for sustainable urban development.

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