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DETERMINING THE RESPONSE OF VEGETATION TO URBANIZATION AND URBAN EXPANSION IN SOKOTO METROPOLIS, SOKOTO STATE,IN NIGERIA

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ABSTRACT

This study assessed the relationship between urban expansion and tree density in Sokoto metropolis from 1990 to 2022, using NDVI (Normalized Difference Vegetation Index) and NDBI (Normalized Difference Built-up Index) differencing techniques. Results show continuous increase in urban vegetation as the city expanded. Over the 32-years, the net vegetation gain was 927.8ha while the urban built-up area expanded by 2918.1ha. Urbanization and urban expansion may have detrimental effects on urban vegetation but with controlled planning, it will have little or no negative impacts especially in the Sahelian area. Management and policy measures can thus be taken in cities to mitigate the negative effects of urbanization on urban vegetation. These findings are relevant to the planning and management of urban forests.

Keywords: Urbanization; Urban Vegetation; NDVI; NDBI; Land use/Land cover Change

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Introduction

Urban areas are unusually complex and diverse ecosystems, made up of different interacting social, economic, institutional and ecological subsystems, each affecting and being affected by all the others (Andersson and Colding, 2014). The urban ecosystem houses more than half of the global human populations and a great diversity of organisms (Douglas, 2012). It is a primary nexus of interaction between human and environmental system (Gao and O'Neill, 2020), providing avenues for examining the interplay among socioecological relationships (Walker et al., 2009; McHale et al., 2015) as well as experimental site for new forms of decision making (Frantzeskaki et al., 2018), leading to understanding the complex interactions between humans and the natural environment at a variety of spatial and temporal scales (Alberti and Marzluff, 2004). Urban areas are large ecological test laboratories (Ranta, 2012) where biological responses to environmental changes that may not be replicated in manipulative experiments could be observed (Zhao et al., 2016).
The global urban population is becoming more urban and by 2050, urban areas are expected to accommodate 6.3 billion people

(United Nations, 2018). Africa and Asia having faster city growth and burgeoning informal settlements (Roy et al., 2018) will account for most of the transformations (Koroso et al., 2021; United Nations, 2018). In Africa, urbanization is surging at an unprecedented speed of 3% (Rana and Sarkar, 2021; UN-Habitat, 2016), from 31.5% of its total population in 1990 to 36% in 2010 and projected to reach 50% in 2030. By 2050, the urban population in Africa will reach 1.34 billion which is about 60% of the continent's total population or 21% of the world's projected urban population (Dangulla et al., 2021; Güneralp et al., 2018; United Nations, 2014; Yao et al., 2019). Associated with this, is the expansion of cities and land use/land cover changes (Biney and Boakye, 2021; Faisal Koko et al., 2021; Liu et al., 2015; Nuissl and Siedentop, 2021), which are important contributors to eco-environmental changes and deterioration (Wu et al., 2016). Consequently, agricultural lands, vegetation, and other natural land cover will be significantly affected (Gao *et al*., 2020; Jianzhu and Maduako, 2018). Continuous urban expansion has been a global phenomenon since the 1900s, affecting almost every part of the world. The reason has generally been attributed to the global urban population growth and in particular, migration of people to urban areas. The world's urban population increased almost 10-fold from 224million in 1900 to 2.9 billion in 1999 (Alberti et al., 2008). This increased to approximately 3.4 billion in 2009 and is expected to reach 4.9 billion and 6.4 billion in 2030 and 2050 respectively (United Nations, 2017). In Nigeria, urban land was reported to have significantly increased by nearly 131% from 2,083 km^2 in 1976 to 5,444 km^2 in 2000 (National Population Commission, 2004). Nigeria will eventually be the 3rd most populous country in the world with an estimated population of 440million and about 330million people living in the urban areas (United Nations, 2017).

Although the response of vegetation to urbanization and accompanying land use and land cover changes depends on the form of urbanization and climatic region (Trusilova and Churkina, 2008), this topic has been discussed with variable opinions. Many scholars (such as Brandalise et al., 2019; de la Barrera and Henríquez, 2017; Gao et al., 2020; Jin et al., 2018; Melliger et al., 2018; Shirazi and Kazmi, 2016; Yao et al., 2019) believe that vegetation is destroyed or at least stunted by urbanization. In this perspective, urban vegetation may initially be lost due to habitat transformation or the landscape fragmentation processes as urbanization progresses, making rapidly urbanized cities have a high probability of vegetation degradation (Liu et al., 2015). On the other hand, however, others such as Knapp *et al*. (2009), Dolan *et al*. (2011), Zhou *et al*. (2014), Qian *et al*. (2015) and Huang *et al*. (2020) believe that vegetation growth is enhanced in urban environments.

In this rapidly urbanizing world, therefore, understanding the response of ecosystems to urbanization is highly desirable for planning and overall sustainability of residents and nature (Cao and Mathura, 2020). This is more pertinent in Africa which has witnessed rapid urbanization in recent decades (Enoguanbhor *et al*., 2022; Jiang *et al*., 2021; Yao *et al*., 2019) and where fewer similar studies (Agyapong et al., 2018; Anarfi et al., 2020; Gashu and Gebre-Egziabher, 2018; Nkwemoh and Afungang, 2017; Yao *et al*., 2019) have been carried out, leading to poor understanding of vegetation dynamics about urbanization.

Materials and methods

The Study Area

The study was conducted in Sokoto Metropolis which lies on latitude 13° 03' 05" and longitude 05° 13' 53" E and covers an area of approximately 94 km^2 (Dangulla et al., 2020). It is geologically located within the Kalambaina formation, belonging to the broad Sokoto group which is part of the extensive Sokoto basin. Kalambaina formation is underlain by cretaceous clayey limestones and shales and varies in thickness between 5 to 20 m (Kogbe, 1981; Kankara et al., 2021). Major rivers draining the area are the Rima and Sokoto rivers which flow into River Niger and subsequently into the Atlantic Ocean (Arogundade *et al*., 2023). The study area is shown in Figure 1.

The city falls within the relatively fragile, Sudan-Sahel region of Nigeria which is generally semi-arid (Nicholson, 2013). The Sahelian region of Africa, traditionally delineated as the southern fringe of the Sahara (Hiernaux *et al*., 2016; Olsson et al., 2005) stretches between latitude 13°N and 20°N and longitude 15°W and 20°E (Foley *et al*., 2003). This region is characterized by the tropical dry and wet climate type (Koppen's Aw) with short rainy and long dry seasons (Salih, 2015). The northern extent of this region which borders the Sahara has a mean annual rainfall of 200mm while the southern extent which borders the relatively wetter areas of the Sudan zone has mean annual rainfall of 600 mm (Hein *et al*., 2011). The mean annual temperature is 34.5ºC, though this may exceed 40ºC (Atedhor, 2015; Orimoloye *et al*., 2018). The vegetation is generally dominated by short, feathery grasses with scattered trees and shrubs (Atedhor, 2015; Gebremedhn *et al*., 2023) but tree cover density is generally low due to low soil water availability especially during the dry season (Hein *et al*., 2011). The soils are ferruginous, light, and porous and of low organic matter (Swindell, 1986) and generally composed of materials such as grit, clay, mudstone, sandstone, limestone and shale (Emujakporue *et al*., 2018).

Satellite data collection and processing

Satellite data for the study was primarily Landsat images for 1990, 2000, 2010, and 2022 covering the metropolis (Path/Row 191/051). These were acquired during the dry season (November and February) to minimize the presence of clouds and also near-anniversary to reduce the effects of seasonal variations in image classification (Dangulla *et al*., 2020; Lal *et al*., 2017). The images were Level-1 Terrain corrected (L1T), freely obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov). This implies that geometric and radiometric corrections have already been carried out at the source (Young *et al*., 2017). As the analysis involved images of different periods and different sensors, the images were further co-registered with each other to eliminate conflict of calibrations and environmentally introduced radiometric effects (Scheffler *et al*., 2017; Tondewad & Dale, 2020) and to determine pixel brightness in the corrected images (Wanga *et al*., 2012). An already processed Landsat 8 (OLI-TIRS) image of the metropolis for 2015 obtained from Dangulla *et al*. (2020) was used as the reference image. This image was initially pre-processed and classified with the Maximum Likelihood Classifier (see Liu and Yang, 2015) to reveal five (5) land cover classes which include the Built-up area, Farmland, Green area, Open space, and Wetland/water. The overall accuracy of the reference image was 90.3%.

Ground truthing and data collection

The study was designed to follow the stratification of the study area into land use/cover classes as per Iverson and Cook (2000). This is considered a fair and convenient way to conduct urban forest research and to analyze the spatial patterns of urban trees and forests (Steenberg *et al*., 2019, 2015). Stratified sampling as used in many related studies (such as Muchayi *et al*., 2017; D.J. Nowak et al., 2008; Strohbach and Haase, 2012) facilitates a reasonable population estimate and generally improves precision (Parsons, 2014). It also takes into account the variation in the size of the different clusters while maintaining the random principle (Piazza, 2010).

Accordingly, a total of 200 pixels were proportionately selected across the land cover classes using the stratified random facility of Idrisi TerrSet software. A sample of 200 points across a city has been found to yield a standard error of about 10% and hence, considered reasonable (Russo *et al*., 2014; Strohbach and Haase, 2012). The coordinates of each sample point were recorded into the waypoint list of Garmin GPSMAP 78s GPS and later traced. At each point, a quadrat of 30 m × 30 m was laid out as obtained from Yao *et al*. (2015) to coincide with the size of the

Landsat pixel used in the classification (Ren *et al.*, 2017). Consequently, land use and tree data were observed and recorded at each sample point.

Urban Expansion and Vegetation Change Analysis

The relationship between urban expansion and tree density in the metropolis was examined using an improved NDBI differencing approach proposed by He *et al.* (2010). This is a modification of the original NDBI developed by Zha *et al.* (2003) which involves a combination of NDVI (Normalized Difference Vegetation Index) differencing and the NDBI (Normalized Difference Built-up Index) differencing methods. Both indices were computed for each of 1990, 2000, 2010, and 2022 Landsat images of the study area. NDVI differencing was used to determine changes in vegetation intensity while NDBI differencing was used to determine change in the proportion of the built-up area over the study period. NDVI differencing is an image differencing technique which is based on a cell-by-cell subtraction between different images in a time-series. In this technique, the estimated NDVI is used as the normalized difference between near-infrared (NIR) and visible red (RED) bands to discriminate vegetation from other surfaces based on the green vegetation chlorophyll absorption of red light for photosynthesis, and the reflection of NIR wavelengths (Mancino *et al*., 2014). The NDVI computation is given in Equation 1.

NDVI = $\frac{NIR - Red}{NIR + Red}$ (Equation 1)

NDVI is a good proxy for vegetation greenness where higher NDVI values imply denser vegetative cover (Wang et al., 2022). It has been established that vegetation indices such as the NDVI are effective indicators of vegetation productivity (Adepoju et al., 2019; Zhao et al., 2016), suitable for describing urban vegetation dynamics since it can indirectly estimate gross and net primary productivity, biomass, and green leaf area (Liu et al., 2015). Hence, this method is being widely used in urban and forest cover change detection at both local and regional scales (e.g. de la Barrera and Henríquez, 2017; Gandhi *et al*., 2015; Sahebjalal and Dashtekian, 2013; Vorovencii, 2014).

NDVI differencing method involves calculating the NDVI for each year (t_1, t_2 … t_3) and then subtracting the earlier NDVI from the latter (t_1 from t_2 and t_2 from t_3) to determine changes (Δ) in vegetation intensity between t_1 and t_2 (Δt_2) and between t_2 and t_3 (Δt_3) respectively. Finally, the overall vegetation change (Δ_T) was determined by subtracting t_1 from t_3 (Equation 2-4).

$\Delta t_2 = NDVI_{t2} - NDVI_{t1}$ (Equation 2)

$\Delta t_3 = NDVI_{t3} - NDVI_{t2}$(Equation 3)

$\Delta_T = NDVI_{t3} - NDVI_{t1}$(Equation 4)

The change images were then reclassified into 3 ranges (left, right and central) based on the selected threshold. The threshold was calculated using the mean and standard deviation (Equation 3) of the pixels digital number according to Mancino et al. (2014b) as:

$\mu \pm n \cdot \sigma$(Equation 5) where,

μ = mean digital number of the ΔNDVI

σ = the standard deviation

n = range of dispersion around the mean.

The left range or tail ($\Delta NDVI < \mu - n \cdot \sigma$) indicates negative changes or tree loss, the right tail ($\Delta NDVI > \mu + n \cdot \sigma$) indicates positive changes or tree gain and the central ($\mu \cdot n \cdot \sigma < \Delta NDVI < \mu + n \cdot \sigma$) indicates no changes.

The NDBI on the other hand was calculated from the SWIR and NIR bands for the same images (Equations 4) and labelled b_1, b_2 …b_3. NDBI allows for the identification of built-up areas at a pixel-by pixel scale since sealed areas such as pavements and roofs have higher reflectance of light in the shortwave-infrared (SWIR) band than in the near-infrared (NIR) (de la Barrera and Henríquez, 2017; Zha *et al*., 2003).

NDBI = $\frac{SWIR - NIR}{SWIR + NIR}$(Equation 6)

To determine and extract the built-up area (BU) for the respective periods, the NDVI of each year was subtracted from the NDBI of that year (Equations 7-9).

$BU_1 = b_1 - t_1$(Equation 7)

$BU_2 = b_2 - t_2$ (Equation 8)

$BU_3 = b_3 - t_3$ (Equation 9)

The resultant images were then reclassified and the built-up areas were separately extracted and calculated. The relationship between these indices was derived through a correlation analysis using the Pearson product-moment correlation (Pearson r).

Results

Rate and Pattern of Vegetation Change in Sokoto Metropolis

The rate and pattern of vegetation change in the metropolis as determined with the Normalized Difference Vegetation Index (NDVI) images for the years 1990 – 2022 generally show increasing pixel intensities. The highest NDVI value for 1990 was 0.408 while the lowest was -0.337 but this increased to 0.668 and 0.037 in 2000 respectively. Urban vegetation and tree density during this period increased moderately in some places though there were significant losses in others. In 2010, NDVI values decreased to 0.546 (highest) and -0.016 (lowest) due to a considerable reduction in total vegetated area. In 2022 however, these values increased to 0.704 and -0.109 for highest and lowest respectively (Figure 2 a, b, c and d).

Most of the increases during the study period (1990 – 2022) occurred in the Green Area and the Wetland/Water Area (Figure 3a) primarily due to the natural growth of trees and a corresponding increase in their canopy size over the thirty-two-year period. This invariably increased the proportion of the area occupied by trees and the intensity of the related pixel values. The losses on the other hand were recorded around the built-up areas which could be explained by human disturbance in the form of residential area expansion and natural death of trees. Between 2000 and 2010, losses were more visible in the central parts as the metropolis expanded outwards. There was also a large wood lot that was cleared for a residential estate (Figure 3b). Between 2010 and 2022 (Figure 3c), most of the gains occurred in the South-East and South-Western parts of the city, around the city centre, and along the Wetland/Water strip. On the contrary, there was a remarkable decrease in tree density in the eastern, north-western and western parts of the city. This signifies a profound effect of urbanization pressure on urban vegetation which may lead to degradation or loss of the native tree species through the initial habitat transformation or landscape fragmentation processes as urban areas expand (Hahs *et al.*, 2009). Areas of no change refer to the non-vegetated portions of the metropolis which remained in their original form throughout the study period. Overall, major gains in urban vegetation were recorded in the southern, central and north-western parts of the city while major losses were recorded in the northern and central parts of the city (Figure 3). The losses in urban tree density recorded in the study were primarily due to expansion of the built-up area due to population increase and increased urban infrastructure. This led to a significant reduction in tree populations across the different land cover classes. The gains on the other hand were as a result of efforts from institutions and private individuals at planting and protecting trees in their areas of influence as well as the natural growth of trees which also led to significant increases in tree canopies and their proportional sphere of coverage. There was generally a consistent trend of increasing tree density with increased expansion of the city throughout the study period but higher increases in tree density were more evident in the Wetland/Water area and the Green Area.

Results of the NDVI differencing from this study showed that while the process of urbanization negatively affected the abundance and density of urban trees and vegetation in general, these were to a large extent compensated by efforts at planting trees in public and private lands across the metropolis. Moreover, the natural growth and replacement of trees play a significant role at tree enhancement after disturbances. As the trees grow, the size of their canopies increases as well which was captured by satellite sensors as an increase in the overall vegetation cover of the metropolis. This conforms with the findings of Zhao *et al*. (2016) in their study of 32 Chinese cities where vegetation enhancement in 85% of the studied places offset about 40% of the total converted urban vegetation.

Rate and Pattern of Urban Expansion in Sokoto Metropolis

Urban expansion as determined with the Normalized Difference Built-up Index (NDBI) technique for the study period revealed continuous increase in the intensity of the built-up area pixels. This correlated with the increasing density of the built-up area during the study period. The highest NDBI value recorded in 1990 was 0.21 while the lowest was -0.6. These values increased to 0.38 and -0.67 respectively in 2000 and 0.46 and -0.25 in 2010 and 0.50 and -0.14 in 2022. Correspondingly, the proportion of the built-up area continuously expanded throughout the study period (Figure 4a, b, c, and d).

The Built-up Area in 1990 occupied a relatively small portion of the northern part of the metropolis with some sparse settlements in other places (Figure 5). By 2000, the built-up area had expanded outwards to the south and eastern parts and the built-up density became more noticeable in the metropolis (Figure 5). By 2010, the built-up area expanded even further, encroaching into the adjacent open spaces and farmlands (Figure 5). This trend continued until 2022 when most of the open spaces and farmlands around the metropolis have been almost completely engrossed (Figure 5). The rate at which the built-up area expanded during this time accounted for much of the conversion of large areas of open space, farmlands and vegetated areas.

The NDBI differential analyses revealed total changes of 937.6ha and 747.8ha in the Built-up Area between 1990 and 2000 and between 2000 and 2010 respectively. These increased to 1232.7ha in 2022. The net change (1990 – 2022) therefore, was a total of 2918.1ha. On the other hand, the proportion of area occupied by urban trees changed by 69.9ha and 231.8ha between 1990 and 2000 and between 2000 and 2010 respectively. These further increased to 626.1ha in 2022 with the net change being 927.8ha. Other areas which comprise of farmlands, open spaces and wetland or water bodies cumulatively reduced by 3867.6ha between 1990 and 2022 (Table 1).

These results show that the built-up area in Sokoto metropolis had continuously expanded and grown in size from 1990 to 2022. The average rate of expansion was calculated at 3.96%, 2.3%, and 2.44% between 1990 and 2000, 2000 and 2010 and between 2010 and 2022 respectively, while the overall average rate of expansion (1990 - 2022) was 2.88%. This was further supported by a Pearson correlation analysis of NDVI and NDBI for the study period (Table 2) which revealed a corresponding increase in urban tree density with the increase of the Built-up Area in the metropolis. This therefore implies a perfect positive correlation between urban expansion and urban tree density in the Sokoto metropolis throughout the study period.

Discussion

The Normalized Difference Vegetation Index (NDVI) was used in the paper as a simple indicator for vegetation vigour since plants absorb the spectrum of visible light and reflect near-infrared light. In contrast, NDBI was used to identify built-up areas at pixel level since sealed areas such as pavements and roofs have higher spectral reflectance in the shortwave-infrared (SWIR) band compared to near-infrared (NIR) (de la Barrera and Henríquez, 2017). Although the NDVI has shown tree losses recorded in many areas due to the expansion of the metropolis and changing land cover, it has also shown an increasing concentration of pixels occupied by trees in many places. The gains in urban tree density were however, more than the losses. The NDBI on the other hand showed an increasing number of pixels occupied by urban Built-up Areas over the study period. These techniques were also employed by Rawat and Kumar (2015) and la Barrera and Henríquez (2017) with similar results. Many studies found that urbanization adversely affected urban vegetation but did not necessarily result in absolute vegetation degradation on a large scale especially when recognizing the positive impacts of vegetation restoration due to increasing demand for high-quality urban environments (Liu et al., 2015). Urbanization causes a rebound in the number of species due to an increased heterogeneity of habitat types in urban environments (Godefroid and Koedam, 2007). This was supported by Chao and Zhang (2014) who found that urbanization did not have obvious impacts on urban vegetation despite the high degree of urbanization in the eastern region of Shandong Province, China. Similarly, Knapp *et al*. (2009) and Dolan *et al*. (2011) found increasing species turn-over associated with urbanization especially an increase in the number of exotic species.

Findings from this study tallied with several studies such as that of Zhao *et al*. (2006) where the green areas of Shanghai, China were found to continuously increase from 1975 to 2005 in parallel to its urban expansion. In the same vein, Berland (2012) carried out a historical study of the effects of urbanization on tree canopy cover in the Twin City Metropolitan Area (TCMA), Minnesota, USA. It was found that while urbanization caused the highest rate of tree canopy cover loss, urban areas recorded an increase of more than 35% indicating net tree canopy cover gain over the 72-year study period. Similarly, Badlani *et al*. (2017) found that urban vegetation increased with urban expansion in Gandhinagar, Gujarat State, India.

With controlled planning, urbanization will have little or no negative impact on urban vegetation. The creation and management of urban green spaces can to a great extent offset the negative effects associated with rising built-up intensities on vegetation (Manninen *et al*., 2010; Zhao et al., 2013). For instance, Huang *et al*. (2020) found that indirect positive impacts of urbanization on vegetation could compensate for 32.3% of vegetation loss incurred through land changes. Similarly, Najihah *et al*. (2017) found vegetation increasing in Jakarta and Metro Manila which have controlled development of the master plans and better master plan strategy compared to Kuala Lumpur which has a rather, uncoordinated and less monitored planning. Under the Adjusted Urban Land (AUL) scenario in Abuja, Nigeria also, Enoguanbhor *et al*. (2022) opined that enough space could be allocated to meet the need for urban expansion with little encroachment into land designated for non-urban development, thereby creating a functional urban environment which protects environmentally sensitive areas. In the same vein, Rawat and Kumar (2015) found a human afforestation program to have facilitated vegetation increase in the Hawalbagh Block, Almora district of Uttarakhand, India between 1990 and 2010 amidst urban development. The same was also exemplified in the medicinal plant schemes and the rehabilitation of the upper river catchments in the northern fringes of Addis Ababa, Ethiopia where biological and physical measures were used to restore the native flora and provide wider ecosystem services (Lindley *et al*., 2018).

It could therefore be deduced, that urbanization and urban expansion may have detrimental effects on urban vegetation as opined by Bourne and Conway (2014) and Shirazi and Kazmi (2016) among others. However, this may not necessarily hold across all spatial and temporal scales (Liu *et al*., 2015). In the Sahelian region for instance, it has been confirmed that re-greening due to precipitation recovery, especially after the drought of the 1980s (Dardel et al., 2014; Herrmann et al., 2005; Olsson et al., 2005; Pausata et al., 2020) has led to increased vegetation across the region (Anchang *et al*., 2019; West *et al*., 2020). According to McGovern and Pasher (2016) also, management strategies, coupled with people’s efforts at planting and protecting trees in residential areas and other private lands as well as the natural growth of existing trees can to a large extent compensate for any loss that may be recorded, thus maintaining or increasing the overall proportion of canopy cover in a particular city. In addition, urban environmental conditions such as warmer temperatures, greater tropospheric CO_2 concentrations, and higher atmospheric nitrogen deposition (Searle *et al*., 2012; Zhou *et al*., 2014) were also shown to improve the productivity (Briber *et al*., 2015) and biomass potentials of plants and facilitate the growth of some tree species such as *Thuja plicata* (O'Brien *et al*., 2012).

Conclusion

The Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Built-up Index (NDBI) have been successfully used in this study to visualize the relationship between urban expansion and vegetation density in the Sokoto metropolis. The built-up area expanded by 2918.1ha at an average annual rate 2.88% while urban vegetation cover increased by 927.8ha during the 32-year study period. Urbanization and urban expansion may have detrimental effects on urban vegetation; however these effects are largely offset by tree planting efforts and the natural growth and replacement of trees which play significant roles in enhancing tree cover after disturbances. With controlled planning therefore, urbanization will have little or no negative impacts on urban trees especially in the Sahelian and other drier environments. Appropriate management and policy measures can be taken in cities to mitigate the negative effects of urbanization on urban vegetation. These findings are relevant to the planning and management of urban forests.

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Legends

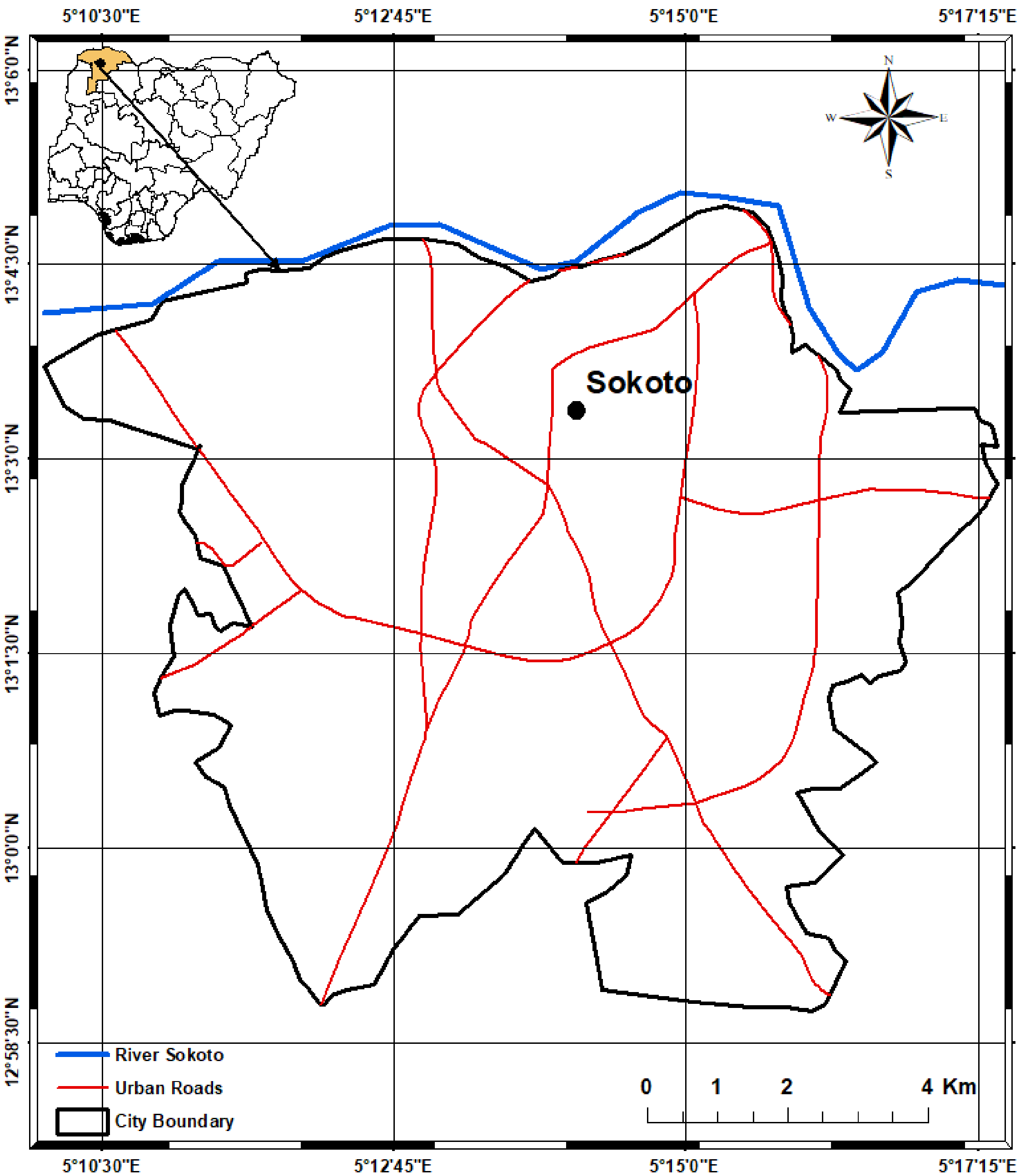

Figure 1: The Study Area (Sokoto Metropolis, inset Nigeria and Sokoto State)

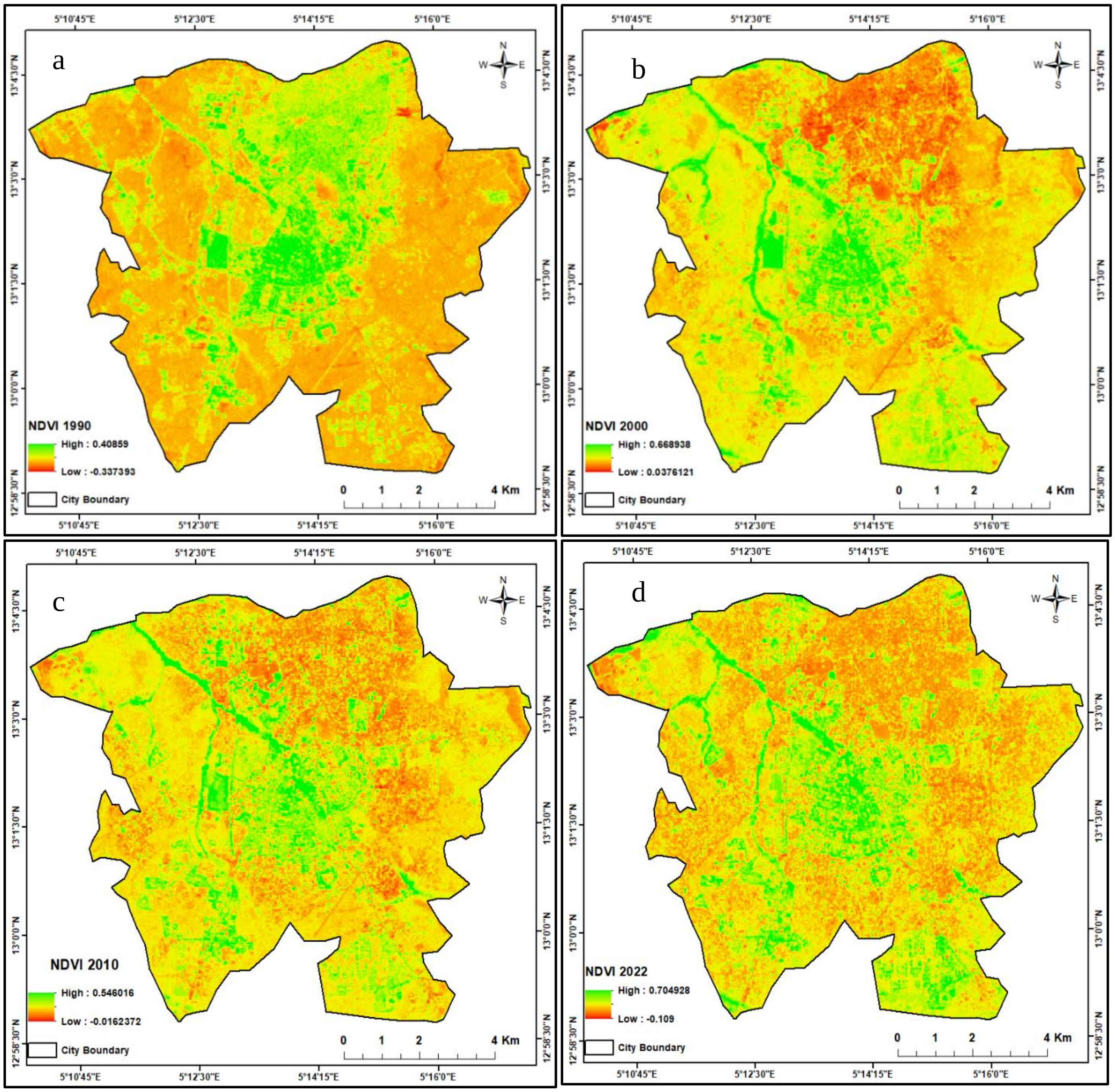

Figure 2: Normalized Difference Vegetation Index (NDVI) for Sokoto Metropolis between 1990 – 2022

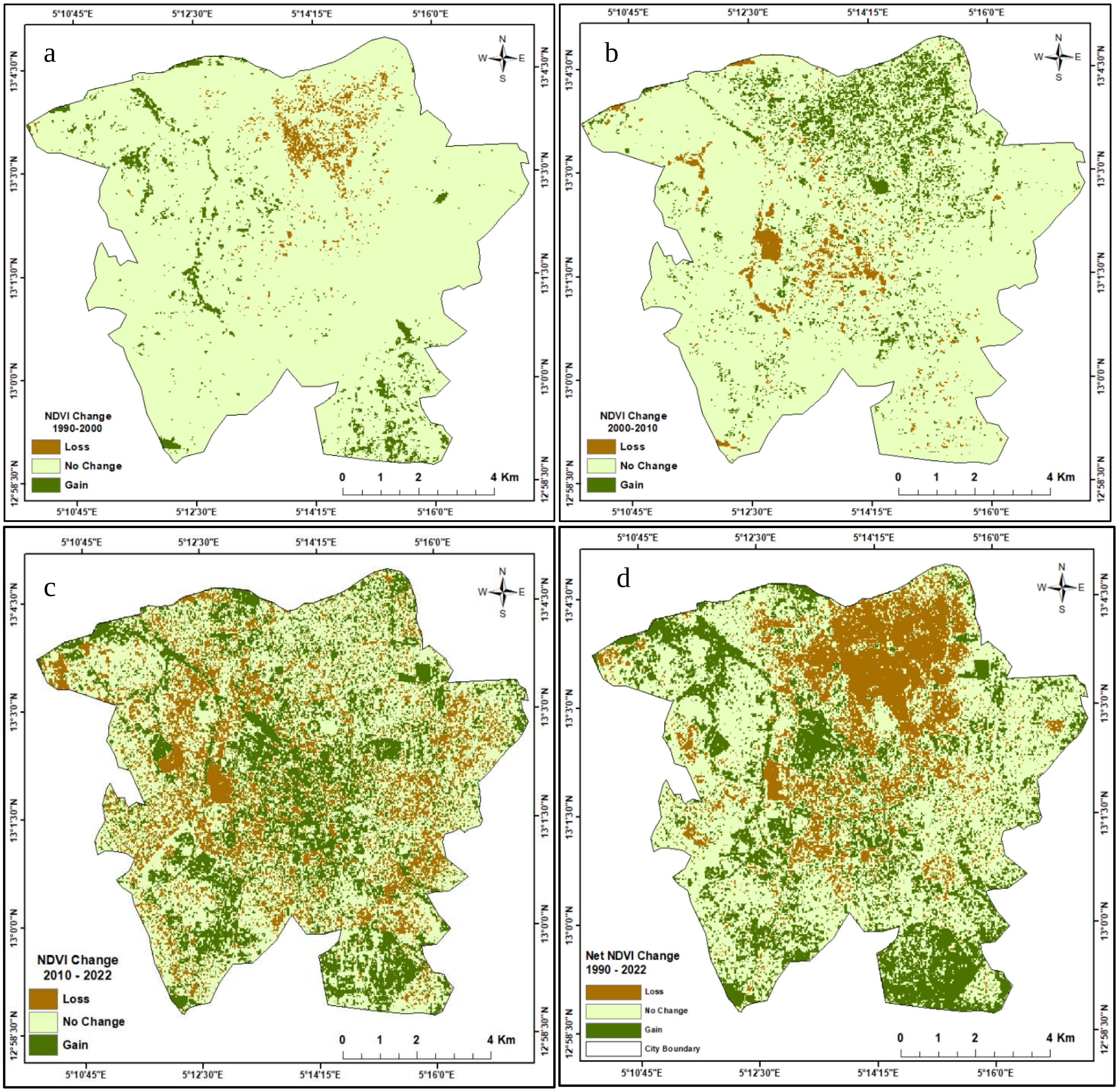

Figure 3: NDVI Changes in Sokoto Metropolis 1990 - 2000 (a), 2000 - 2010 (b), 2010 – 2022 (c) and Net NDVI Change 1990 – 2022 (d).

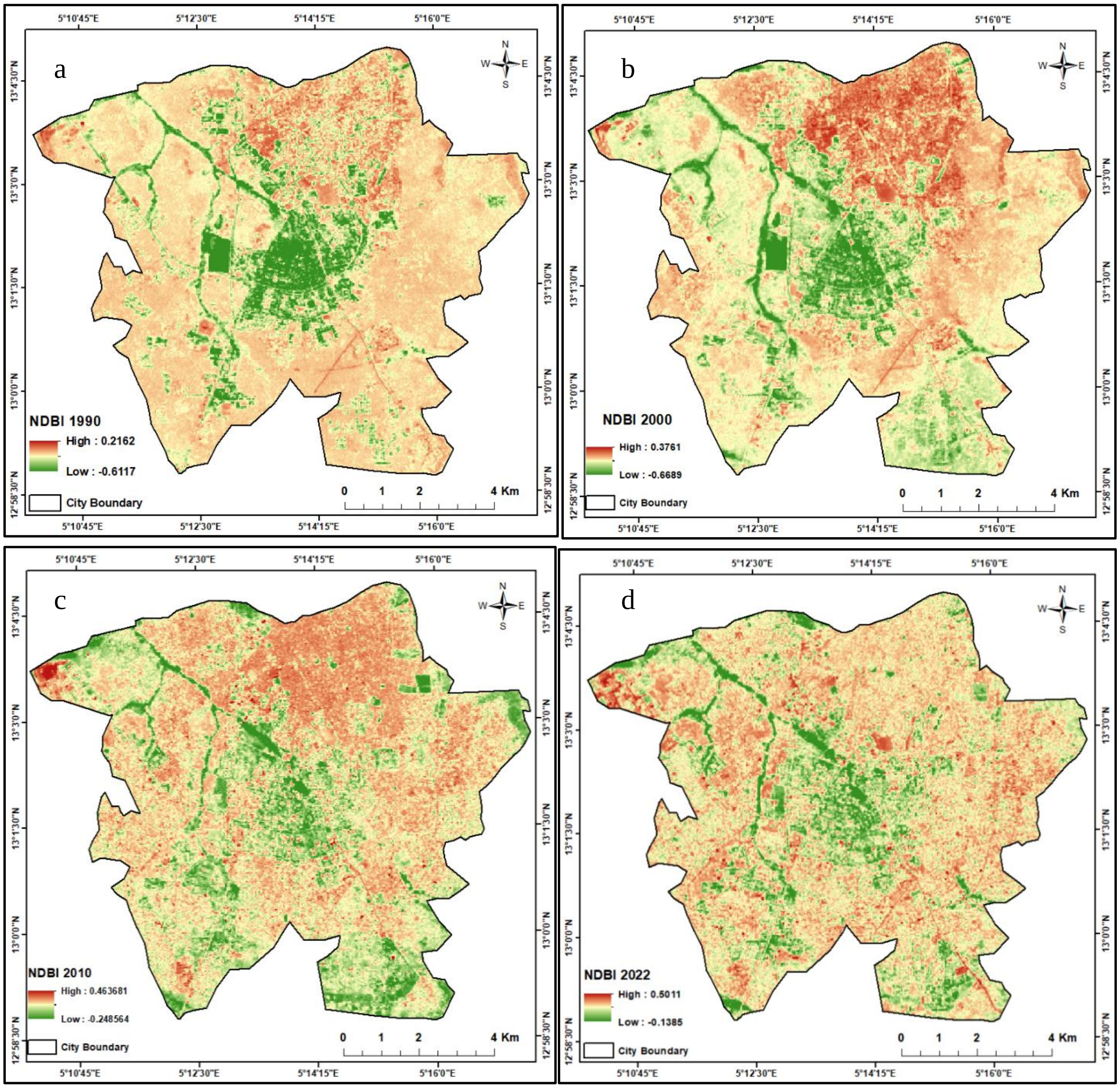

Figure 4: NDBI Values for 1990 (a), 2000 (b), 2010 (c) and 2022 (d)

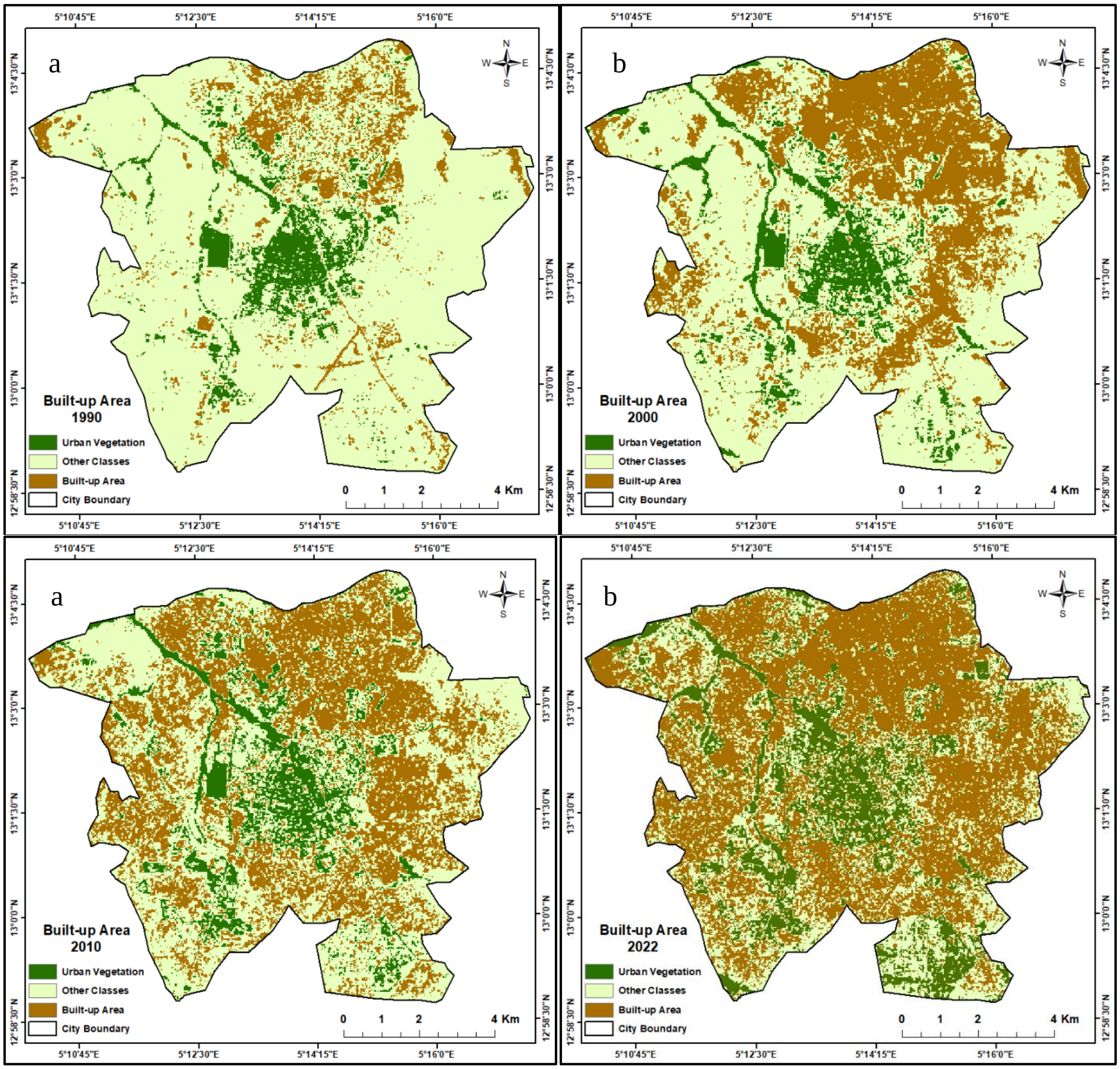

Figure 5: Built-up Area Map 1990 (a), 2000 (b), 2010 (c) and 2022 (d)

Table 1: Built-up Area and Tree Cover Expansion in Sokoto Metropolis from 1990 to 2022 (ha)

S/N	Category	1990	2000	2010	2022	Change
1	Built-up Area	1932.6	2870.2	3618	4850.7	2918.1
2	Other classes	6635.9	5628.4	4627.1	2768.3	-3867.6
3	Urban Trees	873.5	943.4	1175.2	1801.3	927.8
4	No Data	2.3	2.3	24	24	
	Total	9444.3	9444.3	9444.3	9444.3	

Table 2: Correlation Analysis of NDVI and NDBI for the Study Period

S/N	Year	R	p Value
1.	1990	0.990**	0.005
2.	2000	0.973**	0.001
3.	2010	0.926**	0.001
4.	2022	0.806**	0.001

**Correlation is significant at the 0.01 level (2-tailed)