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Exploring the Role of Urban Green Spaces in Building Climate-Resilient Cities: The Case of Nairobi City

Esther Barbara Njiru[1], Antony Abilla[2]

[1]Kenyatta University, Nairobi Kenya; Nairobi, Kenya
Corresponding Author Email: *njirubarbara[at]gmail.com*

[2]University of Nairobi, Nairobi Kenya; Nairobi, Kenya
Email: *tonyabilla[at]gmail.com*

Abstract: ***Urbanization alters urban microclimates by replacing vegetated and permeable surfaces with impervious surfaces that absorb and retain solar radiation, contributing to urban heat island (UHI) effects. This study examined the role of urban green spaces in mitigating urban heat and supporting climate resilience in Nairobi City. A geospatial approach using Landsat imagery from 1986, 2002, 2010, and 2020 was applied to assess land use and land cover (LULC), land surface temperature (LST), and vegetation abundance using the Normalized Difference Vegetation Index (NDVI). The results showed substantial expansion of built-up areas, from 46.7 km² in 1986 to 203.6 km² in 2020, while mean LST increased from 24.52°C to 27.70°C. Forest and other vegetated areas generally recorded lower LST values than built-up and bare or transitional areas. Regression analysis further indicated a predominantly inverse relationship between LST and NDVI, demonstrating the cooling influence of vegetation. These findings highlight the importance of protecting, restoring, and appropriately configuring urban green spaces as part of heat-mitigation and climate-resilient urban planning in Nairobi.***

Keywords: Urban heat island; Urban green space; Climate resilience; Land surface temperature; NDVI; Land use and land cover; Nairobi

1. Introduction

Urban living is becoming the dominant lifestyle globally, with more people currently living in cities and the number is still increasing [1]. By the year 2100, 90% of the global population will be living in cities [2]. The 2010 State of African Cities showed that over one billion people are living in Africa and close to 50% are in urban areas. It is projected that by the year 2050, the total urban population in West Africa would reach 427.7 million. The urban population in East Africa increased from 6 million in 1960 to about 77 million in 2010 and the situation prevails in Northern and Southern Africa [3]. Urban development affects biodiversity and ecosystem functions, as well as local and regional climate and the quality of life [4]. The change of the land surface in the urban area and replacement of vegetation by impervious surfaces (buildings, paved roads), which traps solar radiation in the daytime and re-radiate during the night-time due to decline in albedo, leading to an increase in local temperatures, resulting in the urban heat island effect (UHI).

As a major component of urban climate, urban heat island has been a concern for more than 40 years [5]. The existence of an urban heat island was first measured for London by Luke Howard in 1818 where a significant difference between urban and rural temperatures was observed [6]. Many urban and sub-urban areas experience a higher temperature than the surrounding rural areas. This difference in temperature can be as high as 1° to 3° C for a city with about 1 million people, while on a clear calm night, the difference can be as much as 12°C [7]. Although the heat island climatology is dependent on the city structure and surroundings, the existence of the urban heat island has been confirmed beyond all doubt [8]. UHI causes a lot of undesirable environmental and economic impacts such as the deterioration of living environment, increase in energy consumption, elevation in ground-level ozone and even an increase in mortality rates [9-12]. There is an extreme need to estimate strategies that may mitigate the impacts of urban heat islands in urban areas. An adaptation strategy that has been proposed is to 'green' urban areas, fundamentally by increasing the abundance and cover of vegetation [13].

Urban green spaces (UGS) offer immense benefits to cities; environmentally, economically, and socially. Socially, green spaces provide avenues for recreation and promote social interaction and cohesion, economically green spaces benefits include increment of property values especially houses sited close to green spaces, creation of more job avenues and generation of revenues to augment government expenditure [14]. From the environmental perspective, urban green spaces reduce temperatures by cooling through evapotranspiration, storing and re-radiating less heat than built surfaces and through direct shading. Several researchers have studied the cooling effects of UGS size, type and vegetation density. The cooling effect of a park can extent to as much as 840 m away from the park, and this extent is influenced by the character of the area around each park [15]. Also, the cooling effect of green spaces depends mainly on vegetation species, canopy cover and size and shape of parks [16]. The urban green-space cool island (UCI) intensity is affected by areas of forest vegetation and their spatial arrangements [17]. Urban green space is an important component of UHI mitigation strategies, and its cooling extent display an exponential decay with increased distance from the greenspace [18].

Previous studies have employed various approaches for assessing landscape structure and its impact on the variation of the land surface temperature (LST)-an indicator for UHI. Some of the approaches include (i) observing the pattern of the LST along the urban-rural zone (URZ,) and (ii) variation of the LST concerning land use and land cover [19–22]. However, these approaches necessitate the classification of Land use and land cover (LULC) and the computation of LST. Assessing the composition of the LULC provides necessary information to understand the spatial and temporal distribution pattern of the landscape and the relationship between LST and LULC [23].

The UHI effect has been extensively studied in cities worldwide irrespective of their sizes and locations, mostly concentrating in Europe, America and Asia compared to Africa. Some recent studies examining the relationship of LST and landscape structure in Africa have been conducted [24-27] however, UHI studies are still very uncommon in Africa. The uncontrolled and un-planned urbanization that has been experienced in African cities in recent decades is the leading cause of the rapid depletion of green spaces in the continent despite the immense documented benefits of green spaces. Moreover, African cities will likely experience the highest levels of urban population growth worldwide [28]. The influence of demographic change on future exposure to extreme heat is likely to be substantial and may even be greater, making them interesting case studies for in-depth studies of UHIs.

This study aims to examine the relationship between urban heat island and spatial patterns, composition, and configuration of land use /land cover, to understanding the impact of landscape structure on LST variations. The results of the study regarding the influence of LULC and vegetation on LST could be useful for urban planning and management strategies focused on UHI mitigation and the adaptation of cities to the challenges of climate change. Moreover, it will address the following research questions:

1) What are the changes in the area coverage of each land-cover type?
2) What are the changes in the spatial pattern for LST?
3) What is the relationship between LST and NDVI, land cover type and configuration of land cover?
4) What are the challenges facing urban green spaces management?

2. Materials and Methods

2.1 Study Area

The study adopted a case study approach to primarily provide a deeper understanding about urban green space, their characteristics and influence on the urban climate. Nairobi City was selected as the case study because it is a rapidly urbanizing city that has experienced substantial changes in population, built-up area, and vegetation cover. These changes make Nairobi an appropriate setting for examining relationships among urban land-cover change, vegetation abundance, and surface thermal conditions. Previous studies conducted in Nairobi have documented changes in urban climatic conditions, including variations in wind speed, relative humidity, and near-surface temperature associated with urbanization [29-31].

Nairobi is the capital and largest city of Kenya and covers an area of approximately 696 km². According to the 2019 Kenya Population and Housing Census, the city had a population of 4,397,073. Nairobi experiences a relatively mild highland climate, with an annual mean temperature of approximately 17.7°C. Seasonal variations in rainfall, cloud cover, and temperature influence vegetation conditions and surface temperatures across the city.

The city's landscape comprises densely built-up areas, residential and commercial developments, bare and transitional land, and substantial areas of vegetation, including major forested areas such as Karura and Ngong forests. This diversity of land-cover types provides an appropriate setting for assessing how urban development and vegetation are associated with spatial variations in LST.

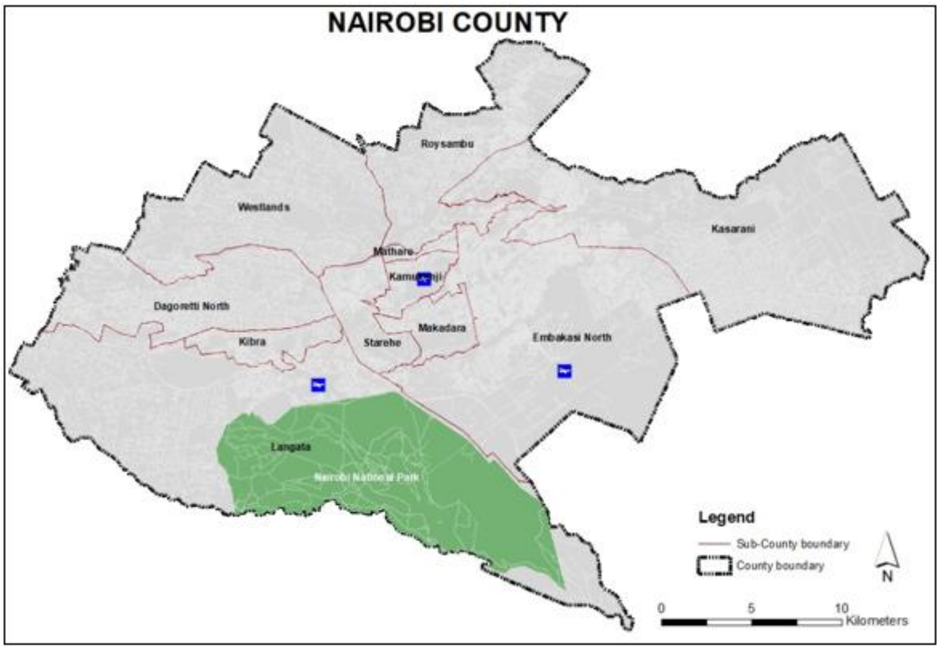

Figure 1: Study area

2.2 Satellite Data and Pre-Processing

Multi-temporal Landsat satellite imagery was used to examine changes in LULC, vegetation abundance, and LST in Nairobi. Images were obtained from the United States Geological Survey (USGS) for four observation years: 1986, 2002, 2010, and 2020. The datasets comprised Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) imagery, with a spatial resolution of 30 m for the multispectral bands used in the analysis. Images with minimal cloud contamination (0% cloud coverage) over the study area were selected to facilitate comparison of land-cover and surface characteristics. The acquisition dates and sensor characteristics are presented in Table 1.

Table 1: Characteristics of Landsat Imagery

Data Type	Date	Spatial Resolution
Landsat TM	1st January 1986	30 meters
Landsat ETM+	10th February 2002	30 meters
Landsat TM	18th August 2010	30 meters
Landsat (OLI)	20th February2020	30 meters

2.2.1 Land cover classification

Land cover properties (such as albedo, soil water content, thermal capacity, and heat conductivity) can significantly impact the heat, water, and energy flux in each area. They are important in expressing the conditions and functions of urban ecosystem. A hybrid classification procedure was performed in Erdas Imagine 2015 for the four images. Initially, unsupervised classification was conducted based on an overall spectral separability. Before adopting a combined method of maximum likelihood classification and decision tree algorithms. Four LULC categories were identified based on the progression of urbanization: built-up, forest/other vegetation, bareland/transitional areas, and water. Each category is briefly defined below.

- Built-Up – Fully urbanized region, void of any green vegetation. Typical examples are downtown areas or central business districts of most major cities.
- Forest/Other vegetation – Land with over 10% tree canopy cover larger than 0.005 km² (0.5 ha), whose primary land use is not agricultural or otherwise non-forest related (forest), together with shrublands, grasslands, agricultural areas and other vegetated land covers that do not meet the forest definition (other vegetation).
- Water – includes waterbodies such as rivers, perennial streams, lakes.
- Bareland/Transitional areas – Land with exposed soil or rock and sparse or no vegetation cover, including land in transition between other land-cover types.

2.3 Retrieval of Land surface temperature

Land surface temperature (LST) for each image were computed from Landsat TM thermal infrared (TIR) band, ETM+ TIR band). The retrieval of land surface temperature involves several processes: sensor radiometric calibrations, brightness temperature calculation, atmospheric and surface emissivity corrections, characterization of spatial variability in land cover. In this study, mono window algorithm [32] was conducted to derive LST data from Landsat-5, 7 and 8 image acquired on January 5, 1986, February 10, 2002, August 18, 2010, and Landsat-8 image acquired on February 20, 2020, respectively. Using the radiance re-scaling factor, the thermal infra-red digital numbers were converted to top of the atmosphere (TOA) spectral radiance using the respective corrections in the metadata file.

$$L\lambda = MLQcal + AL \tag{1}$$

Where: L_λ is spectral radiance at the sensor's aperture, M_L is band-specific multiplicative rescaling factor from the metadata (RADIANCE_MULT_BAND_x, where x is the band number), A_L = is band-specific additive rescaling factor from the metadata (RADIANCE_ADD_BAND_x, where x is the band number) and Q_{cal} is quantized and calibrated standard product pixel values (DN). The next step involved the conversion of spectral radiance to satellite brightness temperature under the assumption that the Earth's surface is a black body (i.e., spectral emissivity = 1), the thermal band data is converted from at-sensor spectral radiance to effective at-sensor brightness temperature using the equation.

$$\mathrm{TB} = \mathrm{K2} / \ln(\mathrm{K1} / \mathrm{L\lambda} + 1) - 273.15 \tag{2}$$

Where: T_B is the effective is effective at-satellite temperature in Kelvin, K_1, K_2 are thermal conversion constants for the thermal bands provided in the Landsat metadata file, L_λ is spectral radiance at the sensor's aperture. The 273.15 in (2) indicates the conversion of the temperature values from degree kelvin into Celsius. The third step involved the computation of the normalized difference vegetation index (NDVI). The index value is used as an indicator of biomass and greenness and is also used as a method for comparing vegetation greenness between satellite images. In this study, the NDVI image for each scene was computed from visible and near-infrared spectral bands of the Landsat imagery, so that the relationship between LST and vegetation greenness can be observed.

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}) \tag{3}$$

Where, NIR is the near infrared band values for the multispectral image (Band 4 for TM and ETM+ and Band 5 for OLI); RED is the red band value of the image (Band 3 for TM and ETM+ and Band 4 for OLI). Calculation of NDVI is necessary to further calculate the proportion of vegetation (Pv) calculated by equation (4), respectively, to obtain land surface emissivity (ε) equation (5) for each year.

$$Pv = [(\mathrm{NDVI} - \mathrm{NDVI\ min}) / (\mathrm{NDVI\ max} + \mathrm{NDVI\ min})]\hat{}2 \tag{4}$$

Where P_V is proportion of Vegetation, *NDVI* is DN values from NDVI Image, $NDVI_{min}$ and $NDVI_{max}$ are the Minimum and Maximum DN values from NDVI Image. Land surface emissivity (ε) was calculated using the values based on the findings of Sobrino *et al.,* (2004), employing the equation.

$$\varepsilon = \mathrm{mPv} + \mathrm{n} \tag{5}$$

Where *m* is 0.004, *Pv* is proportion of vegetation and 0.986 for *n*. Finally, using brightness temperature, wavelength of emitted radiance land surface emissivity, LST was retrieved using the equation.

$$LST = (TB / 1) + \lambda * (BT / p) * \ln(\varepsilon) \qquad (6)$$

Where λ is the wave- length of emitted radiance (band 6 and 10 (for Landsat 5, 7 and 8 respectively), T_B is at- sensor brightness temperature (°C); ρ = h × c/σ (1.438 × 10⁻2 m K), σ = Boltzmann constant (1.38 × 10−23 J/K), h = Planck's constant (6.626 × 10−34 Js) and c = velocity of light (2.998 × 108 m/s); and ε is the land surface emissivity. The LST were derived for each image and the general trends observed.

2.4 Statistical analysis

Descriptive and regression analyses were used to examine relationships among LST, NDVI, and LULC characteristics. Zonal statistics were used to derive mean LST and mean NDVI values for the major land-cover types for each observation year. Water bodies were excluded from the regression analyses because their spectral and thermal characteristics differ substantially from terrestrial land-cover types.

Linear regression analysis was used to assess the relationship between LST and NDVI. Separate regressions were conducted for the selected observation years and individual land-cover types to determine whether the direction and strength of the LST–NDVI relationship varied across land-cover types and over time. The coefficient of determination (R^2) was used to describe the proportion of variation in LST explained by NDVI within the fitted models. A multivariate model was also used to examine the relationship between mean LST and selected landscape characteristics, including the area under built-up land, bare/transitional land, forest/other vegetation, and the aggregation index of vegetated land. The analyses were interpreted primarily in terms of the direction and strength of associations among variables.

The analysis was based on four discrete satellite observations over the 1986–2020 period rather than a continuous time series. The findings therefore represent selected snapshots of Nairobi's changing landscape and thermal environment rather than year-to-year climatic trends.

2.5 Methodological Limitations

Several methodological limitations should be considered when interpreting the results. The four Landsat scenes used in the study were not acquired during the same season: the 1986, 2002, and 2020 images were acquired in January or February, whereas the 2010 image was acquired in August. Seasonal differences in ambient temperature, solar radiation, vegetation phenology, soil moisture, and atmospheric conditions may have introduced variation in the temporal LST and NDVI comparisons in addition to the effects of land-cover change. Consequently, differences in absolute LST between observation years should not be attributed solely to urban land-cover change.

Uniform atmospheric conditions were assumed within each scene, and no atmospheric correction was applied to the thermal bands. This may introduce uncertainty into the absolute LST values and comparisons across acquisition dates, although it is less likely to affect the relative spatial patterns and comparisons among land-cover types that are the primary focus of the study. The land-cover classification was validated visually against high-resolution reference imagery and local knowledge of the study area rather than through a formal accuracy assessment. Classification accuracy statistics are therefore not reported, and the LULC change estimates should be interpreted with appropriate caution. Finally, the analysis is based on four discrete satellite observations over the 1986–2020 period rather than a continuous time series; the findings therefore represent selected snapshots of Nairobi's changing landscape and thermal environment rather than year-to-year climatic trends.

3. Results

3.1 Land use and land cover Pattern and its changes

The study sheds light on the progression of land cover/use change over the 34-year period from 1986 to 2020. Figure 2 shows the spatial distribution of land cover and land uses in 1986, 2002, 2010 and 2020. Over the period of 30 years, rapid urbanization has taken place. The affected areas are areas from the middle to towards the North, Northeast and Northwest of the study area.

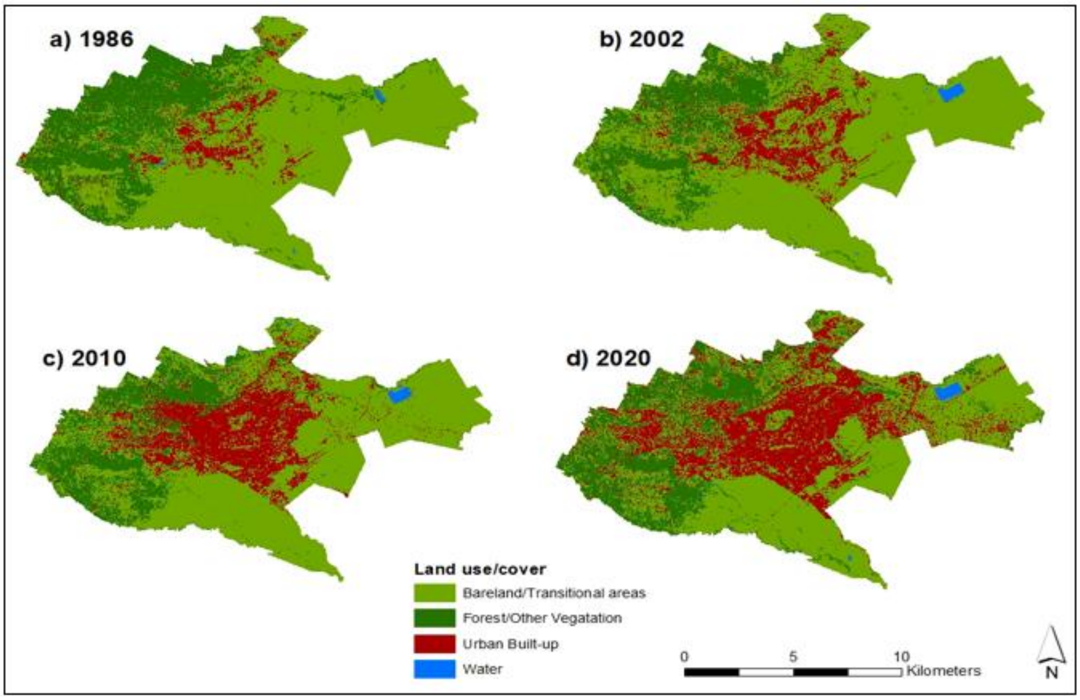

Figure 2: Land use land cover in 1986, 2002, 2010 and 2020.

It is observed that there was a rapid increase in urban built-up area from 46.7 km^2 in 1986 to 203.6 km^2. in 2020. The land cover under forest/other vegetation decreased from 29.4% in 1986 to 18.4% in 2002, increased by 3.6% in 2010, and further increased to 193.2 km^2, a 5.2% increase in 2020. Bareland/transitional area land cover type recorded steady decline over the time periods, with a relatively slight increase between 1986 and 2002. Land cover under urban built-up maintained a steady increase from 6.6% in 1986 to 28.65% in 2020 while the water bodies changed from 0.2% in 1986 to 0.6% thirty-four years later. A summary of LULC statistics is shown on Table 2.

Table 2: Area of land occupied by the four land use/land cover classes.

LULC	1986		2002		2010		2020	
	Area (Km^2)	(%)	Area (Km^2)	(%)	Area (Km^2)	(%)	Area (Km^2)	(%)
Water	1.5	0.2	4.3	0.6	3.5	0.49	4.3	0.6
Forest/Other vegetation	209.3	29.4	130.9	18.4	156.1	22	193.2	27.2
Built-up Area	46.7	6.6	92.2	13	175	24.6	203.6	28.7
Bareland/Transitional areas	452.9	63.8	483	68	375.8	52.9	309.3	43.5
Total	710.4	100	710.4	100	710.4	100	710.4	100

3.2 Spatial and temporal distribution pattern of land surface temperature

The spatial distribution of the LST of Nairobi is as shown in Figure 3 below.

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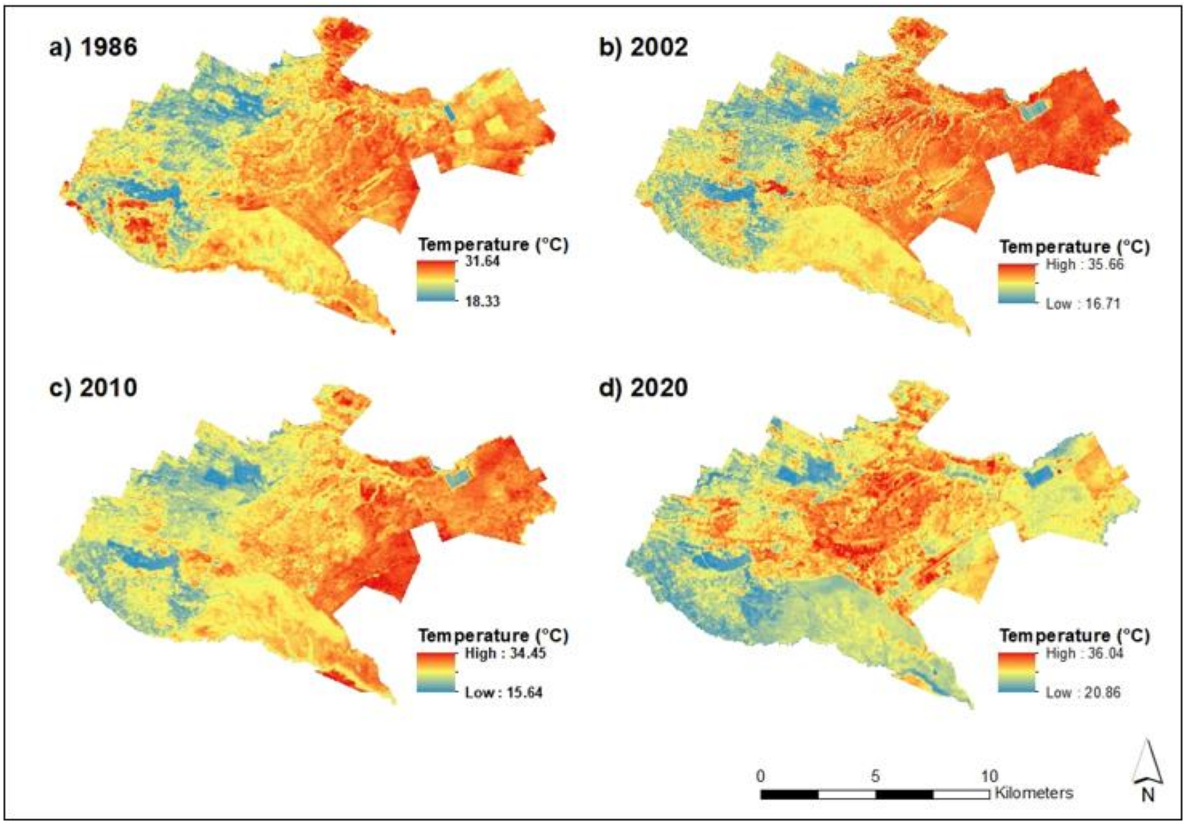

Figure 3: Land surface temperature (LST) in 1986, 2002, 2010 and 2020

Overall study period recorded a minimum temperature had a range of 15 to 20°C, 31 to 36°C for the maximum, and 24-27°C for the mean temperature. In 1986, the LST ranged from 17.01°C to 31.64 °C, with an average of 24.52°C. It ranged from 16.71–35.66°C, and the average was 26.86°C in 2002. LST observed in August 2010 was lower ranging from 15.64°C to 34.45°C as compared to the previous years. In 2020, the LST ranged from 20.86°C to 36.04°C, with an average of 27.70°C. The lowest minimum occurred in 2010 (15.64°C) and the lowest maximum and mean temperature occurred in 1986 with 31.64°C and 24.52°C, respectively. In general, the mean temperature values show an increasing trend from year, despite the slight decrease in 2010. Overall, LST increased by 3.18°C from 1986 to 2020, as shown in Table 3.

Table 3: Land Surface Temperature (1986-2020)

Year	Land Surface Temperature (°C)		
	Min.	Max.	Mean
1986	17.01	31.64	24.52
2002	16.71	35.66	26.86
2010	15.64	34.45	26.11
2020	20.86	36.04	27.7

3.2.1. Land surface temperature variation over land covers

To better comprehend the thermal response of individual land covers, the mean LST of each type was derived by a means of zonal analysis. The highest mean surface temperature was observed in the bareland/transitional areas (25.5°C), followed by urban built -up (25.2°C), and forest/other vegetation (21.8°C) in 1986. The temperatures increased by 3.3°C within the urban built-up area to 28.5°C in 2002. A decrease in surface temperature was observed under the areas covered by urban built-up and bareland/transitional by 2.1°C, 0.6°C respectively in 2010. Meanwhile, in 2020, the thermal gradient of land cover increased in urban built up area (29.9°C), a 3.5°C increase from 2010, bareland/transitional areas (27.5°C), while forest/other vegetation increased to 25.1°C as shown in Table 4.

Table 4: Mean LST values over land cover.

	Urban Built-up		Forest/Other vegetation		Bareland/Transitional areas	
	Mean	SD	Mean	SD	Mean	SD
1986	25.2	1.5	21.8	1.8	25.5	1.5
2002	28.5	2.6	21.4	1.7	28	2.4
2010	26.4	2.1	21.6	2.1	27.4	2.6
2020	29.9	1.7	25.1	1.6	27.5	1.6

3.3 Spatial and temporal distribution pattern of Normalized Difference Vegetation Index (NDVI) (vegetation greenness)

The NDVI value was identified to express the vegetation amount and fractional vegetation cover in estimating emissivity. NDVI values range between -1 and 1 with very low NDVI values of -0.1 to 0.1 indicating presence of rocks, sand, or impervious surfaces. Higher NDVI values of 0.2 indicate presence of vegetation, with denser vegetation having values of 0.6 to 0.9, and deep water having a value of -1. The minimum and maximum NDVI values increased and decreased respectively from 1986 to 2020 with the spatial increase of impervious surfaces or decrease of vegetation cover. A decline was observed in 2002 (0.56), the maximum value increased to 0.68 in 2010 and decline to 0.61 in 2020 as seen in Table 5.

Table 5: Mean NDVI values over land cover.

	NDVI		
	Min	Max	Mean
1986	-0.4	0.69	0.25
2002	-0.59	0.56	-0.09
2010	-0.33	0.68	0.17
2020	-0.25	0.61	0.28

Figure 4 shows the spatial distribution maps of NDVI for the four observed years 1986, 2002, 2010 and 2020. The results showed an increase in minimum values between the years. The minimum values increased between 1986 to 2002, and from 2010 to 2020. NDVI values ranged from -0.40 to 0.69. The maximum values show a mixed gain and decline in the years with 1986 (0.69) recording the highest NDVI value. The bright orange with negative NDVI values indicates the presence of impervious surfaces such as buildings, rocks, roads. The green areas with NDVI values above 0.2 observed corresponded to the vegetation, with the denser vegetation like forests recording NDVI values of 0.6. In general, the areas with the low NDVI values were the areas with built-up and bare land/transitional areas land cover type located in the central and eastern part of the city. Meanwhile, areas with high NDVI values were areas with vegetation cover, mainly the western, southeast, and northwest parts of the city. NDVI pattern for years relatively remained stable especially in the areas covered by forests.

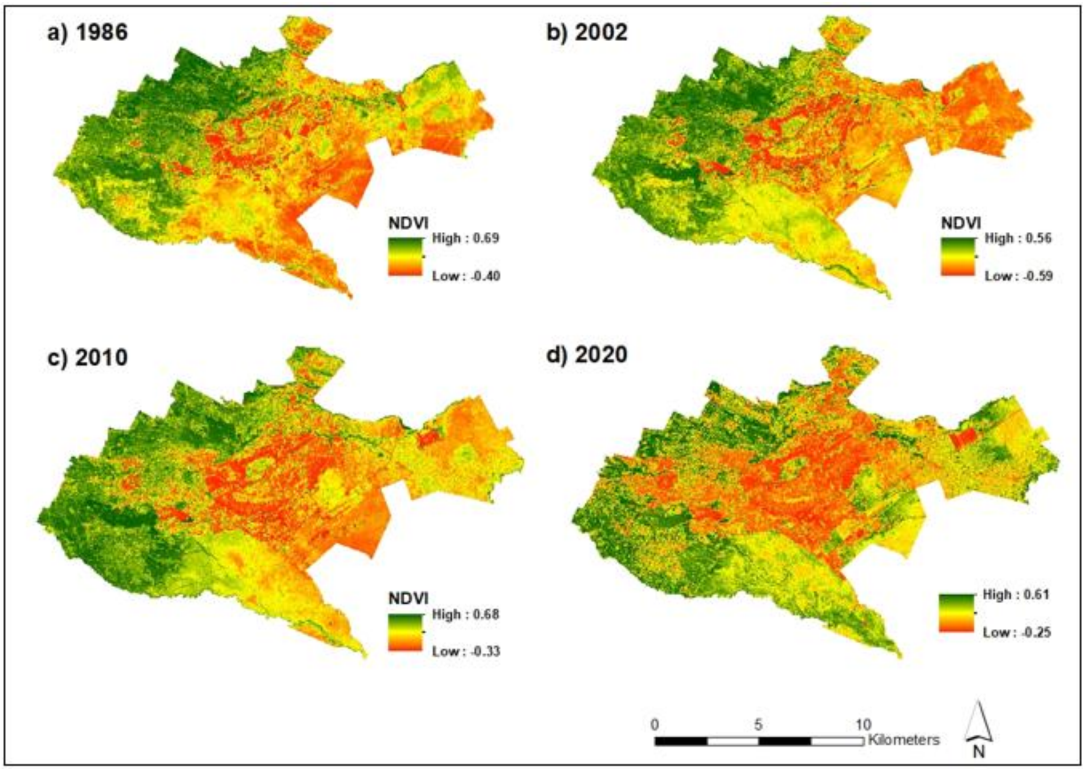

Figure 4: NDVI distribution map of Nairobi: (a) NDVI in 1986; (b) NDVI in 2002; (c) NDVI in 2010 and (d) NDVI in 2020

Table 6 summarizes the mean NDVI values of the different land cover types, with water excluded. The highest mean NDVI was observed in forest/other vegetation (0.42) in 1986, 0.41 in 2020, and 0.37 in 2010. The lowest values in bareland/transitional areas (-0.13), and built-up (-0.19) in 2002.

Table 6: Mean NDVI values over land cover.

	Urban Built-up		Forest/Other vegetation		Bareland/ Transitional areas	
	Mean	SD	Mean	SD	Mean	SD
1986	0.09	0.09	0.42	0.07	0.19	0.06
2002	-0.09	0.11	0.14	0.08	-0.13	0.06
2010	0.06	0.07	0.37	0.07	0.14	0.06
2020	0.14	0.07	0.41	0.04	0.31	0.04

3.4 Difference in mean LST and mean NDVI by land-use/cover types

To understand the relationship between LST and land cover better, vegetation abundance, thermal environment and green space signature of each land cover type was investigated through a zonal summary GIS operation to derive mean values of LST and NDVI associated with each land cover type. The results are shown in figures 5 and 6.

Figures 5(a) depicts mean LST and NDVI values associated with different land-use/cover types within the research years. The bareland/transitional area land cover type exhibited the highest mean LST value in 1986 and 2010. Urban built-up had the highest mean LST in the years 2002 and 2020 as compared to bareland/transitional areas under the same year. In contrast, forest/other vegetation showed the lowest LST values.

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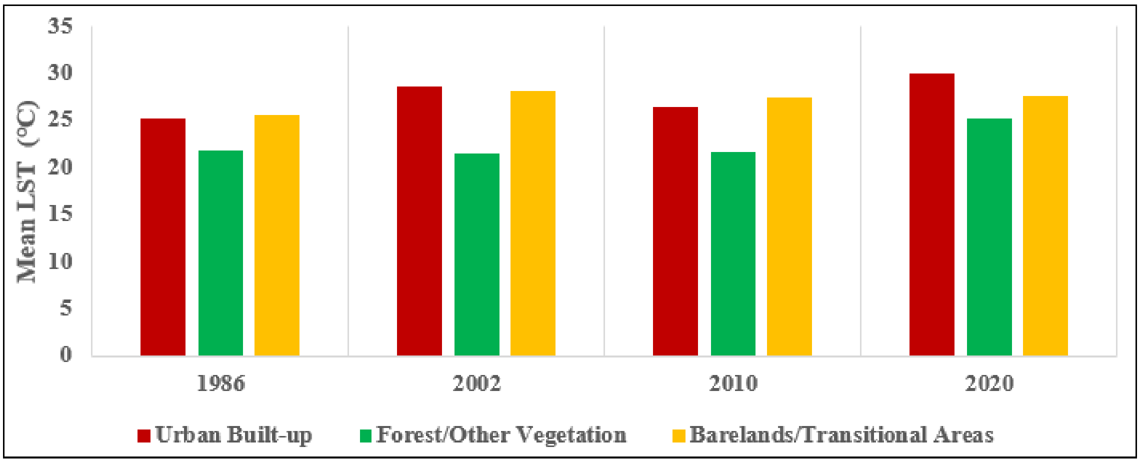

Figure 5: LST associated with land-use/cover type.

At the same time, forest/other vegetation land cover exhibited the highest mean NDVI values in all the years in comparison to urban built-up and bareland/transitional land cover type NDVI values as shown in Figure 6. It is clear that mean LSTs and mean NDVIs have distinct differences with certain different land-use/cover types. For example, for LST there are differences between urban built-up and bareland/transitional land-use/ cover types and the forest/other vegetation land-use/ cover types; so as for NDVI.

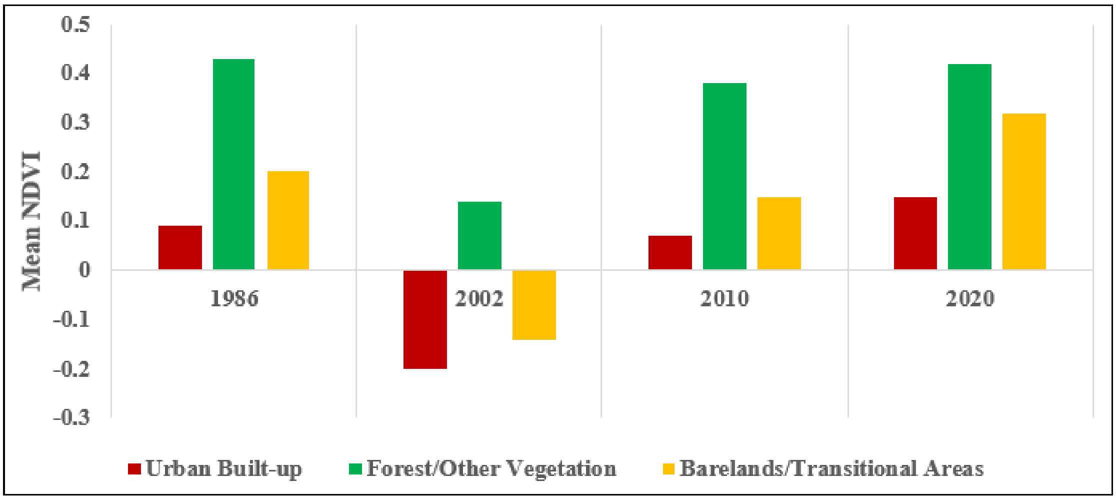

Figure 6: NDVI associated with land-use/cover type.

3.5 Relationship between mean LST and Mean NDVI

Table 7 shows the summary of the average values of surface temperature and NDVI. The year 2002 had the lowest mean NDVI values of-0.09, while the highest mean values for both LST and NDVI were recorded in 2020. A decrease in NDVI leads to an increase in LST as depicted in 2002.

Table 7: Summary of mean values of LST and NDVI

Year	LST	NDVI
	Mean	Mean
1986	24.52	0.25
2002	26.86	-0.09
2010	26.11	0.17
2020	27.7	0.28

A regression analysis between the mean LST and NDVI for land cover types excluding water bodies was conducted to investigate their relationship. The regression results reveal a negative relationship between mean NDVI and LST as indicated in Table 8. The lowest decrease of LST by -15.51 was in 1986, while highest decrease of LST was recorded in 2002 by -25 because of the unit increase and decrease in NDVI in the respective years. In general, NDVI reduces mean LST by 7.3 as shown in the regression function, and accounts for at least 66.6% and a maximum of 84.7% of the variations in mean LST across the years under study.

$$Y = 27.5146 - 7.31501\ NDVI + e \qquad (7)$$

Table 8: Linear Regression function and R^2 value of LST with NDVI

Year	Y= a+ bX +e	R2
1986	Y = 28.5648 - 15.5109 NDVI + e	0.7612
2002	Y= 24.64816 - 25.0041 NDVI + e	0.8472
2010	Y= 30.64729 - 24.6758 NDVI + e	0.6662
2020	Y=34.21545 - 22.4436 NDVI + e	0.7282

Figure 7, 8 and 9 shows the scatter plots of mean NDVI and LST for each land use for the four years. The plots show negative correlations between LST and NDVI for all land cover types for all years. The exception is in 2020 where all land cover types present a negative correlation between LST and NDVI, with the exception of forest and vegetation land cover type where there seems to be no correlation between LST and NDVI.

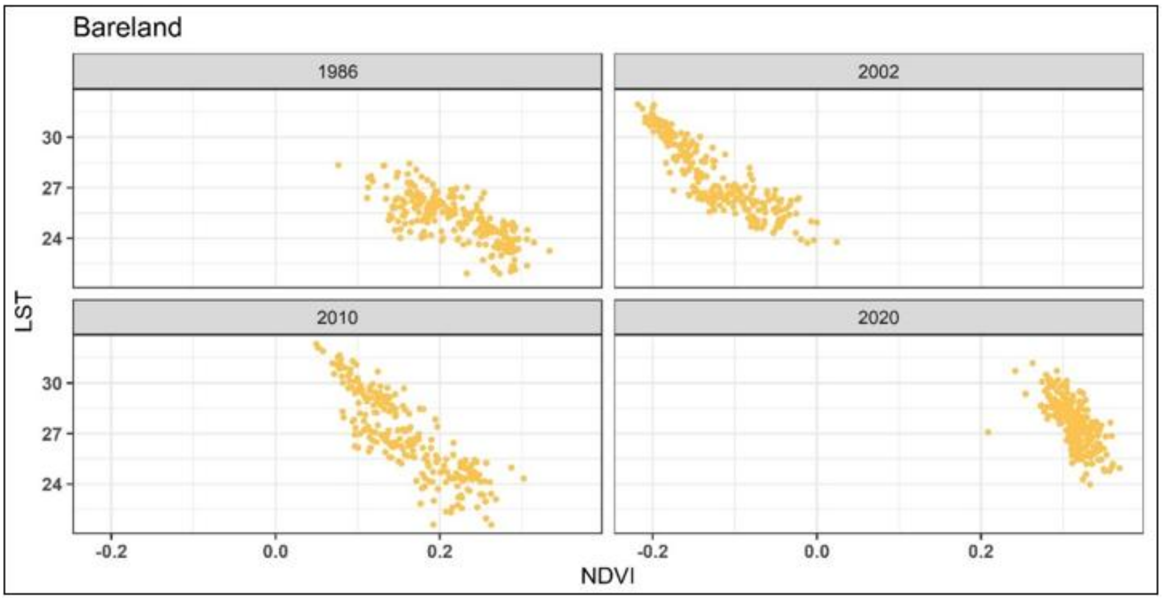

Figure 7: Linear Scatter plots of LST against NDVI for Bareland land use/cover

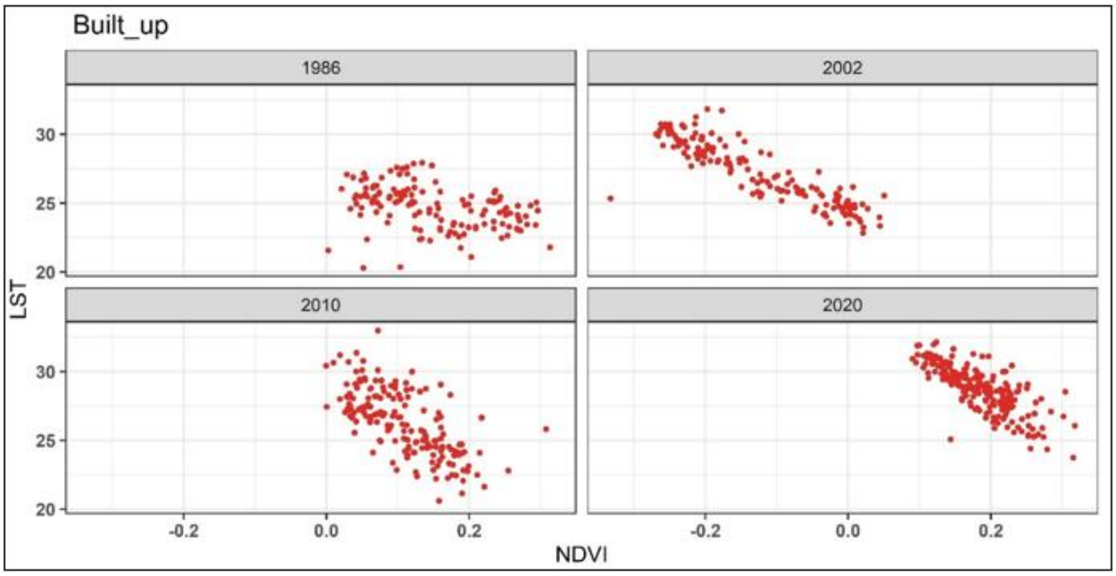

Figure 8: Linear scatter plots of LST against NDVI for built-up land use/cover

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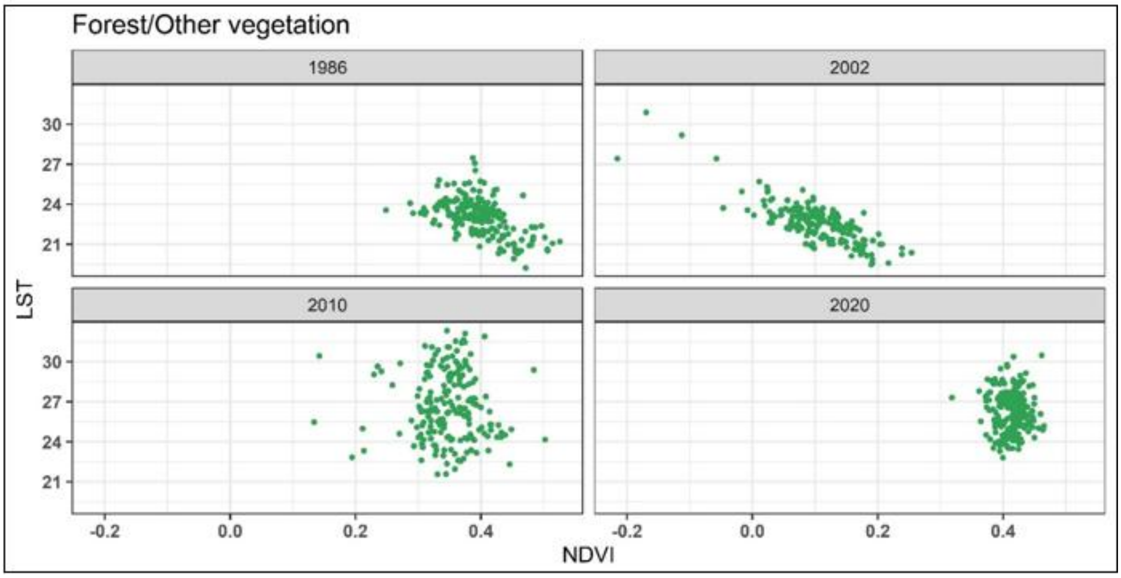

Figure 9: Linear scatter plots of LST against NDVI for forest/other vegetation land use/cover

3.5.1 The relationship between LST and NDVI by land-use/cover types

A second regression analysis between mean LST and mean NDVI associated with the specific land-use/cover type was conducted to evaluate the influence of urban land cover/use accurately. This analysis excluded all pixels corresponding to water bodies to increase the accuracy of regression for mean LST and NDVI values by land-use/cover types. The result of regression analysis between LST and NDVI for all polygons (excluding water bodies) in Nairobi for all the years is shown in Table 9. Where Y is mean LST associated with the land-use/cover type, X is NDVI associated with land-use/cover type. The analysis reveals largely negative relationships between LST and mean NDVI. The r-square values suggest that most of the variations in mean LST are because of the changes in Built-up and Bareland/Transitional areas in recent years with Forest/other vegetation accounting for little or no variation in mean LST. Negative relationships between mean NDVI and LST were detected in all observed land cover types apart from built-up in 2002, forest and other vegetation in 2020 and Bareland/transitional areas in 2002. This implies that vegetation was efficient in decreasing surface temperatures and in mitigating UHI effect.

Table 9. Linear regression and correlation coefficients between LST and NDVI by land-use/cover types.

Land use/cover type	1986		2002		2010		2020	
	Regression functions	R2	Regression functions	R2	Regression functions	R2	Regression functions	R2
Built-Up	Y=280.26-0.298X+e	0.210	Y=289.94+0.825X+e	0.086	Y=580.19-0.916X+e	0.394	Y=940.91-0.946X+e	0.553
Forest/other vegetation	Y=472.95-0.455X+e	0.275	Y=346.79-1.709X+e	0447	Y=603.11-0.139X+e	0.010	Y=554.32+0.002X+e	0.000
Bareland/ Transitional areas	Y=764.26-0.997X+e	0.496	Y=390.42+1.373X+e	0.310	Y=1244.08-2.02X+e	0.732	Y=1817.29-1.57X+e	0.449

3.6 Relationship between mean LST and land cover type size

A multivariate model representing the relationship existing between the LST values, the size of land under built-up, bare land/transitional areas, under forest/other vegetation cover and Aggregation Index (AI) for the years under study is represented by the function below.

$$Y = 0.056x1 + 0.0147x2 + 0.036x3 + 0.030x4 + e \quad (8)$$

In Nairobi, average surface temperature is largely attributed to by the size of the built-up area, the size of bare land and transitional areas, the size of land covered by forest/other vegetation cover as well as the aggregation index of the forest and other vegetation. The size of built-up area contributes the highest to mean LST, followed by the size of bare land and transitional areas with the size of forest and other vegetation contributing the least of the three land sizes. The aggregation index of the forest cover indicates a positive relationship with LST contributing slightly more than half of what is contributed by the size of urban built up and twice as much as what is contributed by the size of forest and other vegetations. Urban built up increases average surface temperature by 0.056, meaning that as more and more areas of the urban land become more built-up, the mean average land surface temperature will also increase.

Forest and other vegetation cover also increased temperature by 0.0147. This means that the forest cover and vegetation in Nairobi raise the average temperature. The more the vegetation grows, the higher the chances that the land surface temperature will increase. Bare land and transitional areas increase average surface temperature by 0.036 much more than the forest and other vegetation covers but less than the size of the urban built-up. The more the land becomes bare and transitional, the higher the chances of temperatures rising but at a relatively lower rate than an increase in urban built up

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area. The Aggregation index of forest and other vegetation areas increases mean LST by 0.030. This means that an increase in forests' fragmentation leads to a rise in temperature.

4. Discussion

4.1 Urbanization and land cover changes in Nairobi City

Nairobi is the capital of Kenya and serves as an important administrative and economic hub for both the country and the wider East African region [33]. Over the past three decades, the city has experienced rapid population growth and spatial expansion compared with other major cities in the region [34], while continuing to attract population from rural areas. The findings of this study reflect this urban transformation, with the area classified as built-up increasing substantially from 46.7 km² in 1986 to 203.61 km² in 2020.

Changes were also observed in forest and other vegetation cover. The area classified as forest/other vegetation declined from 209.3 km² in 1986 to 130.9 km² in 2002. This decline has been attributed to the extraction of forest resources and the clearance of forested land for urban development, particularly during the period from the 1990s to the mid-2000s. By 2010, however, forest/other vegetation had increased to 156.1 km², a change associated with renewed government efforts to increase forest cover through initiatives under Kenya Vision 2030, including the gazettement of forest reserves and the removal of illegal structures within protected forest areas. The area classified as forest/other vegetation subsequently increased further to 193.2 km² in 2020 [35].

The land-cover changes observed in Nairobi reflect the interaction of physiographic, demographic, and socio-economic factors. A key driver has been the city's rapid rate of urbanisation relative to other African cities. Nairobi's urbanisation rate has averaged approximately 4.7% per annum since independence, compared with 3.5% per annum for other major African cities [2], [36]. This accelerated urbanisation has been driven by both natural population growth and rural–urban migration. Nairobi's population increased from 509,286 in 1969 to 827,775 in 1979, 1,324,570 in 1989, 2,143,254 in 1999, 3,138,369 in 2009, and 4,397,073 in 2019 [37–42]. This sustained population growth has increased demand for residential, commercial, industrial, and institutional land, contributing to rapid land-use and land-cover conversion, urban sprawl, and the expansion of informal settlements.

Economic growth and development in Kenya, and Nairobi in particular, have also contributed to the city's urban expansion. Nairobi's Gross Domestic Product (GDP) increased from £254 million in 1975 to £645 million in 1985 and £1.1 billion in 1995, before rising to £1.5 billion, £9.7 billion, and £14.1 billion in 2002, 2010, and 2015, respectively [43–45]. Economic growth was comparatively stronger between 1975 and 1990, coinciding with a higher rate of urban expansion, whereas slower economic growth between 1990 and 2002 corresponded with a lower rate of expansion. Since 2003, renewed economic growth has coincided with another period of accelerated urban development. The LULC change maps produced in this study show that much of this expansion occurred towards the north-eastern, eastern, and southern frontiers of Nairobi. Development in these directions has been facilitated by relatively flat topography and the availability of comparatively cheaper land, which have reduced development costs. Although expansion into these areas was initially constrained by inadequate road infrastructure, improvements in the road network since 2007 have increased their accessibility and supported further urban development [46].

4.2 The relationship between LST, NDVI, land cover types and configuration

Land surface temperature is influenced by the characteristics of land-surface cover, ranging from bare and impervious surfaces to vegetation of varying types and densities. The mean LST values for Nairobi generally show an increasing trend across the observation years, despite the decrease recorded in 2010. This decrease may partly be attributed to the timing of image acquisition, as the 2010 Landsat image was acquired in August, which is among the cooler periods of the year in Nairobi [47]. LST is therefore dynamic and may vary according to seasonal conditions, tending to be higher during warmer and drier periods and lower during cooler periods. Although LST and near-surface air temperature represent different measures of the thermal environment, studies have demonstrated a relationship between the two variables, with daytime LST generally exceeding daytime air temperature [48]. The observed temporal variation in LST is therefore likely to reflect several interacting factors, including seasonal conditions, changes in land cover, and differences in the radiative and thermal properties of land-surface materials. Nevertheless, urbanisation, as reflected in the substantial changes in land cover observed over the study period, is likely to have contributed to changes in Nairobi's surface thermal environment.

Urbanisation alters local thermal conditions through the conversion and removal of vegetation and its replacement with built-up and other impervious surfaces. Previous studies of the urban heat island effect in Nairobi have examined specific parts of the city, including the Central Business District and Upper Hill, over different observation periods [49], [27]. Previous research has also examined the effects of LULC change on surface temperature across Nairobi [35]. Collectively, these studies indicate an association between changes in Nairobi's urban landscape and its surface thermal conditions, consistent with the overall increase in mean LST observed in the present study.The type, extent, and spatial structure of land cover also influence urban LST. In the present study, different land-cover types exhibited distinct thermal characteristics, with built-up and bare/transitional areas generally recording the highest mean LST values. Vegetated surfaces can moderate surface temperatures through shading and evapotranspiration, which favour latent over sensible heat exchange compared with highly developed surfaces [50]. Forest and other vegetation generally recorded the lowest mean LST values. However, thermal variation also occurred within vegetated areas, with forest, agricultural land, shrubland, and grassland exhibiting different surface temperatures. These variations suggest that the thermal characteristics of vegetated surfaces depend not only on the presence of vegetation but also on vegetation type, density, and location within the wider urban landscape.

The spatial location of different vegetation types may further contribute to these variations. Grass and shrub vegetation is distributed within the more intensively developed parts of the city, whereas much of the agricultural land is located farther from the urban centre, where the influence of the urban heat island may be lower and surface characteristics more homogeneous. Overall, LST is closely associated with land-surface characteristics, and differences in the radiative and heat-transfer properties of surface materials, rather than vegetation abundance alone, may explain some of the observed spatial variation in surface temperature [48].

The configuration of land cover also influences surface temperature, although the results suggest that its effect is weaker than that associated with the extent of built-up and bare/transitional land. The aggregation index of vegetation cover showed a moderate relationship with surface temperature. Small and fragmented vegetation patches may provide more spatially limited cooling, whereas larger and more compact vegetation patches can have a greater cooling influence. The cooling effect may also vary according to vegetation type and density; for example, smaller areas with dense tree cover may provide greater localised cooling than larger areas dominated by grassland. Similarly, high-density residential and commercial areas tend to exhibit higher surface temperatures than lower-density residential areas. Within Nairobi, the comparatively lower temperatures observed in areas close to major forested areas, including Ngong and Karura forests, further illustrate the potential contribution of tree cover to moderating surface temperatures. These findings suggest that the provision of urban green spaces for heat mitigation should consider not only the amount of green space but also its size, configuration, vegetation characteristics, and location relative to densely built-up areas.

NDVI has been extensively used as an indicator of vegetation abundance in studies of urban thermal environments because vegetation can contribute to cooling through processes including evapotranspiration, latent heat exchange, and shading by tree canopies [50]. As shown in Sections 3.4 and 3.5, mean NDVI varied across the observation years, alongside changes in vegetative cover reported in Table 2. The regression analyses generally showed an inverse relationship between LST and NDVI, indicating that areas with greater vegetation abundance tended to have lower surface temperatures. However, the strength and direction of this relationship were not uniform across all land-cover types and observation years. The land-cover-specific regressions presented in Table 9 include some positive and weak relationships; the results should therefore be interpreted as demonstrating a generally inverse, rather than universally negative, relationship between vegetation abundance and LST.

The regression results further indicate that the relationship between vegetation abundance and LST varies among land-cover types. In particular, NDVI showed relatively strong relationships with the LST of built-up and bare/transitional areas in several observation years, suggesting that the distribution of vegetation within and around these land-cover types may contribute to moderating surface thermal conditions. Comparable relationships have been reported in previous studies conducted in other urban settings. Research examining LST and NDVI across different land-use/cover types, including commercial, industrial, residential, cropland, grassland, pasture, forest, and water, reported inverse relationships between vegetation abundance and surface temperature [51]. Similarly, research in Huntsville identified a strong negative relationship between vegetation abundance and radiant temperature across residential, agricultural, and vacant/transitional land-cover types [52]. The strength of the inverse relationship between vegetation and surface temperature may nevertheless be moderated by other environmental factors, including soil moisture conditions and surface evapotranspiration [53].

4.3 Challenges hindering the development of green space in Nairobi.

Urban green spaces provide a wide range of ecological, health, social, economic, and planning benefits that consequently improve the quality of the urban environment. In Africa, research conducted in several urban areas reveals low green-space coverage [54]. Consequently, the general approach to green-space planning in Africa is often characterized by impulsive action and direct intervention in response to visible problems [55]. Planning often lacks a long-term strategy and is centred on short-term interventions implemented within limited time frames, compared with regions such as Europe and Asia, where green-space planning has received greater priority within development agendas. This has contributed to the deterioration of urban green spaces in many African cities.

Low green-space coverage has been attributed to poor enforcement of development controls, lack of political will, high rates of urban sprawl and densification, outdated planning regulations, lack of priority given to green spaces in development, and inadequate financial resources [56]. These challenges are also evident in Nairobi and in many African cities more broadly. In Kenya, cities and towns have undergone rapid change, with the ratio of built-up areas to green spaces increasing. Urban planning in Kenya is guided by planning principles that include maintaining a clean and attractive environment and promoting environmental preservation through the maintenance of green spaces. Development plans are intended to ensure equitable access to green and open spaces, promote human health and the quality of air, water, and soil, and support the maintenance of biodiversity [57].

A disjointed governance structure, with multiple centres of authority, presents an additional challenge to green-space management. While the management of public spaces is primarily within the mandate of the Nairobi City County Government, other state and non-state entities are also involved in the management of public spaces. These include private citizens, corporate bodies, the Kenya Forest Service, National Museums of Kenya, Civil Society Organizations, Community-Based Organizations, and Faith-Based Organizations [58]. In terms of the legal, policy, and regulatory framework, the Physical Planning Act, Cap. 286, which was repealed by the 2019 Planning Act, the Urban Areas and Cities Act (No. 13 of 2011), the Forests Act 2005, and the Draft Physical Planning Bill 2014 require city and urban-area authorities to develop local physical development plans that provide spatial development frameworks to guide sustainable development. Among other objectives, these plans are intended to provide appropriately located public spaces and utilities and promote environmental sustainability by creating opportunities for urban greening.

Other policies that promote the creation of green spaces are contained in Kenya Vision 2030, the National Spatial Plan, and the Planning Handbook 2007. For example, the Forests Act 2005 provides for the development and sustainable management, conservation, and rational utilisation of forest resources for the socio-economic development of the country and other related purposes. The Act requires local authorities to establish and maintain arboreta, recreational parks, and mini forests. It further requires developers of housing estates to allocate at least 5% of their total land area for the establishment of mini-forests and requires the Kenya Forest Service to facilitate and provide technical support to local authorities in establishing and maintaining forests and other green areas. However, despite the existence of these policies, many urban areas in Kenya continue to face challenges in their implementation and enforcement, leaving them with limited green spaces and increasing their vulnerability to environmental problems [59].

4.4 The implications of sustainable planning for climate resilient cities

The results of this study show that although Nairobi has a substantial amount of green space, elevated surface temperatures remain evident across parts of the city. With the rapid urbanisation occurring in Nairobi, as demonstrated by the observed land-use/cover changes, mean LST has generally increased over the study period. Vegetation abundance, represented by NDVI, can contribute to the regulation of LST through shading and evapotranspiration, thereby moderating surface thermal conditions [60]. Areas with dense vegetation cover, including Ngong and Karura forests and green spaces located in the north-western, south-western, and central parts of the city, generally exhibit lower LST values. The lower LST observed towards the west, south-west, and north of the city (Figure 3) further demonstrates the association between vegetated land and lower surface temperatures. In contrast, relatively high mean LST values are evident in areas dominated by impervious surfaces, including densely developed areas close to the city centre, high-density informal settlements, and areas undergoing land-cover transition.

Appropriate planning measures are therefore needed to respond to these changing thermal conditions. The results indicate that increasing vegetation abundance represents one potential approach to moderating elevated surface temperatures. Building a climate-resilient Nairobi requires an environmentally friendly, socially acceptable, and economically accountable land-administration and planning process in which the “green” agenda is given greater priority. Urban planners and policymakers in Nairobi, and in African cities more broadly, should therefore consider restoring urban ecosystems and maintaining diverse habitats by increasing vegetation within remaining open spaces while addressing unplanned urban development [61]. Increasing vegetation cover or surface water can contribute to reducing LST and mitigating excess heat in urban areas [62]. In addition, the development and management of urban green spaces should adopt interdisciplinary and integrated approaches that consider economic, political, social, cultural, management, and planning dimensions to improve existing urban green-space facilities and services and strengthen urban green-space policies.

5. Conclusions

The study demonstrates that urban land-cover change has influenced the spatial and temporal distribution of land surface temperature in Nairobi City. Built-up area increased from 46.7 km² in 1986 to 203.6 km² in 2020, while mean LST increased from 24.52°C to 27.70°C. Forest and other vegetated areas generally maintained lower surface temperatures than built-up and bare or transitional areas, and the predominantly inverse relationship between NDVI and LST confirms the important cooling role of vegetation. These findings support the protection, restoration, and strategic distribution of urban green spaces, particularly larger and denser vegetated patches near intensively developed areas. The study was limited to selected Landsat observation years and focused primarily on vegetation density, land-cover characteristics, and surface temperature. Future studies should examine additional characteristics of urban green spaces and their relationships with microclimate and building energy demand, while also integrating georeferenced population data to assess variations in population exposure to elevated surface temperatures across the urban gradient, from densely urbanised areas to rural settings. Such evidence could strengthen the basis for targeting green infrastructure and heat-mitigation interventions and support climate-resilient urban planning and design in Nairobi and other sub-Saharan African cities.

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