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Assessment of Urban Heat Islands (UHIs) Using Satellite-Derived Normalized Difference Vegetation Index (NDVI), and Land Surface Temperature (LST) in Three Metropolitan Cities of Nepal

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Urban Heat Islands (UHIs) are urban areas that are relatively warmer than nearby rural areas due to the presence of infrastructures, such as buildings, roads, and associated development. This study explored the UHIs in Nepal's three largest metropolitan cities, i.e., Pokhara, Bharatpur, and Nepalgunj. Using freely available data, we explored LST dynamics between 2000 and 2019 and how changes in NDVI affect LST and their relationship with UHI. We used the Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day product (MOD11A2) to evaluate LST and the MODIS-derived NDVI 16-day product (MOD13Q1) to quantify land surface characteristics. Using a simple linear regression technique, we explored the relationship between LST and NDVI. The results indicated that LSTs for the urban areas are consistently greater than LSTs for the nearby rural areas, and an inverse relation between LST and NDVI was obtained. The results from Pokhara and Bharatpur showed that increasing LST resulting from declining NDVI is responsible for UHIs. However, the results from Nepalgunj suggested that factors other than NDVI are responsible for variation in LST. These results indicate a need for systematic mapping, planning, and managing open and green areas in large cities. This research also highlights the scope of applying UHI conceptual models to rapidly developing urban areas in different locations of Nepal for better planning and management of open spaces.

Keywords: Land surface temperature, metropolitan cities, MODIS NDVI, Nepal, Urban Heat Islands

Most of Nepal's population lives in rural areas, with less than half are living in urban areas (Bhattarai & Conway, 2021). Nepal is rapidly urbanizing, and demographics are changing rapidly due to income inequalities that have forced the mass out-migration of the rural population (Bhattarai & Conway, 2021). Urbanization refers to the growth and expansion of urban centers due to various factors, including a general shift of people from rural areas to cities (Chapagain, 2018; Hulley, 2012; Welford & Yarbrough, 2021). Nepal has experienced rapid urbanization in recent years (Rimal, Zhang, Keshtkar, Sun, & Rijal, 2018) and is one of the world's top ten fastest-urbanizing countries (Heiling, 2012). Nepal's annual urbanization rate is projected to increase to 1.9 % by 2050 (Bakrania, 2015). Urban expansion is occurring mainly around metropolitan cities, district headquarters (the then administrative centers), inner Terai valleys, and the markets and towns located at highway junctures along the

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east-west highway, which tend to be the primary urban centers (Acharya, 2018; Rimal *et al.*, 2020). Urban centers are the centers of economic activities that attract businesses and workers that tend to be associated with enhanced productivity.

Internal migration is the most significant contributor to urban growth and is increasing over time (Acharya, 2018; KC, 2020). Cities that provide a variety of options for employment and education are drawing more and more people, especially those seeking work in the manufacturing, construction, and service industries. A significant portion of the national economy comes from the urban sector (Bakrania, 2015). With regard to Nepal, urban regions provide around one-third of the country's GDP (GDP). Increased population growth is one of the primary reasons for the gradual transition from rural to urban centers (Bakrania, 2015). The population of Nepal was 26.5 million in 2011, then projected to be 29.1 million in 2022 (Central Bureau of Statistics,2022). Due to both political and economic factors, such as rural poverty and better employment possibilities in cities, Nepal's urban population has grown rapidly during the past ten years. Other driving factors of urban population growth include social, physical, developmental, high net migration, and administrative reclassification (Rijal, Rimal, Stork, & Sharma, 2020; Rimal *et al.*, 2020, 2018). Climate and physiographic features make the area attractive for urban development, along with good government plans and policies (Rijal *et al.*, 2020). For instance, in Nepal, urbanization primarily occurred at the periphery of the East-West, postal highway, and connecting road networks to the mid-hills (Rimal *et al.*, 2020). As a result, the areas accessible from the mid-hill districts were rapidly expanded.

Rapid urbanization poses multiple challenges, such as hazards and uncontrolled growth of built-up areas (i.e., areas populated with residential structures and other anthropogenic facilities that meet the need of the increased population) that require urgent policy attention. Unplanned urban development leads to rapid and uncontrolled sprawl, loss of open spaces, increased vulnerability to disasters such as earthquakes, and decreased human suitability (Aksha, Juran, & Resler, 2018; Pandey, 2013). Urbanization significantly changes the local landscape by replacing open vegetated areas with buildings, roads, and associated infrastructures. Such a shift in landscape from rural to urban leads to the phenomenon called "urban heat island (UHI)." UHIs are urban or metropolitan areas that experience significantly warmer temperatures than their nearby rural areas (Cao, Li, Zhang, & Chen, 2008; Kim, 1992; W. Li, Cao, Lang, & Wu, 2017; Y. Wang & Akbari, 2017). Satellite-based remote sensing technology and a GIS-based approach can dynamically and comprehensively detect change in the urban thermal environment. Land surface temperature (LST) is an important parameter in analyzing UHIs (Cao *et al.*, 2008; Qiao *et al.*, 2020; Shi, Xiang, & Zhang, 2019). LST and normalized difference vegetation index (NDVI) are widely used to explore the relationship between landscape change patterns and UHI characteristics. For instance, C. Li *et al.* (2014) found a negative correlation between NDVI and UHI in Shanghai, China.

Studies have used LST based on various remote sensing data such as NOAA AVHRR, Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Thermal Infrared (TIR) data, Moderate Resolution Imaging Spectroradiometer (MODIS) derived data (Azevedo, Chapman, & Muller, 2016; Grover & Singh, 2015; Mishra, Sandifer, & Gyawali, 2019; Sridhar, Sathyanathan, & Sree Shivani, 2020; R. Wang, Gao, & Peng, 2020) to study UHI. This study used MODIS-derived LST and NDVI data to understand the impact of vegetation changes on UHI. A major advantage of using MODIS imagery is the availability of products made on varying temporal schedules, ranging from raw images to highly processed products (Masuoka, Fleig, Wolfe, & Patt, 1998). In addition, several previous studies have successfully used MODIS data to study the relationship between LST and NDVI (Mishra *et al.*, 2019; Teodoro, Duarte, Barradas, Mateus, & Neto, 2018; R. Wang *et al.*, 2020; Yuan *et al.*, 2017).

MODIS-derived LST and Landsat image-derived LST were used to study UHI phenomena in

Kathmandu Metropolitan City, Nepal (Mishra *et al.*, 2019; Sarif, Rimal, & Stork, 2020). Similarly, Landsat satellite imagery-derived NDVI were used to assess increased urbanization in other metropolitan cities, including Pokhara, Bharatpur, and Nepalgunj (Rai, Yili, Paudel, Khanal, & Acharya, 2020; Rimal *et al.*, 2020). However, the study of UHI phenomena is limited in these metropolitan cities. UHIs raise the demand for energy consumption, such as air conditioning, and contribute to compromised human health and environmental stress. However, studies on LST, UHIs, and their relationship with other possible factors are limited in Nepal. Understanding the distribution of land surface temperature is important because it affects many aspects of life. Therefore, in this study, we explored LST dynamics between 2000 and 2019 and how changes in NDVI affect LST and their relationship with UHI in the three major Nepalese cities.

Materials and methods

Study area

In this study, we focused on three metropolitan cities in Nepal, namely Pokhara, Bharatpur, and Nepalgunj. Indicators of physical and human geography, as well as growth in terms of population size, vary between these three cities. Pokhara is the second-largest and the most rapidly growing city located in the mid-hills of western Nepal, with an annual population growth rate of five percent (Acharya, 2018). The East-West route passes through the urban areas of Bharatpur and Nepalgunj, where populations are dispersed, and agricultural lands have been exploited for residential uses, fragmenting the area. The existing urban agglomerations were spatially expanded along the peripheries of major cities and highways (Rimal *et al.*, 2020). For example, Pokhara is densely populated and is growing towards Prithivi Highway and Pokhara-Baglung Highway. The characteristics of all three cities are provided in table 1. And figure 1 shows the geographic location of Pokhara, Nepalgunj, and Bharatpur.

Table 1: Characteristics of three study cities, Pokhara, Bharatpur, and Nepalgunj

District	Pokhara	Bharatpur	Nepalgunj
	Kaski	**Chitwan**	**Banke**
Area (km^2)	464.24	433	85.94
Latitude	28⁰ 12'30"N	27° 41′ 0″ N	28° 3′ 0″ N
Longitude	83⁰ 59' 20"E	84° 26′ 0″ E	81° 37′ 0″ E
Elevation (m)	1740	208	150
Annual Precipitation (mm/year)	3350	2407	1447.8
Average Annual Temperature (°C)	13.5	23.2	30.2
Population Density (per km^2)	868	503	1592

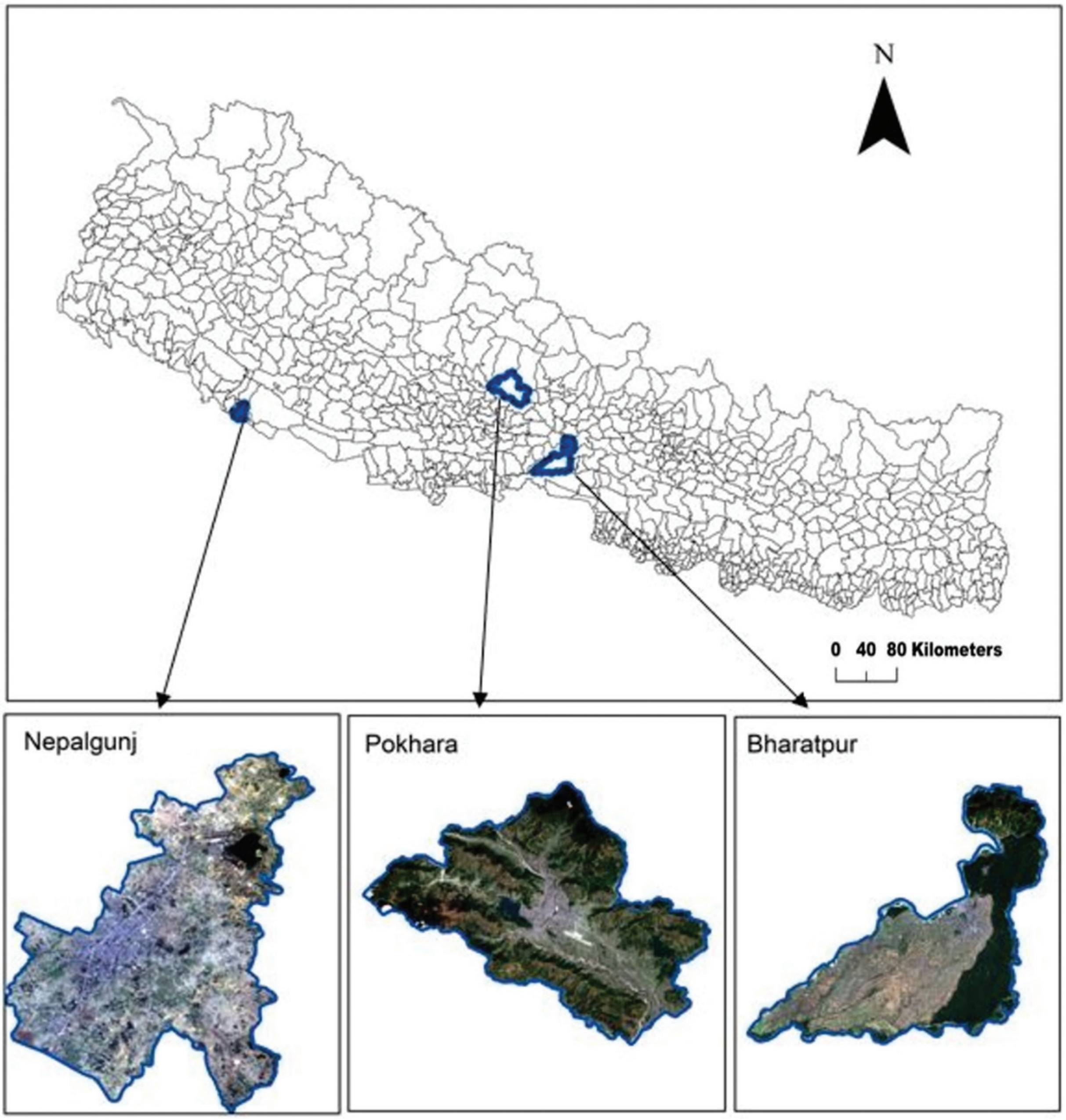

Figure 1: Location (top panel) and land use land cover (bottom panels) of three study cities, Bharatpur, Pokhara, and Nepalgunj

Data acquisition

We downloaded MOD11A2 and MOD13Q1 data from EARTHDATA Search (Table 2). MOD13Q1 represents the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices, which is generated every 16 days at 250-meter spatial resolution. The Land Surface Temperature and Emissivity (LST&E) product of MOD11A2 Version 6 offers an average 8-day per-pixel LST&E with a 1 km spatial resolution.

Table 2: Description of MODIS data used for this study

Data Type	Date of acquisition	Spatial Resolution	Source
MOD11A2	Start: 2000-5-15 End: 2019-5-18	1000 m 250 m	https://search.earthdata.nasa.gov/
MOD13Q1	Start: 2000-5-8 End: 2019-5-23		

Normalized Difference Vegetation Index (NDVI)

Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between the near-infrared band (which reflects vegetation strongly) and the red band (which absorbs vegetation) (Viana, Oliveira, Oliveira, & Rocha, 2019). Its values range from -1 to +1, where values near +1 indicate dense vegetation, low positive values represent grassland, 0 indicates barren areas, and negative values represent water or impervious surfaces. It has been reported that impervious surfaces are warmer than green areas (Kuang *et al.*, 2015); therefore, there is likely a negative relationship between NDVI and LST.

$$NDVI = \frac{(Near\ Infrared\ Band - Red\ Band)}{(Near\ Infrared\ Band + Red\ Band)} \ldots.(1)$$

Land Surface Temperature (LST)

One of the MODIS land products is Land-surface temperature (LST). The MOD11A2 Version 6 product offers an average Land Surface Temperature and Emissivity (LST&E) of 8 days per pixel. Under clear skies, the accuracy criteria for MODIS LST is 1°K at 1 km of spatial resolution. A simple average of all the relevant MOD11A1 LST pixels gathered throughout that 8-day period is used to calculate each pixel value in the MOD11A2 dataset. The 8-day compositing duration was selected since the Terra and Aqua platforms' ground track repeat periods are exactly twice that length of time. Emitted spectral radiance L at wavelength λ from a surface at thermodynamic temperature Ts is given by multiplying the Planck function by spectral emissivity e(λ) (K. Wang *et al.*, 2007).

$L(\lambda, T) = e(\lambda)\ B(\lambda, Ts)$ ………………(2).

Data preparation and analysis

MOD13Q1 and MOD11A2 data were pre-processed and analyzed using Esri geospatial software ArcMap version 10.5. The raster images representing LST were rescaled by multiplying with a scale factor of 0.02, while the raster representing NDVI was multiplied by a scale factor of 0.0001. Rescaling was done to reduce the uncertainties of satellite data and receive the actual data value. Data were projected into the WGS1984 UTM Zone 44N coordinate system. Since the downloaded LST was in degrees Kelvin, we converted it into degrees Celsius. Finally, LST images were resampled to match the spatial resolution of the NDVI image.

About one hundred random points each were created inside the boundaries of Pokhara, Bharatpur, and Nepalgunj (Figure 2). LST and NDVI values of the random pixels were extracted and recorded in the attribute table of the random point feature class. This attribute table with a hundred LST and NDVI values was exported for further statistical analysis in R software Version 1.2.5001 (R Core Team, 2020).

Simple linear regression (alpha level = 0.05) was used to assess the relationship between LST and NDVI for the years between 2000 and 2019. This analysis was applied to all sampled pixels separately for Bharatpur, Pokhara, and Nepalgunj between 2000 and 2019. We considered NDVI as the independent variable and LST as the dependent variable.

$Y = mx + c$ ……… (3)

where y is the dependent variable, x is the independent variable, m is the coefficient, and c is the constant.

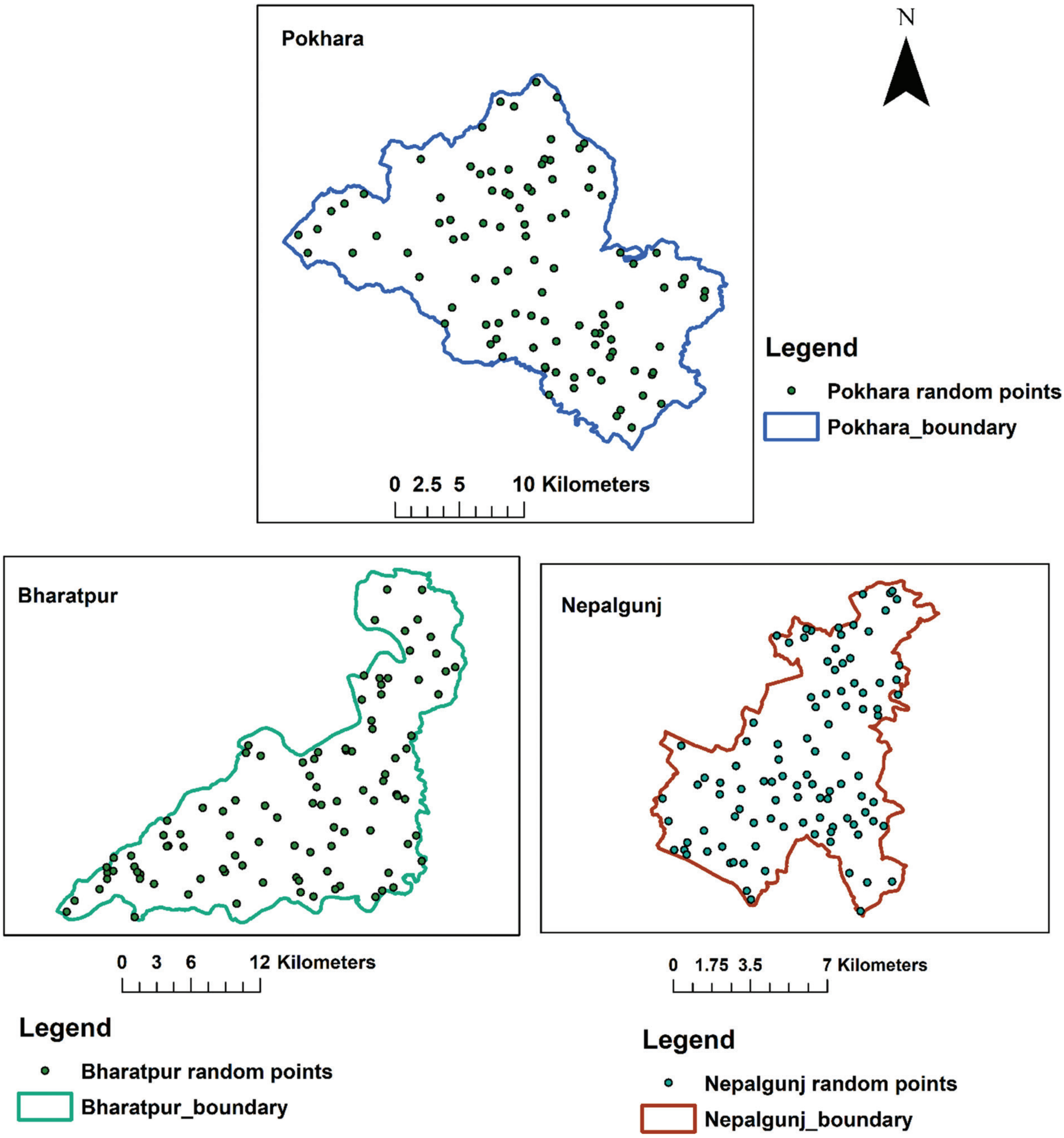

Figure 2: Spatial distribution of one hundred random points were created inside the boundaries of Pokhara, Bharatpur, and Nepalgunj

Results

Change in LST and UHI between 2000 and 2019

From the LST images,we can see UHI effects from past years. It was observed that higher temperatures exist in urban areas, and the distribution of higher LST values has increased over time from 2000 to 2019 (Figures 3, 4, 5). Along with expanding higher temperature zones to the city centers, nearby rural areas also faced increased temperatures. The variation in land surface temperature is observed in the central part of Pokhara, as shown in Figure 3, with more developed infrastructures such as houses and roads, where higher temperature exists between 32°C–33°C. Also, variation in LST distribution from 2000 to 2019 is observed in areas surrounding the core city, where the temperature seems to increase.

In Bharatpur, a higher variation in the distribution of land surface temperature is observed from 2000 to 2019, as shown in Figure 4. During 2000, higher temperatures existed at inner terai, which is located in the southern part of Bharatpur. The distribution of higher temperatures expanded toward the northern part. This is due to the city's expansion in Narayangadh, which is the central hub for trade, business, and transportation for Kathmandu, Pokhara, Hetauda, and western Nepal. Moreover, this urban expansion has influenced suburban temperature in the northernmost part, where high elevation exists, and the southeastern part, which is a forested area and part of Chitwan National Park. The UHI phenomenon mostly influences sub-urban areas.

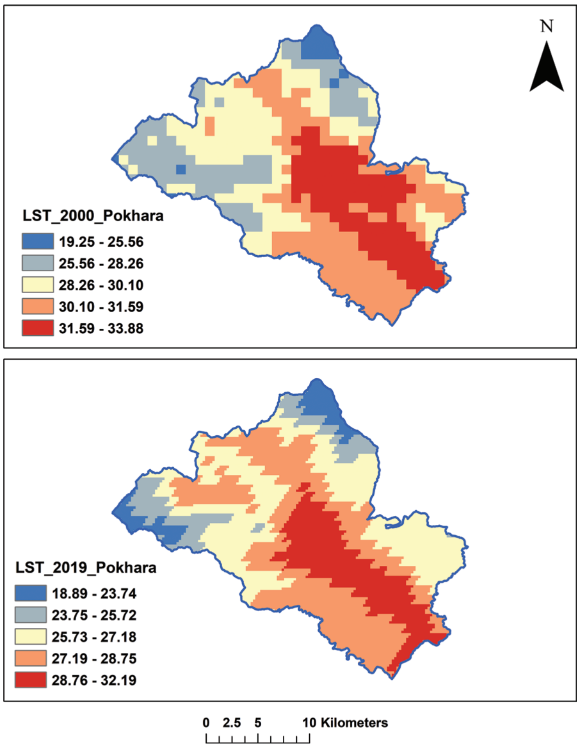

Figure 3: Land surface temperature maps of Pokhara Metropolitan City for the year 2000 (upper panel) and 2019 (lower panel)

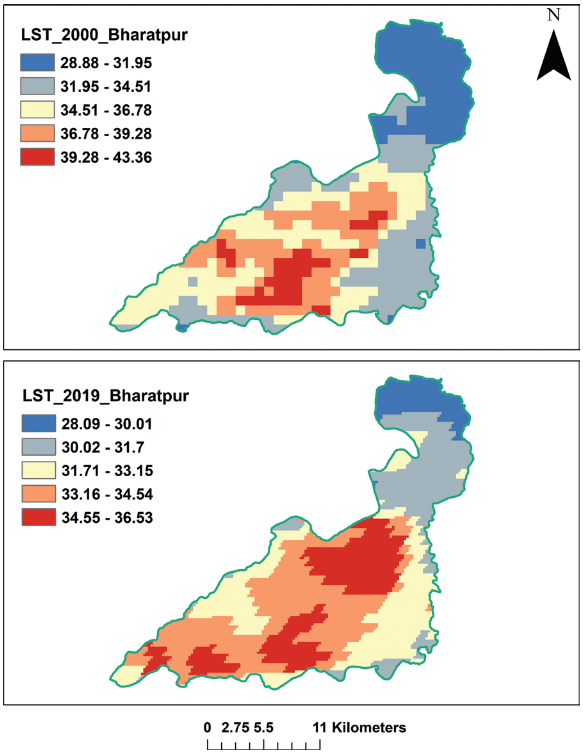

Figure 4: Land surface temperature maps of Bharatpur Metropolitan City for the year 2000 (upper panel) and 2019 (lower panel)

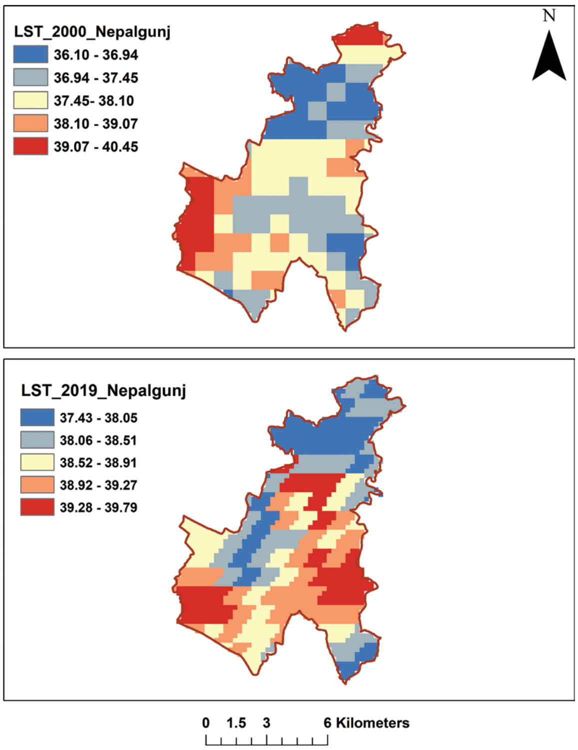

Figure 5: Land surface temperature maps of Nepalgunj Metropolitan City for the year 2000 (upper panel) and 2019 (lower panel)

Similarly, variation in land surface temperature was observed in Nepalgunj sub-metropolitan city from 2000 to 2019, as shown in Figure 5. Higher temperature exists in the central and eastern parts of Nepalgunj. This might be due to heat captured by the impervious surface at the core city area. Nepalgunj is the hottest place in Nepal, which lies at a low elevation, where the highest temperature ever recorded was 45°C during the hot summer months. The lowest temperature of Nepalgunj has risen from 36°Cin 2000 to 37°C in 2019.

Change in NDVI between 2000 and 2019

Our results showed that NDVI value significantly changed between the years 2000 and 2019 in all three cities. Figures 6, 7, and 8 show the range of NDVI values between the years 2000 and 2019 for Pokhara, Bharatpur, and Nepalgunj, respectively. The green indicates healthy vegetation, while the red represents no vegetation or impervious surface. NDVI value is less in the central part of Pokhara in 2019 than in 2000 (Figure 6). This indicates less vegetation and a more impervious surface, as represented by the red color. Pokhara's built-up area has grown specifically along the highways and Phewa lakeside. This can result in increased LST. In the Narayanghad area of Bhatarpur metropolitan city, NDVI values in 2019 are lower and negative compared to NDVI values in 2000. This represents the urbanization of Narayanghad over time. Additionally, the vegetation toward the northern part of Bharatpur decreased gradually from 2000 to 2019. Those are the areas with higher elevation, where development activities like the construction of ungravelled roads occurred, which leave the land barren and also prone to erosion. Barren lands produce higher radiance, giving rise to LST values. Lower NDVI values toward the southern part of Bharatpur during 2000 might be due to drought or less vegetation on the ground. In the case of Nepalgunj sub-metropolitan city, vegetative land has decreased gradually, and areas with lower NDVI values increased from 2000 to 2019. NDVI values indicate the degree of vegetation greenness (Lo & Quattrochi, 2003).

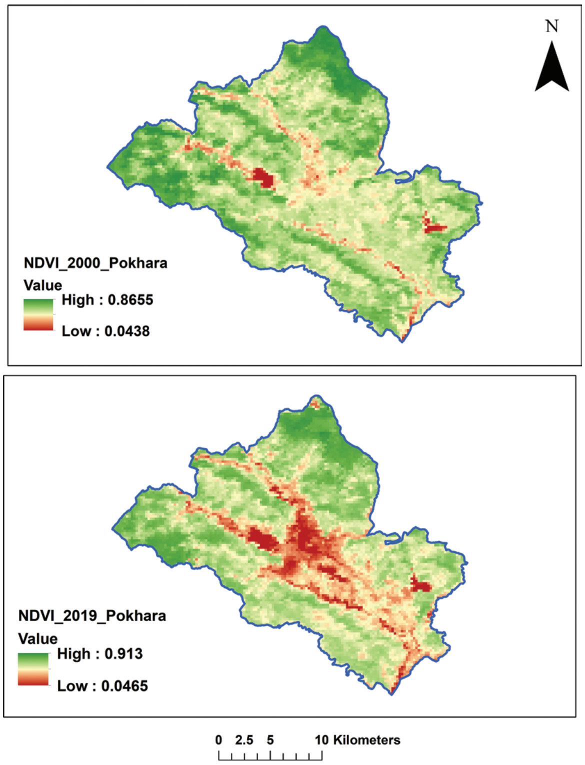

Figure 6: Maps showing NDVI for the years 2000 and 2019 for Pokhara Metropolitan City

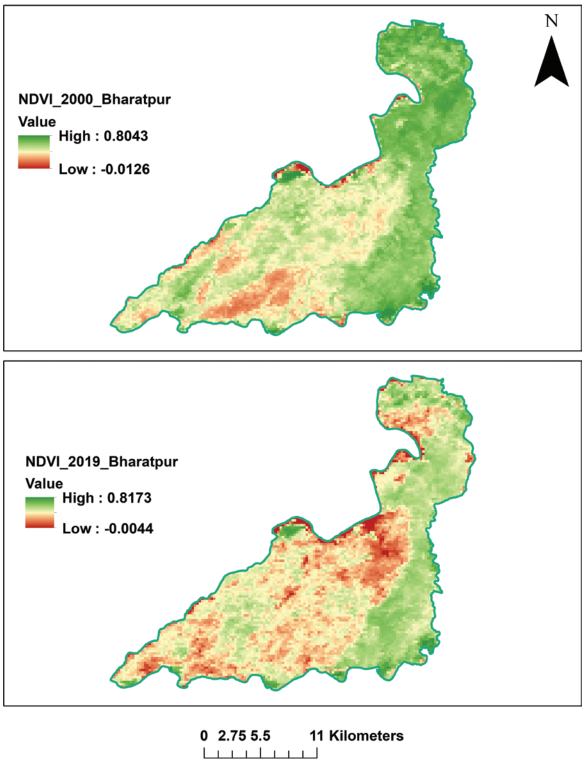

Figure 7: Maps showing NDVI for the years 2000 and 2019 for Bharatpur Metropolitan City

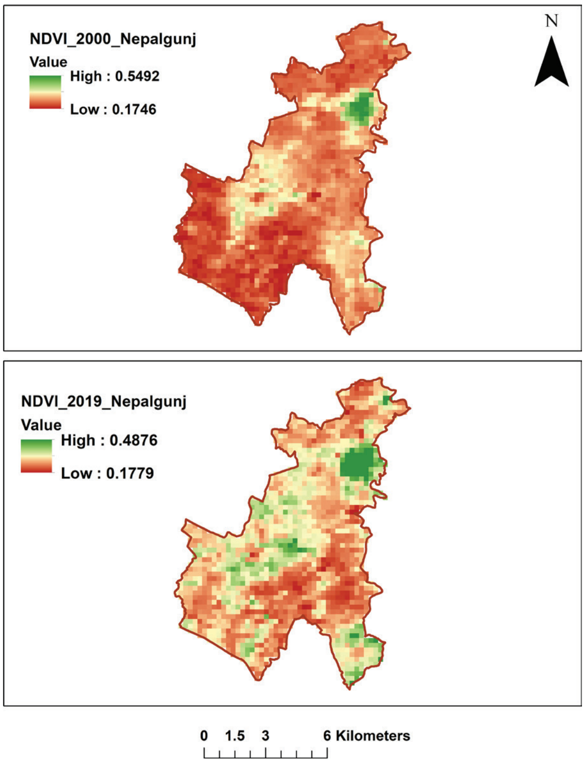

Figure 8: Maps showing NDVI for the years 2000 and 2019 for Nepalgunj Sub-metropolitan City

Relationship between LST and NDVI

Figures 9, 10, and 11 show the relation between temperature and vegetation for the years 2000 and 2019. It is known that an increase in vegetation correlates to decreases in UHI intensity. This shows an inverse relationship between temperature and NDVI (Sridhar *et al.*, 2020).

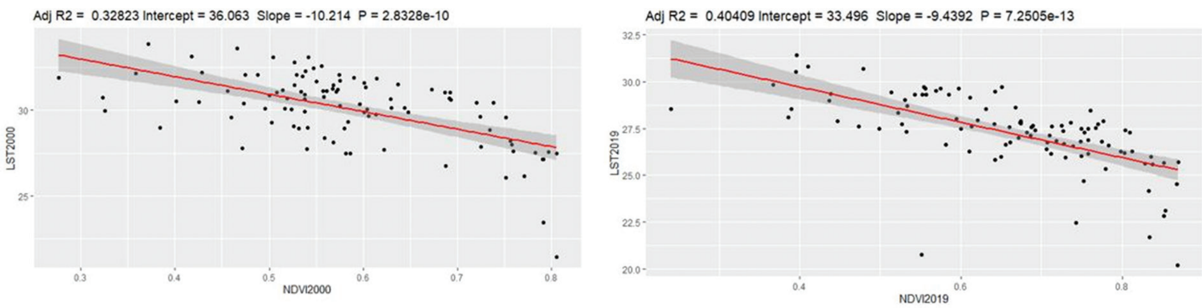

Figure 9: Scatterplots showing the relation between NDVI and LST for the years 2000 and 2019 in Pokhara

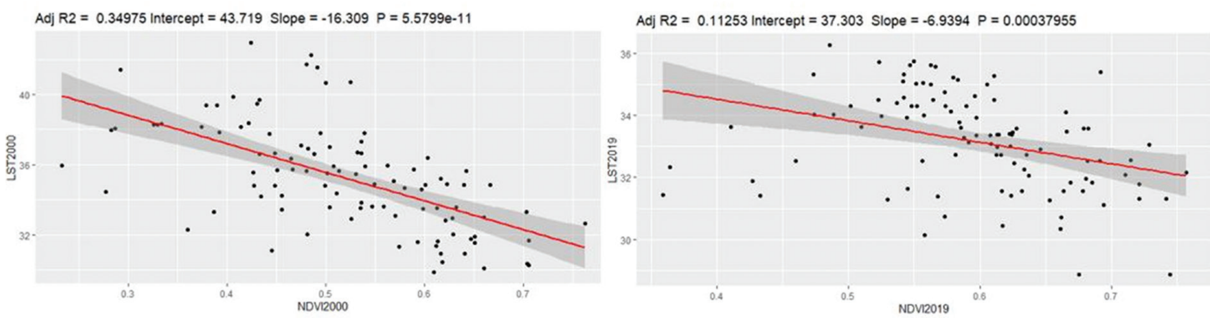

Figure 10: Scatterplots showing the relation between NDVI and LST for the years 2000 and 2019 for Bharatpur

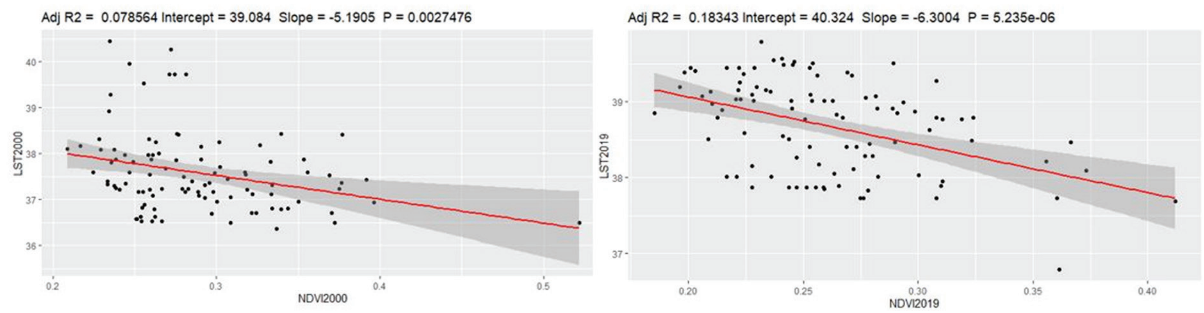

Figure 11: Scatter plots showing the relation between NDVI and LST for the years 2000 and 2019 for Nepalgunj

Discussion

This research investigated the relationship between LST and NDVI concerning UHI in three metropolitan cities viz, Pokhara, Bharatpur, and Nepalgunj of Nepal, which has been facing rapid urbanization in recent years. Our study showed increased LST and decreased vegetation as represented by NDVI in these major urban centers, which resulted in UHI phenomena. Furthermore, LST has been found to be strongly determined by vegetation health (Kant, Bharath, Mallick, Atzberger, & Kerle, 2009; Yue, Xu, Tan, & Xu, 2007). In this study, the high value of LST was found in areas with lower vegetation intensity. Generally, negative NDVI depicts water bodies, positive NDVI depicts bare ground and built-up areas, and NDVI greater than 0.2 depicts vegetation, with higher NDVI denoting better vegetation (Guha & Govil, 2020; Guha, Govil, & Mukherjee, 2017). Several studies have found that LST negatively correlates with NDVI (Grover & Singh, 2015; Guha & Govil, 2020; Mishra *et al.*, 2019).

The dependency between the LST and NDVI for Pokhara, Bharatpur, and Nepalgunj is represented by regression analysis (Figures 9, 10, and 11.). In the case of Pokhara, 40% of the relationship is explained by NDVI, which indicates that the lower vegetation index is responsible for varied LST patterns (Figure 9). About 37% of the relationship between LST and NDVI is reflected in Bharatpur (Figure 10), and only 18% of the relationship is explained by NDVI in Nepalgunj (Figure 11). This reflects that there are other possible factors for high temperature in Nepalgunj, which can be attributed to the humid subtropical climate, the presence of grasslands and shrubs other than the dense forest, and its location in the Terai plains near the border of India. The distribution of water bodies, the amount of impermeable concrete, asphalt, and metal used, as well as the roughness of the surface are a few of the many variables that determine the development and intensity of LST and UHI (Grover & Singh, 2015; Kuang *et al.*, 2015). Furthermore, although the spatial relationship between the change in LST and NDVI is statistically significant, it is not necessarily spatially coincident (Mishra *et al.*, 2019).

People choose to move to urban areas for many different reasons, for example, better access to educational and health institutions, social services, better employment opportunities, and other facilities to improve their lifestyles (Dussault & Franceschini, 2006). Urban regions in Nepal have traditionally seen a noticeable rise in the quantity and size of small urban communities (Bhattarai & Conway, 2021). The main drivers of urban expansion across the nation have been population increase and internal migration. (Ishtiaque, Shrestha, & Chhetri, 2017; Poudel, 2013; Rai *et al.*, 2020). The urban expansion causes a corresponding decrease in cultivated lands. The built-up area in Pokhara has increased mainly along the Phewa lakesides and highways (Pokhara to Kathmandu and Baglung highways) due to its location between mountainous and terai regions, which is an important east-west stage point in the trans-Himalayan trade route (Rai *et al.*, 2020; Rimal *et al.*, 2020, 2018). Moreover, Pokhara is a major tourist destination in Nepal that has surged urbanization (Rimal *et al.*, 2018).

Along with the rapid expansion of places from mid-hill districts such as Pokhara, extensive areas of agricultural land have been converted to urban in the cities of terai districts such as Bharatpur and Nepalgunj (Rimal *et al.*, 2020). Urban areas near major population centers and thoroughfares, particularly those along the East-West and North-South highways and the Indian border, experienced the highest growth (Portnov, Adhikari, & Schwartz, 2007; Rimal *et al.*, 2020). In the western terai of Nepal, including Bharatpur and Nepalgunj, the land was fragmented due to scattered settlements, and agricultural lands were plotted for residential purposes. The trend of the rapid growth of urban areas and associated losses of cultivated land is projected to continue to 2026 and 2036 (Rimal *et al.*, 2020). Furthermore, the trend of urbanization was found to be higher in Bharatpur, with increased built-up area by 500% as compared to Pokhara, where built-up areas increased by 300% during the past 28 years, which is primarily due to migration from the mountain and hill regions into the low-lying plains (Rai et al., 2020).

Since most cultivated areas in Nepal are frequently close to urban areas, farmers and urban dwellers compete for these lands. As a result, there is a high probability of transition of cultivated lands to built-up lands, as reported by various studies(Adhikari, Shrestha, Singh, Upadhaya, & Stapp, 2016; Ishtiaque *et al.*, 2017; Rai *et al.*, 2020; Rimal *et al.*, 2020, 2018). The increase in new urban and semi-urban areas may raise the area's temperature, leading to UHIs. It may also potentially influence local weather conditions, such as the presence of fog, humidity levels, and wind patterns, posing health hazards to the urban people and ecosystem.

Conclusions

LST and NDVI variations were observed during the study period between 2000 and 2019. LST images indicate a significant increase in LST from urban centers to nearby rural areas. This indicates that the temperature of the core city centers is likely to be associated with the temperature of the surrounding semi-urban areas if the increasing trend of LST continues. The increasing patterns of LST and UHI suggest that these metropolitan cities have experienced an unsystematic conversion of open and agricultural lands into urban areas.

Understanding the increase in LST and its relation to NDVI change assists in developing strategies for controlling the UHI phenomenon. For instance, retaining vegetation or planting trees in open or barren lands and regulating land use change practices assist in reducing LST. The urban planners and government agencies should continue to compile and periodically monitor LST, NDVI, and UHIs indicators for the sustainable development of these cities.

Additionally, it is now possible to model LST variation and analyze UHI at higher resolutions and in greater detail, thanks to the availability of free spatial data and the decline in processing costs. So, there is a need to conduct more studies on deriving LST, NDVI, and UHI phenomena in different cities located in different regions of Nepal to understand the pattern of UHI all over the country. Although this study used readily available data and robust methodology selecting three different locations of Nepal as a study area, it still has a few limitations. For example, in this study, we did not consider several probable drivers of UHI, including local population growth, policy, and topography, due to a lack of consistent data for associating with spatially-explicit land-cover change. Therefore, future studies on land-change scenarios, demographic factors, and municipal border expansion should mainly be considered for studying UHI expansion patterns in Nepal.

Author Contributions

Buddhi Gyawali and Smriti Kandel conceptualized the topic; Methodology, Jeremy Sandifer and Smriti Kandel; Analysis, Sandesh Shrestha and Smriti Kandel; Writing-original Draft Preparation, Smriti Kandel; Writing-review & editing, Buddhi Gyawali, Jeremy Sandifer, Suraj Upadhaya and Sandesh Shrestha; All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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