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Estimating the Effect of Urbanization on Ecological Condition and Urban Thermal Comfort: A Case Study in Colombo, Sri Lanka

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Abstract: Urbanization is one of the major factors affecting the ecological condition and urban thermal comfort of cities, particularly in developing countries like Sri Lanka. This study explores the impact of vegetation cover, built-up density, and land surface temperature on urban thermal comfort and ecological condition in Colombo, Sri Lanka using multi-temporal remotely sensed data. Landsat 8 satellite images from 2014 to 2023 were used to assess the spectral indices such as NDVI, NDBI, LST and UTFVI in Colombo. The results show that ecological condition and thermal comfort are fluctuating throughout the study period. Specifically, between 2020 and 2022, Covid-19 pandemic is one of the major influencing factors for the good ecological condition since the air quality was controlled by limited human activities due to lockdown. After people adapted to live with Covid-19 and continued their day-to-day activities, industrial activities returned to their normal conditions again in 2023; a pattern leading to ecological condition going back to worst was identified. So, these findings highlight the importance of incorporating green spaces and built-up density in urban planning to mitigate the adverse effects of surface temperature on ecological condition and thermal comfort.

Keywords: Covid-19, Ecological condition, NDBI, NDVI, UTFVI

1. Introduction

In recent decades, human activities have altered the environment by means of overgrazing, rising population, perception of the local community of land management, increase in socio-economic needs, unplanned and uncontrolled changes of land use land cover (LULC), leading the natural resources to exploit in an unfavourable manner [1, 2]. This directly refers to the urban ecological condition as this leads to the comfort level of the people who are living in a particular location. To assess this ecological condition, urban thermal field variance index (UTFVI) is one of the indicators that can provide precise information on urban thermal comfort in a certain location [3]. However, to calculate the UTFVI, land surface temperature (LST) is the primary component that can be measured by field survey. But conducting such survey will consume time and labour. It will have an effect on the accuracy of the results too depending on the person who is taking the reading and the condition of the place. Hence, remote sensing techniques came into play to fill the gap. Historical remote sensing data availability, reduced data costs, and improved satellite platform resolution make remote sensing technology potentially more influential in planning, organization and land management initiatives, monitoring change in land cover and land use at various spatial scales. These data provide a synoptical view of LULC spectral, spatial and time changes [4, 5, 6]. Currently, almost half of the world's population lives in urban areas [7, 8] and is expected to reach 60 percent by 2030 [9]. Due to the growing trend towards global urbanization, many researchers have been examining the impact of human activity on urban heat environments, such as land surface temperatures (LSTs) and urban heat islands (UHIs) [10], since metropolitan areas are exposed to higher temperatures than the nearby suburbs and rural areas [11]. Moreover, remote sensing indices, such as the normalized difference built-up index (NDBI) and the normalized difference vegetation index (NDVI), help to extract the constructed area and vegetation, respectively [12, 13] .

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In addition, LST is connected to NDVI and NDBI and varies considerably depending on the type and time of LULC [14, 15, 16, 17]. To this end, this study illustrates the condition of urban thermal environment in Colombo area because numerous human activities have an adverse impact on LULC, and locations have seen environmental deterioration. Rapid urbanization converts rural land into built-up regions, significantly impacting the places of thermal condition [18]. Therefore, understanding how urbanization and these patterns interact may have an impact on the creation of more urban friendly environmental management strategies [19, 20]. The large number of individuals who move to new cities and their actions have a very detrimental influence on housing, infrastructure, food security and ecosystem services [21]. Sri Lanka is also a well-liked tourist location. Therefore, improved thermal comfort can enhance both the quality of life for locals and visitors.

2. Methodology

2.1 Study Area

The study covers the Colombo municipal council area (Figure 1), which is located on the west coast of Sri Lanka and is adjacent to Greater Colombo. The major city and financial hub, Colombo, has this municipal governing body and is geographically situated between North latitudes 6°52'0" and 6°59'0" and East longitudes 79°49'0" and 79°53'0" and covers the Colombo and Thimbirigasyaya Divisional Secretariat Divisions. It is a bustling city with a unique blend of colonial architecture, modern life, and monuments.

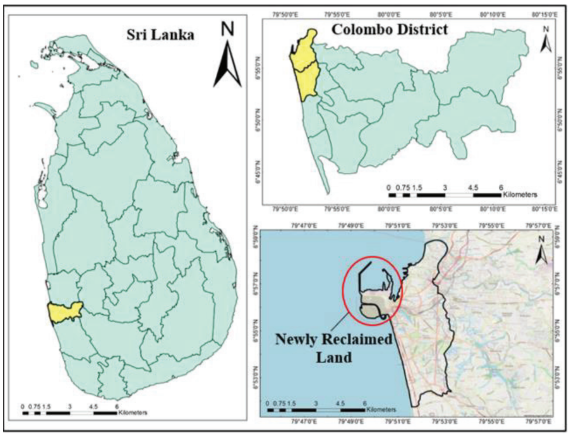

Figure 1 – Study Area

2.2 Dataset

Based on cloud cover and a specific period, six Landsat satellite images from the Landsat 8 Operational Land Imager and Thermal Infrared Sensor (OLI/TIRS) were analysed for this study. Despite the fact that the selected satellite images had cloud cover ranging from 14 to 49 percent (see Table 1), care was taken to ensure that the study area was not covered by clouds when selecting the images. WGS 84 datum and the Universal Transverse Mercator (UTM) map projection (Zone 44N) and ellipsoid using conventional terrain and atmosphere adjustments were used to geo-reference the images. The selected six satellite images represent the period from 2014 to 2023 and spread from January to May. When selecting the images, cloud cover was one of the major problems encountered. Some years had a full cloud cover above the area of interest. That is why the selected images were spread from January to May. Moreover, from January to May, the climate will not vary that much in Colombo since the monsoon period will start after May. The selected satellite images comprised 26 March 2014, 31 March 2016, 17 February 2018, 09 February 2021, 19 May 2022, and 30 January 2023, as displayed in Table 1. Image processing was done using ArcMap 10.7 software.

Table 1 - Detail of Satellite Images Acquired

Acquisition Date	Time (GMT)	Cloud Cover (%)
2014/03/26	04:53:56	23.52
2016/03/31	04:53:19	22.06
2018/02/17	04:53:27	14.89
2021/02/09	04:53:45	29.34
2022/05/19	04:53:36	42.63
2023/01/30	04:54:02	49.00

2.3 Overview of Methodology

The methodology comprised two major steps. The first step involved the detection of spectral indices such as NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-up Index), LST (Land Surface Temperature), and UTFVI (Urban Thermal Field Variance Index). The second step included the correlation and regression analysis of spectral indices with the thermal comfort and ecological condition of the Colombo municipal council based on the above-mentioned findings.

2.3.1 Normalized Difference Vegetation Index (NDVI)

The most important metric of vegetation cover, NDVI, stands out as an indicator of the biomass or greenness of an area [22]. On a variety of scales, including local, regional, and global, it is frequently used to identify changes in vegetation. Due to its simple interpretation, this indicator stands out from many others (including the enhanced vegetation index, ratio vegetation index, and difference vegetation index). It is expressed by Eq. (1) and ranges from -1 to +1 [23]. Negative values often indicate a lack of vegetation, such as bare soil or water bodies, whereas positive ones indicate an abundance of vegetation cover [22]. NDVI was calculated using Eq. (1).

NDVI = (NIR-Red)/(NIR+Red) ...(1)

NIR means the Near Infrared band.

2.3.2 Normalized Difference Built-up Index (NDBI)

NDBI stands out as the most important predictor of the built-up pattern in a certain area [24]. In a manner similar to that of NDVI, NDBI values are calculated using Eq. (2) and range from -1 to +1, where low values denote waterbodies and high values built-up regions [22]. NDBI was calculated using Eq. (2).

NDBI = (SWIR-NIR)/(SWIR+NIR) …(2)

SWIR means the Short-wave infrared band.

2.3.3 Land Surface Temperature (LST)

The land surface temperature was calculated using the USGS formula for the Landsat 8 images using Band 10. This basically comprises the following steps: (i) digital number to spectral radiation conversion, (ii) spectral radiation to top-of-atmosphere brightness temperature conversion, and (iii) brightness temperature to LST conversion [25, 26].

2.3.4 Urban Thermal Field Variance Index (UTFVI)

This is a measure of thermal comfort and urban ecological conditions. This can be employed with UTFVI value [3] and it was calculated using Eq. (3) below.

UTFVI = (LST-LSTmean)/(LSTmean) … (3)

LSTmean is the average LST, and LST is the Land Surface Temperature of a particular pixel within the study area. There are six thermal comfort levels with UTFVI Table 2, and this thermal comfort improves as the UTFVI value decreases, but thermal comfort decreases as the UTFVI value increases.

2.3.5 Correlation and Regression Between Vegetation and Building Density on Thermal Comfort

NDVI and NDBI were used as proxies for independent variables representing vegetation and building density, respectively. UTFVI was used as a proxy for the dependent variable, which represents thermal comfort. Furthermore, a simple linear regression analysis was performed to examine the effect of vegetation and building density on thermal comfort in the study area. Additionally, the area percentages of six urban thermal comfort classes were calculated to evaluate the changes from 2014 to 2023.

3. Results and Discussion

3.1 Assessment of Spectral Indices and their Relationship

3.1.1 NDVI

NDVI distribution of this study area was done for the years 2014, 2016, 2018, 2021, 2022 and 2023. According to the analysis, Healthy vegetation cover, which has a higher value for NDVI, is concentrated primarily in the South-eastern part of the region. However, the metropolitan region, located in the North-western region, is showing a low NDVI value. Therefore, as per the NDVI maps, the vegetation cover of the metropolitan region has slightly reduced between the time of 2014 and 2023. This may be due to the rapid urbanization, leading to the development of new factories, apartments, and offices.

3.1.2 NDBI

The distribution of NDBI in this study area was done for the years 2014, 2016, 2018, 2021, 2022 and 2023. The results reveal that the area occupied by the dense built-up cover, which has a higher value for NDBI, is concentrated primarily in the metropolitan region, which is located in the North-western part of the region. However, the South-eastern region is showing a low NDBI value. Therefore, as per the NDBI maps, the building density of the metropolitan region has increased between the time of 2014 and 2023. With this result, it is indicated that there was a considerable rise in energy consumption in the Colombo metropolitan area during that period. This is mainly because population of Colombo has increased significantly during the period, leading to a higher demand for housing and commercial spaces; a growing economy can lead to an increase in building density, as more businesses

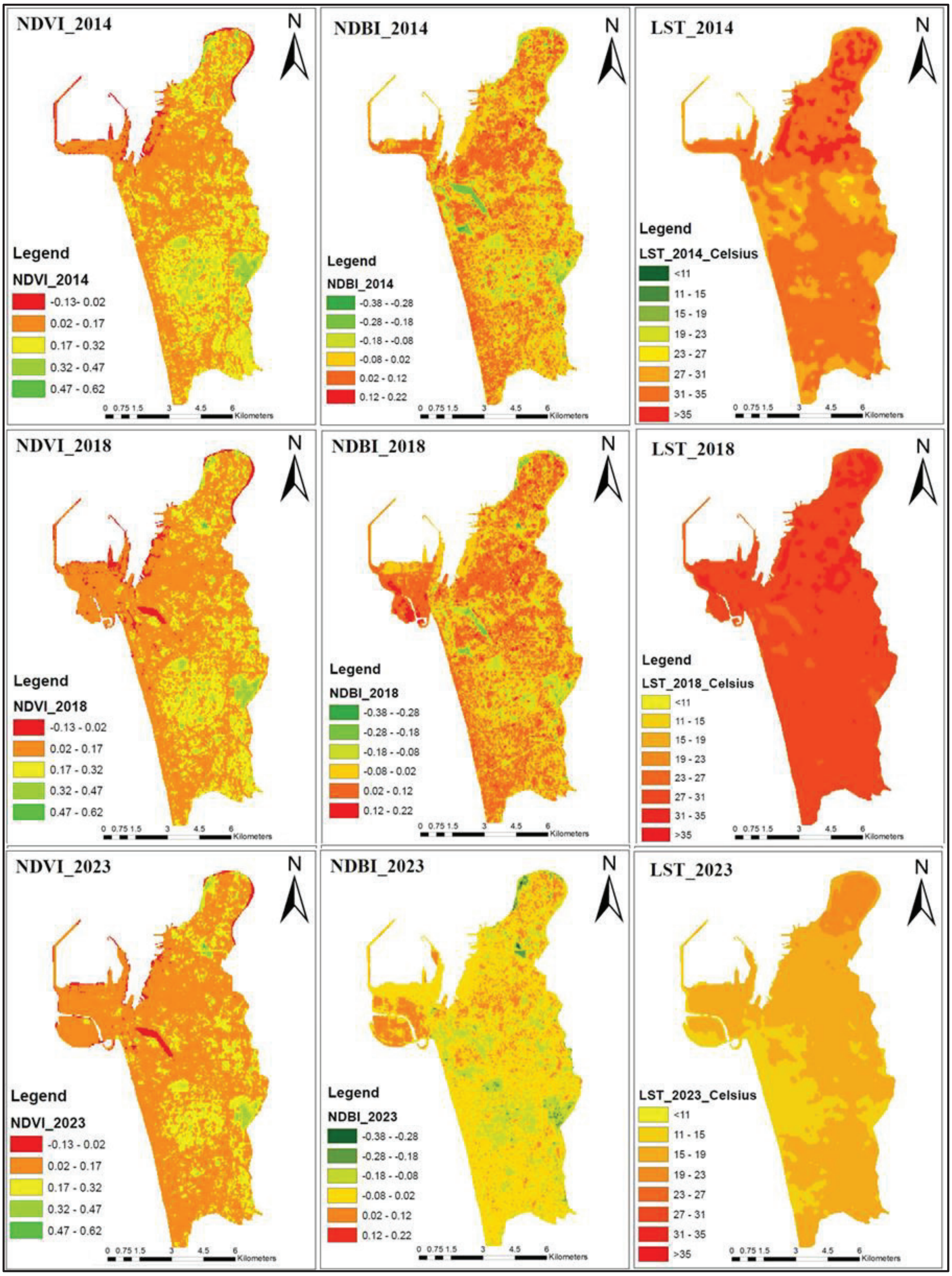

Figure 2 - NDVI, NDBI and LST Distribution Maps in 2014, 2018 and 2023

and investors move into the area and require more space. Moreover, infrastructure in Colombo area could have been improved during this period, making it more attractive for developers to build in the area. Furthermore, there were some projects implemented, for example, UDA: Urban Regeneration Programme [27] and World bank: Metro Colombo Urban Development Project [28] which led to a rapid increase in building density.

3.1.3 LST

LST distribution of this study area was done for the years 2014, 2016, 2018, 2021, 2022 and 2023.

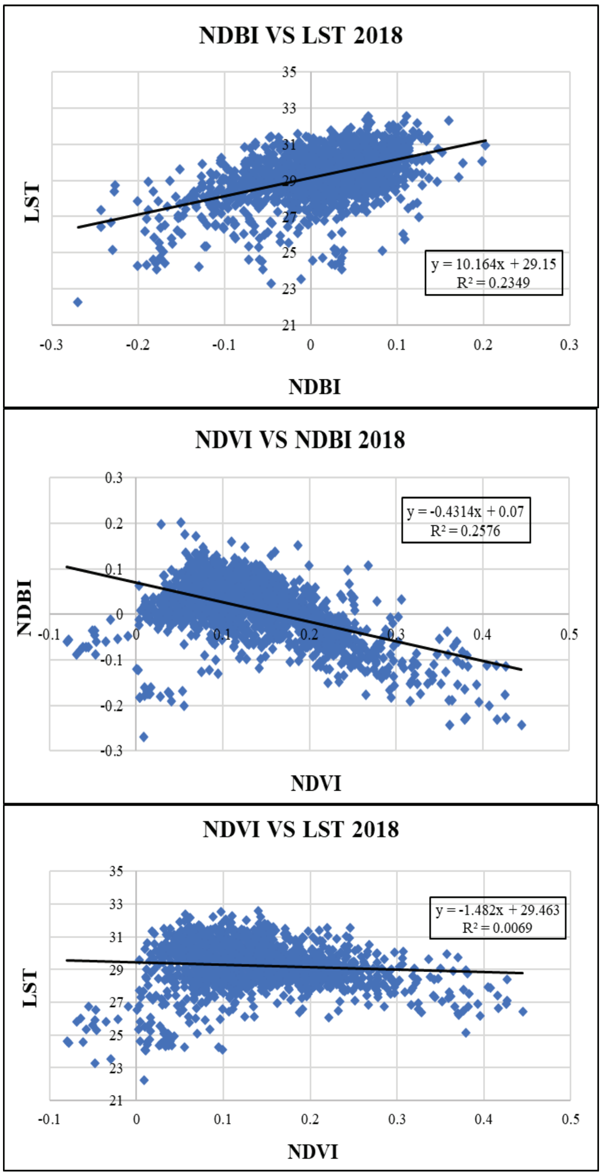

Figure 3 – Correlation between Spectral Indices - 2018

According to the results, the higher LST values can be clearly seen where NDVI and NDBI are low and high. From 2014 to 2021 the temperature ranges from 19°C to 37°C. Nevertheless, in the years 2022 and 2023, a significant temperature decrease can be clearly seen, which might be because of the Covid 19 pandemic. Most of the factories were closed during Covid-19 pandemic, and human activities were significantly reduced because the Sri Lankan government imposed quarantine curfew regulations. As a result, air pollution, heat of the environment and the surface temperature could be reduced.

Moreover, the global carbon dioxide emissions fell by an average of 17% during the peak of the pandemic-related lockdowns in 2020. This reduction in emissions could potentially lead to a short-term cooling effect on the climate [29]. This is also one of the reasons for the temperature reduction in the Colombo area.

3.1.4 Relationship between NDVI, NDBI and LST

NDBI, NDVI, and LST data were qualitatively interpreted to reveal that there exist theoretical correlations between these variables in the years of 2014, 2016, 2018, 2021, 2022 and 2023. In Figure 2 it shows those distributions in the years of 2014, 2018 and 2023. Between 2014 and 2023, the generated maps of NDVI, NDBI and LST revealed that the urbanization is highly clustered in the Colombo metropolitan area with the port city, the newly building financial city connected to Colombo metropolitan area and expanding horizontally towards the northern part of this region.

However, in the analysis between 2014 and 2023, both NDVI and NDBI maps suggested that from 2018 urbanization is highly accelerated. Additionally, by the use of a correlation matrix, quantitative evaluations were carried out for LST, NDVI, and NDBI maps (Figure 3), and according to the results in the year 2018, NDBI and LST have a moderately positive level of correlation, NDVI and LST have a moderately negative level of correlation, and additionally, NDVI and NDBI have a fairly strong negative level of correlation. The same kind of analysis was done for the remaining years, and the correlation between the spectral indices was analysed from the results NDBI and LST, NDVI and LST and, NDVI and NDBI, showing positive, negative, and negative correlations, respectively. The decreasing vegetation cover as the land use transforms into built-up areas is indicated by the substantial negative correlation between the NDBI and NDVI maps. The relationship between the NDBI values and the LST values suggest that built-up and impervious surface areas have a heating effect on surface temperature, whereas the relationship between the LST and NDVI values indicates that forests, woodlands, parks, and other urban green spaces have a cooling effect. Furthermore, a clearly weak negative correlation was found between NDVI and LST between 2014 and 2018. Even though the degrees of the correlations were not as strong, the pattern and the direction are identifiable, and in the period of 2014 to 2018, the Urbanization of Sri Lanka was significantly high. Because of this reason, buildings might be affected more by surface temperature variation rather than vegetation cover.

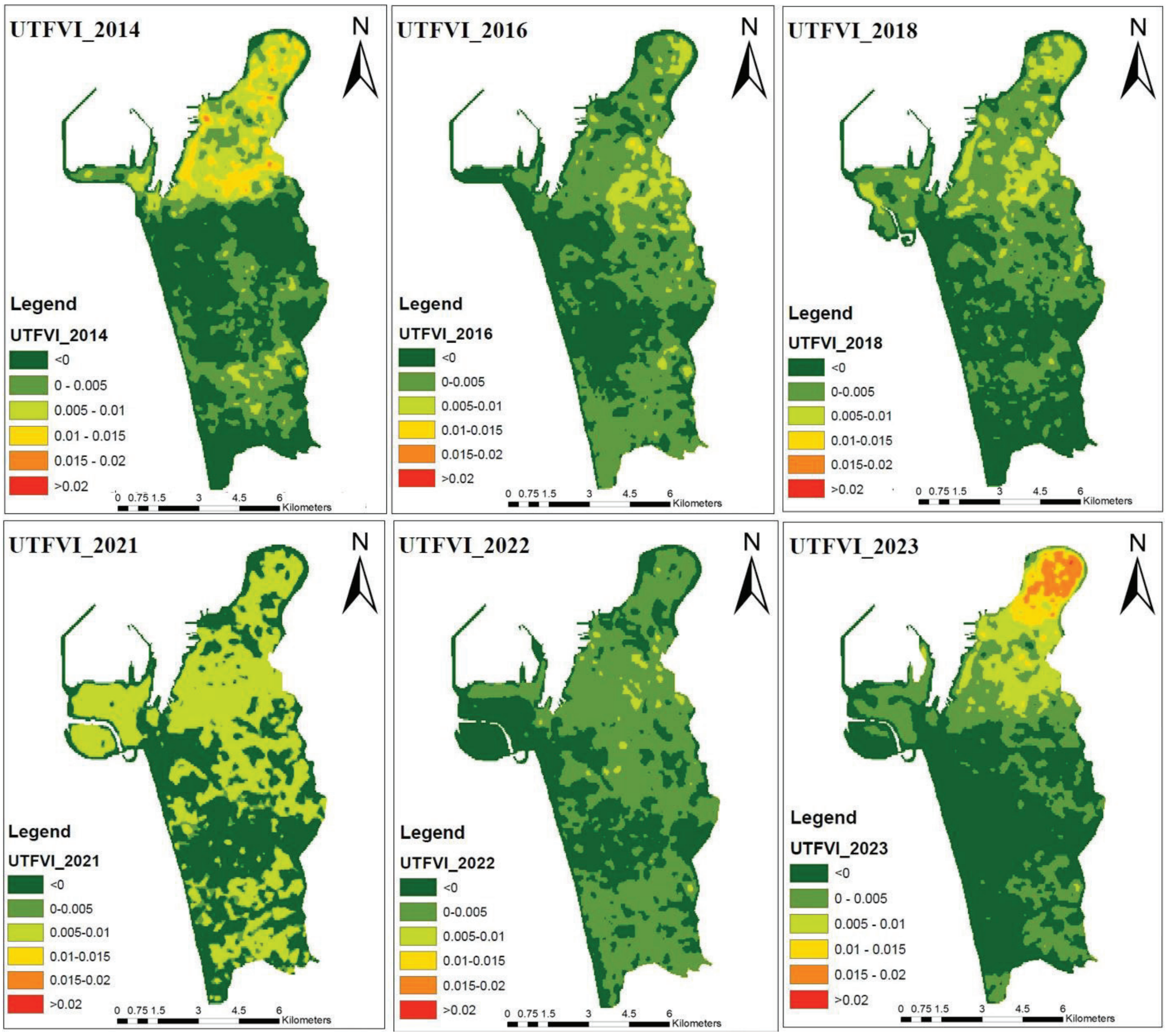

Figure 4 - UTFVI Distribution Maps from 2014 to 2023

3.2 Ecological Evaluation of Colombo

Humans specifically notice and assess their environment's greenness in terms of the quality of the air and the ambiance. Therefore, the best indicator is the pattern of the urban thermal field variance index (UTFVI) values. Figure 4 shows the calculated and mapped UTFVI values. They fall between -0.02 and 0.02. Six groups are created by reclassifying the UTFVI map according to the interpretation standard [3, 30]. Overall, Excellent and Good ecological condition regarding UTFVI ranges from surface temperatures 25°C to 32°C. Furthermore, bad ecological condition in UTFVI falls under the range from surface temperature 32°C to 35°C.

Areas with more than 35°C surface temperature fall under worse ecological conditions and undesirable thermal comfort. Based on this urban thermal comfort index (UTFVI), the ecological condition is improving in Colombo, Sri Lanka.

The area percentage of different urban thermal comfort ranges was calculated and listed in Table 3. These results clearly show that from 2014 to 2023, the bad level of ecological condition reduced to zero in 2018. The excellent condition is decreasing slowly. However, the good ecological condition has been increasing throughout the past nine years. But, from 2023 onwards, a bad trend with regards to ecological condition has gradually increased in a few places in the study area.

Table 3 illustrates how the area percentage has varied with respect to thermal comfort over the past nine years. From 2014 to 2022, there was no worst condition faced by Sri Lanka. However, in 2014, a particular area was occupied by bad and worse conditions, and the ecological condition and thermal comfort are improving yearly. The excellent and good ecological conditions are the dominating ones which occupy more than 50% of the total area each year.

Table 2 - Categorization of Thermal Comfort and Ecological Condition [31]

UTFVI	Thermal Comfort	Ecological Condition
< 0	Excellent	Excellent
0 – 0.005	Good	Good
0.005 – 0.010	Normal	Normal
0.010 – 0.015	Bad	Bad
0.015 – 0.020	Worse	Worse
> 0.020	Worst	Worst

Especially in 2021 and 2022, the ecological condition of Sri Lanka is good compared to other years, and the minimum level of comfort was at a normal level. Since most industries were shut down due to lockdown during the Covid-19 pandemic, and since UTFVI is one of the indicators of air quality, it is apparent that the air quality improved for the years 2021 and 2022. However, in 2023, the ecological condition has become somewhat undesirable, and there is a small area that is occupied by the worst ecological condition as well, and it is in the Northern part of the region. Figure 5 shows how thermal comfort and ecological condition varies over the years between 2014 and 2023. This graph clearly shows that excellent and good conditions fluctuate between those years. However, from 2014 to 2016, bad condition went to zero and continued until 2022. Additionally, after 2022, this graph shows a significant impact on each condition. Especially, bad and worse conditions have again appeared in several areas, particularly in the Northern region of the research area.

Meanwhile, areas affecting the excellent condition have also increased after 2022. This graph, however, only considered the range between excellent and bad conditions. This is due to the fact that only the worst conditions began to exist in 2023, and the area percentage is also minimal (Table 3).

4. Conclusion

This study used the advantages of Landsat-8 satellite images to assess the ecological condition and urban thermal comfort as this data can be achieved free of charge and contain all the necessary bands needed to calculate the selected spectral indices. Even though the resolution is 20 m, the generated images provided enough information for clear and detail analysis on the variation of vegetation cover, built-up area, temperature variation and comfort zone.

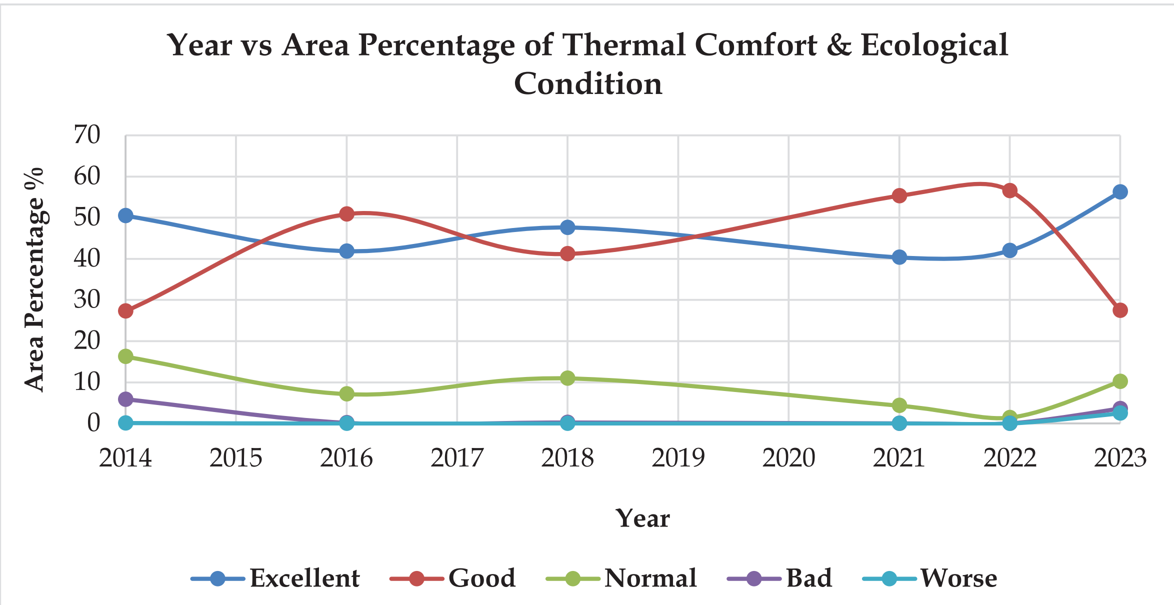

Figure 5 - Year Vs Area Percentage of Thermal Comfort and Ecological Condition

Table 3 - Area Percentage of Different Thermal Comfort Ranges

	2014	2016	2018	2021	2022	2023
Excellent	50.48	41.87	47.62	40.35	42.00	56.21
Good	27.29	50.85	41.20	55.33	56.58	27.47
Normal	16.26	7.15	10.97	4.33	1.43	10.22
Bad	5.86	0.13	0.21	0.00	0.00	3.60
Worse	0.12	0.00	0.00	0.00	0.00	2.48
Worst	0.00	0.00	0.00	0.00	0.00	0.02

Most of the industrial activities such as factory works are carried out in the Northern region of the research area and the polluted gas will be dispersed into the atmosphere due to these activities. However, during the Covid-19 pandemic, most factories were closed or limited their operations due to the lockdown. However, in 2022, these industrial activities started again gradually. Meanwhile, recently, air pollutants mainly fine particulate matters from India, reached the inland areas of Sri Lanka due to the prevailing wind pattern. Air quality is also one of the factors that affect Urban Thermal Comfort and Ecological conditions.

Therefore, air pollutants from India might also have influenced the rise of unfavourable ecological conditions in 2023. A few areas showed bad ecological conditions in Colombo area during 2014 and gradually decreased till 2016 to zero area percentage. Then it continued as zero area percentage till 2022. Recently, most of the buildings and apartments around the Colombo area adapted the green building concept and rooftop solar systems and support the increment of the areas with excellent thermal comfort and ecological conditions. Up to 2023, the study area's thermal comfort and ecological condition remain excellent and good, respectively. Nevertheless, there seems to be an increasing trend in bad to worst thermal comfort level from 2023 onwards.

A reduction in UTFVI values indicates that the thermal environment of the urban area is becoming less intense. This could have positive ecological impacts and could include a reduction in the surface temperature and heat stress in urban areas. A reduction in heat stress can lead to improved air quality, improved human comfort, and reduced energy consumption. Additionally, a reduction in heat stress can also benefit wildlife and plants in urban areas.

However, higher UTFVI values could indicate a decrease in vegetation cover in the urban area, which can negatively impact the local ecosystem because vegetation has a cooling effect on the surface temperature, as it provides shade and transpires water, which helps to regulate the temperature. A reduction in vegetation cover will result in increased surface temperature, leading to higher LST values. High LST values indicate high thermal stress, which in turn will lead to an increase in the UTFVI value. In conclusion, a reduction in vegetation cover will lead to a decrease in NDVI values and increased LST values, which will in turn lead to an increment in the UTFVI value. This increment in UTFVI value indicates a decrease in the overall thermal environment of the urban area, which could have a negative ecological condition. It is possible for Sri Lanka to have a low Urban Thermal Field Variance Index (UTFVI), but it will depend on a number of factors, including the urban design and planning, the use of materials and technologies that regulate temperature, and the overall weather patterns and climate of the region.

Urban design and planning play a crucial role in shaping the thermal environment of a city. Strategies such as increasing green spaces, using reflective materials in building construction, and creating shading can help to reduce the variability of surface temperatures and therefore contribute to a lower UTFVI. In addition, using technologies such as green roofs, cool pavements, and cooling systems can also help regulate temperature and reduce the thermal variability of the urban environment. The overall climate of Sri Lanka, including its average temperature, humidity, and wind patterns, will also play a role in determining the UTFVI. If the climate is characterized by relatively uniform and predictable temperature patterns, this can help to reduce the thermal variability of the urban environment.

In conclusion, while it is possible for Sri Lanka to have a low UTFVI, it will require a combination of factors including urban design and planning, the use of temperature-regulating materials and technologies, and favourable weather patterns and climate.

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