Analysis of Urban Heat Island Phenomenon and Its Relationships with Land Use/Land Cover Characteristics: Case Study in Bangkok Metropolitan Administration Area

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ABSTRACT

Main objective of this research is to study the urban heat island (UHI) incidence in Bangkok Metropolitan Administration (BMA) area and its relationships to land use/land cover (LULC) characteristics based on image data taken by the TM sensor onboard Landsat-5 satellite in winter dates of 1992 and 2008. The LULC components were separated into 4 main groups; (1) Urban-built-up, (2) Vegetation, (3) Bare land, (4) Water body. The obtained results indicate that intensity of the phenomenon over BMA region has significantly increased during period of the study, especially over the central districts, and only at Tambon Bang Krajao that the UHI problem was found still not too severe. It was found that great rise in the UHI intensity is contributed mostly from the rapid urban/built-up growth. However, green vegetation and vast water bodies were found to reduce severity of the phenomenon. In addition, relationships of the UHI intensity and LULC components can be expressed in form of the linear equation of land surface temperature (LST) data and the LULC indices like NDVI, NDBI, and NDBaI.

KEYWORDS: Heat Island/UHI/Urban Growth/LULC/BMA

This work indicates that, in 1992, the highest values of LST data were mostly around core area of Bangkok but in 2008 the peak values have spread outward to occupy most areas in central Bangkok and also moved across to the adjacent areas of its satellite provinces, especially Nonthaburi and Samut Prakarn. Impact of UHI on LST variation is less visible at rural area far from the central Bangkok or from the dense urban area as the dominant land classes there are vegetation and bare land, which are theoretically less vulnerable to the UHI phenomenon than the urban area. In addition, low UHI intensity is clearly seen in coastal areas along Thai Gulf in the south, that also have lowest average LST data. The LST data shown on these maps usually have peak values around 26-30^{o}C and associated peak UHI more than about 2^{o}C. The relationships of chosen LULC indices (NDVI, NDBI, NDBaI) and their associated LST data (pixel-based) were found to exhibit linear form where the correlation level is rather moderate for NDVI (negative correlation with R^2 = 0.408) but rather high (positive correlation) for the other indices with R^2 = 0.734 (NDBI), 0.670 (NDBaI).

INTRODUCTION

Urban heat island (UHI) is a well-known phenomenon being evidenced globally especially in the megacities around the world (Weng, 2001; Streutker, 2002; Hung et al., 2006; Kataoka et al., 2008). This phenomenon is characterized by noticeable increase of urban temperatures when compared to those of the surrounding rural/suburban area (as in Figure 1). As Bangkok is the famous megacity and is home to several millions of residences at present, these make it prone to having severe urban heat island phenomenon as a result. Primary cause of UHI in the cities is due to the absorption of solar radiation by building structures, roads, and other hard surfaces during daytime. Then, part of the absorbed heat is subsequently re-radiated to atmosphere in form of thermal infrared wave which can substantially increase ambient temperature in the urban area. This process keeps urban lands warmer than surrounding areas during both daytime and nighttime (IAUC, 2011).

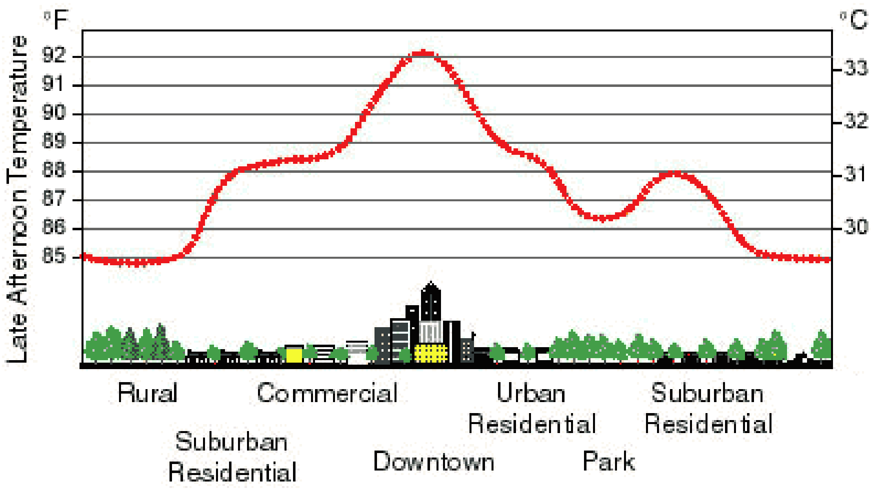


Figure 1 Typical temperature profile represents the urban heat island phenomenon.
From: http://www.eoearth.org/article/Heat_island

Intensity of the UHI phenomenon (ΔT) is usually measured by the temperature differences between urban locations and some refereed rural sites, or,

$$\text{UHI Intensity } (\Delta T) = T_{\text{urban}} - T_{\text{rural (reference)}} \quad (1)$$

In general, UHI intensities for a particular city will have distinct spatial and temporal variations depending on several factors, e.g., land use and land cover (LULC) characteristics, size, population, industrial development topography, physical layout, regional climate, and meteorological conditions. Particular meteorological conditions, including the high temperature, low cloud cover, and low average wind speed, tend to intensify the effect.

Researches on UHIs have shown that the modification of LULC in urban areas can result in the notable increase of both local air and surface temperatures. This is due to the differences in thermal properties of surface areas which are resulting from changing characters of the urban landscape. As a result, a large number of studies have been devoted to find relationships between land surface temperature (LST) and LULC characteristics such as composition of vegetation, water, and urban/built-up land and their changes, e.g., in Dousset and Gourmelon (2003), Weng et al. (2004), Chen et al. (2006), and Jasuf et al. (2007).

To reduce the UHI intensity, several mitigation techniques have been proposed, for examples, using more of white or reflective materials to build houses, pavements, and roads, and increasing more large green areas, such as parks or pacts of large trees, within city area. Urban trees and green areas can reduce UHI impact in two different aspects. First, they reduce air temperature and increases humidity from the evapotranspiration in vegetation foliage where heat in surrounding environment is converted to latent heat thereby lowering neighborhood temperature. And, second, they provide more shaded surfaces to the cities. The solar radiation intensity in the trees' shade could be reduced by up to 10-50% under crowd of the dense trees (Avissar 1996; Georgi and Zafiriadis 2006).

In this research, characteristics of UHI phenomenon in the Bangkok Metropolitan Administration (BMA) area was investigated. The study area covers about 5593.332 km^2 in five provinces: Bangkok, Nonthaburi, Samut Sakhon, Pathum Thani, and Samut Prakan Provinces (Figure 2).

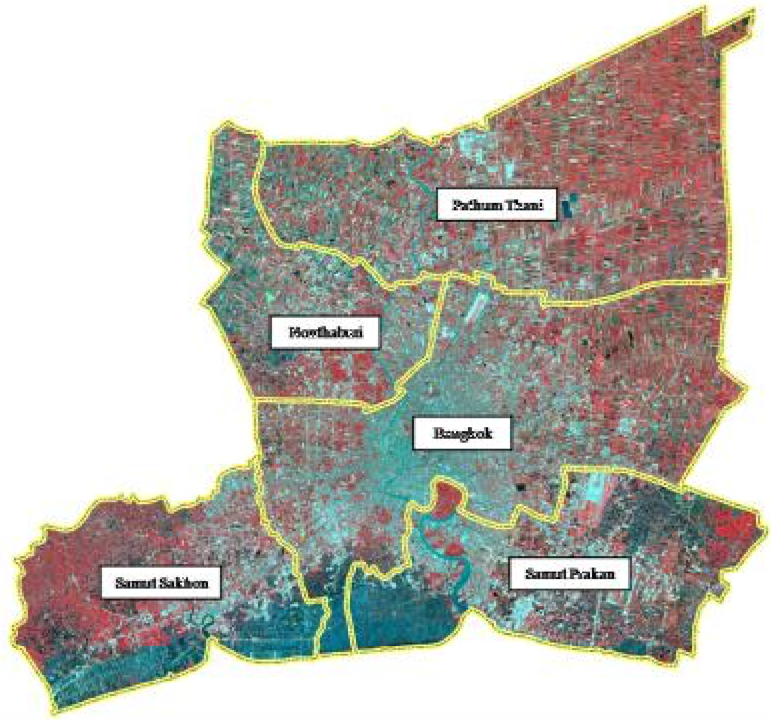


Figure 2: Map of the study area (five provinces within the BMA region).

RESEARCH METHODOLOGY

There are three main steps that were fulfilled in this research:

1. Production of the LST map from the Landsat-TM (TIR band);
2. Evaluation of the LULC and UHI characteristics in years 1992 and 2008;
3. Determination of the relations between UHI intensity and LULC indices (NDVI, NDBI, NDBaI).

In the first step, the LST maps for the selected dates (in 1992 and 2008) were produced from Landsat TM thermal images (band 6) based on the following formula (pixel-based calculation):

$$L_0 = \frac{(L_{max} - L_{min})}{255} xDN + L_{min} \tag{2}$$

$$T_B = \frac{k_2}{\ln\left(\frac{k_1}{L_0} + 1\right)} \tag{3}$$

where, L_0 is the sensor's observed radiance, DN is the digital number of the observed pixel, L_{min} and L_{max} are spectral radiance of the used thermal band at DN = 0 and 255 respectively. T_B is derived LST in Kelvin unit, k_1 and k_2 are the pre-launch calibration constants of sensors. For Landsat-5, k_1= 607.76 W/(m^2.sr.µm) and k_2= 1250.56 K (Rong-bo et al., 2007, Yuan and Bauer 2007). The gained LST data from Eq. 3 were then compared with the actual observed data of the same time period to find their relation. This gained relation was then used to produce the new LST maps that have higher correlation to the actual observed data.

In the second step; the LULC and UHI maps in years 1992 and 2008 were made (based on Eq.1) using the gained LST maps in Step 1. Here, the reference temperatures were ones obtained at the Sukhothai Thammathirat University station (in rural area) for each chosen year, which are 22.58^{o}C (1992) and 23.45^{o}C (2008).

In the third step; relation of UHI intensity and three LULC indices: NDVI, NDBI, NDBaI, were assessed. Definitions of these indices are as follows:

$$NDVI = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red}} \quad (4)$$

$$NDBI = \frac{R_{MIR} - R_{NIR}}{R_{MIR} + R_{NIR}} \quad (5)$$

$$NDBaI = \frac{R_{MIR} - R_{TIR}}{R_{MIR} + R_{TIR}} \quad (6)$$

where R_{NIR}, R_{red}, R_{MIR} and R_{TIR} are DN values in NIR, Red, MIR and TIR bands of the Landsat TM sensor, respectively. NDVI values range between -1 to 1 where larger positive values indicate higher vegetation cover. Definition of the "normalized difference built-up index" (NDBI) and "normalized difference bareness index" (NDBaI) are from Chen et al. (2006). Their values are between -1 to 1 (like NDVI) and they were used to quantify amount of the impervious surface and bare land on the used TM image, respectively.

RESULTS AND DISCUSSION

In Step 1, relation of the reference ground-based LST data along with their associated satellite-based LST data was obtained from about 159 pairs of these temperature data that were grouped and calculated at ranging step of 1^{o}C each (e.g., at 20-21^{o}C, 21-22^{o}C, 22-23^{o}C, etc.). These pairs of the average values (for each defined LST step value) were then plotted against each other to identify the existing relationships and results are reported in Figures 3. The result indicates strong linear relationship between average ground-based temperature and its average satellite-based counterpart at the correlation coefficient (R^2) of 0.8355.

The found relationship is expressed by:

$$\text{TM case:} \quad T_G = 1.4238\ T_S + 10.53 \quad (7)$$

where T_G and T_S are the average ground-based and satellite-based LST, respectively. This relation was assumed to valid for normal LST range of interest (at 20-35^{o}C). The known relation described by Eq.7 was then used as 7tool for the construction of equivalent LST ground-based LST map from the original satellite-based LST map

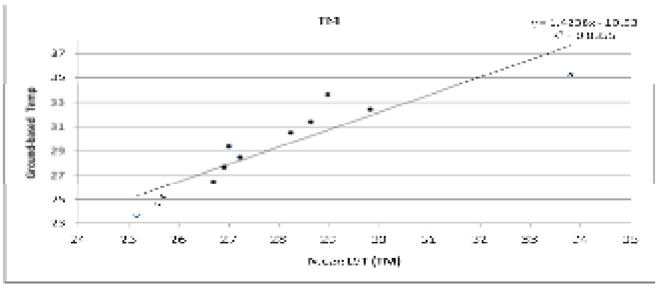
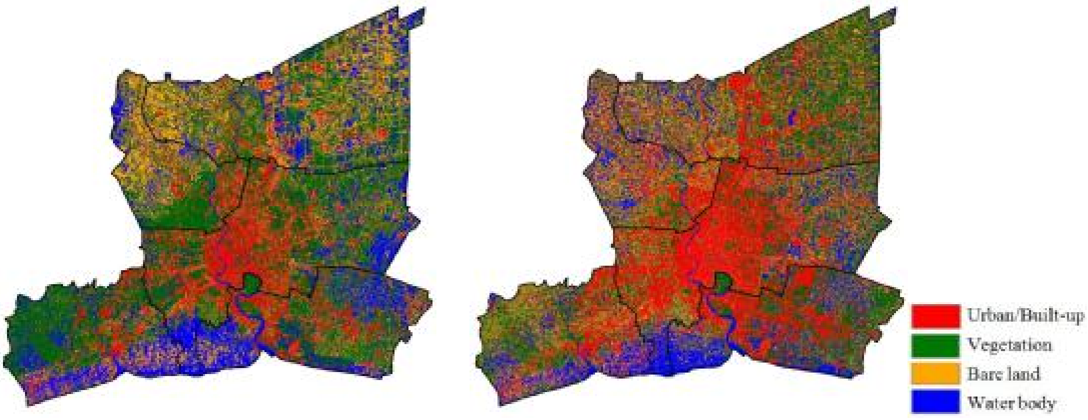


Figure 3: Relation of average ground-based and satellite-based LST data (TM case).

In Step 2, the LULC maps for years 1992 and 2008 were generated from Landsat TM images and results are shown in Figure 4 with overall accuracy of 84.55% with Kappa index of 0.7902 (for 2008 map). There are four main components presented on these maps: (1) urban/built-up (U/B), (2) vegetation (VEG), (3) bare land (BARE), and (4) water body (WAT). The UHI maps in years 1992 and 2008 were also made based on Eq.1 and the gained LST maps in Step 1 and results are shown in Figures 5a and 5b and Table 1, respectively.



(a) 1992 (b) 2008

Figure 4: Classified BMA LULC maps of 1992 and 2008.

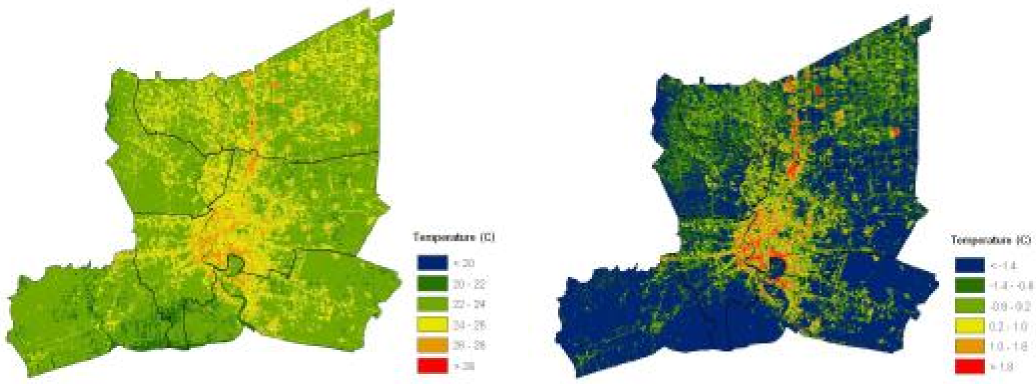


Figure 5a: LST and UHI maps in 1992 (20/11/1992).

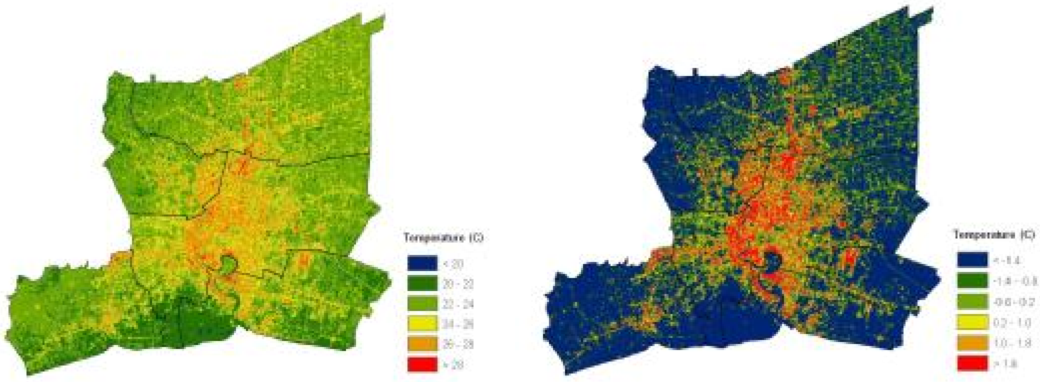


Figure 5b: LST and UHI maps in 2008 (02/12/2008).]

Figures 5a and 5b indicate that, in 1992, the highest values of LST data were found mostly around core area of Bangkok but in 2008 the peak values have spread outward to occupy most areas in central Bangkok and also moved across to the adjacent areas of its satellite provinces, especially Nonthaburi and Samut Prakarn. And when compared these LST maps to their corresponding LULC maps in Figure 4, it was found that the most intense UHI phenomenon occur at core urban area of central Bangkok (like the LST). Impact of UHI on LST variation is less visible at rural area far from the central Bangkok or from the dense urban area as the dominant land classes there are vegetation and bare land, which are theoretically less vulnerable to the UHI phenomenon than the urban area. In addition, low UHI intensity is clearly seen in coastal areas along Thai Gulf in the south, that also have lowest average LST data (due to effect of large water body at sea). The LST data shown on these maps usually have peak values around 26-30^{o}C and associated peak UHI more than about 2^{o}C.

From Table 1, it was found that most area in 1992 (about 70.16%) has the LST of between 22-24^{o}C while about 21.58% has LST between 24-26^{o}C. But in 2008, these numbers have changed to become 53.74% and 19.19% respectively. If consider only for those areas with LST higher than 26^{o}C, the numbers are 3.32% (in 1992) and 10.77% (in 2008), respectively. This result indicates the notable increase in number of the relatively high LST area which might lead to the more severe UHI situation over the BMA region as a consequence. This fact is obviously demonstrated in data of areas with different classes of UHI intensities. It was found that, in 1992, areas with ΔT higher than 0^{o}C are at 9.66% of the total area but, in 2008, this number rises to 19.3%. The very interesting result is that area with $\Delta T > 2.1^{o}$C covers about 0.7% only in 1992 but it has expanded to become 3% in 2008 which indicate great rise in areas with high UHI intensity over BMA region. These areas should be of great concerned if the trend of UHI intensification is still continuing without any mitigation plan implemented by the government or local agencies. As a result from the study, the only area that the UHI problem was found still not too severe is Tambon Bang Krajao.

Table 1: Classification of LST and UHI maps (area in %) in 1992 and 2008.

Year	LST Class (in ^{o}C)							Total
	< 20	20-22	22-24	24-26	26-28	28-30	> 30	
1992	0.03	4.91	70.16	21.58	3.26	0.06	0	100
2008	0.48	15.82	53.74	19.19	9.72	1.02	0.03	100
Year	**UHI Class (in ^{o}C)**							**Total**
	< (-1.4)	(-1.4)-(-0.7)	(-0.7) - 0	0-0.7	0.7-1.4	1.4-2.1	> 2.1	
1992	51.89	23.2	15.25	3.87	4.14	0.95	0.7	100
2008	50.91	19.13	10.66	4.55	7.27	4.48	3	100

In Step 3, The relationships of each LULC index mentioned earlier and their associated LST data (pixel-based) were evaluated and their results are reported Table 2 exhibits relationships between known LST data and their associated LULC indices (pixel-based) in 2008. It was found that trends of the relationship between each LULC index and the LST data were clearly seen (positive or negative correlation). However, the correlation level is rather moderate for the NDVI (negative correlation with R^2 = 0.408) but rather high (positive correlation) for the other indices with R^2 = 0.734 (NDBI), 0.670 (NDBaI).

Table 2: Linear relationships of NDVI, NDBI, NDBaI and LST.

Index pair		Linear relationship formula	Correlation coefficient (R^2)
X	Y		
NDVI	LST	Y = -5.8186x + 26.149	0.4080
NDBI	LST	Y = 8.0277X + 22.795	0.7342
NDBaI	LST	Y = 7.1832X + 25.519	0.6704

CONCLUSIONS

This work indicates that, in 1992, the highest values of LST data were mostly around core area of Bangkok but in 2008 the peak values have spread outward to occupy most areas in central Bangkok and also moved across to the adjacent areas of its satellite provinces, especially Nonthaburi and Samut Prakarn. Impact of UHI on LST variation is less visible at rural area far from the central Bangkok or from the dense urban area as the dominant land classes there are vegetation and bare land, which are theoretically less vulnerable to the UHI phenomenon than the urban area. In addition, low UHI intensity is clearly seen in coastal areas along Thai Gulf in the south, that also have lowest average LST data. The LST data shown on these maps usually have peak values around 26-30^{o}C and associated peak UHI more than about 2^{o}C. The relationships of chosen LULC indices (NDVI, NDBI, NDBaI) and their associated LST data (pixel-based) were found to exhibit linear form where the correlation level is rather moderate for NDVI (negative correlation with $R^2 = 0.408$) but rather high (positive correlation) for the other indices with $R^2 = 0.734$ (NDBI), 0.670 (NDBaI).

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