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URBAN HEAT ISLAND PHENOMENON IN RELATION TO LAND USE/LAND COVER IN BANGKOK METROPOLITAN ADMINISTRATION AREA

ปรากฏการณ์เกาะความร้อนเขตเมืองกับความสัมพันธ์กับลักษณะการใช้ประโยชน์ที่ดินและสิ่งปกคลุมดินในเขตกรุงเทพมหานคร

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Abstract

The urban heat island (UHI) phenomenon can be found in the megacities around the world where near-surface temperatures over the city core area were notably higher than those over the surrounding rural area. Intensity of the UHI phenomenon (ΔT) was usually measured by the temperature differences between urban locations and some refereed rural sites. This situation was resulted mainly from the presence of dense built-up elements, e.g. commercial buildings or houses, as well as human activities that tended to release considerable heat into atmosphere. At present, the UHI monitoring can be done efficiently by using satellite-based thermal infrared (TIR) image.

Main objective of this research was to examine UHI incidence in Bangkok Metropolitan Administration (BMA) area and its relationships with land use/land cover (LULC) characteristics based on image data taken by the Thematic Mapper (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 and (4) water body. The obtained results indicated that intensity of the phenomenon over BMA region had significantly increased during period of the study, especially over the central districts, but 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 was contributed mostly from the rapid urban/built-up growth in the area. 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 satellite-based observed

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land surface temperature (LST) data and the LULC indices like normalized difference vegetation index (NDVI), normalized difference built-up index (NDBI), and normalized difference bareness index (NDBaI).

Keywords: heat island, UHI, urban growth, LULC, BMA

บทคัดย่อ

ปรากฏการณ์เกาะความร้อนเขตเมือง (UHI) สามารถพบได้ในเขตเมืองมหานครทั่วโลก ซึ่งมีอุณหภูมิของอากาศระดับใกล้ผิวดินในเขตเมืองชั้นในสูงกว่าในเขตชนบทรอบเขตเมืองอย่างเห็นได้ชัด โดยระดับความรุนแรงของเหตุการณ์โดยปกติจะคำนวณจากระดับอุณหภูมิที่แตกต่างกันระหว่างค่าที่ปรากฏในพื้นที่เขตเมืองและที่ปรากฏในเขตชนบทซึ่งใช้เป็นจุดอ้างอิง สำหรับสาเหตุสำคัญของการเกิดเหตุการณ์นี้คือปริมาณความหนาแน่นของอาคารสิ่งก่อสร้างในเขตเมือง เช่น อาคารพาณิชย์หรือบ้านที่พักอาศัยรวมถึงกิจกรรมต่าง ๆ ของมนุษย์ซึ่งมีแนวโน้มที่จะปลดปล่อยความร้อนเป็นจำนวนมากขึ้นสู่ชั้นบรรยากาศ ทั้งนี้ในปัจจุบันการตรวจสอบปรากฏการณ์ดังกล่าวสามารถทำได้อย่างมีประสิทธิภาพโดยการใช้ภาพถ่ายดาวเทียมช่วงคลื่นความร้อนอินฟราเรด (TIR)

วัตถุประสงค์หลักของงานวิจัยนี้คือการตรวจสอบปรากฏการณ์เกาะความร้อนเขตเมือง ในเขตพื้นที่กรุงเทพมหานครและปริมณฑล (BMA) และความสัมพันธ์ที่มีกับรูปแบบการใช้ประโยชน์ที่ดินและสิ่งปกคลุมดิน (LULC) โดยใช้ภาพถ่ายจากเครื่อง TM ซึ่งประจำการอยู่บนดาวเทียม Landsat-5 ในช่วงฤดูหนาวระหว่างปี พ.ศ. 2535-2551 โดยรูปแบบของการใช้ประโยชน์ที่ดินและสิ่งปกคลุมดินจะแยกออกเป็น 4 กลุ่มหลัก คือ (1) เมือง/ชุมชน (2) พืชพรรณ (3) ที่โล่ง (4) แหล่งน้ำผิวดิน ซึ่งผลที่ได้จากการศึกษาบ่งชี้ว่าระดับความรุนแรงของปรากฏการณ์เกาะความร้อนเขตเมืองมีค่าเพิ่มขึ้นอย่างมีนัยสำคัญระหว่างช่วงเวลาที่ศึกษา โดยเฉพาะในเขตศูนย์กลางเมือง ยกเว้นที่ตำบลบางกระเจ้าซึ่งปรากฏการณ์ดังกล่าวยังมีความรุนแรงอยู่ในระดับต่ำ โดยปัจจัยหลักที่ทำให้เกิดภาวะการณ์ดังกล่าวคือการเพิ่มขึ้นของพื้นที่เมืองและชุมชนเป็นอย่างมากในพื้นที่ศึกษา แต่พืชพรรณและแหล่งน้ำจะเป็นปัจจัยที่ช่วยบรรเทาปัญหาดังกล่าวลงได้ นอกจากนั้นยังได้พบว่าความสัมพันธ์ของระดับความรุนแรงของเหตุการณ์และองค์ประกอบของรูปแบบการใช้ประโยชน์ที่ดินและสิ่งปกคลุมดิน สามารถอธิบายได้โดยใช้สมการเชิงเส้นระหว่างค่าอุณหภูมิผิวดิน (LST) และดัชนี LULC ต่อไปนี้คือดัชนีพืชพรรณ (NDVI) ดัชนีพื้นที่เขตเมือง (NDBI) และดัชนีพื้นที่โล่ง (NDBaI)

คำสำคัญ: เกาะความร้อน, ปรากฏการณ์เกาะความร้อนเขตเมือง, การเติบโตของเมือง, รูปแบบการใช้ประโยชน์ที่ดินและสิ่งปกคลุมดิน, กรุงเทพมหานครและปริมณฑล

Introduction

UHI is a well-known phenomenon which has been evidenced globally, especially in megacities around the world(1-4). This phenomenon is characterized by noticeable increase of urban temperatures compared to those of the surrounding rural or suburban area (see in Figure 1). As Bangkok is the famous megacity and home to several millions of residences at present, these make it prone to having severe urban heat island phenomenon as a result. This study is therefore to examine relationship between observed LST data (and UHI intensity) in the BMA area and LULC components during years 1992 to 2008.

Material and method

The study area resides within Bangkok Metropolitan Administration (BMA) area covering 5593.332 km^2 in five provinces: Bangkok, Nonthaburi, Samut Sakhon, Pathum Thani, and Samut Prakan (Figure 2 and Table 1).

Temperature data were acquired from several sources, LST derived from Landsat-TM instruments, recorded temperature data near ground air from Thai Meteorological Department and Pollution Control Department.

Period of the satellite-based LST analysis covers 16 years from 1992 to 2008.

LULC data were broadly divided into 4 main categories: (1) urban/built-up, (2) vegetation, (3) bare land, and (4) water body.

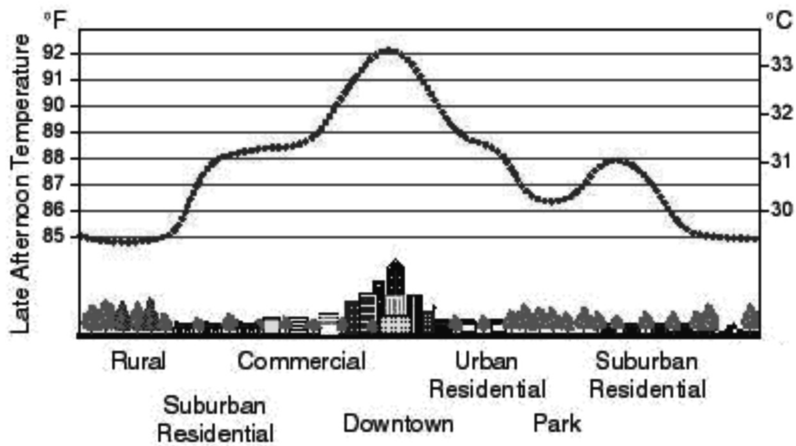

Figure 1 Typical temperature profile represents the urban heat island phenomenon. (http://www.eoearth.org/article/Heat_island)

Table 1 General data for the BMA region.

Official name		Province code	Area (km^2)	Population (2009)	Population density (per km^2)	Number of districts
English	Thai					
Bangkok	กรุงเทพมหานคร	BKK	1,568.74	5,702,595	3,635.15	50
Nakhon Pathom	นครปฐม	NPT	2,168.33	851,426	392.66	7
Nonthaburi	นนทบุรี	NBR	622.30	1,078,071	1,732.39	6
Pathum Thani	ปทุมธานี	PTN	1,525.86	956,376	626.78	7
Samut Prakan	สมุทรปราการ	SPK	1,004.09	1,164,105	1,159.36	6
Samut Sakhon	สมุทรสาคร	SSK	872.35	484,606	555.52	3
Total			**7,761.67**	**10,237,179**	**1,318.94**	**79**

Urban Heat Island Characteristics

The phenomenon is evidenced by a notable increase of the ur ban temperatures compared to temperatures of the surrounding rural or suburban area (Figure 2). 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 the atmosphere in form of the thermal infrared wave which can substantially increase ambient temperature in the area. This process keeps urban lands warmer than surrounding areas during both daytime and nighttime [5].

Intensity of the UHI phenomenon (ΔT) is usually measured by the temperature differences between urban locations and some refereed rural sites (Equation 1).

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

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

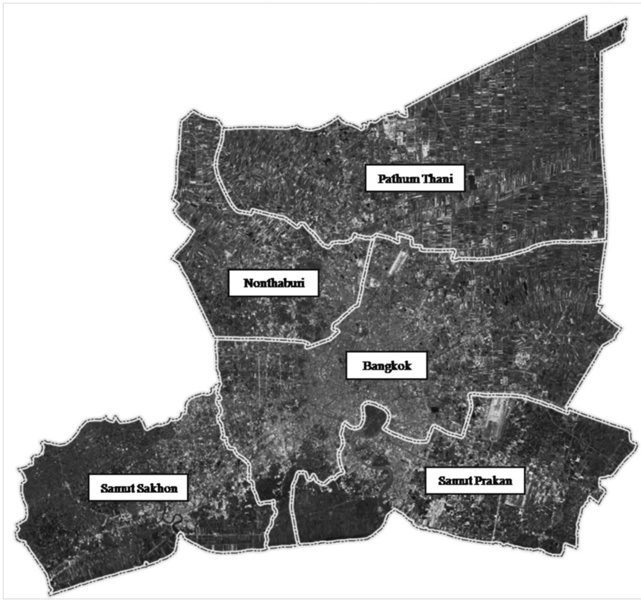

Figure 2 The study area (five provinces within the BMA region).

Conceptual Framework

The analysis was based on LST and LULC maps for 1992 and 2008 produced from the Landsat TM imagery. The prior assumptions of this work are that the UHI phenomenon should be more intensified as urban/built-up area expanding with time and its existences can be effectively observed by the satellite images in use and the relevant ground-based measurements. There are four main LULC categories being identified in the classified LULC maps, which are (1) urban/built-up, (2) vegetation, (3) bare land, and (4) water body.

Table 2 Essential data required in the research.

Data category	Data type/ origin	Scale/format	Source	Date/year
Satellite Imagery	Landsat TM	25x25m	GISTDA	20/11/1992(09:58:43 AM) 02/12/2008 (10:21:35 AM)
Temperature data	Landsat TIR	120x120m	GISTDA	As listed above
	Ground-based	Point map	TMD, PCD	1996-2009
LULC data	TM	25x25m	GISTDA	As listed above

Note: GISTDA = Geo-Informatics and Space Technology Development Agency,
TMD = Thai Meteorological Department, PCD = Pollution Control Department

Methodology

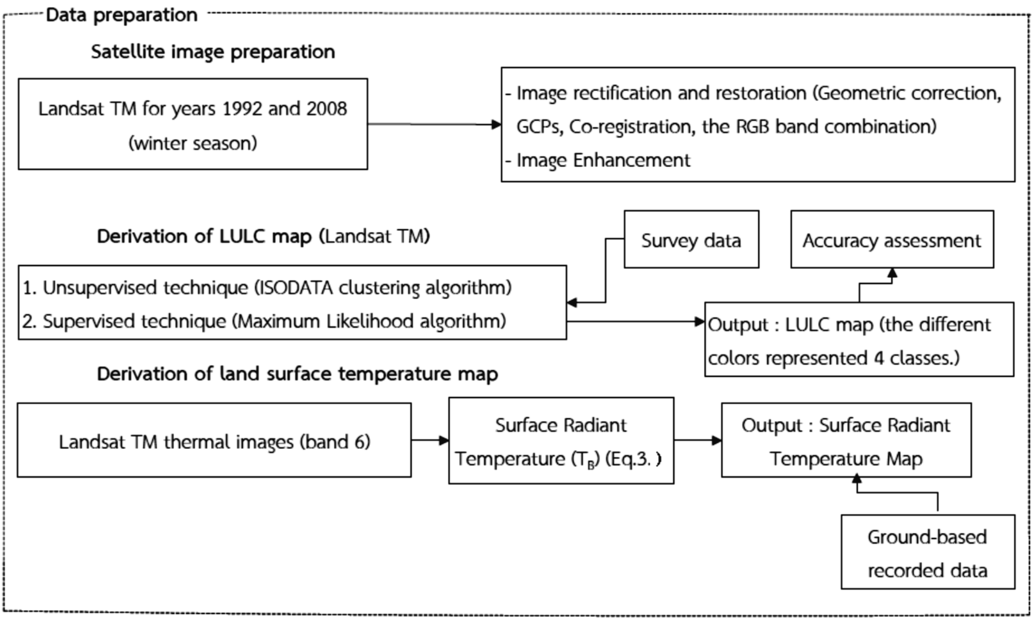

Figure 3 Data preparation.

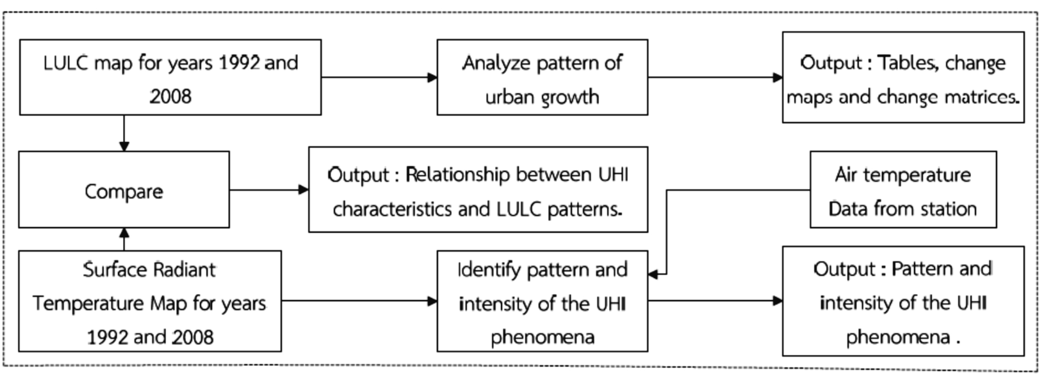

Figure 4 Relationship between UHI characteristics and LULC patterns.

The LST maps were generated from Landsat TM thermal images (band 6) based on Equations 2-3 formula (pixel-based calculation):

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

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

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 TM, k_1 = 607.76 W/(m^2.sr.μm) and k_2 = 1250.56 K [6-7].

Results

1. Relationships between ground-based and satellite-based temperature data

As discussed earlier, the preferred LST maps for further UHI analysis are the equivalent ground-based LST maps generated based on knowledge of the relationship between original satellite-based LST and their associated ground-based temperatures. These relationships were determined for the TM case only as it is most crucial to our research and both temperature data set are appropriate to be compared with each other.

The first step was acquiring reference ground-based LST data along with their corresponding LST data that were obtained from the satellite-based LST maps. Using data during the year 1992 to 2008, about 159 pairs of these temperature data were accumulated and then rearranged in order of ground-based LST values from minimum to maximum. Then, average values of these ground-based LST and their associated satellite-based data were calculated at ranging step of 1°C each (e.g., at 20-21°C, 21-22°C, 22-23°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 Figure 5. The plotting 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 in Equation 4:

$$\text{TM case: } T_G = 1.4238\, T_S + 10.53 \quad (4)$$

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°C).

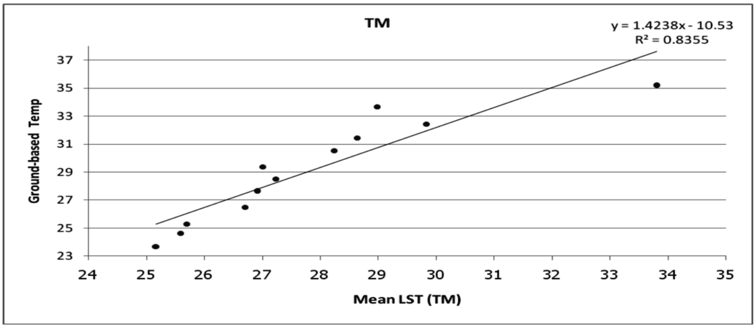

Figure 5 Relation of average ground-based and satellite-based LST data (TM case).

The known relation described by Equation 4. was then used as essential tool for the construction of equivalent LST ground-based LST map from the original satellite-based LST map.

Table 3 Values of TG and TS pair (in °C) used in Figure 5

T_G	23.67	24.63	25.29	26.49	27.66	28.49	29.37	30.52	31.42	32.43	33.65	35.21
T_S	25.15	25.58	25.69	26.70	26.91	27.23	27.00	28.23	28.63	29.82	28.97	33.80

Note: T_G = Average ground-based temperature data (data during 1992 to 2008.)
T_S = Average satellite-based LST data (data during 1992 to 2008.)

2. Urban growth and LULC changing pattern

To quantify pattern or rate of urban growth effectively, the temporal LULC maps of the area (with urban/built-up as a main LULC component) must be synthesized first. This was accomplished by generating classified LULC maps during 1992 - 2008 of BMA region based on Landsat TM. 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) (Figure 6). Accuracy assessment of the obtained 2008 classified LULC map was computed based on 440 stratified sampling points. This number is derived from the multinomial distribution theory with a level of confidence of 90% and a precision of 5%. In this case, the overall accuracy of 84.55% with Kappa index of 0.7902 were achieved indicating satisfied result of the gained LULC map for further use, especially the fairly high accuracy of the urban/built-up class.

Figure 6 Classified BMA LULC maps of 1992 - 2008

Table 4 Proportion of LULC components in 1992 and 2008.

LULC Class	1992		2008	
	km^2	%	km^2	%
U/B	806.38	14.49	1552.14	27.88
VEG	2352.96	42.27	1811.94	32.55
BARE	1315.93	23.64	1310.73	23.55
WAT	1091.15	19.60	891.59	16.02
Cloud	0.00	0.00	0.00	0.00
Total	5566.4	100	5566.4	100

Table 5 Periodic change rates (gain/loss) of LULC components during 1992-2008.

Period	Class	U/B	VEG	BARE	WAT
1992-2008	km^2(total)	745.77	-541.01	-5.20	-199.56
	% (total)	92.48	-22.99	-0.40	-18.29
	km^2(annual)	46.61	-33.81	-0.32	-12.47
	% (annual)	5.78	-1.44	-0.025	-1.14

Note: $\%\,(\text{total}) = \dfrac{\text{Year2} - \text{Year1}}{\text{Year1}}\text{x}100; \%\,(\text{annual}) = \dfrac{\%(\text{total})}{\text{Number of years}}$

From the LULC maps depicted in Figure 6 and their associated descriptive data provided in Tables 4 and 5, it can be primarily concluded that, among all the known LULC classes, the vegetation cover has highest proportion of occupying area for all years of interest followed by the bare land and water body, or urban/built-up, classes respectively. However, percentages in area cover of vegetation have dropped continuously, in general, from 42.27% in 1992 to 32.55% in 2008 (about 23% decrease from its original area in 1992). But, during the same period, urban/built-up area has substantially expanded from about 14.49% in 1992 to 27.88% in 2008 (about 92.5% increase from the original area in 1992). No obvious changing trends appear for water body and bare land classes during period of the study.

3. Intensification of the UHI phenomenon

The LST maps of 1992 and 2008 were derived from Landsat TIR imagery, based on Equations 2 - 3., along with their UHI intensity maps and results are presented in Figures 7 - 8. The calculation of UHI intensity was done based on the definition given in Equation 1. The reference rural data were taken from the Sukhothai Thammathirat University station for each chosen year due to their relatively colder environment when compared to the warmer urban atmosphere in the BMA inner area. The reference data for each year are as follows: 22.58 ^{o}C (1992), 25.5 ^{o}C (1996), 21.71 ^{o}C (2000), 24.74 ^{o}C (2004), 23.45 ^{o}C (2008).

Figure 7 shows 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 maps to their corresponding LULC maps in Figure 6. 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 the rural area far from the central Bangkok or from the dense urban area as the dominant land classes 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 the 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.

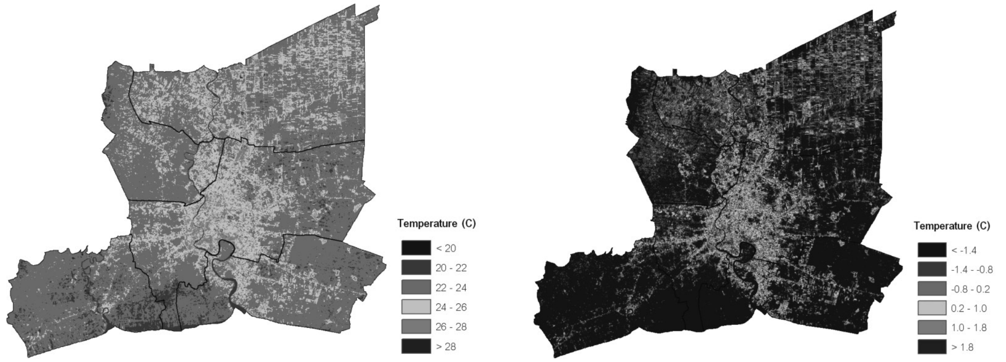

Figure 7 LST and UHI maps in 1992 (20/11/1992)

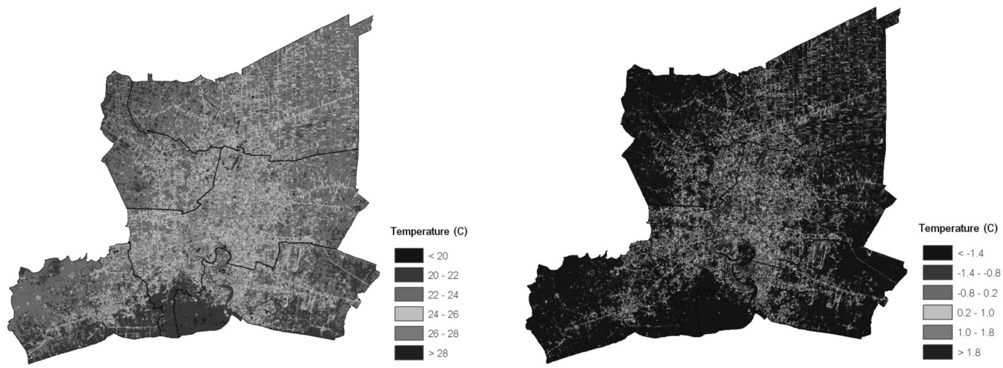

Figure 8 LST and UHI maps in 2008 (02/12/2008)

Table 6 Area coverage of LST and UHI classes (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

From Table 6, 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 of responsible local agencies. Note that the observed scales of UHI intensity here are mostly less than approximately 2 ^{o}C which are similar to those results found in several researches, e.g., Weng et al.[8] and Weng and Lu[9] at Indianapolis, Indiana State, US; Memon and Leung [10] at Hong Kong, China; and Hu and Jia [11] at greater Guangzhou , China.

4. Relationships of LST and LULC indices

The relationships of each LULC index mentioned earlier and their associated LST data (pixel-based) were evaluated and their results are reported in Table 7 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) and 0.670 (NDBaI). The explicit relations in term of the linear regression formula are described in Table 7 The low to moderate correlation between NDVI and LST was also found in other studies, e.g., Hu and Jia [11] with R^2 = 0.6145; Yuan and Bauer[7] with $R^2 < 0.1$; and Srivanit et al.[12] with $R^2 < 0.56$. This makes the NDVI less favorable as an indicator to measure UHI variation than some other urban-related indices like NDBI which is found to have more consistence output with relatively high correlation level all year round [13-15].

Table 7 Linear relationships of NDVI, NDBI, NDBaI and LST.

Index pair X	Index pair Y	Linear relationship formula	Correlation coefficient (R^2)
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

1. Urban growth and its impact on UHI phenomenon

From data of the derived LULC maps, it can be primarily concluded that, among all known LULC classes, the vegetation cover is the highest proportion of occupying area for all years of interest followed by bare land and water body, or urban/built-up, classes respectively. However, percentages of vegetation have dropped continuously, in general, from 42.27% in 1992 to 32.55% in 2008 (about 23% decrease from its original area in 1992). But, during the same period, urban/built-up area has substantially expanded from about 14.49% in 1992 to 27.88% in 2008 (about 92.5% increases from the original area in 1992).

The expansion of urban/built-up area (at about 46.61 km^2 per year) occurs mostly along major roads traversing from central Bangkok to its satellite cities nearby and within Bangkok outskirt in most directions. Mixed classes of vegetation, bare-land, and inland water body usually signify agricultural zone (paddy fields in particular) surrounding the more developed urban/built-up space.

In term of the changing pattern between 1992-2008, out of about 1552.15 km^2 found of urban/built-up area in 2008, just only 518.19 km^2 existing in 1992 while the rest was converted from the other LULC classes, which are, vegetation (530.91 km^2), bare land (350.63 km^2) and water body (152.22 km^2). The transformations of original urban/built-up land to other LULC classes were also observed, especially to the vegetation (138.82 km^2) and bare land (115.94 km^2). These usually occur at remote areas far from city centers.

The gained LST maps during 1992-2008 indicate that, in 1992, the warmest zone were found mostly around central area of Bangkok but in 2008 peak. LST values have spread outward to occupy most areas in central Bangkok and across to the adjacent areas of its satellite provinces, especially Nonthaburi and Samut Prakarn also. The most intense UHI intensity occurs at core urban area of central Bangkok (like case of LST). Impact of UHI on LST variation is less visible at the rural area far from the central Bangkok as the dominant land classes are vegetation and bare land, which are less vulnerable to the UHI phenomenon than the urban area.

Proportions in area cover for the LST and UHI classes indicates dramatic increase in severity of UHI phenomenon during period 1992-2008. Most severity areas are still mostly visible in Bangkok territory but its neighboring provinces have also suffered more with UHI event in recent years due to great expansion of urban area crossing over from Bangkok border. In central Bangkok, only at Bang Krajao sub-district that is still not experienced much of the severe UHI.

2. Relationships of LULC Components and LST Data

It was found from obtained results that different LULC components have different impact on the UHI intensity. In general, the increase of urban/built-up area can enhance UHI intensity notably while the green vegetation tends to reduce UHI severity noticeably (like at the Bang Krajao sub-distict). Large water body also substantially helps to diminish the UHI intensity for the surrounding environment.

It was evidenced that relatively high temperature pixels tend to locate within the urban/built-up class (with average values of 25.11^{o}C in 2008) while colder pixels were significantly found within the vegetation and water body classes (with average values of 22.96^{o}C and 22.09^{o}C in 2008). It was found that, the correlation levels are rather moderate for LST and the NDVI (negative with R^2 = 0.408) but rather high (positive) for the other indices: R^2 = 0.734 (NDBI), and 0.670 (NDBaI).

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