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Article

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Research Article

Time series analysis of land use and land cover changes related to urban heat island intensity: Case of Bangkok Metropolitan Area in Thailand

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ABSTRACT

This study focuses on time series analysis of land use and land cover (LULC) characteristics and its relationships with urban heat island (UHI) intensity in Bangkok Metropolitan area. The study is aimed at examining impact of LULC changes on the greenness and land surface temperature (LST) as well as the relationship of LST, LULC and Normalized difference vegetation index (NDVI). We consider the heat intensity, hot spot zones, and land use characteristics related hotspot areas. LULC classification based on satellite images taken by Landsat data in summer dates of 1991, 1997, 2005 and 2016, were classified into four LULC types: built up area; vegetation area; barren land; and surface water. UHI was studied by deriving LST based satellite images method using the thermal band of Landsat satellite in the same periods as of LULC classification. The results show that the built up area was approximately 30% in 1991, then, it was sharply increasing to approximately 55% of the total area in 2016. The changing trends of LST tend to be increasing while the value of NDVI with dense vegetation meaning tend to be declining over the study period. The significant negative correlation between LST and NDVI implied that the lower biomass can higher LST. UHI intensity was also continually rising from 11.91 °C in 1991 to 16.21 °C in 2016 leading to nearly 5 °C increase in Bangkok. High density of buildings, no vegetation areas and large area of concrete pavement are the most significant related to the hot spot areas.

1. Introduction

Urban heat island is one of the most critical urban environmental problems and has become an important challenge for many cities. Over the last decade, there are numerous researches on urban heat island in mega cities around the world. In 2017, Estoque and Murayama studied the formation of surface urban heat island (SUHI) in a tropical mountain city, case of Baguio city in Philippines, monitoring by using Landsat data from 1987 to 2015. During the study period, the result illustrates that the temperature difference between impervious surface and green space increased from 2.7 °C to around 3.4 °C. Correspondingly, the temperature difference between an urban and a rural zone also rose from 4.0 °C to roughly 8.2 °C (R. Estoque & Murayama, 2017). In 2018, Ranagalage et al.

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examined quantifying SUHI in Kandy City, the world heritage tropical mountain city of Sri Lanka. The result presents that most of natural surfaces have changed to impervious surfaces, a SUHI increase from 3.9 °C in 1996 to 6.2 °C in 2017 (Ranagalage et al., 2018). In 2019, Ranagalage et al. also investigated the changes of the landscape in relation to the impact on LST intensity in the tropical mountain city of Nuwara Eliya, Sri Lanka, from 1996 to 2017 based on the Google Earth Engine (GEE) interface. The grid-based analysis showed a positive relationship between mean LST and built up land density as well as the temperature difference between an urban and a rural area also increased from 1.0 °C to 3.5 °C, during the study period (Ranagalage, Murayama, Dissanayake, & Simwanda, 2019). In addition, Simwanda et al. (2019) studied the relationship between LST and the spatial patterns, composition and configuration of impervious surface/green areas in four African cities: Lagos (Nigeria); Nairobi (Kenya); Addis Ababa (Ethiopia); and Lusaka (Zambia). The results show the strong positive correlation between mean LST and urban landscape metrics of impervious surfaces (patch density, size, shape, complexity and aggregation) and the strong negative correlation between mean LST and green spaces. All four cities illustrate high UHI intensity in the city center areas, a higher percentage of the impervious surface were warmer approximately 3–4 °C (Simwanda et al., 2019).

Bangkok Metropolitan Area (BMA) is the capital city of Thailand. Bangkok is one of cities that encounters particular problems related to the local climate as many areas in Bangkok have become hotter than the surrounding areas. The observations made by the Department of Meteorology of Bangkok show that the average maximum air temperature in Bangkok increased from approximately 32 °C in 1961 to nearly 34 °C in 2007 (BMA et al., 2009). There are many researches that discuss the urban heat island in Bangkok. Boonjawat et al. (2000) examined urban heat island in Bangkok by using transformed vegetation index (NDVI). The result showed that the surface temperature at Chulalongkorn University (as city center area) was higher than temperature at Asian Institute of Technology (as rural area) of around 3.5 °C during 6.00–7.00 a.m. (Boonjawat et al., 2000). Arifwidodo and Tanaka (2015) studied the current status of UHI in Bangkok by using air temperature record comparing between one rural area and three urban areas. The result showed that the maximum UHI intensity is approximately 6–7 °C during summer season and roughly 0.8 °C for the average annual air temperature (Arifwidodo & Chandrasiri, 2015; Arifwidodo & Tanaka, 2015). Estoque et al. (2017) examined the relationship between LST and green space and impervious surface pattern in the metropolitan areas of Bangkok, Jakarta, and Manila. The study found a significant strong correlation between mean LST and the density of impervious surface (positive) and green area (negative), the size and shape of impervious surface and green space also had significant relationships with the average of LST. Moreover, the mean LST of impervious surface is approximately 3 °C higher than green area in the metropolitan areas of the three case studies (R. C. Estoque et al., 2017). The existing UHI studies in Bangkok, have been finding only the temperature difference between urban area (BMA) and rural area (peri-urban, agriculture area and the surroundings of BMA). There are no studies on UHI intensity in different land use and land cover (LULC) types and how LULC changes affect the greenness and LST. Moreover, as the current literature, there is a lack of detail regarding the physical and land used characteristics in relation to the hot spot area.

To bridge the gap in the existing UHI studies, this research concentrates on four major parts. First, this research studies on the time series analysis of LULC changes in Bangkok from the past to the present. The LULC is classified using Landsat satellite images of 1991, 1997, 2005 and 2016. Second, examination of how the impact of LULC changes on the greenness and surface temperature as well as the relationship of LULC, LST and NDVI. We used NDVI to examine correlation between surface temperature and live green vegetation cover on earth's surface. Third, the study focuses on surface urban heat island (SUHI) and heat intensity in the BMA area. Finally, we determine the hot spot and cooler areas in Bangkok and examine the physical and land use characteristics in relation to these hot spot areas. This understanding of LULC changes, vegetation loss, UHI intensity, hot spot and cooler areas are of interest to both the academic community and city authorities to mitigate warming in urban areas.

2. Methodology and data

2.1. Study area

Bangkok Metropolitan Area (BMA) is selected as the study area for this research which is the center of economy, manufacture, and commerce of Thailand. BMA occupies about 1568.7 square kilometers. Registered population in BMA was 5.56 million in 1991, it was slightly increasing to 5.68 million in 2016 with the growth rate only 0.078% (Statistics, 2018). Meanwhile, that census population was sharply increasing from 6.19 million in 1991 to roughly 8.75 million in 2016. Over 25 years, the growth rate of census population in BMA is approximately 1.40% (CityPopulation, 2018). As an economic magnet, the gross provincial product (GPP) of BMA rose dramatically from 1.96 trillion in 1995 to 3.46 trillion in 2016 (at 2012 prices), with the average annual growth rate approximately 2.75%. Correspondingly, the gross domestic product (GDP) of Thailand from 1995 to 2016 sharply increases from 5.07 trillion to 9.82 trillion with the average annual growth rate nearly 3.20% (GPP, 2018). In addition, Bangkok Metropolitan Region refers to the urban region surrounding the metropolis of Bangkok. The political definition is defined as the metropolis and the five provinces surrounding: (i) Nakhon Pathom, (ii) Pathum Thani, (iii) Nonthaburi, (iv) Samut Prakan, and (v) Samut Sakhon. This region covers an area of 7761.6 square kilometers with population 10.76 million as registered population and 15.93 million as census estimated population, in 2016 (CityPopulation, 2018; Statistics, 2018). BMA is located on the lower Chao Phraya river delta plain, the river flowing through the center of the city. There are the 50 districts of Bangkok which serve as administrative subdivision under the authority of Bangkok Metropolitan Administration (BMA). The population density ranges from approximately 700 to 19,500 people per km² (reference in 2016). The high population density located at the city core along the Chao Phraya river. Tropical wet and dry climate is mainly found in Bangkok. There are three seasons in Bangkok: rainy, winter, and summer season. The months of March to May are the warmest with air temperatures reaching 40 °C (BMA et al., 2009).

The high growth rate of non-registration population and economic growth in Bangkok has resulted in the process of rapid

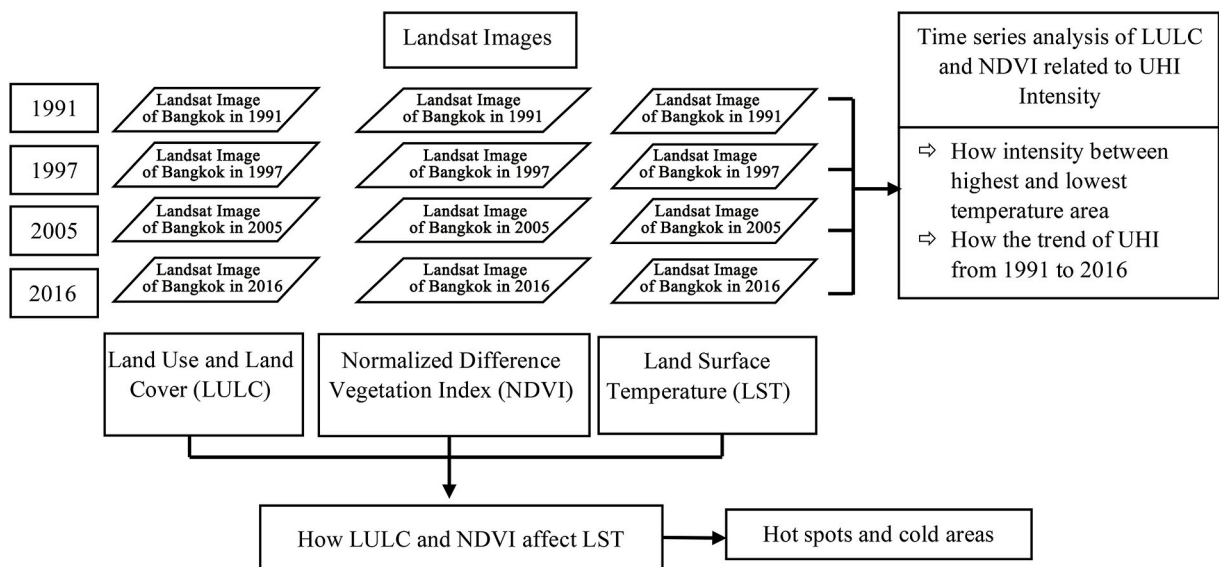


Fig. 1. Analysis framework.

urbanization and various environmental problems, especially city warming. The observations made by the Department of Meteorology of Bangkok show that the number of days on which the temperature exceeded 35 °C increased from approximately 20 days in 1991 to approximately 110 days in 2007 (BMA et al., 2009). Although, Bangkok City is currently facing the problem of heat island effects, BMA has not provided any specific planning or policies to mitigate warming in the city. Therefore, BMA could be the good area for the case study. Scope of this study deals with only Bangkok Metropolitan Administration (BMA) area which suffers more from the increasing population and rapid urbanization as well as city warming problems.

2.2. Data sources

This research focuses on the time series of UHI in Bangkok by analyzing through land cover change and vegetation loss. It selects four period which are 1991, 1997, 2005 and 2016. Data is required on how the change of surface temperature from the past to present took place. Landsat 5 and 7 images data acquired for 1991, 1997, 2005, and 2016 were used. Classification of LULC include: (1) built-up areas; (2) vegetation areas; (3) water; and (4) bare land.

This study used Landsat 5 and 7. Bands 1 to 5 and band 7 were used to categorize LULC types by supervised method with maximum likelihood classification and using the thermal band 6 to estimate for LST values. The spatial resolution of bands 1 to 5 and bands 7 are 30 m. For the thermal band 6, the resolution provides at 120 m for Landsat 5 and 60 m for Landsat 7, but the products are resampled to 30 m. This examination requires the location of fine changes in surface reflectance in order to understand changes processes and their impact on temperature over the study areas (Schroeder et al., 2006; USGS, 2016a, 2016b). To examine how LULC changes related LST and UHI intensity over the study period, we required Landsat images of 4 different years three with three sets of data as followed.

- (1) Land use and cover classification, the digital numbers (DNs) value of bands 1 to bands 5 and 7 were used. The DN values were converted into at-surface reflectance and then classified into land use and land cover types.
- (2) NDVI (Normalized Difference Vegetation Index), band 3(Landsat TM red) and band 4 (Landsat TM near-infrared) were used. The DN values were turned into at-surface reflectance and then estimated to NDVI values
- (3) Land surface temperature, the thermal band 6 was used. The DN values were converted to top-of-atmospheric radiance, then estimated for land surface temperature

2.3. Methodologies

The objective of this research is to examine characteristics of LULC change related UHI phenomenon in Bangkok. Fig. 1 shows framework of analysis to study how LULC and NDVI changed affect LST from 1991 to 2016.

This study analyzes through the comparison of LULC, NDVI, and LST map over four periods (1991; 1997; 2005; and 2016). LULC, NDVI, and LST were classified and estimated based on satellite images of Bangkok taken by Landsat data. The Landsat satellite images were acquired from the USGS (United States Geological Survey). The results show the relationship between LST and LULC pattern, the intensity between the highest and lowest temperature, and the trend of urban extension and warming from 1991 to 2016. The relationship between LST of each LULC and NDVI was analyzed by Pearson's correlation coefficient. The Pearson correlation coefficient is a statistical metric; it has been widely employed as a measurement of relationships between two variables which is also called a

Table 1
Land use and land cover classification for the study.

Classified	Description
Built-up areas	Urban or built-up land is defined as areas characterized by buildings, asphalt, concrete, suburban gardens, and a systematic street pattern. Classes of urban development include as follows. (i) residential areas; (ii) commercial areas; (iii) industrial areas; (iv) transportation or communications areas, (v) utilities
Vegetated areas	Vegetated areas are the area is covered with plant and tree which including, as follows. (i) agriculture areas; (ii) forest land; (iii) shrub and brush; (iv) green areas in city such as park
Water bodies	Water bodies is the water collects of flows beneath the Earth's surface which including as follows. (i) streams and Canals; (ii) river; (iii) lakes; (iv) reservoirs
Barren land	In general, it is an area of thin soil, sand, or rocks which including transitional area. Transitional area is the area that change from one land use activity to another; for example, forest lands are cleared for agriculture, wetlands are drained for development, or when any type of land use ceases as areas become temporarily bare as construction is planned for such future uses as residences, road, industrial sites, etc.

Sources: United States Geological Survey: USGS (USGS, 2016a)

bivariate correlation. The coefficient value (r value) ranges from minus one (-1) to plus one (+1). A value higher than zero (0) through plus one (+1) means that when the value of one variable increases, the other variable tends to also increase. While, a value less than zero (0) through minus one (-1) indicates a negative relationship; as one variable increases, the other variable tends to decrease. The value of zero (0) means no correlation between the two variables (Akoglu, 2018; Zhou et al., 2016). The investigation of the relationship between LST, LULC and NDVI allows us to determine how the changes of NDVI and LULC would have an impact on LST.

Hot spot areas in this study indicate the areas that have temperature higher than other areas, cooler areas refer to the districts that are cooler than others which are based on land surface temperature estimation. Hot and cold spots were calculated by a zonal statistics tool in ArcMap (Version 10.4.1) which performed the statistics with the high and low value of LST in the district area. Hot spot area is defined as the zone that has clusters of LST over 32 °C and cold areas refer to the districts that have the majority of LST less than 27 °C.

2.3.1. Classification of land use and land cover types

Land cover is indicated as the characteristics of ground surface for example, vegetation areas, surface water areas, bare soil or sand. For land use, refers to the area that has been used by various human activities for some purposes such as agriculture areas, residential areas, and commercial areas. In general, the land that is used by human activities could affect the change of land cover. The result of LULC changes also affects biodiversity, surface water, solar energy absorbed by earth's surface, radiation budgets, trace gas emissions, as well as local climate (Riebsame et al., 1994). In this study, we classified land use and land cover into four classes: (1) built-up areas; (2) vegetation areas; (3) water bodies; and (4) bare land, by using the supervised classification method.

LULC classification mapping based on satellite images taken by Landsat data in summer dates of 1991, 1997, 2005 and 2016, the classification was divided into three key steps as follows. First, creating LULC training areas (polygons that represent distinct sample areas of the different LULC types to be classified) by categorizing areas into four classes, the classification and definitions are presented in Table 1. Second, using a Landsat satellite image to classify through a supervised method with a maximum likelihood classification in ArcMap (Version 10.4.1). Landsat image was classified using spectral signature such as reflectance values, which obtained from our training area samples. Finally, all maps were assessed the accuracy of the LULC classification. (Khamchiangta & Dhakal, 2019; Ranagalage, Wang, Gunarathna, Dissanayake, Murayama, 2019; Rawat & Kumar, 2015).

2.3.2. Normalized difference vegetation index determination

Normalized difference vegetation index or NDVI has been widely employed as a measurement of greenness of vegetation cover on earth's surface and observation of contains live green vegetation or not, by remote sensing measurements (Chen & Brutsaert, 1998; Gillies et al., 1997; Weng & Lo, 2001). NDVI value represents vegetation on the ground surface which is related to the local climate variables, for example, precipitation (Schmidt & Karnieli, 2000; Xiao & Weng, 2007). NDVI values range from minus one through plus one (-1 to +1), a value around zero representing poor vegetation such as barren land and built up areas. A value close to plus one (+1) indicates very good vegetation such as dense tree or forest cover while a value close to minus one (-1) represents water body areas. In this study, we used NDVI to examine correlation between surface temperature and live green vegetation cover on earth's surface. The calculation is $NDVI = (NIR - Red) / (NIR + Red)$. Red is TM band 3, the vegetation absorbs and NIR is TM band 4, the vegetation reflects.

2.3.3. Land surface temperature determination

Land surface temperature (LST) is indicated as the skin temperature of ground surface. LST affects energy partitioning between ground surface and vegetation and has a significant influence on air temperature. LST can be derived from satellite thermal data. There is a two-step process for converting Landsat thermal data to land surface temperature value: (1) converting of the DN_s value of thermal band to top-of-atmospheric radiance, and (2) Land surface temperature calculation (Bonafoni, 2016; Chander & Markham, 2003; Keeratikasikorn & Bonafoni, 2018; USGS, 2016a, 2016b). For this study, LST was determined from the individual thermal images and afterward used the result to compare with other periods. The method of determination is as follows (Yuan et al., 2005).

(1) Converting the digital numbers (DN_s) values to top-of-atmospheric radiance. The DN_s value in Landsat thermal band 6 was turned into the top-of-atmospheric (TOA) radiance, calculated with Equation (1) (Chander & Markham, 2003).

$$L\lambda = ((L \max - L \min) / (QCAL \max - QCAL \min)) * (DN - QCAL \min) + L \min \quad (1)$$

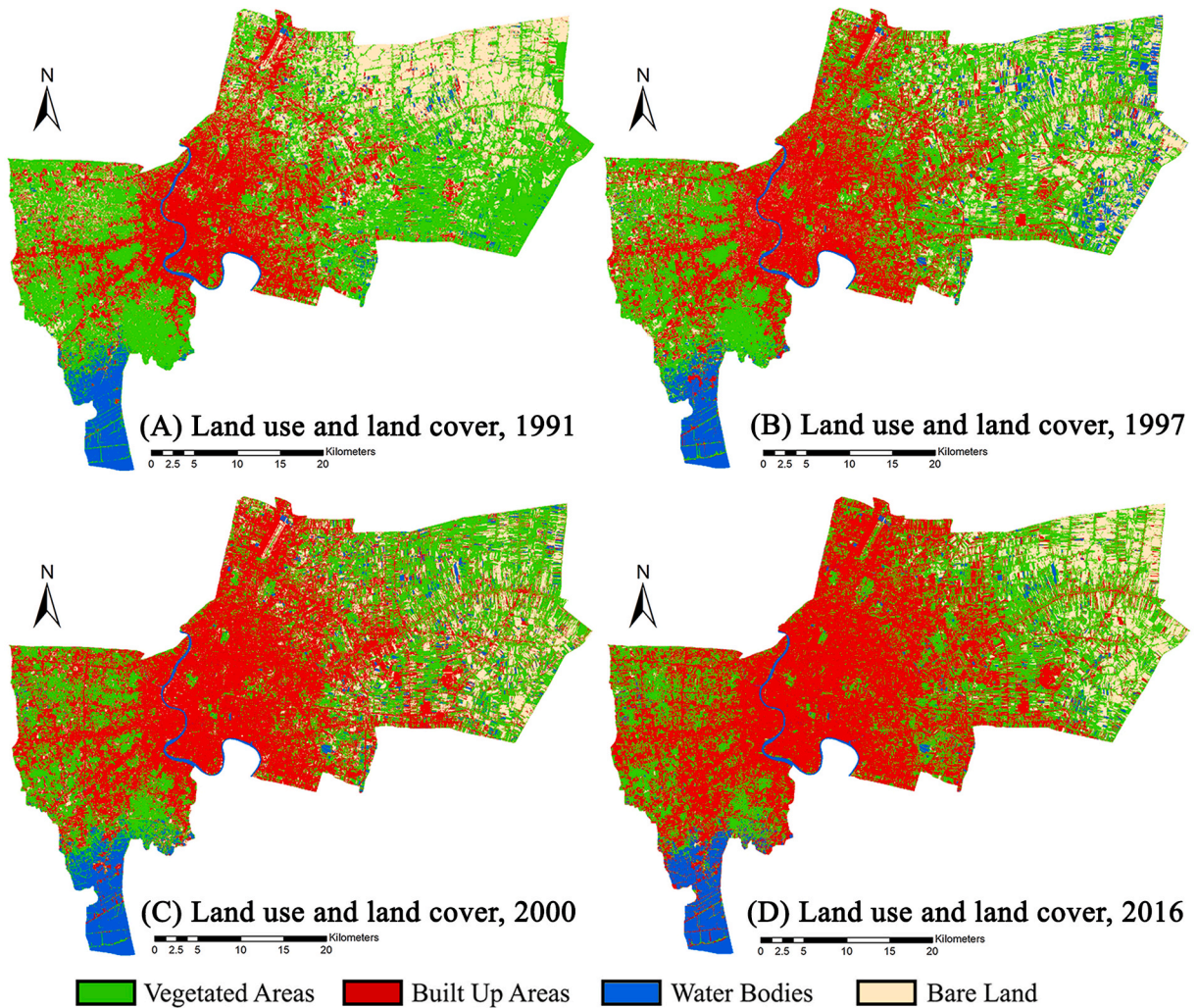


Fig. 2. Land use and land cover in Bangkok from 1991 to 2016
 Sources: Derivation from Landsat images data, United States Geological Survey: USGS (USGS, 2016b).

“Where, L_{λ} is top-of-atmospheric radiance in watts/(meter squared*ster* μm), DN is the digital number value of Landsat thermal band 6, $QCAL_{max} = 255$, and $QCAL_{min} = 0$ for the products processed before 4/5/2004 and 1 for the products processed after 4/5/2004, L_{max} and L_{min} is in watts/(meter squared*ster* μm), the values are provided in the metadata file of Landsat image data” (Chander & Markham, 2003).

(2) Estimation of Land surface temperature (and atmospheric correction) by inversion of radiative transfer equation (2)

$$L_{sens,\lambda} = [\epsilon_{\lambda} B_{\lambda}(T_s) + (1 - \epsilon_{\lambda}) L_{\lambda}^{\downarrow}] \tau_{\lambda} + L_{\lambda}^{\uparrow} \tag{2}$$

where “ $L_{sens,\lambda}$ is the at-sensor radiance at the top of the atmosphere; ϵ_{λ} is the surface emissivity; $B_{\lambda}(T_s)$ is the Planck’s law, where T_s is the LST; L_{λ}^{\downarrow} is the downwelling atmospheric radiance; τ_{λ} is the total atmospheric transmissivity; and L_{λ}^{\uparrow} is the upwelling atmospheric radiance. The LST is retrieved from (2) via the inversion of the Planck’s law, known as “surface emissivity” (Bonafoni, 2016; Keeratikasikorn & Bonafoni, 2018).

“The atmospheric parameters (τ_{λ} , L_{λ}^{\downarrow} , and L_{λ}^{\uparrow}) were computed using the National Centers for Environmental Prediction (NCEP) modeled atmospheric profiles in a web-based tool (J A Barsi et al., 2003; Julia A Barsi et al., 2005), which provides the parameters for the thermal band of the Landsat sensor. The land surface emissivity (ϵ_{λ}) was computed using the NDVI method as provided in previous studies” (Oltra-Carrió et al., 2012; Sobrino et al., 2004).

Table 2
Land use and land cover areas in bangkok from 1991 to 2016.

Year	Land Use and Land Cover Types							
	Built Up Areas		Vegetated Areas		Bare Land		Water Bodies	
	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)
1991	471.84	30.09%	606.21	38.66%	407.26	25.98%	82.62	5.27%
1997	530.92	33.86%	675.37	43.07%	250.00	15.95%	111.64	7.12%
2005	720.97	45.98%	564.52	36.00%	185.00	11.80%	97.44	6.21%
2016	861.16	54.95%	518.20	33.06%	119.15	7.60%	68.79	4.39%

Sources: Estimated from Landsat images data, United States Geological Survey: USGS (USGS, 2016b)

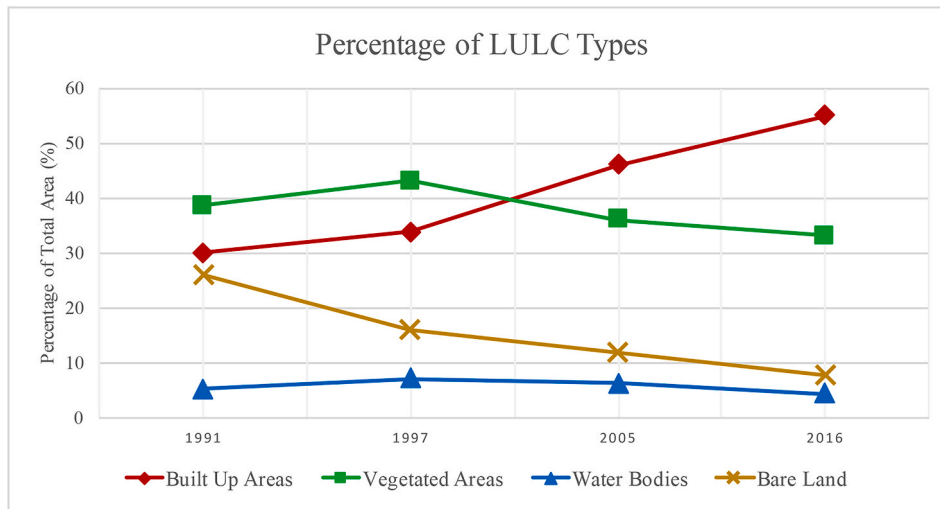


Fig. 3. Percentage of LULC types in Bangkok from 1991 to 2016
Sources: Estimated from Landsat images data, United States Geological Survey: USGS (USGS, 2016b).

3. Results and discussions

The research focuses on the present time (2016) as the base year of study. Then, we tried to find Landsat image data that was available as long as possible which could compare with the present time data. Therefore, there are Landsat 5 and 7 images data available from 1991 to 2016 which have the same resolution and can be used to compare and analyze in the study. This research narrows down the specific time of studying to the summer season in Thailand which is from February to May in each year. This study tried to find out the clear scene and less cloud cover available in Landsat data. Four satellite images were selected for this study as follows.

- (1) Landsat 5 TM image on February 3, 1991(Early Summer), (Path/Row: 129/050 and 129/051), Local time: 10:58:18 p.m. (Local time is +7.00 from coordinated universal time (UTC time))
- (2) Landsat 5 TM image on April 24, 1997(Summer), (Path/Row: 129/050 and 129/051), Local time: 10:05:24 p.m.
- (3) Landsat 5 TM image on March 13, 2005 (Early Summer), (Path/Row: 129/050 and 129/051), Local time: 10:24:42 p.m.
- (4) Landsat 7 ETM + image on March 3, 2016 (Early Summer), (Path/Row: 129/050 and 129/051), Local time: 10:39:44 p.m.

3.1. LULC changes in bangkok from 1991 to 2016

Fig. 2 shows four maps of LULC in Bangkok in 1991, 1997, 2005 and 2016 which are classified into four LULC types. The classification was divided into built-up areas, vegetation areas, water surface, and bare or soil areas. The overall classification accuracy of LULC classification in 1991, 1997, 2005, and 2016 are 88.40%, 91.80%, 93.00%, and 93.80%, respectively. In addition, the kappa coefficients of four periods are 0.827, 0.879, 0.894, and 0.899 (see supplementary document). Over 25 years, urban expansion in Bangkok is characterized by ineffectively regulated and was dramatically expanding from the city center to the surrounding. Normally, agriculture land was converted to urban areas.

In 1991, Built up areas was approximately 30% then, it was sharply increasing to nearly 55% of the total area in 2016. In contrast, green areas and bare land were continually decreasing from roughly 38% in 1991 to 33% in 2016 and 25% in 1991 to 7% in 2016,

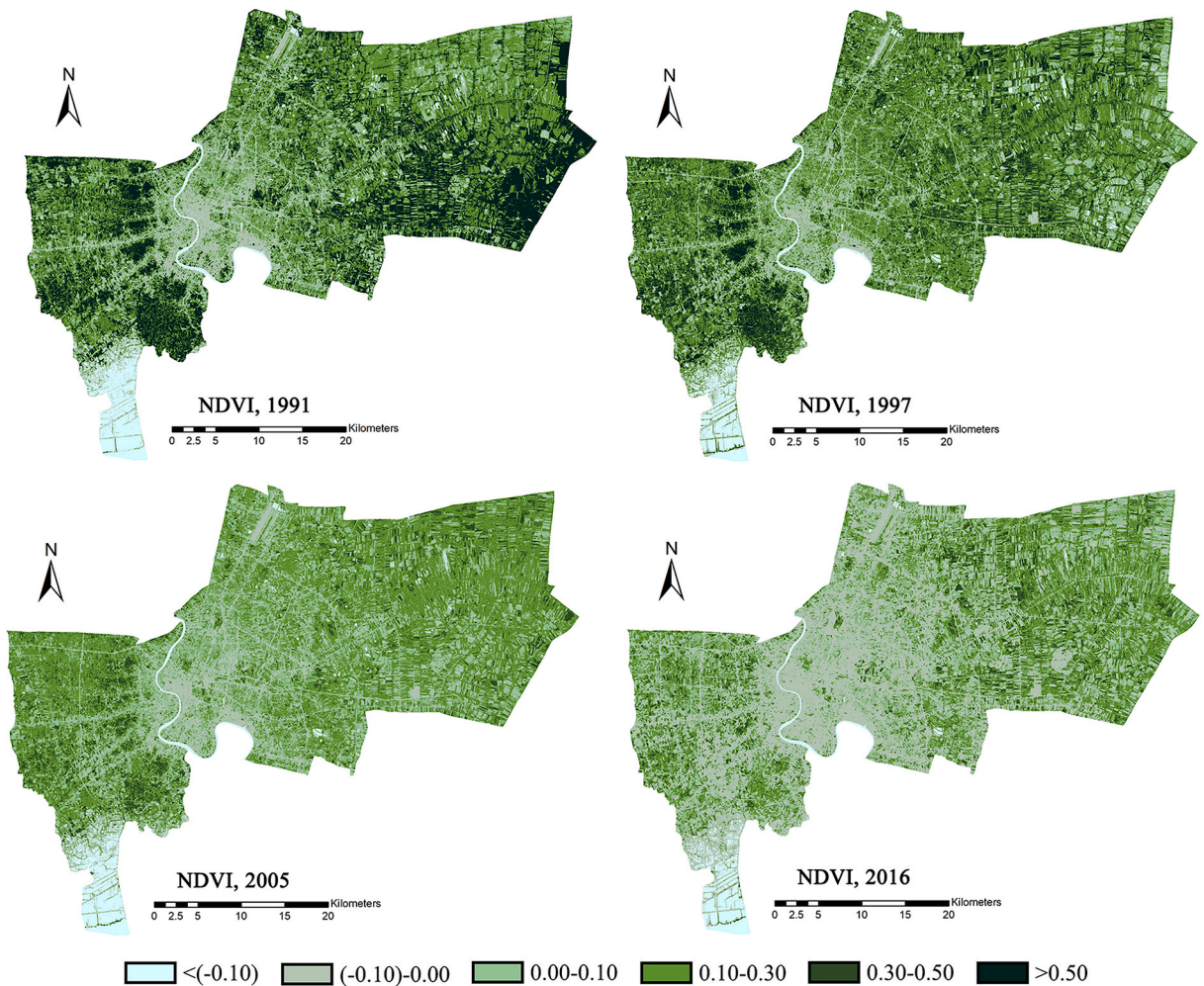


Fig. 4. NDVI in Bangkok from 1991 to 2016

Sources: Derivation from Landsat images data, United States Geological Survey: USGS (USGS, 2016b).

respectively (see Table 2.). In addition, over 25 years, vegetation areas and water bodies in Bangkok was just slightly fluctuation because of rainwater harvesting for agriculture and farming areas in the Eastern part of Bangkok.

Fig. 3 shows the trends of each LULC area as percentages. The trend of urban areas is sharply rising during the study period. Conversely, bare land is dramatically decreasing over 25 years. For vegetated areas and water bodies, fluctuations are seen but the trend is clearly decreasing. The fluctuation changes of vegetation and water body areas in Bangkok related to agriculture areas and harvesting ponds in farming areas. Table 2 shows the result of LULC areas from 1991 to 2016, urban areas had increased nearly 25% while vegetated areas, bare land and water bodies had decreased approximately 5%, 18% and 0.8%, respectively. LULC classification maps in Fig. 2, illustrate that most of urban expansion was as the result from the converting of vegetated, bare land and water body areas.

3.2. Impact of LULC changes on the greenness from 1991 to 2016

The values of NDVI are illustrated as a ratio, the value ranging from minus one (-1) to plus one (+1). As the result of this study, extreme negative values refer to water surface and positive values close to zero (between (-0.10 to 0.30) represent poor vegetation which is barren land and built up area. The value between 0.31 to 0.50 represents a good vegetation as shrub and grassland. In term of dense tree and forest cover area was showed in positive values higher than 0.50.

Fig. 4 presents NDVI maps for four dates which show the decline of NDVI level. Proportion of the positive value over 0.3 which included dense tree, forest, shrub and grassland tend to be declining over the last 25 years. While, positive and negative values around zero such as minus 0.10 to plus 0.30 which represent built up area and bare land, turn to be increasing from 1991 to 2016. There are NDVI values with higher than 0.5 which represent forest area and dense tree cover showing only in 1991 and 1999. This high NDVI value (>0.50) did not illustrate in 2005 and 2016. It is notable that dense vegetation areas had been changed to grassland, agriculture or built up areas.

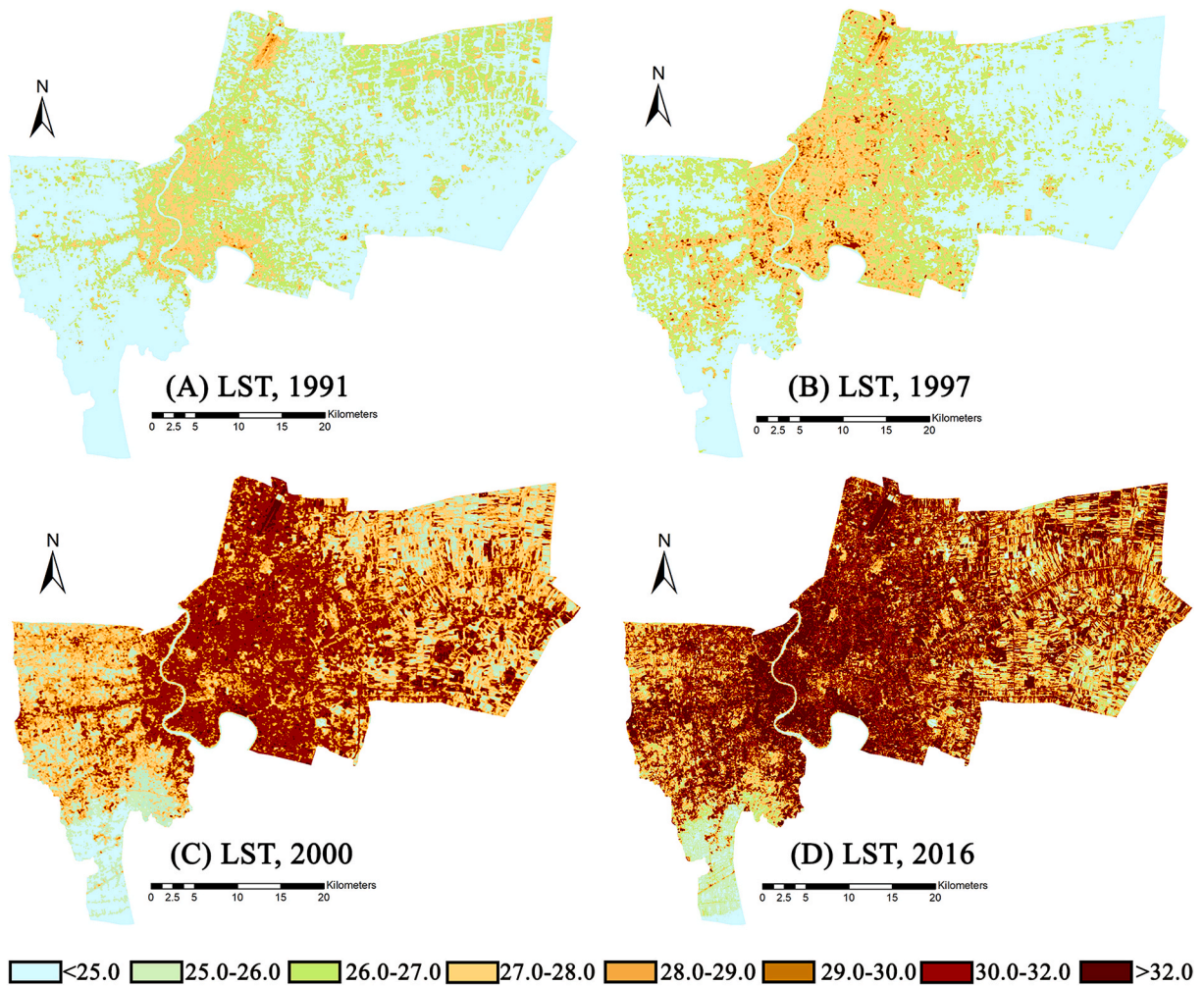


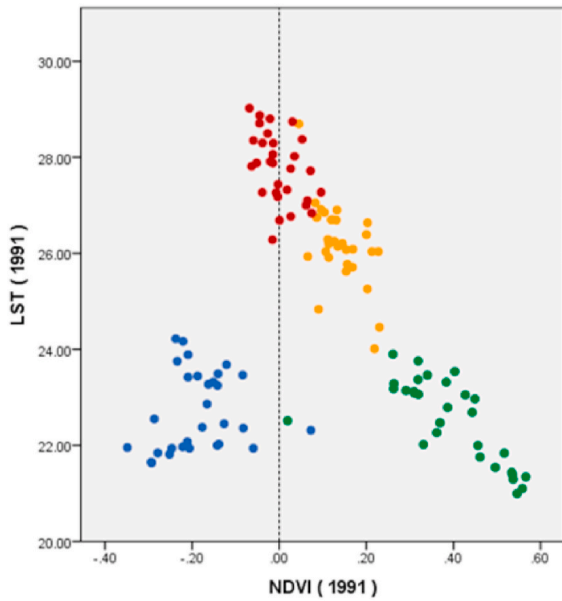
Fig. 5. Land surface temperature in Bangkok from 1991 to 2016
 Sources: Derivation from Landsat images data, United States Geological Survey: USGS (USGS, 2016b).

Table 3
 Average of LST related LULC types in Bangkok from 1991 to 2016.

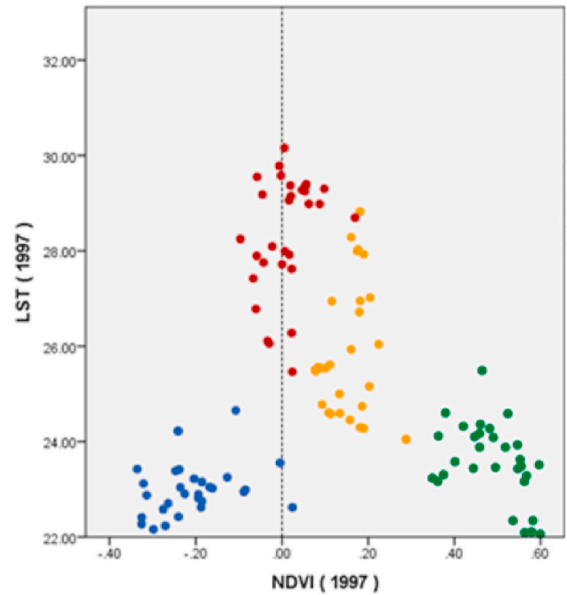
Year	Land Use and Land Cover Types							
	Built Up Areas		Vegetated Areas		Bare Land		Water Bodies	
	LST	(+SD)	LST	(+SD)	LST	(+SD)	LST	(+SD)
1991	26.11	(+1.15)	23.87	(+1.10)	25.35	(+1.18)	22.65	(+0.92)
1997	26.92	(+1.45)	24.72	(+1.17)	25.29	(+1.37)	23.36	(+0.71)
2005	29.87	(+1.23)	27.96	(+1.33)	30.08	(+1.40)	25.76	(+1.19)
2016	31.15	(+1.79)	28.64	(+1.60)	31.52	(+1.64)	25.48	(+0.79)

3.3. Impact of LULC changes on LST from 1991 to 2016

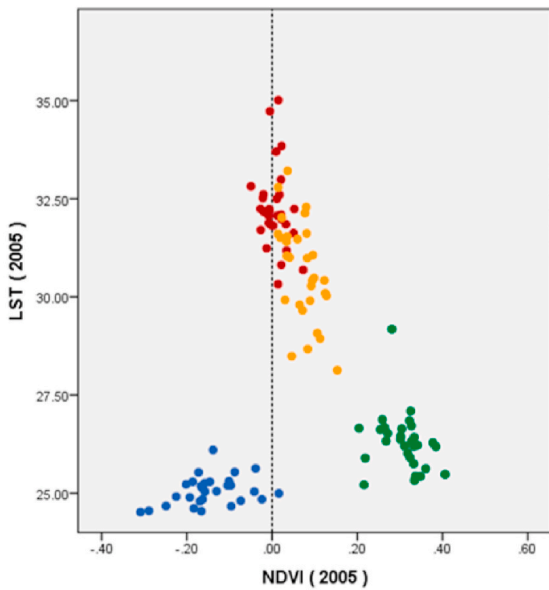
The result of four dates LST comparison, depicts that surface temperature in BMA was dramatically increasing from 1991 to 2016. More than half of the Bangkok area contained temperatures less than 25 °C in 1991. Meanwhile, there were just tiny fragments with less than 25 °C in 2016 (see Fig. 5). Table 3 shows the average LST value related to each type of LULC. The lowest temperature shows in water surface areas, while the highest is in built up areas. Over 25 years, the mean surface temperature of all LULC types continues to increase, especially in built up areas, the temperature was dramatically increasing from around 26 °C–31 °C. It is no wonder that the built-up area is the highest contributor to city warming.



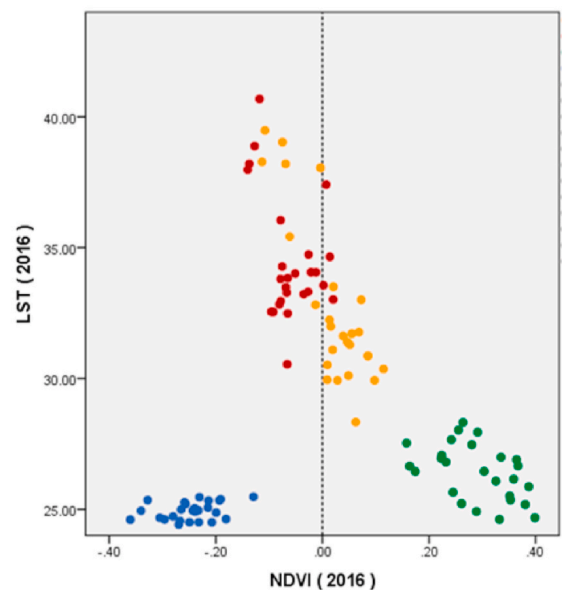
(A) LST related NDVI, 1991



(B) LST related NDVI, 1997



(C) LST related NDVI, 2000



(D) LST related NDVI, 2016

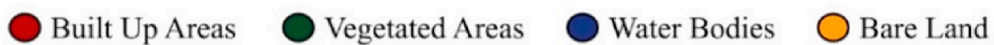


Fig. 6. Relationships of LULC, NDVI and LST in Bangkok from 1991 to 2016.

3.4. Relationship of LST, LULC, and NDVI

A sample randomly generated points was used to investigate the relationships of LST to NDVI for the various LULC Types. Fig. 6 explains the pattern among, LULC, LST and NDVI in the scatter plots.

Fig. 6 illustrates that LST values are relatively higher in the urban surface, non-vegetated and bare land. As for NDVI, values in the

Table 4

Pearson's correlation coefficients between LST and NDVI.

LULC types	1991	1997	2005	2016
Built up area	-0.448*	-0.503**	-0.539**	-0.398*
Vegetated area	-0.692**	-0.464**	-0.753**	-0.470*
Water body	0.151	0.339	0.349	0.328
Bare land	-0.574**	-0.442**	-0.571**	-0.831**

Note: * = Significant at P = 0.05; ** = Significant at P = 0.001.

Table 5

Statistic of LST and UHI intensity in Bangkok from 1991 to 2016.

Year	Max of LST (°C)	Min of LST (°C)	Mean of LST (°C)	UHI Intensity (°C)
1991	31.64	19.73	24.86 (+1.56)	11.91
1997	33.66	21.50	25.46 (+1.71)	12.16
2005	36.83	24.11	28.95 (+1.78)	12.72
2016	39.56	23.35	30.12 (+2.29)	16.21

Sources: Estimated from Landsat images data, United States Geological Survey: USGS (USGS, 2016b)

built-up area are far lower than in the green area. The relation between LST and NDVI in Bangkok shows an obvious inverse correlation. In addition, the changing trends of LST tend to be increasing while the value of NDVI with dense vegetation meaning tend to be declining over the study period.

Table 4 presents Pearson's correlation coefficient between LST of each LULC and NDVI from 1991 to 2016. The result shows that built up areas, vegetated areas, and bare land types illustrate the negative correlation with NDVI. This significant negative correlation implied that the lower biomass of each LULC can higher its LST. This relationship has determined that due to the changes of NDVI of each LULC would have an indirect impact on LST.

3.5. Temperature trend and UHI intensity in bangkok

Urban heat island intensity is indicated as urban warming which is calculated as a difference between urban temperature and the surrounding areas. While, UHI intensity in this research was indicated as the difference between minimum and maximum of LST to see heat intensity from 1991 to 2016. The average surface temperature in BMA was sharply rising from approximately 24 °C–30 °C, from 1991 to 2016. Similarly, the minimum and maximum of LST was also increasing from 19 °C to 23 °C and 31 °C–39 °C, respectively. Table 5 shows UHI intensity has increased steadily from 11 °C in 1991 to 12 °C in 1997 and jump to 16 °C in 2016.

3.6. Hot spots and cooler areas in bangkok

Fig. 7 shows the comparison between (A) LULC in 2016, (B) main transportation in BMA, green zone and BMR area (C) LST in 2016, (D) hot spot and cooler areas in 2016. The growth of built-up areas occurred along the main transportation in BMA including main road network, mass rapid transit routes and expressway network. The result of LST shows that temperature values are relatively higher in the urban surface, non-vegetated or bare land. Built up area has higher LST value than other LULC types, especially around the city center. In addition, hot spot areas in this study indicate the areas that have temperature higher than other areas with LST over than 32 °C which represents 10 zones in Fig. 7(D). While cooler areas refer to the districts that are cooler than others with LST less than 27 °C. Most cooler areas show in the western and eastern part of BMA which represents green areas in Fig. 7(D). It can be noticed that the cooler area is the vast green open space located in the same areas of green zone regulation of BMA. Green zone in BMA was indicated as the rural and agriculture conservation zone as well as maintaining green open space for floodway to prevent flooding in urban areas. This study also shows that the existing green spaces of the green zone also provide cooling benefits for Bangkok.

Table 6 illustrates physical land use characteristics of 10 hot spot areas in BMA. We have categorized 10 hot spot areas (see Fig. 7 (D)) into 2 groups which take aerial photographs from Google Earth satellite images. Firstly, number one and two of hot spot zones are large low-rise building areas with few or no tree cover and large low-rise buildings surrounded by big areas of concrete paved. The result shows that warehouse and airport sites are in this category. Secondly, number three through number ten are areas that have high density of buildings with few or no green area surroundings, mix of high-rise, mid-rise and low-rise buildings. Most of the areas in this group are the central business district (CBD), high density of commercial zone and high density of residential zone in BMA.

4. Conclusions

Over the 25 years, from 1991 to 2016, dense vegetation areas in BMA have been changed into built up areas. In addition, built-up areas continually expanded from the city center to the surroundings; the growth occurred along the main road and the districts which connect to the province's surroundings. Nevertheless, urbanization remains low in the eastern part of Bangkok because of the green zone regulation with protected zoning. Moreover, the eastern part of BMA has no connection area with the five adjacent provinces

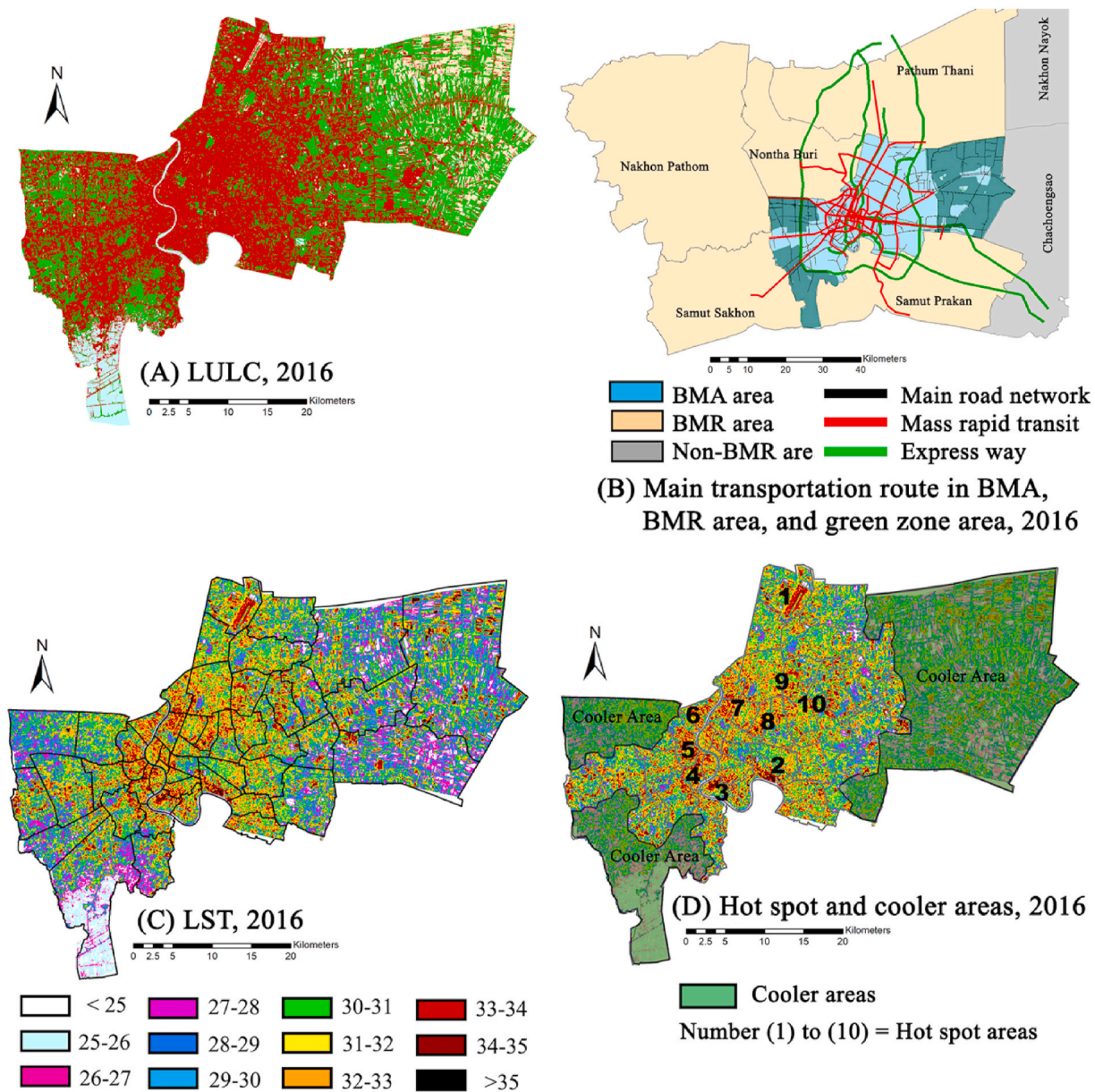




Fig. 7. LULC, Main Transportation Routes in BMA, LST, Hot Spot and Cooler Areas in Bangkok, 2016
 Sources: Derivation from Landsat images data, United States Geological Survey: USGS (USGS, 2016b).

(Bangkok Metropolitan Region area). For LST examination, the average of LST in BMA was sharply increasing from approximately 24 °C–30 °C. Similarly, urban heat island intensity was rising from 11 °C in 1991 to 16 °C in 2016. In general, hot spot areas in BMA have two physical LULC characteristics, firstly, large low rise building with few or no tree cover and surrounding by big area of concrete paved, secondly, dense mix of high-rise, mid-rise, and low-rise building with few or no green area surroundings.

The temperature trend in this study means that the city will be facing more serious warming in the future if no mitigation action is taken. As a result of high density of buildings, lack of vegetation areas and concrete pavement are strongly related to hot spot areas. Large green areas also provide cooling benefits in the city. It is therefore essential to consider the mitigation strategies. These results mean that the following mitigation measures would be the key.

- Strengthening green zone protection in order to limit built up expansion and infrastructure development into the existing vast green space.

Table 6
Hot Spot area and physical land use characteristics in Bangkok, 2016.

Hot spot areas	Images from Google Earth	Physical and land used characteristics
Number 1 and 2		Large low-rise building with few or no trees cover and surrounding by big area of concrete paved (airport and warehouse zones)
Number 3 to 10		High density of mix of high-rise, mid-rise, and low-rise buildings with few or no green area surrounding (CBD, high density of commercial and residential zones)

Sources: Google Earth (GoogleEarth, 2016).

- More vegetation or green areas within the city's boundary can cool down temperature within built up areas, for example, expanding urban park in city center, option include planting trees or shrubs on both sides of street, pedestrian and between buildings to create more green space in the city.
- Using cool roofing material for large buildings and cool paving material for large areas of concrete pavement. Landscape ordinance has potential to be used in controlling this in the city, for example, requiring to plant trees or shrubs on parkways and parking lots, loading docks and other large areas of paved concrete including new construction and renovation projects.
- Limitation of building density in city centers, for example, lower the proportion of coverage in the zoning regulation of BMA to keep low density of building in the city center. Shifting urban structure from mono-centric to multi-centric, for example, BMA could develop new CBD and sub-centers in the BMR area in order to spread the building settlements and lower infrastructure development in the city center.

BMA will have more potential to reduce warming in the city in the future if all mitigation strategies were effectively implemented. However, government support and capacity building also play important role in the achievement of all these strategies.

Declaration of competing interest

The authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jum.2020.09.001>.

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