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Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia

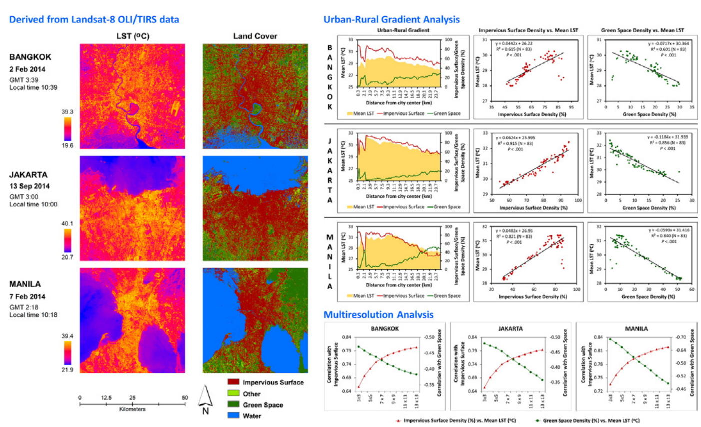
Ronald C. Estoque [a,*], Yuji Murayama [a], Soe W. Myint [b]

[a] Faculty of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba City, Ibaraki 305-8572, Japan
[b] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA

HIGHLIGHTS

- We examined LST's relationship with IS and GS in Bangkok, Jakarta and Manila.
- On average, the mean LST of IS is about 3 °C higher than that of GS.
- LST had a significant strong correlation with IS and GS along urban-rural gradient.
- LST's correlation with IS density increases in larger grids (smaller grids for GS).
- Aggregation of IS and GS had consistent significant strong correlation with LST.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to its adverse impacts on urban ecological environment and the overall livability of cities, the urban heat island (UHI) phenomenon has become a major research focus in various interrelated fields, including urban climatology, urban ecology, urban planning, and urban geography. This study sought to examine the relationship between land surface temperature (LST) and the abundance and spatial pattern of impervious surface and green space in the metropolitan areas of Bangkok (Thailand), Jakarta (Indonesia), and Manila (Philippines). Landsat-8 OLI/TIRS data and various geospatial approaches, including urban-rural gradient, multiresolution grid-based, and spatial metrics-based techniques, were used to facilitate the analysis. We found a significant strong correlation between mean LST and the density of impervious surface (positive) and green space (negative) along the urban-rural gradients of the three cities, depicting a typical UHI profile. The correlation of impervious surface density with mean LST tends to increase in larger grids, whereas the correlation of green space density with mean LST tends to increase in smaller grids, indicating a stronger influence of impervious surface and green space on the variability of LST in larger and smaller areas, respectively. The size, shape complexity, and aggregation of the patches of impervious surface and green space also had significant relationships with mean LST, though aggregation had the most consistent strong correlation. On average, the mean LST of impervious surface is about 3 °C higher than that of green space, highlighting the important role of green spaces in mitigating UHI effects, an important urban ecosystem service. We recommend that the density and spatial pattern of urban impervious surfaces and green spaces be considered in landscape and urban planning so that urban areas and cities can have healthier and more comfortable living urban environments.

* Corresponding author.
E-mail addresses: estoque.ronald.ga@u.tsukuba.ac.jp, rons2k@yahoo.co.uk (R.C. Estoque).

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1. Introduction

Urban heat island (UHI), a phenomenon first described in 1818, refers to the phenomenon of higher atmospheric and surface temperatures occurring in urban areas than in the surrounding rural areas (Howard, 1818; Oke and Hannel, 1970; Voogt and Oke, 2003; Voogt, 2004; EPA, 2008). There are two types of UHIs: surface UHI and atmospheric UHI. Surface UHIs are measured based on land surface temperature (LST), while atmospheric UHIs are measured based on air temperature and are often classified into canopy layer UHIs and boundary layer UHIs (EPA, 2008). This study focuses on surface UHI. Surface UHIs are typically present day and night, but tend to be strongest during the day due to the radiation from the sun (EPA, 2008).

Cities produce UHI regardless of size and location, though the effect often decreases as city size decreases (Oke, 1973, 1982; Aniello et al., 1995; EPA, 2008). Generally, the formation of UHI is caused mainly by landscape changes due to urban development, which result in higher LST. More specifically, the UHI phenomenon is influenced by the reduced vegetation in urban areas, properties of urban materials, urban geometry, anthropogenic heat, weather, and location (Voogt, 2004; EPA, 2008). Some of the major negative impacts of UHI include increased energy consumption, elevated emissions of air pollutants and greenhouse gasses, compromised human health and comfort, and impaired water quality (Voogt, 2004; EPA, 2008). Thus, due to its adverse impacts on urban ecological environment and the overall livability of cities, the UHI phenomenon has become a major research focus in various interrelated fields, including urban climatology, urban ecology, urban planning, and urban geography.

Many UHI studies have shown the usefulness of remote sensing satellite data for examining the relationships between urban landscape pattern and LST (e.g. Weng, 2001, 2009; Voogt and Oke, 2003; Weng et al., 2004, 2007; Xiao et al., 2007; Yuan and Bauer, 2007; Connors et al., 2013; Zhou et al., 2011, 2016a; Myint et al., 2013; Maimaitiyiming et al., 2014; Fan et al., 2015; Ma et al., 2016; Morabito et al., 2016; Wang et al., 2016). Today, urban-rural gradient analysis, multiresolution analysis, and the use of spatial metrics are among the most popular approaches for quantifying the effects of urban landscape pattern on LST. Each of these approaches aims to contribute some insights into the advancement of UHI studies, as well as into landscape and urban planning, in order to mitigate UHI effects so that urban areas and cities can have healthier and more comfortable living urban environments.

Urbanization generally results in a differential heating process between impervious surfaces, generally made of concrete and other heat-absorbing materials, and urban green spaces and the surrounding naturally vegetated landscapes (Howard, 1818; Weng, 2001; Voogt and Oke, 2003; EPA, 2008; Imhoff et al., 2010). The increase of green space generally decreases LST because green space can generate cool island effects by evapotranspiration and emissivity, combined with lower thermal inertia, in contrast to impervious surface (Lambin and Ehrlich, 1996; Voogt, 2004; Weng et al., 2004; EPA, 2008; Hamada and Ohta, 2010; Li et al., 2012). Green space can produce shades that cover land surfaces, preventing direct heating of the surface from the solar radiation emitted by the sun (Zhou et al., 2011; Li et al., 2012). Thus, the relationship between LST and the abundance and spatial pattern of impervious surface and green space is among the main subjects of various studies across different regions in the world (e.g. Weng et al., 2004; Xiao et al., 2007; Yuan and Bauer, 2007; Zhou et al., 2011; Li et al., 2012; Myint et al., 2013; Maimaitiyiming et al., 2014; Morabito et al., 2016).

Indeed, there have been a number of studies examining the relationship between LST and the abundance and spatial pattern of impervious surface and green space. However, a study of this type in the megacities of Southeast Asia is still lacking. Hence, this study sought to examine the relationship between LST and the abundance and spatial pattern of impervious surface and green space in the metropolitan areas of Bangkok (Thailand), Jakarta (Indonesia), and Manila (Philippines). Landsat-8 OLI/TIRS data and various geospatial approaches, including urban-rural gradient, multiresolution grid-based, and spatial metrics-based techniques, were used to facilitate the analysis.

Each of these metropolitan regions has >10 million population, hence in this article they are called megacities. In 2015, Bangkok Metropolitan Region (Krung Thep Mahanakhon Lae Parimonthon) had a population of 15.6 million (projection), the Special Capital City District of Jakarta (DKI Jakarta) had 10.2 million (census), while Metro Manila had 12.9 million (census) (www.citypopulation.de). As the primary urban centers in their respective countries, these cities have been experiencing rapid population growth and built-up expansion. Among the various problems and issues they face today include congestion due to the increasing population, built-up density, and number of vehicles (including motorcycles), and urban environmental degradation due to pollution, continuous built-up expansion, and loss of urban green spaces, among others. Hereafter, these megacities are simply referred to as Bangkok, Jakarta, and Manila.

2. Methodology

2.1. Study areas

The study areas include the city cores of Bangkok, Jakarta, and Manila. Each study area covers a 50 km × 50 km landscape, with 25 km radius from the city center, pin-pointed at the center of each city's central business district (Fig. 1).

These three metropolitan regions are all located in the coastal zones of Southeast Asia. The climate in these cities is characterized by two pronounced seasons: wet and dry: Bangkok's wet and dry seasons last from June to October and from November to May, respectively (Morknoy et al., 2011). For Jakarta, its wet season is from October to May, while its dry season is from June to September. The climatic pattern in Manila is similar to that of Bangkok as they are both located north of the equator, unlike Jakarta. Manila's wet and dry seasons last from May to October and from November to April, respectively (Estoque and Murayama, 2015a).

The landscapes of these three cities are a mosaic of built-up lands (impervious surfaces), croplands, grasslands, forests, and bodies of water, which include parts of the sea, lakes, rivers and ponds. The urban area of Bangkok has been expanding in all directions, except toward the southern part due to the Gulf of Thailand (Fig. 1b). Likewise, the urban area of Jakarta has also been expanding in all directions, except toward the northern part due to the Java Sea (Fig. 1b). By contrast, the expansion of Manila's urban area has been limited only to the north-south direction due to Manila Bay on the west and Laguna Lake on the south-eastern side (Fig. 1b) (see also Estoque and Murayama, 2015b).

2.2. Data descriptions and pre-processing

In this study, we used Landsat-8 Operational Land Imager and Thermal Infrared Sensor (Landsat-8 OLI/TIRS) imagery, all acquired in 2014 in the dry season (Table 1a). The successful launch of Landsat-8 OLI/TIRS on February 11, 2013 envisions lengthening the 40-year Landsat record for at least another five years, enabling a continuous support for the advancement of global change research (Roy et al., 2014). Today, the USGS Landsat distribution scheme (http://landsat.usgs.gov/CDR_LSR.php) allows the user to choose between a preprocessed dataset and a raw dataset. In this study, we used preprocessed datasets, downloaded from http://earthexplorer.usgs.gov/.

A Landsat-8 OLI/TIRS image contains 11 bands, including eight multispectral (Bands 1–7 and 9), one panchromatic (Band 8) and two thermal (Bands 10 and 11) (Table 1b). In the preprocessed datasets we used, the digital number (DN) values of the multispectral bands, except for Band 9, have been converted into surface reflectance values, while those of the thermal bands have been converted into top of atmosphere brightness temperature expressed in Kelvin (USGS, 2016a).

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