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Geospatial analysis of urban landscape patterns in three major cities of Southeast Asia

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Abstract

Using a geospatial approach that integrates gradient analysis and landscape metrics, this study examines and compares the urban landscape patterns of three major cities of Southeast Asia, namely Bangkok, Jakarta, and Manila. Landsat-8 imageries for 2013 and 2014 were used to classify the urban land-use/cover of the three cities. Furthermore, various class-level landscape metrics were computed to facilitate spatial analysis. The results reveal that the proportional extent or density and physical connectedness of built-up lands in the three cities are inversely related to the gradient of the distance from the city center. In contrast, the fragmentation of built-up lands is directly related to the gradient of the distance from the city center. In the comparison of the three cities, the density of the urban development of Manila is relatively higher than that of Bangkok, but more especially that of Jakarta. The urban landscape of Jakarta is relatively more fragmented or dispersed than that of Bangkok, but more especially that of Manila. In terms of physical connectedness, Manila's urban landscape is relatively more aggregated than that of Bangkok, but more especially that of Jakarta. The study results show that the gradient analysis and landscape metrics integrated approach can be used to examine and compare the spatial patterns of various complex urban landscapes.

Key words: fragmentation, gradient analysis, landscape metrics, landscape pattern, urbanization

1. Introduction

Knowledge of urban landscape patterns is important for understanding human-environment interactions, provision of urban ecosystem services, as well as disaster risk management and urban sustainability. This is because environmental and landscape patterns influence ecological processes (Turner 1989; McGarigal *et al*. 2012).

In the past few decades, the emphasis of landscape ecological research has been on the development of methods to quantify landscape patterns, which are deemed essential in the study of pattern-process relationships (McGarigal *et al*. 2012). Some of the developed and commonly applied methods for computing landscape or spatial metrics can be found in McGarigal *et al*. (2012).

Gradient analysis, which uses the concept of 'gradient', i.e. the variation in the values of a given variable, for example, distance from the urban center, was first developed in the context of vegetation analysis (Whittaker 1975). Since then, gradient analysis has been used to investigate the effects of urbanization on species diversity, vegetation composition and structure, soil nutrients, water quality, and ecosystem properties (see Luck and Wu 2002 and Weng 2007 for more details). More recently, the concept of gradient analysis has also been used in land change modeling studies (Chen and Pontius 2010; Estoque and Murayama 2014).

In the field of urban ecological research, McDonnell and Pickett (1990) were the first to introduce the gradient paradigm. Based on this paradigm, experimental plots or units of analysis can be established in a transect along the 'urban-rural' gradient (McDonnell and Pickett 1990; Luck and Wu 2002; Weng 2007). In the early 2000s, Luck and Wu (2002) attempted to combine gradient analysis with landscape metrics. Their study reveals how landscape patterns change along the urban gradient or the gradient of the distance from the urban center. Other empirical studies have also been done employing this integrated approach (e.g. Weng 2007).

In the context of comparative analysis, there have been a number of studies that, in one way or the other, attempted to compare the urban landscape patterns of various cities around the world, including the major cities in Southeast Asia (e.g. Yamashita 2011; Angel *et al*. 2012; Bagan and Yamagata 2014). However, the gradient analysis and landscape metrics integrated approach has not been applied, especially in the major cities of Southeast Asia. The urban landscape patterns of these cities are complex. Thus, such an integrated approach might help us understand these complex patterns in a way that has never been done before.

Hence, the main purpose of this study is to examine and compare the urban landscape patterns of the three major cities of Southeast Asia, namely Bangkok (Thailand), Jakarta (Indonesia), and Manila (Philippines) (Fig. 1), using a geospatial approach that integrates gradient analysis and

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landscape metrics. The comparison focuses on three aspects of urban landscape patterns, namely landscape composition or density, fragmentation or dispersion, and aggregation or physical connectedness.

2. Methodology

2.1. Land-use/cover (LUC) mapping

We classified Landsat-8 imageries acquired on January 17, 2014 (Bangkok), August 25, 2013 (Jakarta), and February 7, 2014 (Manila) using a Random Forest (RF) image classification approach. Only three LUC classes, namely built (meaning built-up lands), non-built (meaning non-built-up lands), and water (meaning bodies of water), were considered since the main focus of this study is on the spatial patterns of the built-up lands in the three cities.

RF is a machine learning method that uses a collection of tree-structured classifiers for classification (Breiman 2001; Breiman and Cutler 2005; Akar and Gungor 2012; Rodriguez-Galiano *et al*. 2012; Grinand *et al*. 2013). The key advantages of RF algorithms are their non-parametric nature, high classification accuracy, and capability to determine variable importance (Rodriguez-Galiano *et al*. 2012). We used the randomForest package (Liaw and Wiener 2002) available in R (R Core Team 2012) to classify all the satellite images. In this study, 500 trees were used to construct the RF model. The parameter mtry, which represents the number of variables to be considered at every node, was specified as 2. For this RF model, mtry is the square root of the total number of variables used for classification. The classified LUC maps of the three cities are presented in Fig. 1. The extent or size of each LUC map was influenced by the extent of the individual images that are cloud-free. Clouds and cloud shadows are a common problem in the Southeast Asian region with regard to using optical remote sensing products like Landsat-8 imageries.

The individual accuracy of the classified LUC maps was assessed using at least 360 sample reference pixels or points for each map verified from Google Earth imageries. The LUC map of Bangkok had an overall accuracy of 92.64%, while the LUC maps of Jakarta and Manila had 92.78% and 93.06% overall accuracy, respectively.

2.2. Defining the spatial unit of analysis along the gradient of the distance from the city center

In order to compare the urban landscape patterns of the three major cities of Southeast Asia, a common spatial unit of analysis had to be defined. Therefore, we created an 18-km buffer zone around the city center of each study area (see Fig. 1). It should be noted that there is no suggested minimum or maximum size of buffer zone for such a purpose. In this study, the size of the buffer zone was influenced by the extents of the classified LUC maps, especially the LUC map of Jakarta, which has the smallest extent (Fig. 1).

The 18-km buffer zone was used to clip the LUC map of each study area. Within this buffer zone, six smaller multiple ring buffers around the city center, each with a zone size of 3 km, were created in all study areas. Using each of these 3-km buffer zones, the LUC maps were further clipped. Subsequently, all the LUC maps clipped with the 18-km and 3-km buffer zones were used as inputs in the analysis as explained below.

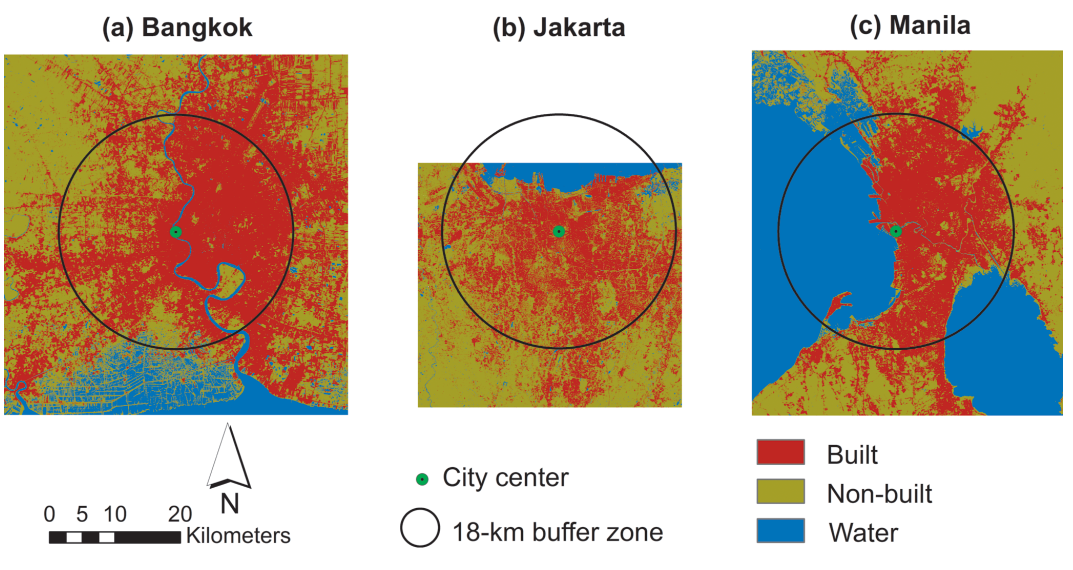

Fig. 1 Land-use/cover maps of the study areas. Notes: The water class was not included in the analysis. The figure also shows the geographic location of the centers of the three cities, and the 18-km buffer zone around each city center. (a) Bangkok City center: Grand Palace, Bangkok; (b) Jakarta City center: The National Monument, Central Jakarta; and (c) Manila City center: Kilometer Zero (KM 0) in Rizal (Luneta) Park, Manila. These city centers were identified based on geographical and socio-cultural (symbolism, historical) significance.

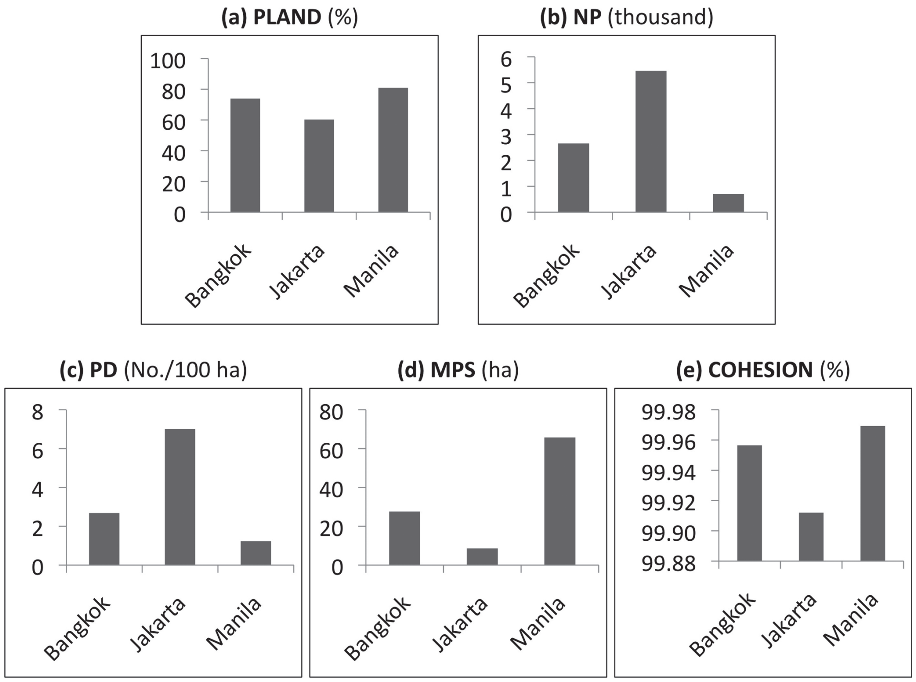

Fig. 2 The five landscape metrics of the built class based on the 18-km buffer zone spatial unit of analysis.

2.3. Landscape metrics: selection and derivation

To capture the urban landscape patterns of each of the three major cities based on the 18-km buffer zone spatial unit of analysis (i.e. 0-18 km from city center), and 3-km buffer zones created across the gradient of the distance from the city center (i.e. 0-3, 3-6, 6-9, 9-12, 12-15, and 15-18 km from city center), five class-level metrics were derived. These include the percentage of landscape (PLAND), number of patches (NP), patch density (PD), mean patch size (MPS), and patch cohesion index (COHESION). These metrics were selected with the aim to reveal the spatial patterns, e.g. composition, fragmentation, and aggregation, of the urban landscapes of the three major cities. All these metrics have been applied in previous studies (e.g. Luck and Wu 2002; Kamusoko and Aniya 2007; Weng 2007; Thapa and Murayama 2009; Estoque and Murayama 2013). The FRAGSTATS program (version 4; McGarigal *et al*. 2012) was used to derive these metrics from the input clipped LUC maps (with 18-km and 3-km buffer zones) of the study areas.

In the calculation of the landscape metrics, the water class in the LUC maps (Fig. 1) was excluded. Furthermore, the 8-cell neighbor rule was used to determine the membership of each pixel to a patch. In this rule, all the four orthogonal and four diagonal neighbors of the focal cell are used. In the 8-cell neighbor rule, two cells of the same LUC class that are diagonally touching are considered as part of the same patch, but in the case of the 4-cell neighbor rule, these are considered separate patches (McGarigal *et al*. 2012). We selected the 8-cell neighbor as it has been used in various studies (e.g. Townsend *et al*. 2009; Estoque and Murayama 2013; Tian *et al*. 2014).

More specifically, PLAND, a fundamental measure of landscape composition, is the proportion of the total area occupied by a particular LUC class, e.g. built. It can be used as a measure of density of built-up land or urban development, ranging from greater than 0 to less than or equal to 100 % ($0 < \text{PLAND} \leq 100$ %). NP can be used as a measure of fragmentation, diversity, and aggregation. This equals the number of patches of the corresponding LUC class ($\text{NP} \geq 1$). PD is a measure of fragmentation. It equals the NP divided by the total Landscape area (ha), multiplied by 100 (to convert to 100 ha) ($\text{PD} > 0$). MPS is also a measure of fragmentation; the average area of all the patches of a particular LUC class ($\text{MPS} > 0$ ha). Finally, COHESION is a measure of aggregation or physical connectedness, which approaches 0 as the proportion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected. It increases as the patch type becomes more aggregated in its distribution; hence, more physically connected ($0 < \text{COHESION} < 100$ %). These descriptions are based on the FRAGSTATS documentation (see McGarigal *et al*. 2012).

3. Results and discussion

3.1. Landscape metrics based on the 18-km buffer zone spatial unit of analysis

Fig. 2 presents the five derived landscape metrics of the built-up lands of the three cities based on the 18-km buffer zone spatial unit of analysis. The results reveal that Manila has the highest PLAND, followed by Bangkok (Fig. 2(a)). This shows that based on the defined spatial unit of analysis, Manila has the highest proportional extent or density of built-up land.

In terms of the NP of the three cities' built-up lands, Jakarta has the highest followed by Bangkok (Fig. 2(b)). This indicates that based on the NP, the urban landscape of Jakarta is the most fragmented among the three cities. This result conforms to the results of the PD (Fig. 2(c)) in which Jakarta also has the highest, indicating that it has the most fragmented urban landscape based on the density of built-up land patches.

In terms of MPS, Manila has the highest, followed by Bangkok (Fig. 2(d)). This indicates that the patches of the built-up lands of Manila are relatively larger than those of the other two cities. The COHESION of the patches of the built-up lands (Fig. 2(e)) also revealed the same pattern as the MPS for the three cities (Fig. 2(d)), indicating that Manila's patches of built-up lands are relatively more aggregated or physically connected than Bangkok, but more especially Jakarta.

3.2. Landscape metrics along the gradient of the distance from the city center

The following results were based on the individual 3-km buffer zones created along the gradient of the distance from the city center. Since each zone had to be individually analyzed, the LUC maps had to be clipped using each of the zones. Because of this, it was inevitable that the patches of built-up lands that lie on the border between two zones were divided. In effect, a single patch in the context of the entire 18-km buffer zone might have been divided into two or more patches in this zone-based gradient analysis. Aware of this situation, we present below the results of the gradient analysis and landscape metrics integrated approach.

Percentage of Landscape (PLAND)

Fig. 3 presents the PLAND of the built-up lands of the three cities along the gradient of the distance from their respective city centers. Overall, the results show an inverse relationship between PLAND and the distance from the city center in all three cities, i.e. the PLAND of their respective built-up lands decreases as the distance from the city center increases. This indicates that the density of built-up lands in all three cities is relatively higher in the zones closer to the city center.

It can be observed that in the 0-3 km zone, the PLAND of the built-up lands of Manila is relatively much lower than in the 3-6 km zone (Fig. 3). This is due to the presence of a golf course, parks, and other vegetated areas within this zone. From the 3-6 km zone to the 15-18 km zone, however, the PLAND of the built-up lands of Manila shows a decreasing trend as in the case of the other two cities.

It can also be observed that the pattern of the density of built-up lands of Manila shows some evidence for the presence of a "central density crater with a rim or crest", which can be likened to the Newling's model of urban population density (see Newling 1969). Zone by zone, Bangkok has the highest density of built-up land in 0-3 km zone, followed by Manila. From the 3-6 km zone to the 15-18 km zone, however, Manila shows consistency as the highest, followed by Bangkok, also in a consistent manner (Fig. 3). These results conform to Fig. 2(a), i.e. in the context of the 18-km buffer zone spatial unit of analysis and based on the PLAND, the urban development of Manila is relatively more intense than that of Bangkok, but more especially that of Jakarta.

Number of Patches (NP)

Fig. 4 presents the NP of the built-up lands of the three cities along the gradient of the distance from their respective city centers. Overall, the results show a direct relationship between NP and the distance from the city center in all three cities, i.e. the NP of their respective built-up lands increases as the distance from the city center increases. The proximity to the city center might have an influence on the NP, and so does the area of each buffer zone, which increases as the distance from the city center increases. The results indicate that the urban development in the three cities is relatively more fragmented in the zones farther from the city center.

The results also show that Jakarta is consistently the highest among the three cities in terms of NP across the gradient of the distance from the city center, which is also consistently followed by Bangkok (Fig. 4). It can also be observed that as the distance from the city center increases, the difference zone by zone in the NP of the built-up lands of the three cities also increases. These results conform to Fig. 2(b), i.e. in the context of the 18-km buffer zone spatial unit of analysis and based on the NP, the urban landscape of Jakarta is relatively more fragmented than that of Bangkok, but more especially that of Manila.

Patch Density (PD)

Fig. 5 presents the PD of the built-up lands of the three cities along the gradient of the distance from their respective city centers. Overall, the results show a direct relationship between PD and the distance from the city center in all three cities, i.e. the PD of their respective built-up lands increases as the distance from the city center increases.

This indicates that the urban development in the three cities is relatively more fragmented or less aggregated in the zones farther from the city center. This result conforms to the NP results.

It can be observed that Jakarta also shows consistency as the highest in terms of PD zone by zone, followed by Bangkok. The results also show that the PDs of the built-up lands of Bangkok and Manila are relatively much closer, whereas the PD of the built-up lands of Jakarta increases dramatically as the distance from the city increases (Fig. 5). These results also conform to Fig. 2(c), i.e. in the context of the 18-km buffer zone spatial unit of analysis and based on the PD, the urban landscape of Jakarta is relatively more fragmented or less aggregated than that of Bangkok, but more especially that of Manila.

<u>Mean Patch Size (MPS)</u>

Fig. 6 presents the MPS of the built-up lands of the three cities along the gradient of the distance from their respective city centers. Overall, the results show an inverse relationship between MPS and the distance from the city center in all three cities, i.e. the average size or area of the patches of their respective built-up lands decreases as the distance from the city center increases. The size of built-up land patches is relatively larger in the zones closer to the city center. This indicates that the urban landscape of the three cities is relatively more fragmented and less aggregated in the zones farther from the city center. This result conforms to the NP (Fig. 4) and PD (Fig. 5) results.

It can be observed that in the 0-3 km zone, the built-up lands of Bangkok have an exceptionally high MPS. This is due to its relatively high PLAND (Fig. 3), despite having a relatively low NP (Fig. 4) and PD (Fig. 5) in this zone. From the 3-6 km zone to the 15-18 km zone, however, Manila shows consistency as the highest in terms of MPS, followed by Bangkok. It can also be observed that, in the middle zones, the gap between the MPS of the built-up lands of Manila and the other two cities is wider than the gap between Bangkok and Jakarta (Fig. 6). Overall, these results conform to Fig. 2(d), i.e. in the context of the 18-km buffer zone spatial unit of analysis and based on the MPS, the patches of the built-up lands of Manila are relatively larger and less fragmented than those of Bangkok, but more especially those of Jakarta.

<u>Patch Cohesion Index (COHESION)</u>

Fig. 7 presents the COHESION of the built-up lands of the three cities along the gradient of the distance from their respective city centers. Overall, the results show an inverse relationship between COHESION and the distance from the city center in all the three cities, i.e. the physical connectedness of the patches of their respective built-up lands decreases as the distance from the city center increases.

It can be observed that the decline in the COHESION of the patches of the built-up lands of Bangkok as the distance from the city center increases is relatively smoother than that of the other two cities (Fig. 7). For Jakarta, the results show that the COHESION of its patches of built-up lands is stable in the first three zones but abruptly decreases in the succeeding zones. By contrast, the COHESION of the patches of the built-up lands of Manila shows an upward-downward-upward or a wavy pattern as it descends across the gradient of the distance from the city center. The results seem to show, however, that the urban landscape patterns of Bangkok and Manila are relatively more aggregated or physically connected than those of Jakarta as can also be observed in Fig. 2(e).

3.3. The use of zones for the gradient analysis and landscape metrics integrated approach

In the previous application of the gradient analysis and landscape metrics integrated approach, Luck and Wu (2002) constructed a transect that is 165-km long and 15-km wide and runs in an east-west direction, passing through the urban center of Phoenix metropolitan area, Arizona, USA. The transect was equally divided into 33 blocks, which served as units of analysis and from which various landscape metrics were derived. In another study in Dane County, Wisconsin, USA, Weng (2007) established a 60-km long transect, spanning from one rural area to the urban area and onto the other rural area, also in an east-west direction. Inside the transect, an almost equally spaced seven plots, with a size of 2,500 ha per plot, were established and used as units of analysis.

As demonstrated in the above-mentioned studies, the establishment of transect and plots can help in urban landscape pattern analysis, especially when the assessment is focused on a particular location, e.g. east-west direction. However, due to landscape heterogeneity, this approach might not be able to capture the pattern of the entire landscape of a given spatial unit of analysis. It is because the landscape pattern in the east-west direction may not always reflect the landscape pattern in the north-south direction, and so forth. This is especially so if several landscapes are to be compared.

In this study, by using a common spatial unit of analysis across the three urban landscapes, i.e. 18-km buffer zone around the city center, it was possible to capture the landscape pattern not only from an east-west or north-south direction, but rather the entire urban landscape within the zone. Furthermore, the six smaller zones created within this spatial unit of analysis, i.e. along the gradient of the distance from the city center, provide a common platform for a direct comparison, i.e. zone by zone, of the spatial patterns of three different urban landscapes. Thus, this technique is an alternative method for applying the gradient analysis and landscape metrics integrated approach.

4. Conclusions and future prospects

The results provide evidence that the proportional extent or density and aggregation of built-up lands in all three cities are inversely related to the gradient of the distance from the city center. By contrast, the fragmentation of built-up lands is directly related to the gradient of the distance from the city center. In other words, built-up lands have relatively higher density and are relatively more aggregated near the city center, but are relatively more fragmented in areas farther from the city center.

In the context of the entire 18-km buffer zone spatial unit of analysis, the results show that the urban development of Manila is relatively more intense than that of Bangkok, but more especially that of Jakarta. There is also evidence to conclude that the urban landscape of Jakarta is relatively more fragmented or dispersed than that of Bangkok, but more especially that of Manila. Furthermore, the urban landscape of Manila is also relatively more aggregated or physically connected than that of Bangkok, but more especially that of Jakarta.

Overall, the use of the gradient analysis and landscape metrics integrated approach, as applied in this study using a common spatial unit of analysis, has helped capture and, at the same time, compare objectively the spatial patterns

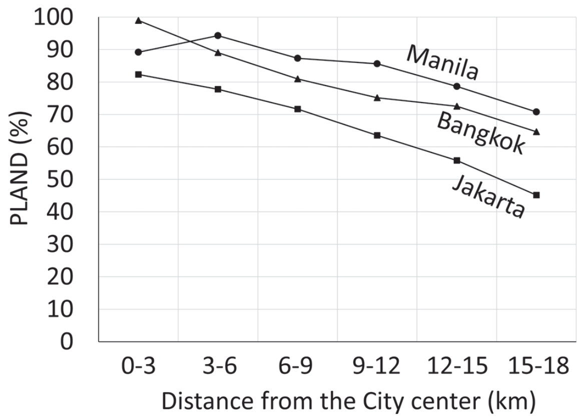

Fig. 3 PLAND of the built class along the gradient of the distance from the city center.

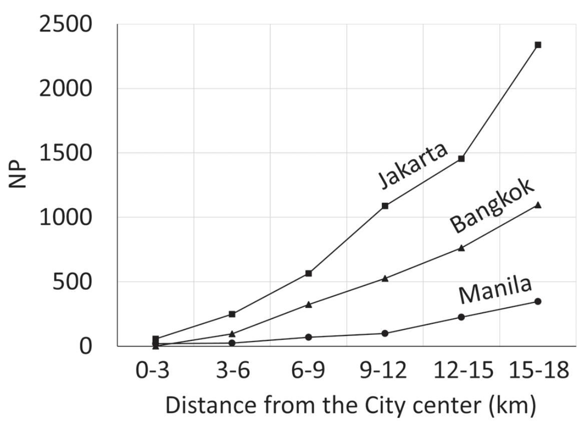

Fig. 4 NP of the built class along the gradient of the distance from the city center.

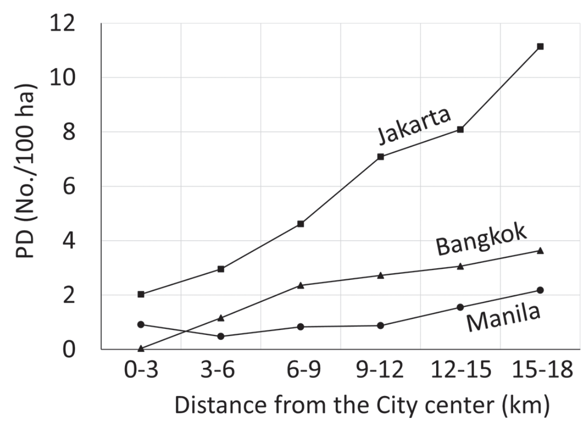

Fig. 5 PD of the built class along the gradient of the distance from the city center.

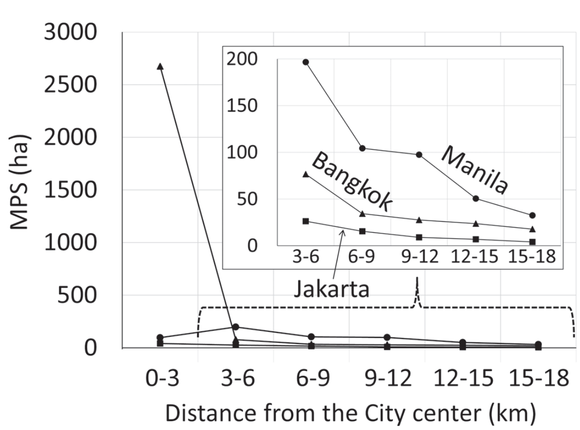

Fig. 6 MPS of the built class along the gradient of the distance from the city center.

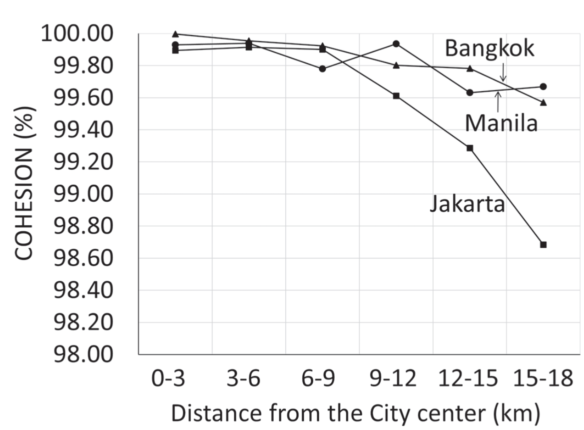

Fig. 7 COHESION of the built class along the gradient of the distance from the city center.

of three different urban landscapes. However, there are also some caveats and limitations that need to be considered in future studies. For example, the common spatial unit of analysis was set to an 18-km buffer zone only around the city centers of the three cities. This was limited by the extent of the LUC maps, especially for Jakarta, which lacked quality satellite imageries for the epoch considered. In future studies, there is a need to focus on a much larger common spatial unit of analysis. However, this could only be done once the limitation on the extent of the LUC maps has been overcome.

Additionally, in order to contribute further to the field of urban ecological research, more detailed and accurate LUC maps are needed in future studies. For example, the non-built class can be separated into several more detailed classes, including those that can represent vegetated areas such as forest, cropland and grassland. These more detailed LUC maps might be useful in the analysis of the potential environmental or ecological impacts of urbanization in the major cities of Southeast Asia, which is important in the context of urban sustainability studies.

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