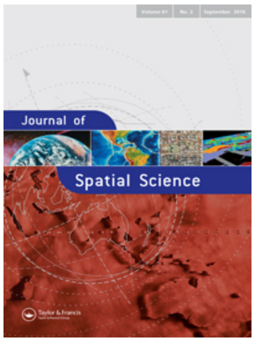

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Modelling building proximity to greenery in a three-dimensional perspective using multi-source remotely sensed data

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Urban vegetation is important for the well-being of urban residents. Remotely sensed datasets can be used to efficiently quantify urban green spaces (UGSs) across broad spatial extents. Different methods have been developed to quantitatively describe UGSs using remotely sensed datasets. However, few studies have taken the vertical dimension into consideration in evaluating human interactions with nearby greenery. In this study, a new index, called the '3D building proximity to greenery index' (3DBPGI), is proposed to evaluate the proximity of a building to its nearby urban greenery within a buffer distance by accounting for the building's height and different vegetation types. The 3DBPGI values for buildings in a Hungarian city, Székesfehérvár, were calculated. The results of the case study show that this index can indicate to some extent the human proximity to greenery for each building block in urban areas, which further can help planners to find critical areas for urban greening programmes.

KEYWORDS
urban green space (UGS); 3D building proximity to greenery index (3DBPGI); building's nearby greenery (BNG)

1. Introduction

Urban areas are the places of mass interactions between human and nature, and homes to a large proportion of the global population. Whereas only 10 percent of the global population lived in urban areas in 1900, the percentage now exceeds 50 percent (Grimm *et al*. 2008). The increasing population and spatial prominence make urban areas an important focus of study (Pickett *et al*. 2011). While human beings are increasingly living in urban areas, they continue to depend on the natural world for survival (Bolund & Hunhammar 1999). Urban green spaces (UGSs), including urban forest, shrubs, lawns and other kinds of green areas, are important element of the cityscape and have long been recognised for their importance in the urban environment. UGSs can mitigate the urban heat island effect, air pollution, noise pollution and even the probability of floods after heavy rainfalls (Miller 1997; Chen *et al*. 2006; Jim & Chen 2008; Onishi *et al*. 2010). Studies have indicated that exposure to green

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spaces contributes to public health (Wendel *et al*. 2011; Gidlow *et al*. 2012; van Dillen *et al*. 2012). The distribution of UGSs is thus an important indicator of urban environmental quality (Nichol & Wong 2005; Dwivedi *et al*. 2009; Seymour *et al*. 2010).

The aim of this paper is to analyse and evaluate the urban dwellers' proximity to nearby greenery. For this purpose, we examined 'building's nearby greenery' (BNG), as buildings are the main places where urban residents live, work and spend their free time. The BNG refers to all of the green vegetation located adjacent to a building within a short distance (Li *et al*. 2014). The BNG provides many important ecological services to people living or working in buildings (Costanza *et al*. 1997; Dimoudi & Nikolopoulou 2003; Ong 2003; Oliveira *et al*. 2011; Mackey *et al*. 2012; Ng *et al*. 2012; Srivanit & Hokao 2013). Evaluation of BNG can aid in quantifying the ecological benefits which residents receive directly from neighbouring vegetation. Generally, methods for measuring green spaces can be categorised into two types: subjective methods and objective methods. Subjective methods include the self-report method involving questionnaire surveys and the audit method, which requires trained raters to apply specific criteria to assess the environment (Ellaway *et al*. 2005; Hoenher *et al*. 2005). Subjective measures are both time-consuming and cost-consuming, and are always subject to differences in raters (Gupta *et al*. 2012). Objective measures of green spaces include the distance from a location to and the proportion of green spaces within a certain boundary, which can be derived using GIS and remote sensing technologies (Boone *et al*. 2009; Leslie *et al*. 2010; Zhou & Kim 2013). Remotely sensed imagery enables a rapid and efficient quantification of vegetation characteristics across a broad spatial extent (Garrity *et al*. 2008) and may provide new insights for city studies. Recently, Li *et al*. (2014) proposed a BPGI (building's proximity to green spaces index) to evaluate the proximity of a building to nearby green spaces, and found that the index held great potential for evaluating the proximity of residents to green spaces at the building level.

However, so far studies that considered the vertical dimension in evaluating human interactions with urban greenery are rare. Yang *et al*. (2009) proposed a green view index to quantify the visibility of greenery on the ground at different locations using street-level images. However, the evaluation process is tedious and time-consuming, which limits the application of the index to only small urban areas. Gupta *et al*. (2012) developed an urban neighbourhood green index (UNGI) to measure the distribution of UGSs at neighbourhood level using remote sensing techniques. The UNGI took the spatial distribution of UGSs, their interactions with urban built-up areas and the general height of the urban built-up areas into consideration. Schöpfer and Lang (2006) proposed a 'green index' by incorporating the percentage of multi-storey buildings, the percentage of green vegetation and the distances between buildings. By considering the vegetation volume and built-up volume, Tompalski and Wezyk (2012) developed a couple of 3D spatial indices to represent the living quality in a city in terms of greenery. However, in these studies the height of the urban built-up area was only used with the density of urban structures for determining neighbourhood types in residential areas or explicitly considered into the built-up volume, and the effect of the height of a specific building on its proximity to greenery was not studied. The heights of buildings are constituent parts of urban density, which further denote the density of people living in urban areas. In addition, the heights of buildings can affect human accessibility to green spaces or greenery outside the buildings. Places with larger greenery coverage but lower buildings may be perceived as much greener, and the height of buildings may decrease human-perceived greenery (Schöpfer & Lang 2006).

In this paper, a simple model for measuring the proximity of a building to nearby greenery was developed with consideration of the spatial distribution of greenery, vegetation types, and the horizontal and vertical dimensions of the building. A three-dimensional building proximity to greenery index (3DBPGI) was then proposed to evaluate the proximity of buildings to nearby greenery by extending the recently proposed building proximity to green spaces index (BPGI) (Li *et al*. 2014).

The remainder of this article is arranged as follows. Section 2 describes the index, Section 3 introduces the study site and data preparation, and Section 4 analyses the 3DBPGI maps. Section 5 discusses the pros and cons of the index. Section 6 offers conclusions.

2. Methodology for estimating building proximity to greenery

Housing-related information is closely connected to population (Webster 1996). Studies have shown that the distribution of buildings could represent the distribution of population to a large extent (Lu *et al*. 2010; Alahmadi *et al*. 2013). This paper aimed to develop an index for describing building proximity to greenery with consideration of building height, so as to provide a more objective measurement of the proximity of urban dwellers to nearby greenery. For simplification, in this study the index only considers the physical access (i.e. visiting) of urban dwellers to nearby greenery, considering the fact that people living in a high-rise building have to spend more time and energy to reach the ground (Thill *et al*. 2011).

Modified distance from a building to nearby greenery

Figure 1 shows an example of the spatial configurations of building blocks and nearby greenery. One can see that the horizontal distance between a building block and nearby greenery cannot indicate the proximity of the building to greenery exactly. People living on different stories generally do not have the same proximity to nearby greenery. Therefore, in this study we used the visiting distance as the measure of the proximity of a building to its BNG. The average distance from different stories of a specific building to its BNG was used to represent the modified distance from the building to its BNG. Figure 2 illustrates a three-dimensional view of the proximity of a building to a tree (representing nearby greenery).

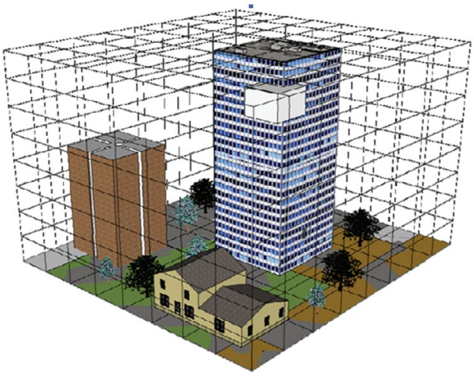

Figure 1. Illustration of a three-dimensional spatial configuration of building blocks and urban vegetation (Figure from Li, 2011).

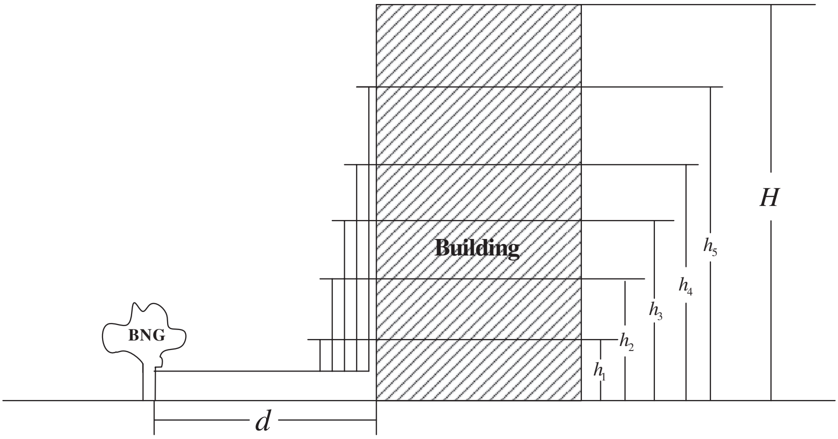

Figure 2. Illustration of the proximity of a building to nearby greenery.

In Figure 2, H is the height of a building block. By assuming the height of each storey is 3 metres, we can get the approximate number of stories of a building based on its H. Assume h_i is the height of the ith floor, and d is the horizontal distance between greenery (a tree or a piece of grassland) and a building. The visiting distance from the ith floor to a nearby greenery d_i (metres) can be calculated as:

$$d_i = d + 3 \times (i - 1) \tag{1}$$

The averaged visiting distance from different floors of a building to nearby greenery was used as the measure of the proximity of the building to the nearby greenery. We therefore computed the modified distance between a building and nearby greenery, D (metres), as

$$D = \frac{1}{n} \sum\nolimits_{i=1}^{n} d_i = d + \frac{3}{n} \sum\nolimits_{i=1}^{n} (i - 1) = d + 3(n - 1)/2, \tag{2}$$

where n is the integer number of stories in a building, which was calculated by dividing H by 3. If $H/3$ is not an integer, the decimal part is discarded to keep the number of stories as an integer.

Three-dimensional building proximity to greenery index (3DBPGI)

Figure 3 shows an example of the spatial configurations of buildings and nearby greenery in the horizontal dimension. The BNG for a specific building block is the sum of the green areas within the buffer line surrounding the building. The buffer line was drawn based on a constant horizontal distance from the building. Thus, when the buffer areas of neighboring buildings have some overlaps, these neighboring buildings share some greenery as their respective BNG.

If we only consider the greenery within a buffer zone of a building, a simple BPGI (building proximity to green spaces index) (Li *et al.* 2014) may be defined as

$$BPGI_i = \frac{green\_area_i}{buffer\_area_i}, \tag{3}$$

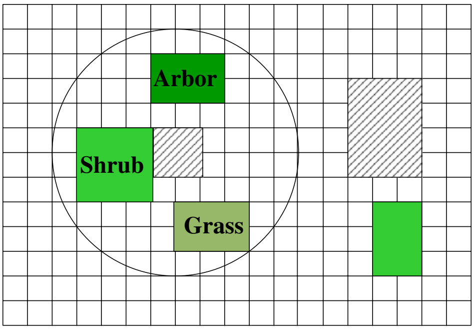

Figure 3. Illustration of a two-dimensional spatial configuration of buildings and vegetation areas. Green represents vegetation areas and shaded areas denote individual building blocks. The circle represents the buffer line surrounding a building.

where $green\_area_i$ refers to the greenery area within the buffer line of the *i*th building, and $buffer\_area_i$ is the buffered area of the *i*th building, which does not include the area of the *i*th building. The value of this BPGI ranges from 0 to 1: when the buffer zone is completely filled by green areas, the BPGI value is 1; when no green areas exist in the buffer zone, the BPGI is 0. Here *i* ranges from 1 to *n*, with *n* denoting the number of buildings in the study area. In this study, we used a simple method to calculate the distance between each pixel and the building boundary pixels by searching the whole image. The building boundaries were generated using the morphological operators from the binary building map. If the minimum distance is less than 20 m, we regarded the pixel to be in the buffer zone. Distance transformation was considered in the computing of minimum distances.

To account for the visiting distances of people in the building to its nearby greenery, we defined an *access coefficient* (AC) to modify the above BPGI. The AC represents the degree of ease for people in the building to visit its nearby greenery, and it is calculated as:

$$AC = \frac{buffer\_dist}{D} \tag{4}$$

where *buffer_dist* is the chosen buffer distance and *D* is the modified distance from a building to its nearby greenery, which is calculated by Equation (2). The *buffer_dist* is used to replace the *d* in Equation (2) for computing the modified distance *D*. AC values range from 0 to 1: when the modified distance *D* is the buffer distance, that is, when a building has only one story, its AC value equals 1, but when the modified distance *D* is very large, the AC value is close to zero. Thus, the 3DBPGI for a building may be simply defined as:

$$3DBPGI_i = AC_i \times BPGI_i = AC_i \times \frac{green\_area_i}{buffer\_area_i} \tag{5}$$

It is called a 3DBPGI because of its incorporation of the building height effect. Note that this 3D index takes into account only the effect of the physical visiting distance, particularly the effect of building height (i.e. stories), and the window view from a building to the nearby green spaces and other impact factors are ignored.

However, the $green\_area_i$ here is simply the horizontal area of greenery. If we consider the ecological differences among grasses, shrubs and arboreals, the $green\_area_i$ parameter may be modified to reflect the differences. The leaf area index (LAI) is usually used to indicate the total leaf area of plants in a UGS. This index is related to a range of ecological processes such as photosynthesis, transpiration and metabolism, which play key roles in providing ecological benefits (Ong 2003). We therefore used LAI to replace $green\_area_i$ in Equation (5) for computing the 3DBPGI:

$$3DBPGI_i = AC_i \times \frac{LAI_{BNG\_i}}{buffer\_area_i} \tag{6}$$

where LAI_{BNG_i} is the total leaf area of the BNG for the *i*th building. However, for simplicity we do not differentiate the distances from a building to different types of vegetation.

According to the 'Global Leaf Area Index Data from Field Measurements, 1932–2000' data-set (Scurlock *et al*. 2001), LAI values of various biomes range from 1 to 2 for grasslands, 2 to 4 for shrubs and 6 to 8 for plantations and wetlands. Based on the summary of this data-set, Ong (2003) simplified the LAI inversion process by setting LAI values for arboreals, shrubs, and grasses to 6, 3 and 1, respectively. Using the LAI values set by Ong (2003), Equation (6) is further transformed into:

$$3DBPGI_i = AC_i \times \frac{area_g + 3area_s + 6area_a}{buffer\_area_i} \tag{7}$$

where $area_g$ is the total area of grasses, $area_s$ the total area of shrubs and $area_a$ the total area of arboreals, in the BNG of the *i*th building. In this study, we used Equation (7) as the final equation for calculating the 3DBPGI, which not only considers the total green area around a building within a buffer distance, but also takes into account the effects of visiting distances and vegetation types.

3. Study area and data preparation

Study area

Székesfehérvár is the 10th largest city in Hungary and is located in the Middle-Transdanubian region of Hungary. This region has a continental climate with an average temperature of 14°C. Annual precipitations vary between 400 and 700 mm. In 2010, the region had a human population of 101,973, with a population density of 594 people/km^2. Székesfehérvár ranks amongst the medium-sized cities in the country (Wojtaszek *et al*. 2012).

A 5-km^2 area, located in the centre of the city, was chosen as the study area. The study area covers the major part of the urban area in Székesfehérvár (Figure 4). Downtown and commercial areas are located in the centre and lower left of the study area, and the residential areas are mainly distributed in the upper right and periphery regions.

Data preparation

The land cover information, vegetation map and digital surface model (DSM) used in this study were from Li *et al*. (2014) by processing LiDAR data and aerial imagery. LiDAR data and aerial imagery were acquired during a flight mission undertaken on 30 May 2008. Based on

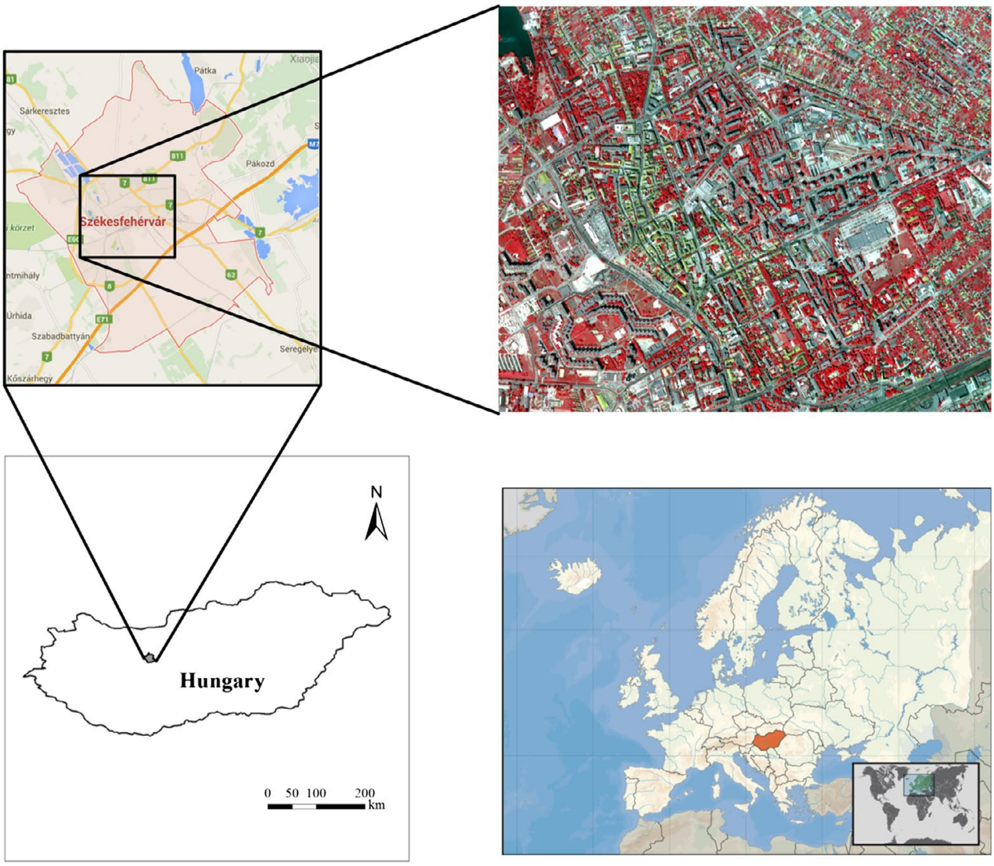

Figure 4. The location of the research area.

the DSM generated from LiDAR data, the building height model was further generated by combination of the DSM with the binary building map, and vegetation was further categorised into three categories, namely, grass, shrub and arboreal. In the vegetation map, vegetation with a height below 0.4 m was identified as grass, that with a height between 0.4 m and 2 m was regarded as shrub, and all other areas were assumed to be arboreal. Note that there is no farmland in the study area, where the land is typically urban with densely distributed buildings; thus crops and vegetables were considered as one category – vegetation. Figure 5 shows the land cover map, and the building height model of the study area.

4. Results

3DBPGI and its relation to buffer distance

3DBPGI values were calculated for each building block using Equation (7) based on the vegetation map (Figure 5(a)) and the building height model (Figure 5(b)). Considering the difficulty of choosing an exact buffer distance for calculation of 3DBPGI maps, we generated a series of 3DBPGI maps at a series of buffer distances. Figure 6(a) shows a series of buffer lines (buffer distances of 10, 20, 30, 40, 50, 60, 70 and 80 m) around each of the two selected

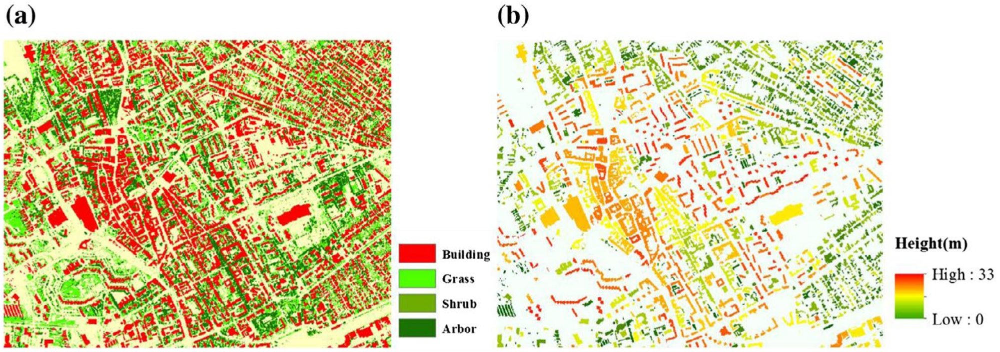

Figure 5. The classification map of buildings and different vegetation types (a), and the building height model (b) in the study area.

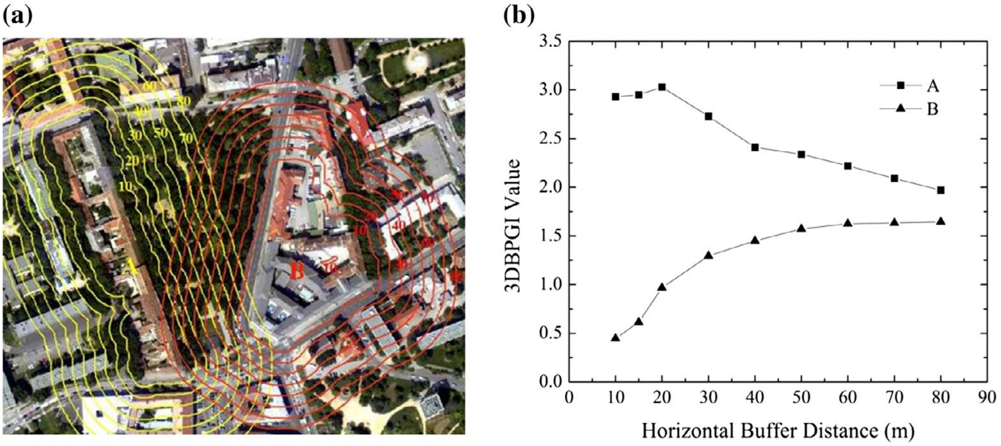

Figure 6. (a) Buffer lines drawn with different horizontal buffer distances from 10 m to 80 m for each of the two chosen buildings (building A and building B). (b) Changes of the 3DBPGI values with increasing horizontal buffer distances (i.e. from 10 m to 80 m) for building A and building B, respectively.

buildings (building A and building B) in the study area. As shown in Figure 6(a), when the buffer distance is greater than 20 m, the buffer zone of a building (e.g., building A and building B) may cover some areas of vegetation that are closer to other buildings. This means that when the buffer distance is relatively large, neighbouring buildings may share some vegetation areas in their buffer zones as their respective BNGs. Such a situation is normal when buildings are in close proximity.

Figure 6(b) shows the changes of the 3DBPGI values of building A and building B at different buffer distances. The changes of the 3DBPGI values of these two buildings show very different trends as the buffer distances increase. For building A, its 3DBPGI values first increase a little at shorter buffer distances (i.e. 10, 15 and 20 m), then quickly drop down with increasing buffer distances (i.e. after 30 m). However, the 3DBPGI values for building B first quickly increase and then gradually arrive at a stable status with increasing buffer distances. This is in accordance with the fact that buffer zones will cover some green spaces closer to other buildings when the buffer distance is greater than 20 m (Figure 6(a)). Therefore, a buffer

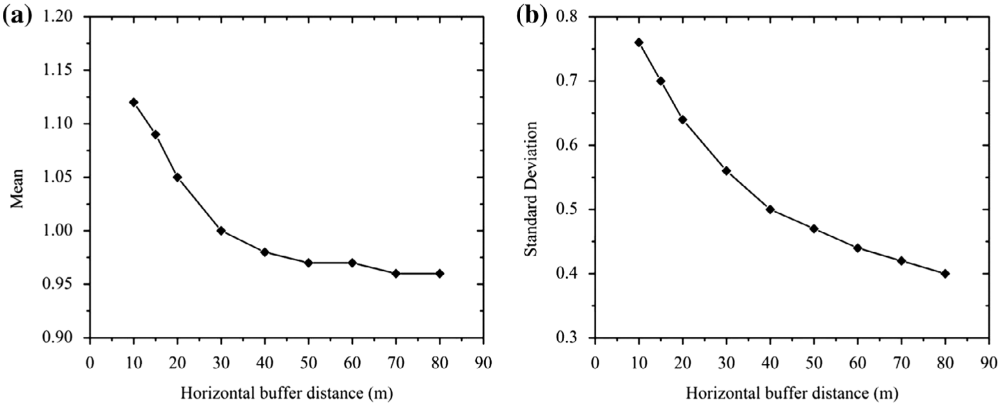

Figure 7. Changes of the mean values and standard deviations of the 3DBPGI data with different buffer distances in the study area.

distance of 20 m may be more suitable for calculation of 3DBPGI based on the above analysis. When buffer distances are greater than 40 m, the 3DBPGI values for both buildings become relatively stable, and the differences of the 3DBPGI values between the two buildings become smaller. Figure 7 shows the changes of the mean values and standard deviations of the 3DBPGI values for all buildings in the study area with increasing buffer distances. The 3DBPGI mean values at different buffer distances show a value change range from 0.96 to 1.12. They first decrease quickly with increasing buffer distances, then keep stable at the buffer distances greater than 40 m (Figure 7(a)). The standard deviations of the 3DBPGI values, however, always decrease with increasing buffer distances. The standard deviation at a buffer distance of 10 m is 0.76. It goes down sharply to 0.40 at a buffer distance of 80 m (Figure 7(b)). The changing of the mean values and standard deviations of 3DBPGI with increasing buffer distances strengthens the understanding that a large buffer distance will smooth the differences in a building's proximity to nearby greenery for buildings in the study area. Therefore, the buffer distance was chosen as 20 m in this study.

Comparison of 3DBPGI with a two-dimensional index

The comparison of the 3DBPGI and a two-dimensional green space index was conducted. We chose the BPGI_LAI defined below as a representative of the two-dimensional greenery indices to illustrate the merits of the 3DBPGI. BPGI_LAI is an adjusted version of the BPGI recently proposed by Li *et al*. (2014). The following formula defines the BPGI_LAI:

$$BPGI\_LAI_i = \frac{LAI_{BNG\_i}}{buffer\_area_i} \tag{8}$$

where LAI_{BNG_i} is the total leaf area of the BNG for the *i*th building and $buffer\_area_i$ is the buffered area of the *i*th building, which does not include the area of the *i*th building. Figure 8 shows the two-dimensional BPGI_LAI map and 3DBPGI map together with the difference map generated by dividing BPGI_LAI by 3DBPGI. In the two-dimensional index map, the value for each building was determined by the total leaf area of nearby greenery, while

3DBPGI takes the building height into consideration. The height of a building tends to reduce the human-perceived environmental amenity of the building's nearby greenery. By comparing the difference map (Figure 8(c)) and the building height model (Figure 5(b)), it is apparent that high buildings have relatively lower values in the 3DBPGI map (Figure 8(b)) than they have in the BPGI_LAI map (Figure 8(a)), and the differences are larger for higher buildings. This means that the 3DBPGI is more reasonable for measuring the distribution of a building's proximity to nearby greenery by considering the building height.

Spatial distribution of 3DBPGI

A larger 3DBPGI value indicates that a building has closer proximity to greenery, which may be a sign of more opportunities for urban dwellers in the building to enjoy the benefits provided by the BNG. It is obvious that the 3DBPGI values are distributed unevenly across the study area (Figure 8(b)). Larger values are mainly located in the upper left and the lower right parts, and apparent smaller values appear close to the lower left corner. The spatial distribution of high 3DBPGI values is in accordance with the spatial distribution of vegetation, especially arboreal. This point can be explained by Equation (7). The distribution of 3DBPGI values is also influenced by the building height model. In the building height model, several high-rise buildings located in the middle and right areas are much higher than the rest of the buildings; consequently, in the 3DBPGI map (Figure 8(b)), these high-rise buildings show relatively low values. This can be explained by the fact that a higher building has a larger average distance for people in the building to visit the BNG (see Equation (2)), which leads

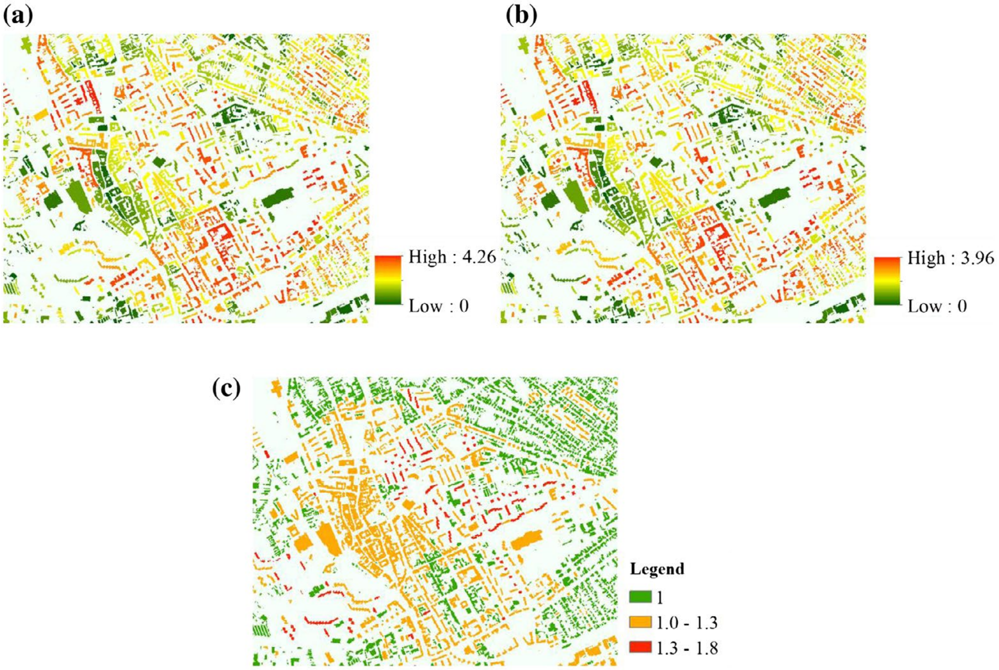

Figure 8. Comparison of the 3DBPGI map with the two-dimensional BPGI_LAI map in the study area. (a) BPGI_LAI map, (b) 3DBPGI map, (c) the difference map generated by dividing BPGI_LAI by 3DBPGI.

to a lower access coefficient (see Equation (4)) and consequently a lower 3DBPGI value based on the Equation (7).

Uncertainty analysis of 3DBPGI

Uncertainty analysis is helpful for understanding how reliable and meaningful the estimates of the 3DBPGI are. In this study, the LAI estimation, which is used to calculate the 3DBPGI values, has obviously spatial and seasonal variability and thus may impact the spatial distribution of the 3DBPGI values. Therefore, uncertainty analysis of 3DBPGI was conducted using a mathematical simulation approach. Based on analysis of the 'Global Leaf Area Index Data from Field Measurements, 1932–2000' provided by Scurlock *et al*. (2001), we assumed that the LAI values for arboreal, shrub and grass follow normal distributions, that is, $LAI_{Arboreal} \sim N\,(6, 4)$, $LAI_{Shrub} \sim N\,(3, 2)$, and $LAI_{Grass} \sim N\,(1, 1.5)$, respectively, for simplification.

We further generated the LAI maps of arboreal, shrub and grass randomly based on the above normal distributions 10 times, and calculated the corresponding 3DBPGI maps at a buffer distance of 20 m based on the randomly generated LAI maps of different vegetation types. Figure 9 presents the standard variance of 3DBPGI values for each building block and changes of the mean 3DBPGI values from different simulations. The largest standard deviation of 3DBPGI values from the 10 simulations is less than 0.04 (Figure 9(a)), which is negligible compared with the 3DBPGI values. The narrow range of 3DBPGI values from different simulations demonstrates the reliability of 3DBPGI in relation to the LAI variations of different vegetation types. Figure 9(b) shows that the mean values of 3DBPGI from different simulations range from 1.050 to 1.052. Compared with the mean value of 3DBPGI, the mean value changes from different simulations are also negligible, which further proves the stability of the 3DBPGI in relation to the LAI variations.

5. Discussion

The 3DBPGI proposed in this study integrates the building height effect and vegetation types into an index for measuring the proximity of buildings to nearby greenery by

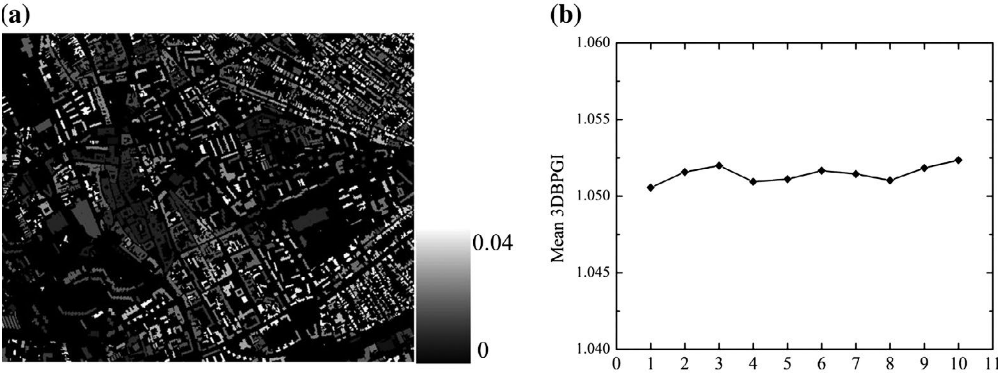

Figure 9. (a) Spatial distribution of standard variance of 3DBPGI values for individual building blocks based on different simulations. (b) Changes of the mean values of the 3DBPGI from different simulations with a buffer distance of 20 m.

considering visiting distances. This index may serve as a new quantitative measure of human proximity to greenery at the building level. In the proposed 3DBPGI, it is assumed that the proximity of a building to its nearby greenery can indicate the possible benefits that humans get from urban greenery, considering that most urban residents spend a majority of their time in buildings. Unlike the previously proposed green metrics in the literature to measure urban greenery at either areal level or neighbourhood level, the 3DBPGI proposed in this study is defined at building level. This entails consideration of the three-dimensional effect of a building on measuring human proximity to its nearby greenery. It is difficult, if not impossible, to use the percentage method or other traditional methods to reflect the three-dimensional effect. Different from the existing greenness indicators, the proposed 3DBPGI can map the distribution of human proximity to urban greenery at building level (Figure 8(b)), and thus can help to find the critical areas for further urban greening projects. Generally, a higher 3DBPGI value means more opportunities for the building's dwellers to enjoy the environmental benefits of nearby greenery. In the study area, there exists obviously uneven 3DBPGI distribution. Those buildings with large 3DBPGI values are mainly located in the upper left and the lower right parts, and buildings with small values appear close to the lower left corner. The 3DBPGI values are influenced by the heights of buildings and the LAI values of nearby greenery. To increase the 3DBPGI values, planners have two choices: one is to increase vegetation nearby; the other is to decrease the heights of buildings. In most cases, planners cannot change the heights of the existing building blocks. In this situation, planners need to add more green vegetation to increase the 3DBPGI values to the level of the low-rise buildings.

Quantifying the three-dimensional effect of a building and its nearby greenery on the proximity of humans to urban greenery is a complex issue. There may be several aspects in the three-dimensional effect in terms of human perceptions of greenery at the building level: (1) the visiting distance for direct visits to nearby greenery; (2) the viewing scope from building windows or balconies to outside greenery; (3) building types; (4) building volume; and (5) blocking from close nearby buildings, among other factors. What we took into account in the index computation is the first aspect. Although the other aspects, especially the window viewing, are very important, they are difficult to quantify. For example, for a residential building, it is difficult to determine the number of windows, the sizes of windows, the sides on which windows are located in the building, the viewing angles of humans, and whether there are balconies on the building, while all of these can impact the human viewing scope to the outside greenery. It is also difficult to allocate weights for the effects of these factors based on current understanding and knowledge.

Building volume may be used to measure the adequacy of surrounding greenery. Using the building volume to represent the population in a building is more intuitive. However, since our current 3DBPGI mainly aims to measure the human proximity to nearby greenery (i.e., accessibility), incorporating building volume will inevitably change its meaning. Nevertheless, from the angle of the adequacy of greenery, building volume should indeed be considered. Future studies may be conducted to further explore this issue. More work needs to be done to compare the 3DBPGI map with human perception of greenery and urban dwellers' opinions on the nearby greenery, or other subjective ratings.

Further, using LiDAR-based canopy density may be better for representation of urban greenery than using LAI. However, since the current 3DBPGI method is calculated based on the ratio of total leaf area and the area of non-building area in the buffer zone and both of these two variables have units of m^2, we used LAI instead of LiDAR-based canopy density for calculating 3DBPGI. This could make the 3DBPGI independent of the unit. In addition, LAI is much easier to use for urban planning applications. Uncertainty analysis result shows that the proposed 3DBPGI is stable and reliable in relation to potential spatial and seasonal LAI variations. Although the 3DBPGI does not incorporate all of the factors that impact human perceptions of nearby greenery at the building level, it has demonstrated some interesting characteristics, as shown in the above analysis. Apparently, this index can indicate to some extent the human proximity to greenery from each building block in urban areas. It may also be used to represent residents' perception of UGSs at the district level, because the mean or median values of the 3DBPGI data of all buildings in a specific district or city may indicate the overall proximity of buildings to greenery at the district or city level. Therefore, this index is expected to be useful in future applications. Urban planners may use this index to maximise human proximity to greenery when planning the limited space in crowded urban areas. Estate sectors may use it to evaluate the environmental amenity of buildings from the greenness perspective, as urban green spaces such as parks have a strong impact on residential property values (Lin *et al*. 2013).

In addition, sometimes building blocks extracted from remotely sensed imagery may be connected. In this study the connected building blocks were treated as one single building. How to exactly extract each single building block is an issue to explore in further studies. With the help of municipal buildings maps, this problem may be overcome.

6. Conclusions

We suggested a 3DBPGI for representing the human proximity to urban greenery at the building level with a specific buffer distance and mapping its spatial distribution in a study area. The index takes into account the greenery and vegetation types within a buffer distance around a building and the effect of the building height on the visiting distances from the building to nearby greenery. Because the 3DBPGI value for a building is determined by the building height, the total leaf area of BNG and the buffer distance, high-rise buildings tend to have smaller 3DBPGI values compared to low-rise buildings, and larger vegetation coverage in the buffer area can result in a higher 3DBPGI value. As the LAI values of arboreals are normally higher than those of grasses and shrubs, increasing arboreal areas within the buffer line will also increase the 3DBPGI value.

The current version of 3DBPGI only considers the distances between greenery and a building, vegetation types, and the building height effect on the visiting distances from the building to its nearby greenery within a buffer line, and does not consider other factors impacting human perceptions of the proximity to greenery, such as the window-viewing to outside greenery and the different types of buildings (e.g., residential, commercial). However, these ignored factors do have impacts on the human perception of proximity to nearby greenery at the building level. In future studies, human window-viewing to greenery outside buildings and building types should be considered in measuring the 3DBPGI.

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