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Effective green equivalent—A measure of public green spaces for cities

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ABSTRACT

Quantifying the public green space required by urban residents is a fundamental aspect of sustainable urban planning and management. This paper proposes a metric of effective green equivalent (EGE), which is defined as the area of green space multiplied by corrected coefficients of quality and accessibility. Based on the EGE values of individual residents, two city-level indicators are developed: (1) average EGE, which refers to the average level of EGE values of all urban residents within the urban boundary; and (2) an inequality coefficient, which measures the inequality of EGE distribution across the urban area. Three indicators (EGE, average EGE, and the inequality coefficient) were used to measure the real green spaces of the urban residents of Beijing, China. The results showed that the EGE values for individual residents in Beijing follow a normal distribution. The average EGE value is 355.49 ha per resident and the inequality coefficient value is calculated to be 0.24, indicating that the current public green spaces of Beijing can basically meet residents' requirements. These indicators can thus be applied to urban public green space planning practice.

1. Introduction

Urban green spaces are an indispensable infrastructure in cities and can provide urban residents many essential benefits, including recreation, culture, and education (Bolund and Hunhammar, 1999; Cameron et al., 2012; Smith et al., 2013). Urban residents are entitled to the benefits of conveniently accessible green spaces (Bastian et al., 2012; Chiesura, 2004). Compared with private green spaces, public green spaces (PGS) should play a major role in the urban green system, especially in more densely populated urban areas (Coolen and Meesters, 2012; Niemelä, 2014). As public goods, PGS are important sources of urban residents' environmental welfare, and the quantity of PGS has a huge influence on their quality of life (van Kamp et al., 2003).

A series of measurement approaches have been used to quantify the PGS resources of urban residents. Most of these have simply focused on the total and per capita area to measure the richness of PGS in cities. Moreover, this indicator—per capita area—is inconsistent with the concept of urban PGS as a public good. It is instead incorrectly based on the concept of personal property, which by default divides PGS into equal independent areas in line with the number of residents, and then distributes the PGS throughout the urban system accordingly (Lauf et al., 2014; Witte and Geys, 2011). However, while residents are equally entitled to all of the PGS resources within an urban boundary, factors such as quality and accessibility affect the real benefits acquired (Gupta et al., 2012; Wright Wendel et al., 2012). Therefore, the total area of PGS, without considering quality and accessibility, is an overly optimistic measurement.

Accessibility is thus important. The green area within an accepted range, commonly within walking distance from residential areas, is generally used as a measure of the available PGS resources (Langford et al., 2008; Schipperijn et al., 2010; Villeneuve et al., 2012). However, it may be necessary for multiple-level accessibility to be calculated to obtain the actual green area for each level of user (Barbosa et al., 2007; Wright Wendel et al., 2012). The quality of green space is also an important factor in the calculation of effective PGS (Romero et al., 2012), because high-quality PGS can provide many more benefits than low-quality areas (Tian et al., 2014). Thus, data on the effective area of PGS should be corrected by incorporating quality differences between green spaces (Wendel et al., 2011). For example, ecological green equivalent space is taken as the quality measure for green spaces with different vegetation covers (Liu et al., 2002). These measurements can more reliably quantify the effective urban PGS area from the perspectives of accessibility and quality.

There are few case studies of the integrated evaluation of the accessibility and quality of green spaces in relation to residential PGS resources. In this paper, we develop three new indicators of effective green equivalent (EGE), average EGE, and an inequality

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coefficient (IC), as supplements for the conventional measurement of green spaces. Section 2 describes the methodology of the proposed indicators. Section 3 documents a case study of Beijing to illustrate the use of these indicators, and Section 4 presents the results of this case study. Finally, Section 5 gives a brief discussion of the effectiveness of these indicators.

2. Methodology

2.1. Effective green equivalent

2.1.1. Definition of EGE

Here we develop an indicator for measuring the PGS resources that truly benefit every resident. For convenience, the PGS system is denoted as $\{g_k, k = 1, 2, \ldots, n\}$, where g_k is the kth green patch in n independent green patches. Similarly, the population of urban residents is denoted as $\{p_i, i = 1, 2, \ldots, m\}$, where p_i is the ith individual in all m urban residents. We take green patch g_k and resident p_i as an example. Theoretically, the amount of PGS resources that g_k provides for p_i is equal to the area of g_k. In practice, the two factors of g_k, quality and accessibility, may weaken its effectiveness for p_i. Only when the quality, accessibility, and area of g_k are all in ideal conditions are residents able to acquire maximal benefits. Therefore, the area of g_k should be corrected by integrating its quality and accessibility factors in order to accurately measure the services or benefits that g_k provides for p_i. This corrected area of green spaces is called the effective green equivalent (EGE).

The EGE that g_k provides for p_i can be expressed as

$$\mathrm{EGE}(p_i, g_k) = S(g_k) \times q(g_k) \times a(g_k, p_i) \tag{1}$$

where $S(g_k)$ denotes the area of g_k, and $q(g_k)$ and $a(g_k, p_i)$ are correction coefficients that quantify the performances of the quality and accessibility factors, respectively. If all of the green spaces are taken into consideration, then the total EGE of resident p_i may be expressed as

$$\mathrm{EGE}(p_i) = \sum_k \mathrm{EGE}(p_i, g_k) = \sum_k S(g_k) \times q(g_k) \times a(g_k, p_i) \tag{2}$$

where $\mathrm{EGE}(p_i)$ quantifies the PGS that truly benefit resident p_i. The calculation of the two correction coefficients, $q(g_k)$ and $a(g_k, p_i)$, is described below.

2.1.2. Quantification of $a(g_k, p_i)$

We took p_i and g_k as examples to quantify $a(g_k, p_i)$, the correction coefficient based on accessibility. Accessibility is mainly determined by the least road distance $d(g_k, p_i)$, which is the minimum total length of all possible paths from p_i residence to green patch g_k. When $d(g_k, p_i) = 0$ (i.e., the place of residence adjoins the target green patch) then the accessibility is in an ideal state, denoting as $a(g_k, p_i) = 1$. When $d(g_k, p_i)$ gradually increases within the tolerable daily walking range, the accessibility value will decrease steadily; when exceeding the threshold, the accessibility value will decline rapidly. If $d(g_k, p_i)$ keeps increasing, accessibility will enter a poor state and no longer be sensitive to distance, and theoretically, when $d(g_k, p_i)$ is infinite there is no accessibility at all [i.e., $a(g_k, p_i) = 0$]. These features of $a(g_k, p_i)$ are similar to the symmetrically rotated form of an S-shaped growth curve. Here, the formula of $a(g_k, p_i)$ is derived based on the classic Logistic Equation and by taking into account the boundary conditions, 0–1. The correction coefficient based on accessibility is expressed as follows:

$$a(g_k, p_i) = \left(1 + \frac{1}{r_1}\right) \times \left(1 - \frac{1}{1 + r_1 e^{-r_2 d(g_k, p_i)}}\right) \tag{3}$$

where r_1 and r_2 are positive parameters and are determined by the residents' experiences about accessibility.

2.1.3. Quantification of $q(g_k)$

When the quality of green patch g_k is significantly poor, it is almost impossible for the residents to acquire benefits and this situation can be denoted as $q(g_k) = 0$. However, it is difficult to determine what qualities are most desirable in PGS. In practice, green space g_0 can be pre-selected as a reference template that is able to provide the residents with satisfying recreation experience. Under this condition, $q(g_0)$ is set as 1. The quality of other green patches can be evaluated by referring to the green space g_0. Here we adopt a normalized difference vegetation index (NDVI) to evaluate the quality of green spaces. The average NDVI over green patch g_k is equal to $q(g_k)$, the correction coefficient based on quality, which is expressed as follows:

$$q(g_k) = \frac{\int_{S(g_k)} \max(\mathrm{NDVI}, 0)\mathrm{d}s}{S(g_k)} \tag{4}$$

where max(NDVI, 0) denotes the maximum value between NDVI and 0, ranging from 0 to 1.

Substituting Eqs. (3) and (4) into Eq. (2), we calculate EGE as

$$\mathrm{EGE}(p_i) = \sum_k \left[\left(1 + \frac{1}{r_1}\right) \times \left(1 - \frac{1}{1 + r_1 e^{-r_2 d(g_k, p_i)}}\right) \times \int_{S(g_k)} \max(\mathrm{NDVI}, 0)\mathrm{d}s \right] \tag{5}$$

2.2. Average effective green equivalent

A city-level indicator is defined to measure the average EGE of all residents within the city boundaries, termed the average effective green equivalent (AEGE). The value of AEGE equals the mean of all individual-resident's EGE and can be expressed as

$$\mathrm{AEGE} = \frac{1}{m} \sum_i \mathrm{EGE}(p_i) \tag{6}$$

where m is the total number of urban residents.

Regardless of individual differences among residents, the higher a city's AEGE value is, the more PGS resources are available to its urban residents. The urban AEGE also follows the law of diminishing marginal utility. When AEGE exceeds a certain threshold, the utility growth acquired by a continuous increase of unit AEGE declines. Meanwhile, excessive PGS will occupy the space needed for other socio-economic activities, negatively affecting coordinated development of the city as a whole. Therefore, it is necessary to find out the residents' basic demand and utility saturation threshold.

2.3. The inequality coefficient

The inequality coefficient (IC) is proposed directly using the Gini coefficient in economics as a reference, and measuring the income inequality of residents. It is calculated by drawing the Lorenz curve (Dorfman, 1979). Here we replace income with the EGE of urban residents to derive the IC. It can be expressed as

$$\mathrm{IC} = \frac{1}{m} \left[m + 1 - 2 \left(\frac{\sum_i (m + 1 - i) \times \mathrm{EGE}(p_i)}{\sum_i \mathrm{EGE}(p_i)} \right) \right] \tag{7}$$

where IC ranges from 0 to 1 and $\mathrm{EGE}(p_i)$, $i = 1$ to m, is indexed in non-decreasing order $[\mathrm{EGE}(p_i) \leq \mathrm{EGE}(p_{i+1})]$.

The higher a city's IC value is, the more unequal the PGS distribution is among the urban residents. A set of reference values should be established to explain the meaning of IC values. For example, we can directly adopt the reference values of the Gini coefficient, where <0.2 is basically equal, 0.2–0.4 is an acceptable range, and >0.4 is highly unequal.