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The cooling effect of urban green spaces as a contribution to energy-saving and emission-reduction: A case study in Beijing, China

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ABSTRACT

Urban green spaces have been proven to significantly decrease ambient air temperature and mitigate heat islands created by urbanization. However, the environmental benefits of cooling provided by urban green spaces have rarely been measured. In this paper, we estimated the energy-savings and emission-reduction contribution of urban green spaces in Beijing, applying a empirical model. Our calculations suggest urban green spaces play a major role in reducing energy demand and increasing CO_2 sequestration. Urbanized Beijing has 16,577 ha of green space which could absorb 3.33×10^{12} kJ of heat via evapotranspiration during the entire summer. The cooling effect reduced the air conditioning demand by 3.09×10^{8} kWh which amounts to a 60% reduction in net cooling energy usage in Beijing. The annual reduction in CO_2 emissions from power plants associated with electricity saving would reach 243 thousand tons with an average of 61 kg/(ha day). Also, the cooling effect and the environmental benefits of urban green space in Beijing largely depend on the green space's structure and size. Urban managers and landscape planners should take advantage of this research to plan, design and manage green spaces in heat island areas.

1. Introduction

Climate change is the most serious problem people face in the 21st century. Luke Howard first described the concept of an urban heat island (UHI) as early as 1833 [19]; an UHI is the characteristic area of warmth found in urban areas when compared with their non-urbanized surroundings [55]. When non-reflective, water-resistant or impervious surfaces which absorb a high percentage of incoming solar radiation replace naturally vegetated surfaces, an UHI is often created. Taha (1997) and Shahmohamadi et al. (2011), [53,48] investigated the impact of anthropogenic heat on formation of urban heat island, and proposed the three important strategies to minimise the impact of UHI on energy consumption: landscaping, using albedo materials on external surfaces of buildings and urban areas, and promoting natural ventilation. Many scientists agree higher temperatures not only impact the comfort of urban dwellers, but also increase energy use for cooling, ozone production, and the risk of death for humans during a heat wave [14,20,41].

Under a scenario of rapid urbanization around the world's cities, the development of UHIs has recently become a critical environmental issue in many places [30,35,45]. Fortunately, trees and vegetation in an urban environment can greatly improve the microclimates, as well as mitigate UHI development by reducing summer air temperatures [12]. Urban vegetation cools climates through two major processes: shading and evapotranspiration [46,50]. The direct effect of shading refers to the interception of solar radiation by leaves and branches of trees; this reduces the sunlight reaching the ground below the canopy of a tree or plant. An investigation in Australia demonstrated that, tree shade could reduce wall surface temperatures by up to 9 °C and external air temperatures by up to 1 °C [4]. The indirect effect of evapotranspiration is the sum of evaporation and plant transpiration, which reduces air temperatures because of the use of energy required for transpiration. A systematic study in Chania of Greece showed that, urban green areas could reduce air temperature 3.1 °C, mainly through evapotranspiration [16].

Studies in western countries have mainly focused on the tree-shading effects which provide cooling energy at the local scale in

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low-density residential neighborhoods. Oliveira et al. (2011) [37] observed that a small green space (0.24 ha) was cooler than the surrounding areas. The greatest observed temperature difference was 6.9 °C, which occurred between a shaded site in the garden and a sunny during the hottest month of the year in Lisbon, Portugal. Correa et al. (2012) [10] measured the thermal comfort in forested urban canyons of low building density in the city of Mendoza, Argentin. The evaluation showed that the road channels forested with Platanus acerifolia had the best behavior. There also have been many similar studies in Brazil [51], Mexico [21], Switzerland [34], USA [2,49], England [17], and Germany [56]. Since 1970, many new megacities have arisen in Asia because of rapid urbanization [54], and the interactions between urban green spaces and microclimate conditions in high-density cities have been paid much attention [9,52,57,62]. Mahmoud (2011) [33] measured user's thermal comfort in an urban park in Cairo, Egypt, and revealed an alteration in human comfort sensation between different landscape zones. A preliminary study in Taipei, randomly surveyed the cool-island intensity of 61 city parks, and found that during summer the cooling effect of parks was stronger than in winter [8]. The study in high-rise high-density residential developments of coastal Hong Kong, suggested that increasing the tree cover from 25% to 40% in the pocket parks could reduce daytime urban heat island intensity (UHI) by further 0.5 °C [18]. Another experience from Hong Kong revealed that roof greening was ineffective for human thermal comfort near the ground, and trees were more effective than grass surfaces in cooling pedestrian areas [43].

However, studies in Chinese mainland cities usually centered on the effect of evapotranspiration in urban green space on microclimate, because almost all residents live in multi-story buildings (e.g. Refs. [24,64,65]. Because of the lack of the information related to the direct cooling effect, public and city managers in China often ignore or underestimate the environmental contribution of urban green spaces to the cooling effect. More importantly, the influences of species composition, size, growth, crown density, and the spatial arrangement of urban green spaces in large and dense cities on cooling potential have been recognized [22,42,47], but few studies paid attention to the cooling effect and the environmental benefits of urban green spaces with various structural characteristics.

The objective of this research is to measure the ecological benefits of the cooling effect associated with the use of green spaces where heat islands are more likely to occur. We specifically focus on the environmental contribution of the cooling effect on energy-savings and carbon-emission-reduction, which generated from seven types of urban green spaces in Beijing. After this introduction related to current research we next elaborate on the methods and data used in this study followed by findings and concluding remarks.

2. Materials and methods

2.1. The study area

The densely populated northern city of Beijing is the capital of China (39°28′–41° 05′N, 115°25′–117°30′E), with a land area of 16,808 million km^2 and a population of 19.61 million [3]. Beijing is also a representative metropolis with rapid urbanization and was 86.2% urbanized by the end of 2011. The city is divided into four zones: the city center (Dongcheng and Xicheng districts), the main urban area (Chaoyang, Fengtai, Haidian, and Shijingshan districts), and two suburban areas (Changping, Daxing, Fangshan, Huairou, Mentougou, Pinggu, Shunyi, and Tongzhou districts and Miyun and Yanqing counties). The road network of Beijing City consists of the recently constructed ring roads and radial arteries. The road around the Forbidden City is called be the first ring road, and the outer ring roads are the second, third, fourth, fifth and sixth ring roads, respectively, in terms of distance from the city center [63].

Urban heat island conditions have been observed for more than a half century in Beijing [66,67]. Based on the climatic data from 11 weather stations in Beijing during the period of 1961–2008, Wang et al. (2009) found the UHI intensity increased slowly from the mid-1960s to the late 1970s and subsequently continued to intensify starting in the early 1980s (see Fig. 1). The summertime UHI in Beijing city currently averages 4.5 °C [60]. Also, the areas of UHI rapidly expanded from 111 km^2 in 1987 to 292 km^2 in 2009, and the extent of UHI sharply increased from 11% to 27% of the urbanized area [29] (see Fig. 2). These space-time dynamics of UHI change can be mainly attributed to the rapid urbanization of Beijing [39].

Green spaces are beneficial to UHI mitigation through shading and evapotranspiration [37]. The urban green space in Beijing sprawls across 61,695 ha. We chose 6387 green-space patches totaling 44,356 ha as the study area, all located within the 6th Ring Road (see Fig. 3). Also, we analyzed the structural type of urban green space defined as the combination of different growth forms such as trees, shrubs, or herbs. The statistics revealed seven structural types of urban green spaces in Beijing, which were composed of 21.89% Tree (as a category), 0.09% Shrub, 0.42% Grass, 13.55% Tree-Shrub, 12.52% Shrub-Grass, and 2.38% Shrub-Grass; for a total green space area of 22,556 ha. The remaining 49.15% consists of Tree-Grass-Shrub. Table 1 provides the definition (or description) and percentage of each structural type of urban green space in Beijing; Fig. 3 shows the spatial distribution of these different structural types.

2.2. Research methods

A three-step approach was developed. First, an empirical model was designed to represent the heat absorbed by urban green spaces via evapotranspiration, based on a statistical analysis of eight field measurements in Beijing. Second, the energy savings for environmental cooling was calculated by employing the transform coefficient between electrical energy and heat. Finally, an average CO_2 emission parameter in Beijing was adopted to estimate the amount of CO_2 emission reduction.

2.2.1. Heat absorbed through evapotranspiration

Evapotranspiration in green vegetation allows the ambient atmosphere to absorb the latent heat of vaporization during the vaporization of water used by plants [22] and significantly decreases the ambient air temperature. The thermal effects of green

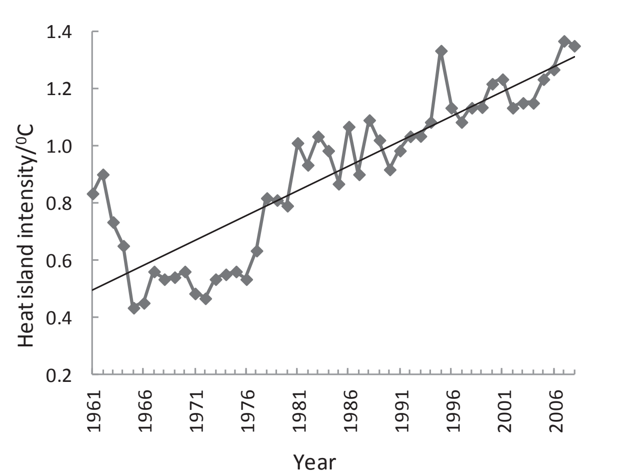

Fig. 1. Dynamic change in the intensity of Beijing's heat island from 1961 to 2008.