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How can urban water bodies be designed for climate adaptation?

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ABSTRACT

With rapid urbanization and population growth in Beijing, urban heat island (UHI) effects have become ever stronger. Methods for reducing the UHI effects by landscape design are becoming increasingly critical in urban planning studies. Water bodies form urban cooling islands (UCI) to mitigate the UHI effects. This study investigated the UCI intensity and efficiency of 197 water bodies in Beijing, and their relationships with four descriptors of microclimatic landscape design, including the water body area (WA), geometry (landscape shape index, LSI), location (DIST) in reference to a defined city center, and surrounding built-up proportion (PB). Data of land cover and land surface temperature (LST) were extracted from ASTER images of August 8 of 2007. The UCI intensity was defined as the maximum LST gradient outside a water body area, while the UCI efficiency was used to represent the UCI intensity per unit area of a water body. The results indicated that: (1) the mean UCI intensity and efficiency was 0.54 °C/hm and 1.76 °C/hm/ha, respectively; (2) the UCI intensity was positively correlated with WA and PB, and negatively correlated with LSI and DIST; and (3) the UCI efficiency was positively correlated with PB, and negatively correlated with WA, LSI and DIST. Results of this study may help urban planners and designers in decision making to achieve optimal urban landscape designs for a more ecologically sound and pleasant living environment.

1. Introduction

The urban population in the global total population has risen dramatically from 13% in 1900 to 46% in 2000, and is likely to reach 69% by 2050 (UN-DESA, 2010). The rapid urbanization is accompanied by high levels of concentration of the urban population and built-up areas in many countries. The urban heat island (UHI) effect develops when cities replace their natural land with impervious surfaces, buildings, and other infrastructure (Jauregui, 1997; Liu & Weng, 2008; McMichael, 2000). The main reasons of UHI effects are changes in the thermal properties of surface materials and lack of evapotranspiration through lack of vegetation and water bodies in urban areas. The negative impacts of UHI are well known such as increasing energy consumption, compromising human health and comfort, and intensifying carbon dioxide emissions (Patz, Campbell-Lendrum, Holloway, & Foley, 2005; Rizwan, Dennis, & Liu, 2008; Vanos, Warland, Gillespie, & Kenny, 2010; Xu, 2009).

Urban microclimate is closely correlated with the types and patterns of landscape in the urban environment. The fundamental goal of landscape design is to create a living area that matches the local environment and meets the human needs (Forman, 1997; Givoni, 1998; Simonds, 2007). As Zhao pointed out (2011), “Feng Shui” is one of the venerable ideas in China, and climate consideration of which has usually be employed to find desired locations according to the type and configuration of the surrounding landscape. Principally, ecological landscape design needs to integrate inputs from landscape ecology and design with an ultimate aim to reinforce the natural and cultural spirit of a living place (Lovell & Johnston, 2009; Makhzoumi, 2000; Shashua-Bar, Pearlmutter, & Erell, 2009). While these concepts are important as guiding principles, collection and use of urban environmental data is essential to substantiate ecological landscape designs on a more scientifically sound basis.

The unreflected radiation of total solar radiation reaching the Earth’s surface is called net radiation, which is transformed into sensible heat, latent heat through the evaporation of water, conductive sensible heat, and energy accumulated in the biomass via photosynthesis (Bristow, 1987; Kravcik, Pokorny, Kohutiar, Kovac, & Toth, 2008). The primary importance of water bodies for the urban climate is in its influence on the transformation of sensible and latent heat fluxes. On the one hand, the high heat capacity produces the “thermostat effects” of water bodies in comparison to surrounding building materials (Spronken-smith, Oke, & Lowry, 2000). On the other hand, the high evaporation leads to obvious “oasis effects” of water bodies and plays an important role in reducing surrounding surface air temperature (Oke, 1987). Water

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bodies thus function as cooling islands (UCI) in urban area due to temperature difference to its nearby environment in summer (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Chang, Li, & Chang, 2007; Rizwan et al., 2008). Attempts have been made to study the microclimate of city parks and gardens using in situ measurements and meteorological station data (Barradas, 1991; Chen & Wong, 2006; Huang, Li, Zhao, & Zhu, 2008; Jauregui, 1991; Saaroni, Ben-Dor, Bitan, & Potchter, 2000; Shashua-Bar & Hoffman, 2000). These studies were conducted at single sites, thus mainly reflect site-specific cooling effects of city-parks on a local scale. Likewise, there are many regional studies focusing on the thermal environment on citywide scales, particularly with regards to the intensity of UHI effect (Buyantuyev & Wu, 2010; Rajasekar & Weng, 2009) and their influencing factors, such as city size, population, traffic loads, vegetation, and evaporation (Bonan, 1997; Bottyán & Unger, 2003; Hung, Uchihama, Ochi, & Yasuoka, 2006; Liu & Weng, 2008; Spronken-smith et al., 2000; Streutker, 2003; Xiao et al., 2008; Zhao, Fu, Liu, & Fu, 2011). However, these regional studies placed little focus on the site-specific microclimatic conditions, and provided even less information on the factors influencing the cooling effects of water bodies. Although more recent efforts have been attempted to study the UCI effect on both local and regional scales (Cao, Onishi, Chen, & Imura, 2010; Chang et al., 2007), relatively less results is available to explain the UCI effect in relation to the descriptors used in a particular landscape design.

Quantitative relationship of the UCI effect with the landscape design descriptors is important for making specific recommendations to best urban land use optimization. For example, knowledge about the exact extent to which a specific water body design would impact the wider urban thermal environment, and whether these effects are due to water bodies alone may help the development of an ultimate tool for city planners and designers to more efficiently manage the urban thermal environment. In this study, we extracted spatial information on the land cover and land surface temperature (LST) using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images. The objectives of the study are to: (1) identify the UCI intensity of water bodies inside the sixth ring-road of Beijing; and (2) quantify the relationship between the UCI effects of multiple water bodies and landscape design descriptors, including water body area, geometry, location in reference to a defined city center, and surrounding built-up proportion. The ultimate goal of this study is intended to provide useful information on the microclimates within a city scale and landscape design measures for managing the urban thermal environment.

2. Study area and data

2.1. Study area

Beijing is the capital of China and is densely populated, with a total population exceeding 19.7 million and with 5 million automobiles by the end of 2010. The rapid urbanization and city expansion started from the late 80s, resulting in significant UHI effects. Previous studies have found that the mean daily temperature in urban areas is 4.6° higher than that in the suburbs (Song & Zhang, 2003). Beijing is characterized by a warm temperature zone and has a typical continental monsoon climate with four distinct seasons (Ding, Zheng, & Liu, 2010). The intensity of UHI effect is highest in autumn in Beijing (Cai, Du, & Xue, 2011). Our study area targeted the region inside the sixth ring-road of Beijing, with an area of 2000 km^2 (Fig. 1). This region has faced rapid urban development (Xiao et al., 2008). The water bodies in this area are thus particularly valuable for mitigating the UHI effects.

2.2. Land surface temperature

LST data were extracted from ASTER images taken at 11:00 a.m. on August 8, 2007 by the Center for Earth Observation and Digital Earth, Chinese Academy of Sciences. The ASTER images are multispectral data with a 16-day recurrent cycle onboard NASA's EOS-Terra satellite, covering a wide spectral region of visible to near infrared bands (VNIR, 15-m spatial resolution), shortwave infrared bands (SWIR, 30-m spatial resolution), and thermal infrared bands (TIR, 90-m spatial resolution). The ASTER LST products were calculated from five TIR bands between 8 and 12 μm using the temperature and emissivity separation algorithm (Fig. 1A). These ASTER LST data have been used to estimate radiation budgets and heat-balance parameters in urban climate studies (Buyantuyev & Wu, 2010; Gillespie, Rokugawa, Hook, Matsunaga, & Kahle, 1998; Nichol, Fung, Lam, & Man, 2009; Weng, 2009).

2.3. Land cover classification

The land cover types (i.e., water area, green land, and built-up land) were extracted from the three VNIR bands of ASTER images with a 15-m resolution. An interactive spectral classification procedure was adopted. Ground reference data were first obtained for land cover classification using GPS-guided field surveys. At least 20 areas of interest (AOI) were selected for each class, with each AOI containing 50–200 pixels. Two thirds of the pixels were used to compare the spectral reflectance value for each land cover type, and the rest were used for the classification accuracy assessment.

After analyzing the spectral reflectance value of AOIs, we classified water bodies, green land, and built-up land using the normalized difference vegetation index (NDVI) and spectral reflectance value. The NDVI was calculated from the near infrared (*Band3*) and red (*Band2*) bands of ASTER images, defined as:

$$\text{NDVI} = \frac{Band3 - Band2}{Band3 + Band2} \tag{1}$$

The pixels were defined as green land when $\text{NDVI} > 0$ and $Band3 > Band1 > Band2$. In the non-green areas ($\text{NDVI} < 0$), pixels with $b1 < 70$ and $Band1 > Band3$ were classified as water. Otherwise, the pixels were classified as built-up land (Fig. 1B).

Lastly, we evaluated the classification results using the Kappa coefficient and overall accuracy index in the ERDAS software. The overall accuracy index was 94.25% and the Kappa coefficient was 0.92. To obtain the LST for small water bodies and match the land cover map, the 90-m ASTER LST data were resampled with a 15-m resolution.

3. Data processing

3.1. Analytical units

Data for water bodies larger than one hectare (ha) inside the sixth ring-road of Beijing were used excluding rivers and canals. Moreover, the selected water bodies should have locations separated by 1500 m or more between each other. A total of 197 water bodies were finally selected under the above selection criterion (Fig. 1B).

Fifteen buffers around each water body were created with 1 hectometer (hm) interval using the buffer analysis module in ArcGIS software. The LST gradient was calculated as the temperature difference per unit buffer distance outside a water body. The maximum LST gradient was used as the measure of the UCI intensity (°C/hm) for a given water body. Accordingly, the UCI scale (m) was defined as the distance between the water body and the buffer corresponding to the maximum LST gradient. The UCI efficiency