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Cooling effects of wetlands in an urban region: The case of Beijing

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ABSTRACT

The cooling effects of wetlands, which form "urban cooling islands" (UCIs), are important for mitigating urban heat island effects. Ten reservoirs/lakes and five rivers in Beijing are selected to investigate UCI intensity using ASTER images. The UCI intensity is quantified by the temperature difference and gradient between the wetland and surrounding landscapes. The results indicate that: (1) the UCI intensity is correlated with the landscape shape index (LSI) of the wetlands, and the Spearman Rho is 0.679 between LSI and temperature difference, and 0.568 between LSI and temperature gradient; and (2) the UCI intensity is also determined by the wetland location in relation to the downtown, and the correlation coefficient is 0.691 between the location and temperature difference, and 0.706 between the location and temperature gradient. Our results suggest that wetland shape and location are significant indicators influencing the UCI intensity in an urban region, and are important to consider in quantifying the microclimate regulation services of wetlands as well as in designing urban landscape to mitigate UHI effects.
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1. Introduction

Urbanization is a global issue, particularly for many developing countries, and about 60% of the world's population will live in cities by the year 2030 (Golden, 2004). Rapidly growing urban areas result in obvious increases in temperature in comparison to temperatures in adjacent rural regions, an effect which is known as the urban heat island (UHI) effect (Tiangco et al., 2008; Weng, 2009). As UHI effects lead to increased temperatures within cities, they contribute to worsened air quality and compromised human health (Xu, 2009; Pataki et al., 2011). In metropolitan areas, various landscape types and their spatial mosaic patterns create a complicated energy balance and microclimate system (Oke, 1982), and this landscape heterogeneity may lead to large intra-urban surface temperature differences (Buyantuyev and Wu, 2010).

Wetlands include reservoirs, lakes, and rivers, and form many "urban cooling islands" (UCIs) (Chang et al., 2007; Cao et al., 2010). The cooling effect of wetlands is regarded as an important ecosystem regulating service (Costanza et al., 1997). The environmental benefits of ecosystem regulating services have long been valued in economics (Wilson and Carpenter, 1999; Jaarsveld et al., 2005; Hein et al., 2006; Troy and Wilson, 2006; Li et al., 2010; Lautenbach et al., 2011). However, little information is available for individual wetlands because most UHI studies are implemented at the scale of an entire city. For example, we do not know how different the temperatures in wetlands are from those in the surrounding landscapes, or whether there are different spatial scales within which the cooling effects of wetlands are effectively provided. We need to know the temperature difference and influence scale of wetlands which are the determinants for the existence of UCI. Also, which factors impact the UCI intensity is still unknown. Answering these questions could help us adopt more appropriate indicators to quantify the microclimate regulation services of wetland ecosystems, and could provide us with practical measures for urban landscape design.

The UHI effect refers to the difference in air temperature above ground between urban and adjacent rural regions. Air temperature has proved to be highly correlated with the land surface temperature (LST) (Nichol and Wong, 2008; Weng, 2009). LST has often been used to assess the UHI effect because LST can be extracted easily from remote sensing data at a given moment and over broad areas (Weng, 2001; Nichol and Wong, 2008; Rajasekar and Weng, 2009; Buyantuyev and Wu, 2010). In this study, we also investigated the cooling effects of wetlands by using LST and land cover data derived from ASTER (advanced spaceborne thermal emission and reflection radiometer) images. The objectives are: (1) to devise a method to quantify the UCI intensity of wetlands, (2) to assess the impacts of wetland area, shape, and location on UCI intensity in Beijing, and (3) to discuss the implications for ecosystem services assessment and landscape design in urban regions.

2. Data and methods

2.1. Study area

Beijing city is situated in north China, has an area of 16,808 km^2, and ranges from 39°28′ N to 41°05′ N and from 115°25′ E to 117°30′ E (Fig. 1). Beijing is the capital of China and is densely populated. The

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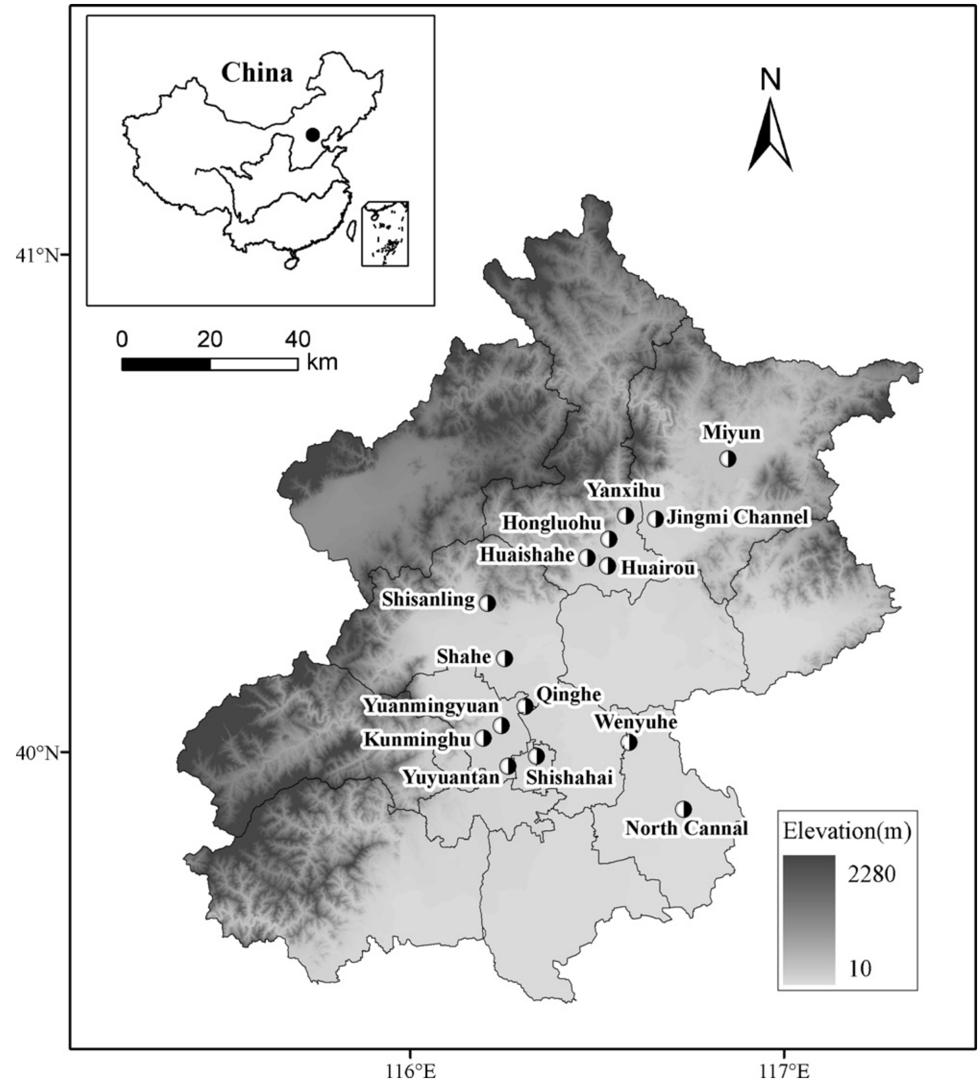

Fig. 1. Location of the 15 wetlands in Beijing.

total population exceeded 20 million and the number of automobiles reached 5 million by the end of 2010. Environmental problems are becoming increasingly serious with the expansion of built-up areas. Among these problems, the UHI effect is one of the most obvious (Liu et al., 2007; Xiao et al., 2008). Historically, about 15% of the total area of Beijing was wetland, declining to 7% in the 1960s, and covering only 3% of the total area recently (Zhao et al., 2006). It is highly important to better understand the cooling effect of wetlands for landscape design to mitigate the UHI effects.

2.2. Information on LST and land cover

This study used four ASTER images from 11:00 a.m. on August 8, 2007, covering a belt (approx. 180 km × 60 km) from downtown to the suburbs of Beijing. The ASTER images have 14 bands including visible and near-infrared bands (VNIR, 15-m spatial resolution), short wave infrared bands (SWIR, 30-m spatial resolution), and thermal infrared bands (TIR, 90-m spatial resolution) (Nichol et al., 2009). The ASTER LST products are calculated by the temperature emissivity separation algorithm (Gillespie et al., 1998), and have been atmospherically emissivity corrected by the Center for Earth Observation and Digital Earth, Chinese Academy of Sciences. To match the land cover map, the 90-m ASTER LST data were resampled with a 15-m resolution (Fig. 2a).

The ASTER VNIR data were used to identify land cover types (i.e., green land, built-up land, and wetlands). First, we obtained ground reference data for land cover classification using GPS-guided field surveys. At least 20 areas of interests (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 type of land cover, and the rest were used for the classification accuracy assessment. Second, we classified green land, built-up land, and wetlands using the normalized difference vegetation index (NDVI) and spectral reflectance value. The NDVI was calculated from the near infrared and red bands of ASTER VNIR data (Jensen, 2005). The pixels were defined as green land when $NDVI > 0$ and $Band3 > Band1 > Band2$. In the non-green areas ($NDVI < 0$), pixels with $b1 < 70$ and $Band1 > Band3$ were classified as wetlands. Otherwise, the pixels were classified as built-up land (Fig. 2b).

Lastly, a standard procedure was applied for accuracy assessment of land cover classification in the ERDAS software (Jensen, 2005). The overall accuracy of the land cover classification was at 92.25%, and the overall Kappa coefficient was at 0.91. The final accuracy of land cover classification indicated that the image processing procedure developed has been effective. The total area of wetlands was 274 km^2, smaller than the areas of the green land (5825 km^2) and built-up land (2084 km^2). 5 rivers and 10 reservoirs/lakes in Beijing were extracted from the land cover map (Fig. 1). The area

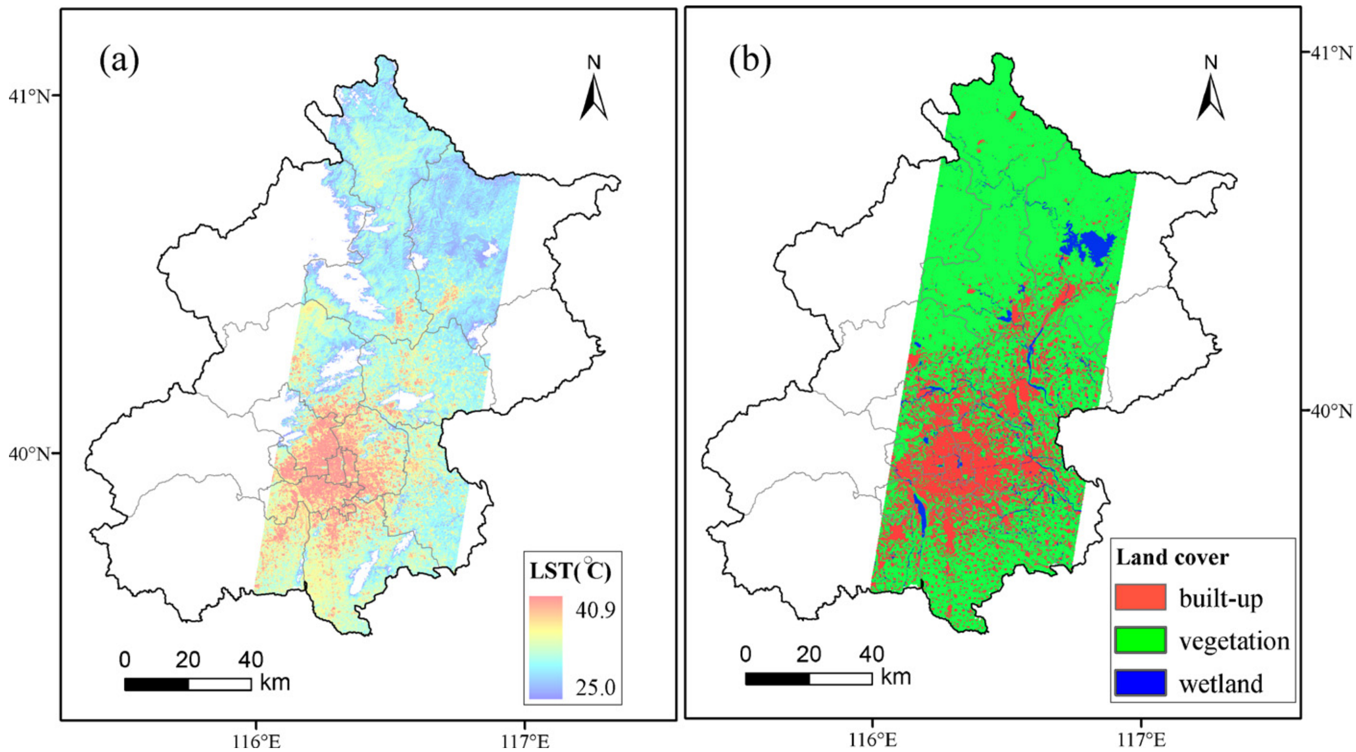

Fig. 2. Land surface temperature (LST, a) and land cover (b) in 2007 in Beijing.

of 15 wetlands was 146 km^2 accounting for 53% of the total area of wetlands.

2.3. Descriptors of UCI intensity

Continuous buffers around each wetland were created with 50-m interval using the spatial analytical module in ArcGIS software. We averaged the LST in each buffer and plotted the LST curves for the 15 wetlands. The turning point of LST curve was selected manually where the slope of LST curve changed sharply or reached a relatively flat level (Fig. 3). LST around a wetland may be influenced by other adjacent wetlands, such as the interaction between Qinghe River and Yuanmingyuan Lake. LST variation was also influenced by surrounding mountains such as in Miyun, Huairou, and Shisanling Reservoir. These impacts can make LST curves increasing firstly and then decreasing. Therefore, we designated the first turning point of LST curves to measure the turning distance of each wetland. Temperature difference was calculated between the wetland temperature and the buffer temperature at the turning point. Temperature gradient was defined by the temperature difference and the turning distance of each wetland.

2.4. Descriptors of wetland characteristics

Spearman rank correlation coefficient (Spearman Rho) was used to quantify the relationship between wetland characteristics and descriptors of UCI intensity. The wetland location was defined as its distance from the center of the downtown designated as the center point inside the second ring-road of Beijing. The wetland area was extracted from land cover maps. The wetland shape was characterized by using three descriptors including landscape shape index (LSI), perimeter–area ratio (PAR), and patch–fractal dimension (PFD). The LSI was found highly correlated with other descriptors, and the Pearson correlation coefficients reached 0.78 and 0.89 for PAR and PFD, respectively. The LSI has proved effective in evaluating the compactness of city parks (Cao et al., 2010). Therefore, only LSI was used in the current analyses. Ideally, the LSI equals 1.00 for a circle and 1.13 for a square, and it will increase with increasing landscape shape irregularity (McGarigal and Marks, 1995).

$$\mathrm{LSI} = \frac{L}{2\sqrt{\pi \times A}} \qquad (1)$$

where L is the total perimeter of a wetland, and A is the wetland area.

3. Results

3.1. Spatial characteristics of wetlands and UCI intensity

The mean area of the fifteen wetlands was 9.76 km^2, ranging from 0.46 km^2 for the Yuyuantan Lake to 98.68 km^2 for the Miyun Reservoir (Table 1). The mean LSI was 7.25, ranging from 1.58 for the Shisanling Reservoir to 21.88 for the Jingmi Channel. The mean LSI of the rivers (14.78) was significantly larger than that of the lakes and reservoirs (3.49).

The mean temperature of wetlands was 28.33 °C, lower than the average green land temperature (28.43 °C) and the built-up land (31.82 °C). The turning distances ranged from 400 m in the Yanxihu Lake to 2500 m in the Miyun Reservoir, with an average of 963 m. The mean temperature difference was 2.6 °C, ranging from 0.7 °C in the Jingmi Channel to 5.84 °C in the Yuyuantan Lake. The mean temperature gradient was 3.34 °C/km, ranging from 0.52 °C/km in the Miyun Reservoir to 6.88 °C/km in the Shichahai Lake. Wetlands with a temperature gradient greater than 5 °C/km were all inside the fifth ring road of Beijing. Turning distance of 15 wetlands had no significant correlation with temperature difference and gradient, whereas temperature difference was correlated to temperature gradient with a Spearman Rho of 0.795 ($p < 0.01$).

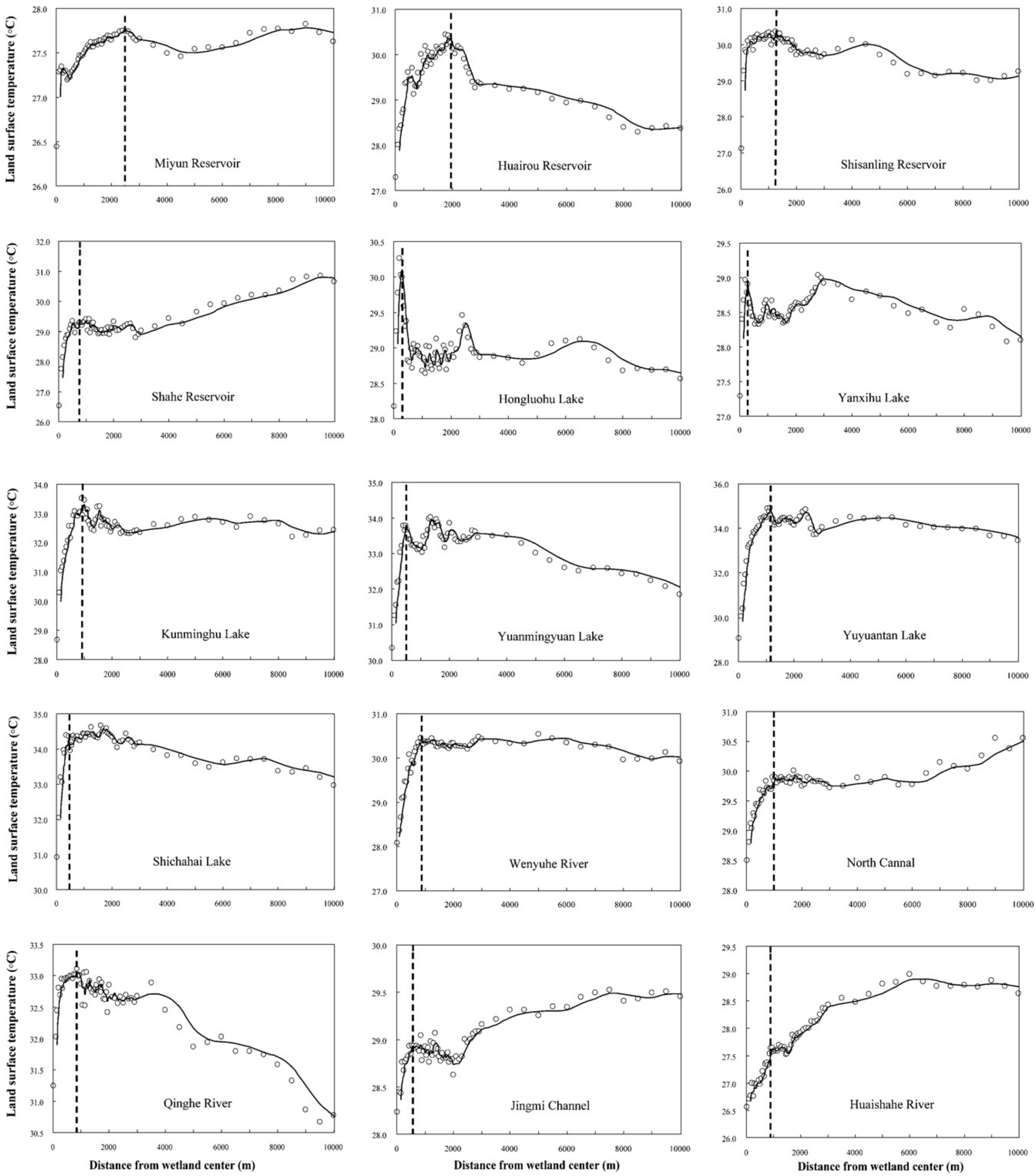

Fig. 3. Mean land surface temperature (LST) in each buffer outside the 15 wetlands in Beijing. Black dots represent LST, black lines represent the moving average LST, and dashed lines indicate the turning point of LST.

3.2. Relationship between wetland characteristics and UCI intensity

Area and shape can impact the cooling effect of wetlands in urban regions. Although the flow velocity of water may also impact the cooling effect of wetlands, it was not considered in this study because most rivers are blocked by dams and sluices in urban areas. As shown in Fig. 4a–c, wetland area is positively correlated to the turning distance of LST whereas negatively correlated to the temperature difference and gradient. The Spearman Rho is 0.539 ($p < 0.05$) and 0.677 ($p < 0.01$) between the wetland area and temperature difference and temperature gradient, respectively. This indicates that the influencing scale of cooling effects may extend but the extend rate slows down as wetland area increases. Correspondingly, the temperature difference and gradient decrease with increased wetland area. This means that given the same total area of wetlands, more small wetlands can offer more beneficial effects.

Table 1
Statistic of wetland characteristics and land surface temperature in Beijing. Wetlands marked with an asterisk lie outside the fifth-ring road of Beijing.

Wetland type	Wetland name	Wetland area (km^2)	LSI	Distance from downtown (km)	Wetland temperature (°C)	Turning temperature (°C)	Turning distance (m)	Temperature difference (°C)	Temperature gradient (°C/km)
Reservoir and lake	Miyun*	98.68	9.00	82	26.44	27.74	2500	1.30	0.52
	Huairou*	7.07	2.49	55	27.30	30.43	2000	3.13	1.57
	Shisanling*	1.89	1.58	40	27.12	30.34	1200	3.22	2.68
	Shahe	2.82	3.03	30	26.53	29.35	800	2.82	3.53
	Hongluohu*	0.48	1.85	48	28.17	30.03	450	1.86	4.13
	Yanxihu*	2.49	3.91	50	27.29	28.91	400	1.62	4.05
	Kunminghu	2.36	1.68	14	28.68	33.52	900	4.84	5.38
	Yuanmingyuan	0.67	5.54	13	30.35	33.78	500	3.43	6.86
	Shichahai	2.26	3.41	0	30.92	34.36	500	3.44	6.88
	Yuyuantan	0.46	2.43	8	29.05	34.89	1100	5.84	5.31
River	Wenyuhe	9.46	15.97	20	28.09	30.45	900	2.36	2.62
	North Canal	10.01	13.32	30	28.50	29.90	1000	1.40	1.40
	Qinghe	1.16	9.67	25	31.24	33.11	800	1.87	2.34
	Huaishahe*	2.47	13.05	50	26.56	27.79	900	1.23	1.37
	Jingmi Channel*	3.89	21.88	40	28.23	28.93	500	0.70	1.40

The wetland shape is negatively correlated to temperature difference and gradient as shown in Fig. 4d–f. The Spearman Rho is 0.679 ($p < 0.01$) between LSI and temperature difference, and 0.568 ($p < 0.05$) between LSI and temperature gradient. Although the mean temperature of reservoirs and lakes (28.19 °C) is similar to the rivers (28.52 °C), the mean temperature difference of reservoirs and lakes (3.15 °C) is higher than that of rivers (1.51 °C). Also, the mean temperature gradient is 4.09 °C/km for the reservoirs and lakes, higher than 1.83 °C/km for the rivers.

Like the wetland shape, the wetland location is also negatively correlated to the temperature difference and gradient (Fig. 4g–i). The Spearman Rho is 0.691 ($p < 0.01$) between the wetland location and temperature difference, and 0.706 ($p < 0.01$) between the wetland location and temperature gradient. The temperature difference and gradient of rivers are found to be smaller than those of the reservoirs/lakes at the similar location. This difference in UCI intensity may be due to the different shape of rivers and lakes/reservoirs.

4. Discussion

4.1. Implications for ecosystem service assessment

Although the assessment of wetland ecosystem services has received ample attention since the late 1960s, most studies focus on a specific part of these ecosystem services, such as aquatic product provision, water flow regulation, water quality purification, biodiversity maintenance, or the provision of recreation and tourism (Jaarsveld et al., 2005). Ecosystem services are generally quantified by the product of a weighted constant and the wetland area (Chen and Zhang, 2000; Li et al., 2010; Kozak et al., 2011; Pataki et al., 2011). Two main findings in this study may provide some implications on the assessment of ecosystem services. First, the case study of Beijing shows that wetlands are, on average, cooler than their surrounding landscapes. This indicates that cooling effects of wetlands are significant in urban environments, and should be included in the assessment of wetland ecosystem services. Second, the UCI intensity is not found to be linear correlated to wetland area, whereas it is highly correlated with wetland shape. This is consistent with previous findings in city parks showing that irregular and belt-shape parks tend to have low cooling effects (Cao et al., 2010). Moreover, we demonstrate an interesting finding that the UCI intensity is determined by the wetland location within an urban region. Our results indicate that spatial heterogeneity indicators, including shape and location, need to be considered in the assessment of microclimate regulation services for wetland ecosystems.

This result is particularly important when the evaluation of wetland ecosystem services is applied to the wetland management and planning. For example, the policy of wetland mitigation banking has been used as an economic incentive for restoring and preserving wetlands in the U.S. since the 1980s (BenDor and Brozovic, 2007; Bendor, 2009). Wetland losses in and near urban areas are often compensated by wetland mitigation in rural areas to produce additional estate values for urban development (Ruhl and Salzman, 2006). While the mitigation bank may have preserved wetland acreage, there can be a “net loss” in wetland ecosystem services due to the change of wetland shape and location. There may also be a “relative loss” due to the redistribution of wetland benefits among specific population groups in this process of spatial rearrangement. Our study indicates that a comprehensive spatial understanding of ecosystem services is needed before ecosystem management measures are implemented to improve a specific ecological benefit.

4.2. Implications for urban landscape design

Urban wetland design are often recommended to improve the runoff regulation, pollutant removal efficiency, cultural and recreational services (Shutes et al., 2005; Zhang and Mitsch, 2005; Wahl et al., 2010), as well as reduce adverse environmental effects, such as increased salinity, mosquito habitats, and greenhouse gas emissions (Nassauer, 2004; O’Geen et al., 2010). Overall, the current criteria used for urban landscape design are mainly focused on economic benefits and less on ecological benefits, including the cooling effects to mitigate UHI effects. Multifunctional landscape has proved quite meaningful in urban areas by using multiple approaches for connecting sites to their surroundings (Lovell and Johnston, 2009).

This study showing the relationship between wetland characteristics and UCI intensity can provide useful action points for urban landscape design to mitigate the UHI effects. First, the cooling effect of wetlands is particularly significant near the downtown region. Thus, it is necessary to add water areas in big cities and keep them evenly distributed in dense, built-up areas, even though land use development pressures are also very high in those areas. Second, the cooling effect of wetlands does not linearly correlate with wetland area. This indicates that the cooling effect has a threshold as the wetland area increases, and it is reasonable to benefit more stakeholders by substituting a large water body

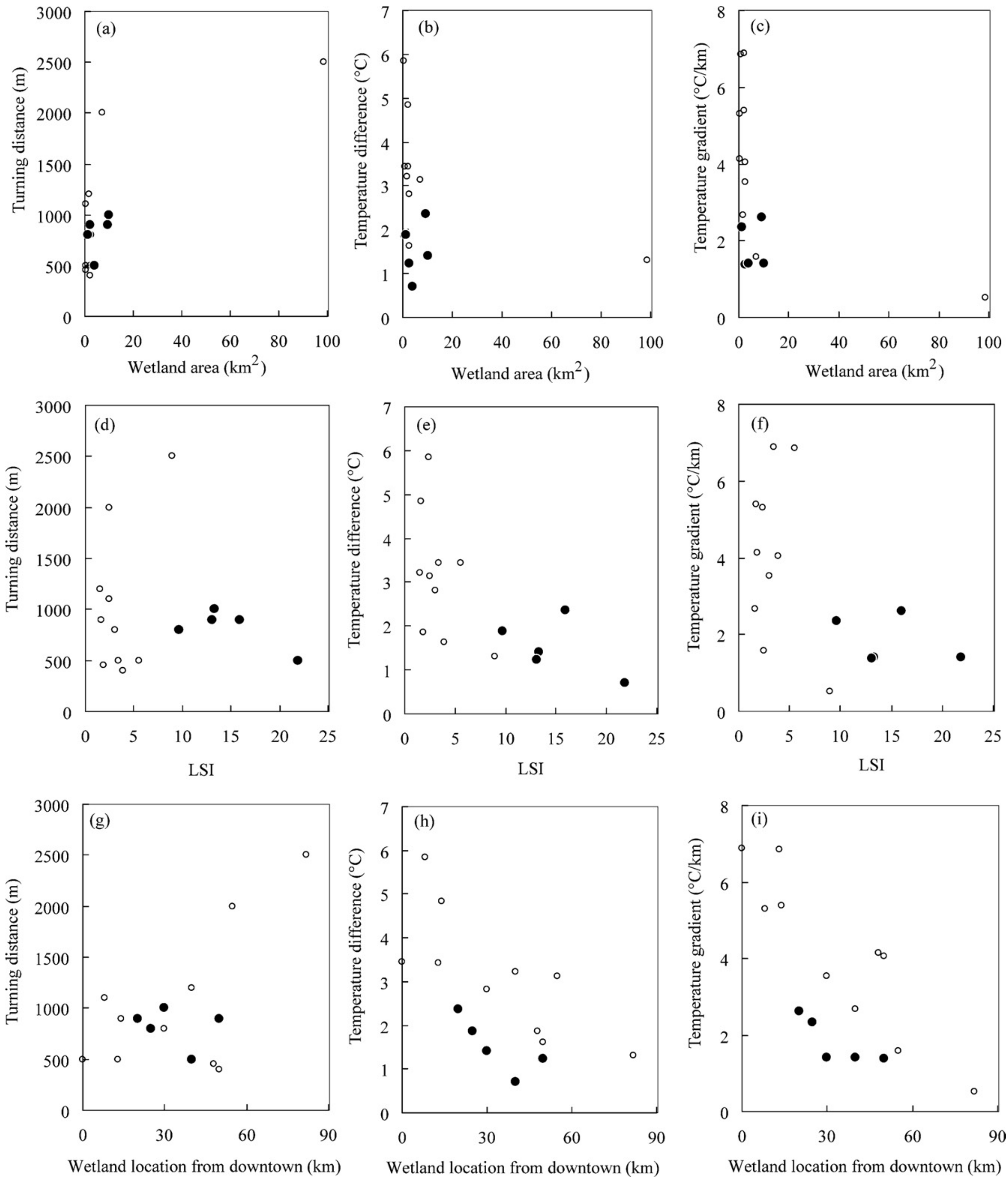

Fig. 4. Bivariate relationships between dependent (turning distance, temperature difference, temperature gradient) and independent variables (wetland area: a–c, LSI: d–f, location from downtown: g–i) for the 15 wetlands in Beijing. Black dots represent rivers, and white circles represent reservoirs and lakes.

with several small water bodies of the same total area. Lastly, the cooling effect of wetlands may be intensified by constructing them in a relatively regular shape because we do not have enough urban land to create wetlands. This study indicates that landscape design in urban areas requires appropriate patch size, density, and spatial arrangement. The optimal choice and combination of wetland characteristics in relation to the cooling effects should be studied in the future.

4.3. Applicability and limitation of the method

Choosing an appropriate observational unit is critical when examining the quantitative relationship between wetland characteristics and the UCI intensity descriptors. Cao et al. (2010) calculated the cool island intensity of city parks in Nagoya by comparing the mean LST inside a park and within the 500 m buffer zone outside the park. Other studies defined UCI intensity as the distance of one park-width away from the park, calculated using the square root of the park area (Chang et al., 2007). We designed a new method to identify the influence scale for a wetland by assessing the actual LST distribution around the wetland. This method was meaningful to evaluate the UCI intensity than the simple average temperature in a fixed buffer outside a wetland.

While the methods formulated in this study have been quite efficient in quantifying the UCI intensity, there may be some limitations. First, the UCI intensity of wetlands was derived from LST data. While LST are related to air temperature above ground, distinct differences between LST and air temperature may remain in various times and regions. Also, street directions as well as main wind directions have been found to impact the cooler air from city parks to enter the surrounding urban regions (Slater, 2010). Further climate data on air temperature and wind directions are useful in relation to quantify the UCI intensity of wetlands. Second, LST outside the wetlands is very likely influenced by the underlying land cover. This factor needs to be controlled in further analysis by collecting more data in a high spatial resolution including road, vegetation, building density and height. Another possible limitation is that the turning point of LST around a wetland is selected manually. A continuous measurement of LST from different buffer-size around a wetland is more desirable to quantify the UCI intensity. Lastly, the present study only discussed the spatial variation in cooling effects of wetlands, whereas the temporal change is also worthy to investigate in urban areas (Buyantuyev and Wu, 2010). And a more comprehensive understanding of cooling effects of wetlands in urban environments could be possible if we could have selected remote sense images in multiple times with varying LST and land cover characteristics. These potential limitations open some room for our further research.

5. Conclusions

We assessed the UCI intensity of 15 wetlands in Beijing using ASTER images. The results show that wetland shape and location had significant impacts on the surrounding thermal environment. The methods included several geospatial techniques, including image identification, buffer analysis, and graphic analysis. An image identifying technique was used to derive the information on land cover and LST from ASTER images. Buffer analysis was used to produce observational units from which LST values were evaluated in different spatial scales. Graphic analysis was a simple and effective technique used in the current study to identify the turning distance, temperature difference, and temperature gradient for each wetland. This study provides useful implications for the choice of indicators in ecosystem services assessment, and provides practical approaches to guide decisions in urban landscape design targeted to mitigate UHI effects.

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