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The impact of thermal image spatial enhancement on the estimation of the urban green cooling effect

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HIGHLIGHTS

- Spatially enhanced thermal image was used in the estimations of cooling effect of urban greenery.
- Spatial enhancement of thermal image improves the spatial details of cooling effect estimations.
- Green Cool Island (GCI) method showed more clear details of cooling effect after the TSE process.

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ABSTRACT

Remotely sensed thermal data are applied widely in ecology studies, although the resolution of them is usually low. The spatial enhancement of thermal images (TSE) will play an important role in ecological applications. This paper used emissivity modulation (EM) for the TSE, and then used the images to estimate the urban cooling effect with three popular approaches: the local climate regulation index (LCRI), cooling intensity (CI), and green cooling island (GCI). After TSE process, the results of LCRI and CI showed little statistical difference, although the spatial differences should not be overlooked. The GCI results changed clearly after the TSE, with a 38.1% decrease of the area of cooling extent. Therefore, the TSE is recommended for GCI and green patch level CI, and not for LCRI or regional CI.

1. Instruction

Thermal conditions are important in urban environments, and can be evaluated using remotely sensed thermal images. For example, the low-resolution thermal images of the Moderate Resolution Imaging Spectroradiometer (MODIS) have been used to study the urban heat island (UHI) effect across biomes in the continental USA [1], while the Advanced Very-High Resolution Radiometer (AVHRR) was used to study the growth of UHIs across Houston in 1985–2001 [2]. High resolution thermal images like bands from Landsat or the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) are more often applied to study the UHIs of a particular city [3–5]. In addition to UHIs, thermal images can be used in ecology studies. For example, local climate regulation mapping, soil moisture studies, and plant heat stress measurement are usually interpreted using the changes in the land surface temperature (LST) [6–11]. The estimation of the cooling effect of urban greenery is a branch of ecology that is of interest to city designers or managers and commonly uses thermal images [12–14].

The remotely sensed thermal images in current use have a resolution of about 100 m. To make full use of the data, the thermal spatial enhancement (TSE) was developed using spectral unmixing (SU) and pixel block modulation (PBM). Taking the introducing of thermal endmember as the distinguishable mark, different SU are developed by Gillespie [15], Collins [16], and Gustavson [17]. However, the output is computationally complex and has not been verified. Guo and Moore proposed a PBM method that enhanced the resolution by incorporating ancillary data, but this may not be applicable to nighttime images and flat terrain [18]. Emissivity Modulation (EM) is another PBM approach that enhances the thermal image resolution by resampling the pixels according to the emissivity image [19]. EM is a simple, more applicable approach so that we adopted it for this study.

Despite the development of TSE, few ecologists or urban planners have applied it, perhaps because of its interdisciplinary nature or because the 100-m resolution is sufficient for ecological applications. A few reports have studied the impact of TSE on ecological

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applications. Therefore, we explored this using urban cooling estimation as an ecological application.

2. Study area

A 19.6 × 20.6 km rectangular region (about 405.61 km^2) in southwest of urban Beijing was selected as the study region (Fig. 1). Within this area, the most developed urban areas were distributed in the northeastern part of the study area, with suburban area in the southwest, and a hilly area in the northwest.

3. Data and methodology

3.1. Overview

The satellite data used in this work comprised one scene of Landsat 8 dataset (acquired on Aug. 22, 2015 with no more than 5% cloud cover) and one GF2 scene (acquired on Sep. 03, 2015 with no more than 2% cloud cover). The Landsat data were geometrically corrected with a GF2 image as the base map; the optical bands were calibrated with the FLAASH model using ENVI 5.3 for atmospheric correction, and the thermal infrared data were radiometrically calibrated for LST retrieval. The date of satellite data is close to each other to avoid the uncertainty with the comparability of further application of the retrieved LST when applied to different remotely sensed data sources. We retrieved 30-m spatial resolution LST map, and used the EM to attain a spatially enhanced (4 m) LST map of the study area. Then, we used the images to evaluate the urban green cooling effect using three popular methods, as shown in Fig. 2.

3.2. The process of thermal image enhancement

Emissivity modulation is a popular approach for enhancing the spatial resolution of thermal images [20,21], and incorporates spatial enhancement steps into the process of LST retrieval. The LST calculation used here combined the emissivity values and the brightness temperature. If the emissivity is obtained using high-resolution remotely sensed data, the brightness should be resampled to match the pixel size of the emissivity image to build a high-resolution LST image. The process is outlined in Eqs. (1)–(4).

$$T_s = T_b/\varepsilon^{1/4} \tag{1}$$

where T_s is the value of LST in pixel, T_b is the brightness temperature and ε represents the emissivity value. These are calculated using Eqs. (2) and (3)–(4), respectively.

$$T_b = K_2/\ln(K_1/L_{10} + 1) \tag{2}$$

where L_{10} is the 10th band in the Landsat 8 dataset, for which the $K_1 = 774.89$ $(W/m^2 \cdot sr \cdot \mu m)$, and k_2 is 1321.08 k.

$$\varepsilon = 0.979 - 0.035\rho_{red} \tag{3}$$

$$\varepsilon = 0.986 + 0.004[(NDVI - X_1)/(X_2 - X_1)]^2 \tag{4}$$

where ρ_{red} is the red band, the Normalized Difference Vegetation Index (NDVI) is calculated using the red and near infrared bands. The emissivity is an important variable obtained from the NDVI values. When $NDVI < X_1$, the image pixel was deemed to be the pure soil, and its emissivity could be calculated using the red band with Eq. (3). When $NDVI > X_2$, the pixel was assumed contain pure vegetation and its emissivity was assigned a value of 0.99. When $X_2 > NDVI > X_1$, soil and vegetation formed the pixel and Eq. (4) was used to calculate the emissivity. X_1 and X_2 need to be assigned depending on the situation in the study area to differentiate pure soil, vegetation, and mixed covers effectively [22,23].

3.3. The methods used to estimate the cooling effect

The thermal condition is an important element in assessing the comfort or grading the level of ecosystem services [24]. The first method used to estimate the urban green cooling effect is called the Local Climate Regulation Index (LCRI), which is the ratio of

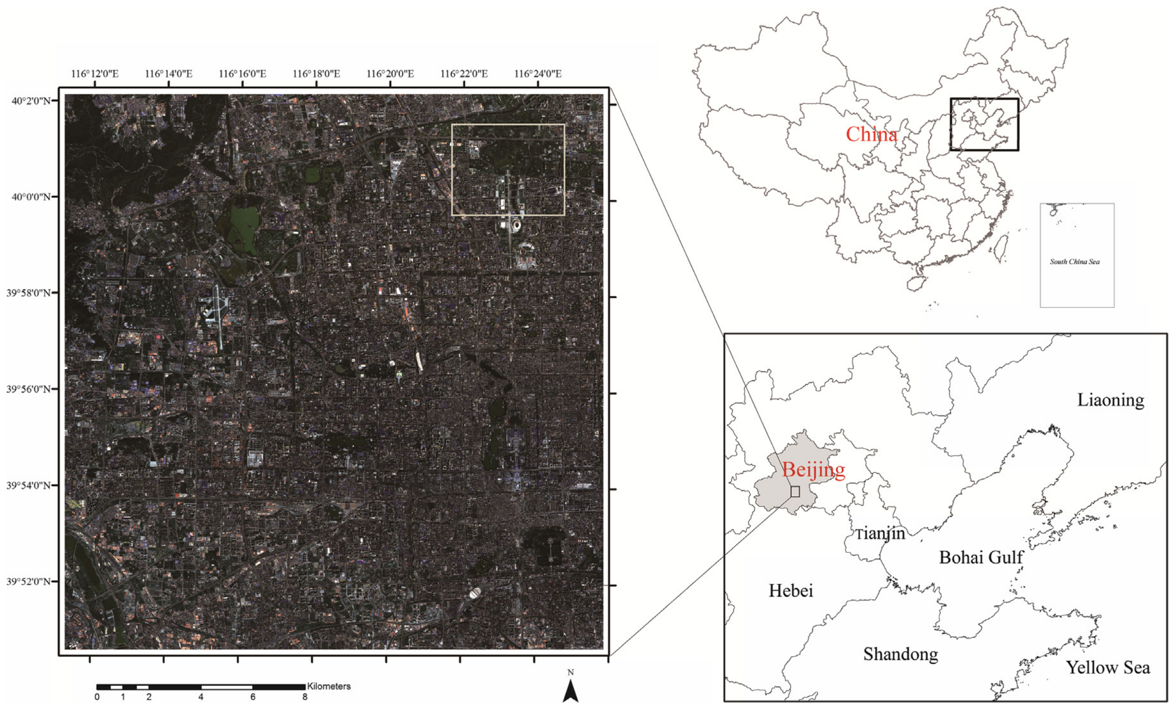

Fig. 1. The location of study site (the white rectangle is used to show the details of spatial distribution in Section 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)