

Urban percent impervious surface and its relationship with land surface temperature in Yantai City, China

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Abstract. This study investigated percent impervious surface area (PISA) extracted by a four-endmember normalized spectral mixture analysis (NSMA) method and evaluated the reliability of PISA as an indicator of land surface temperature (LST). Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images for Yantai city, eastern China obtained from USGS were used as the main data source. The results demonstrated that four-endmember NSMA method performed better than the typical three-endmember one, and there was a strong linear relationship between LST and PISA for the two images, which suggest percent impervious surface area provides an alternative parameter for analyzing LST quantitatively in urban areas.

Key words. Land surface temperature; Percent impervious surface area; Four-endmember normalized spectral mixture analysis; Landsat TM/ETM+

1. Introduction

The rapid urban expansion is highly concerned due to its urban heat island effects, which is typically indicated by change in land surface temperature (LST). Remote sensing data (i.e. Landsat TM/ETM+) provide potential opportunities for mapping and monitoring urban surface land use and LST. Therefore, understanding urban land use and its relationship with LST become an important research topic. Recently, a percent impervious surface area was proposed to represent for the fraction of urban area within a pixel. Various algorithms for image classification and LST retrieval are proposed by scholars from multiple disciplines, but the spectral heterogeneity of urban land surface has still posed a great challenge to accurately estimate fractions of land use type within a pixel. The objectives of this study were to (1) extract percentage of impervious surface area using a four-endmember NSMA method and compare the extracting accuracies with that of the typical three-endmember NSMA; and (2) explore the relationship between percent impervious surface area and LST.

2. Study area and data preprocessing

Yantai is one of the most important coastal cities of the Circum Bohai Sea Industrial Region (Fig. 1) with an area of about 175 km². The China CityYearbook (2010) reported that urban area of Yantai city in 2009 increased by 62.23% of that in 1989, amounting to 92.23 km², ranks the 13th in China. Rapid sprawling of urban area has resulted in a great change in percent impervious surface area, and thus urban heat island effects.



Two representative Landsat images from two years obtained from the USGS were selected as the study images to minimize the interference of annual variation: Landsat-5 Thematic Mapper (TM) images (Row 120/Path 34), acquired on July 15, 2009, and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) images (Row 120/Path 34), acquired on October 20, 2006. The land use map, Google Earth™ images and measured percent impervious surface area maps of 2006 and 2009 were obtained and used as auxiliary data.

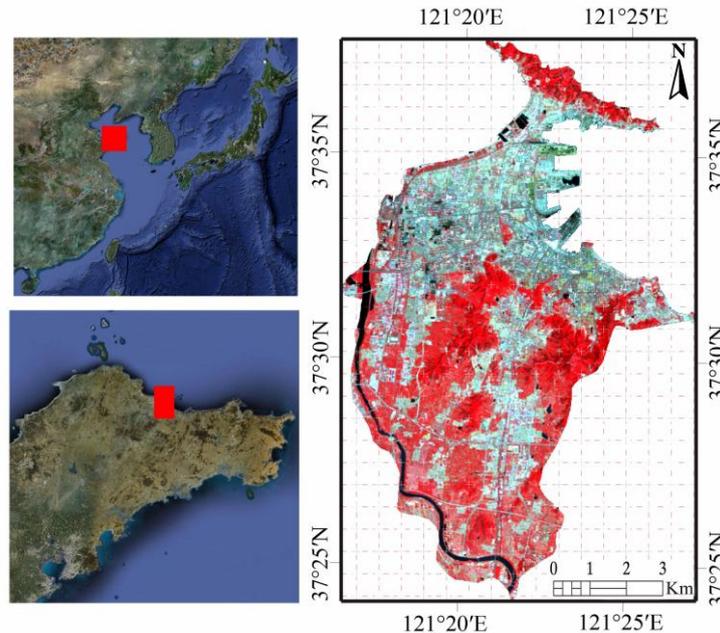


Figure 1. Location of Yantai city. The color composite imagery on the right side was obtained on July 15, 2009 (RGB= Landsat TM bands 4, 3, 2); the location maps on the left were from Google Earth™ imagery data.

The study images were rectified to the UTM projection system (Datum WGS-84, Zone 51) based on about 60 evenly distributed ground control points (GCPs) to ensure the root mean square errors (RMSEs) less than 0.25 pixels (7.5 m) for each image. The original digital numbers (DN) of the TM/ETM+ images were converted to exo-atmospheric reflectance based on the methods provided by Chander and Markham [1] and Landsat 7 Science Data Users Handbook [2].

3. Methods

3.1 Calculation of LST

The thermal infrared band(s) (10.4-12.5 μm) of TM/ETM+ images were used to derive LST in three steps. Firstly, Eq. (1) was used to convert the DN to the top of atmospheric (TOA) radiance [1]:

$$L_{\lambda} = (L_{\text{max}} - L_{\text{min}}) \left(\frac{DN - Q_{\text{min}}}{Q_{\text{max}} - Q_{\text{min}}} \right) + L_{\text{min}} \quad (1)$$

where L_{λ} is the TOA radiance at the sensor's aperture in $\text{W}/(\text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$, Q_{max} (= 255) is the highest points of radiance in DN, and Q_{min} (= 1) is the lowest points of radiance in DN; L_{min} and L_{max} are the minor and max top of atmosphere (TOA) radiance, respectively.

Secondly, the TOA radiance was converted to surface radiance by removing the effects of the atmosphere. In this study the atmospheric correction tool developed by Barsi et al. (2005) was applied:

$$L_T = [L_\lambda - L_\mu - \tau(1 - \varepsilon)L_d] (\tau\varepsilon)^{-1} \quad (2)$$

where L_T is radiance of a blackbody target of kinetic temperature T , L_λ is TOA radiance calculated by Eq. (1), L_μ is atmospheric path radiance, L_d is sky radiance, τ is atmospheric transmission, and ε is surface emissivity of the target land cover type with the value obtained from Snyder et al. (1998). The emissivity for all non-urban land covers of the winter image (Feb. 21, 2000) was presumed to be the same as snow.

Thirdly, L_T was converted to LST T using the Planck curve, as shown in Eq. (3):

$$T = K_2 \left(\ln \left(K_1 (L_T + 1)^{-1} \right) \right)^{-1} \quad (3)$$

where K_1 is pre-launch calibration constant 1 in $W/(m^2 \cdot sr \cdot \mu m)$ and K_2 is pre-launch calibration constant 2 in Kelvin (K). For Landsat 5 TM imagery, $K_1 = 607.76 W/(m^2 \cdot sr \cdot \mu m)$, $K_2 = 1260.56 K$; for Landsat 7 ETM+ imagery, $K_1 = 666.09 W/(m^2 \cdot sr \cdot \mu m)$ and $K_2 = 1282.71 K$.

3.2 Calculation of PISA using four-endmember NSMA

In 2004, Wu [3] proposed a typical normalized spectral mixture analysis (NSMA) method developed by modeling a mixed spectrum as a linear combination of vegetation-impervious surface-soil (V-I-S) endmembers, which was known as three-endmember NSMA. In this model, urban environments are described as a linear combination of vegetation, impervious surface and soil (water bodies are excluded). However, we found that the spectral variations of high and low albedo surface in urban area remained to be different after the normalization processing (Fig. 2), the mean impervious surface endmember can't represent for all the high and low albedo impervious surfaces.

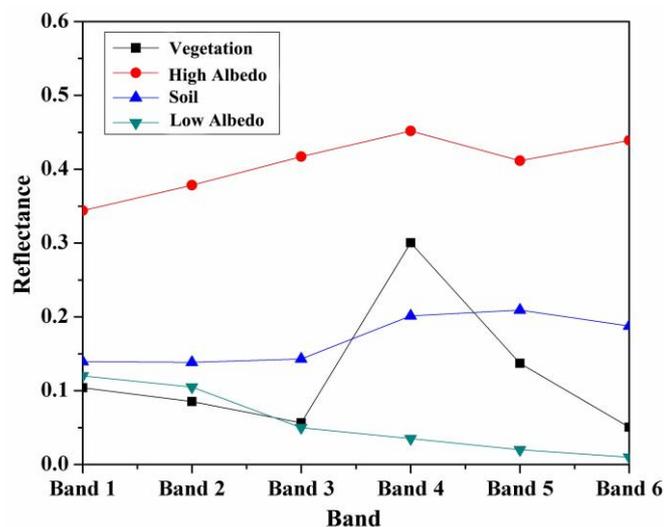


Figure 2. Spectral variations of vegetation, high albedo and low albedo urban area and soil components.

Therefore, a four-endmember NSMA method was used in this study to extract impervious surface information. It modeled a mixed spectrum as a linear combination of four-endmember (i.e. vegetation, high albedo ISA, low albedo ISA and soil). This method starts by implementing normalization of the original TM/ETM+ data with Eq. (4), followed by calculation of the reflectance of ISA with Eqs. (5) - (7).

$$\bar{R}_b = R_b m^{-1} \times 100 \quad (4)$$

where $m = \frac{1}{n_1} \sum_{b=1}^{n_1} R_b$, \bar{R}_b is normalized reflectance for band b in a pixel; R_b is original reflectance for band b ; m is average reflectance for all pixels; and n_1 is total number of bands (six for TM/ETM+ imagery).

$$R_{I,b} = f_{LA} R_{LA,b} + f_{HA} R_{HA,b} + e_b \quad (5)$$

$$f_{LA} + f_{HA} = 1 \quad (6)$$

$$f_{LA} \geq 0, f_{HA} \geq 0 \quad (7)$$

where R_{I,b_i} is reflectance of ISA for band b_i , f_{LA} and f_{HA} are fraction of low Albedo and high Albedo endmembers, R_{LA,b_i} and R_{HA,b_i} are reflectance of low Albedo and high Albedo reflectance for band b_i , e_b is the residual of four-endmember NSMA model. The fraction of each land cover type (i.e. vegetation, high & low albedo impervious surface, or soil) in a pixel can be derived with a least squares method by minimizing the residual e_b . When field or laboratory measurements are not available, endmembers could be selected from the TM/ETM+ images [4, 5]. In this study, endmembers of each land cover type were identified by visual interpretation.

4. Results

4.1 Accuracy of four-endmember NSMA

The accuracies of PISA extracted by three- and four-endmember NSMA methods were determined by comparing the Landsat-estimated PISA to the measured PISA in 2006 and 2009 (Fig. 3). The estimated PISA extracted by the two methods are both highly correlated ($R^2 > 0.80$) to the measured DATA, and the four-endmember NSMA performed better. PISA information extracted by the four-endmember NSMA was used as the input in studying the relationships between PISA and LST.

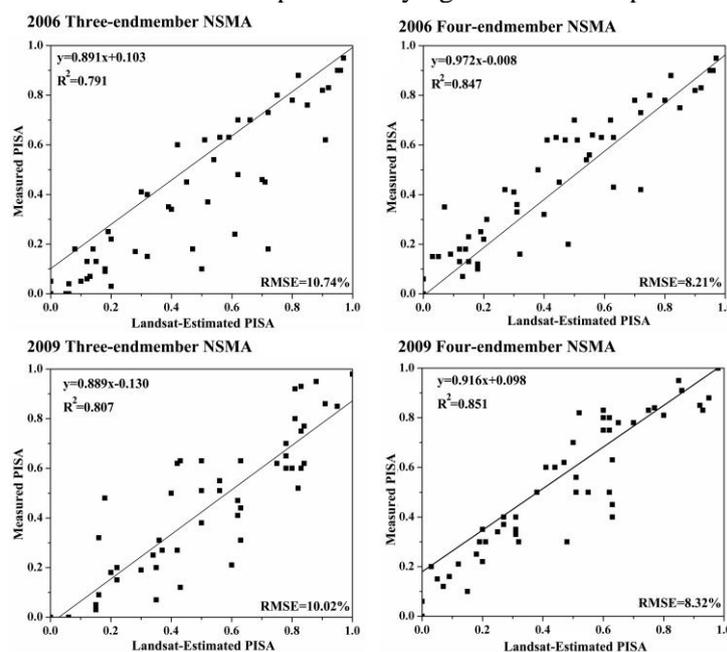


Figure 3. Maps of impervious surface area extraction accuracy assessment for the images of 2006 and 2009 in Yantai city, China.

4.2 LST patterns and accuracy assessment

Fig. 4 showed LST maps extracted from the thermal bands of the two Landsat images. In 2006, LST had a range of 282–299 K with the highest surface temperatures located in the north central bare land areas (Fig. 3a). In 2009, LST ranged from 285 to 310 K, showing a striking land surface heat island effect with urban and rural surface temperature contrasts. Air temperature data obtained from the China meteorological administration was compared to the Landsat estimated LST (Tab. 1). The Landsat-based LST were higher than the mean near-ground air temperatures for the two dates, respectively. This phenomenon is reasonable for the daytime land surface temperatures are generally warmer than that of air temperature, especially in summer season. Because the surface energy fluxes over complex terrain is too complicated, it is difficult to correct the difference between LST and the near-ground air temperature based on satellite thermal sensing data [1], for not only concurrent in-situ ground data (e.g. surface and soil temperatures) but also accurate models relating the surface and near-ground air temperatures are required [8].

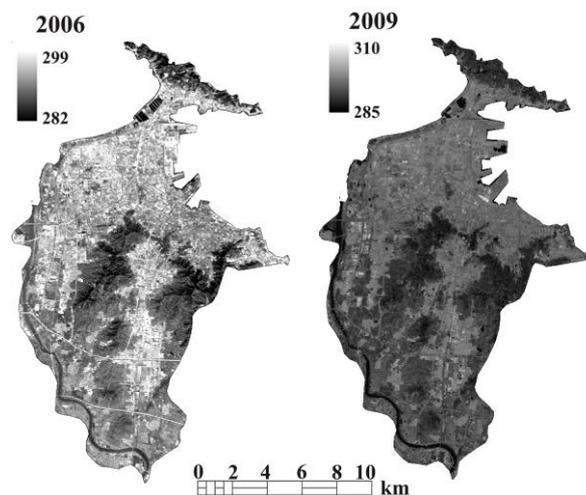


Figure 4. LST derived from Landsat TM (a, b) and ETM+ (c, d) imagery for two different dates.

Table 1. Records of China meteorological administration temperature observations compared to the Landsat estimated LST (K)

Station name	County	Latitude		Longitude		Elevation		
Zhifu	Yantai city	37° 29' 56.13" N		121° 23' 20.67" E		365m		
Date	2006				2009			
	T_{max}	T_{min}	T_{mean}	LST	T_{max}	T_{min}	T_{mean}	LST
	301.4	277.8	288	291.5	307	290.9	297	302.2

4.3 PISA map and its relationship to LST

PISA maps derived from four-endmember NSMA method with a range from 0–100% were mapped for the years of 2006 and 2009 in Fig. 5. The variations of PISA for 2006 was from 0 to 86%, with the standard deviation of 0.0798. For 2009, PISA varied from 0% to 98%, which had the highest mean value of 47% among the four dates.

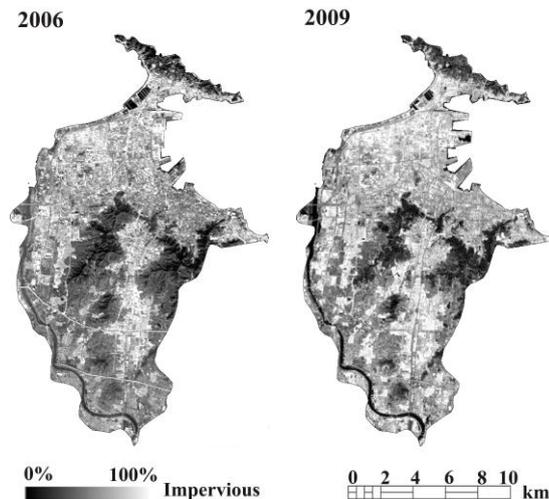


Figure 5. Percent impervious surface area derived from imagery of 2006 and 2009

Fig. 6 indicates a consistent linear relationship between LST and PISA for two dates ($R^2 > 0.90$), suggesting the variation in LST can be indicated very well by PISA. For the last twenty years, researches showed that the surface radiant temperature response is determined by both surface soil water content and vegetation cover [6, 7]. In the urbanized area of Yantai city, LST typically represents the radiometric temperature of vegetated and non-vegetated surfaces (mainly impervious surfaces). The variation in the pixel temperatures may be mostly related to the fraction and characteristics of PISA since vegetated surfaces vary less in temperature than sunlit impervious surfaces [8]. This may explain the linear pattern between LST and PISA.

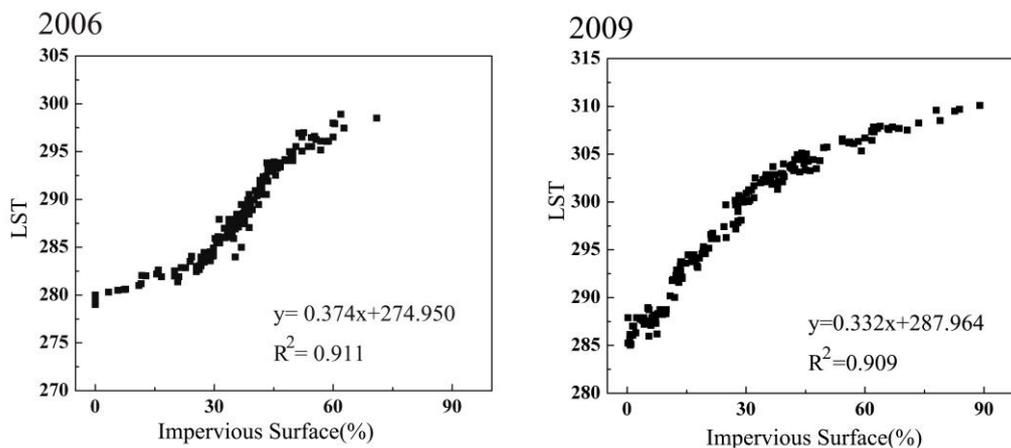


Figure 6. Relationships of LST to PISA

5. Conclusions

This study investigated the relationships between LST and PISA in Yantai city, China by proposing a four-endmember NSMA method. The results indicate that the four-endmember NSMA method performed better than the typical three-endmember NSMA model, it can provide more accurate percent impervious surface area information in studying the urban environment issues. The linear relationship between PISA and LST confirmed that impervious surface area is an important indicator for explaining the LST variation in urban areas. We realized that the conclusions were based on one study area and one satellite imagery data set, and further studies of additional urban areas with more

imagery data such as MODIS and AVHRR are recommended.

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