Eco-Environmental Effects of Industrial Cities Based on Remote Sensing Images: A Case Study of Shenyang, China

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Abstract. With Landsat remote sensing image and GIS spatial analysis method, the ecological environment of the built-up urban area in the third ring of Shenyang was studied, which was an industrial city. The LST and NDVI were extracted to analyze the urban spatial patterns and the relationship with urban land use types. The results showed that LST and NDVI were negatively correlated in urban ecosystem. The urban surface temperature and vegetation index of different land use types were significantly different. On the scale of 1 km, LST was weakly positively correlated with SHDI, while NDVI was negatively correlated with SHDI; LST increased with the increase of land use type diversity, while NDVI decreased with the increase of land use type diversity.

Keywords. Remote sensing image, land surface temperature, normalized vegetation index, urban land use type, ecological environment effect.

1. Introduction

With the acceleration of the global urbanization process, the urban ecological environment has become more important to the global climate and ecological environment [1]. With the urbanization, water and vegetation are gradually replaced by large quantities of impervious surfaces such as asphalt and cement, leading to a series of changes, such as the decrease of surface water transpiration, the acceleration of runoff, the increase of sensible heat storage and transmission, and the decrease of water quality, which causes drastic changes in the ecological environment [2].

Thermal environment is an important factor affecting urban ecological environment [3], which comprehensively summarize and reflect the state of urban ecological environment. It has been getting a lot of attention. It is influenced by both the coverage of the urban surface and human activities. The urban heat island effect is becoming more and more serious due to the change of urban underlying surface properties, air pollution and artificial heat emission, etc. Urban thermal environment has become one of the most important issues in urban development and planning in China. Urban vegetation is an important part of urban ecosystem. By selectively absorbing and reflecting solar radiation energy, regulating the exchange of latent heat and sensible heat, it affects the city’s various natural ecological processes [4]. Urban vegetation has become a highly comprehensive index of urban ecological environment evaluation.

Wilson et al. evaluated the rationality of urban functional zoning by using the relationship between ground brightness temperature and vegetation index from remote sensing images [5]. Chen Xu et al. (2015) used single-phase Landsat remote sensing data to retrieve normalized difference vegetation
index (NDVI) as a reflection index to explore the relationship between urban green space and urban thermal environment. It was found that the cooling effects of different green space types in different urban functional areas were significantly different [6]. Jiang Zhangyan et al. (2006) used single-view Landsat imagery to analyze the correlation between NDVI and LST, which showed that there was a negative correlation between them [7]. Ling Liyuan et al. (2016) used multi-temporal Landsat images to analyze the NDVI and LST. They found a significant negative correlation between NDVI and LST [8]. Weng et al. studied the relationships between vegetation coverage and land surface temperature in Indiana with the remote sensing images with different spatial resolutions. It was found that vegetation coverage was negatively correlated with temperature and the correlation was different in several resolution images [9]. However, there are few studies on the eco-environmental assessment of the industrial cities in China.

Shenyang is a traditional industrial city in northeast China. The development of industrial production and urbanization brought many problems to the ecological environment of the city (urban heat island, air pollution, etc.). The study to the environmental effects with urban land use is the key to solve the problems of urban ecological environment. In the study, the built-up area within the third ring road of Shenyang is taken as the study area. Based on the spatial analysis method, the two eco-environmental indicators, land surface temperature and vegetation index were traced from the remote sensing images to analyze the urban ecological environment conditions and the urban land use types and their spatial combinations in order to provide a new idea for urban ecological environment evaluation and urban ecological planning.

2. Data Sources and Research Methods

2.1. Study Area
Shenyang lies in the north-central part of Liaoning province and its geographical location is between 122º25′9″~123º48′24″′′ E and 41º11′51″~43º2′13″ N. Shenyang belongs to a semi-humid continental climate affected by monsoon climate in the northern temperate zone, with an average annual temperature of 7.6°C.

The urban area was expanded from the first ring road to the outside through several concentric ring roads. The area in the third ring road is mature and stable and is a built-up area of the city, with a total area of about 455 km².

2.2. Data Acquisition and Processing Classification of Urban Land Use Types
The data source in this paper was the 8-band Landsat OLI image on August 20, 2017, with track number 130, line number 35, and resolution 30m×30m. The remote sensing image was preprocessed by ENVI. The geometric correction was performed by the polynomial method of selected ground control points. According to the Shenyang urban master plan (2011-2020) and on-site surveys, the remote sensing images were manually interpreted to obtain the spatial vector data of land use types in the built-up area within the third ring road of Shenyang (figure 1).

Land use types were classified from a functional perspective. With Urban Land Classification and Planning and Construction Land Standards (GB50137-2011) and the differences in land use status and service functions in Shenyang, the land use types were divided into eight types: green land, residential land, public land, industrial and storage land, commercial services, traffic land, agricultural and forest land, and unused land.
2.3. NDVI Calculation

The technical methods for monitoring surface vegetation coverage and growth conditions through remote sensing have been relatively mature. The normalized vegetation index (NDVI) is the best indicator to reflect the coverage of surface vegetation \[10\]. ENVI software was used to perform radiometric calibration and atmospheric correction on Landsat 8 OLI remote sensing image. Then the following equation was used to obtain the NDVI index within the third ring road of Shenyang:

\[
NDVI = \frac{(NIR - R)}{(NIR + R)}
\]  

(1)

In the equation, NIR is the reflectivity in the near infrared band; R is the reflectivity in the red band.

The value range of NDVI is -1 to 1, which is closely related to the coverage of urban vegetation and vegetation types. The more lush the vegetation and the higher the coverage, the greater the NDVI. When NDVI is negative, it indicates the ground covers by clouds, water or snow; When NDVI is 0, it means rock or bare soil is on the surface; When NDVI is positive, it means that there is vegetation coverage, and it increases with the increase of coverage.

2.4. Calculation of Urban Land Surface Temperature

2.4.1. Inversion Equation for Surface Temperature. The surface temperature is the core information of the energy exchange on the surface. It directly affects the sensible heat and latent heat exchange between the atmosphere, ocean and land. The surface temperature is the main body of the ambient temperature and the basic embodiment of the urban heat island. In this paper the surface temperature is used to represent the intensity of the urban thermal environment.

Firstly, the atmospheric data synchronized with the time of the satellite pass was used to estimate the influence of the atmosphere on the surface thermal radiation. The atmospheric influence was then subtracted from the total thermal radiation observed by the sensor at the altitude of the satellite to get the intensity of surface heat radiation. Then the heat radiation intensity was converted into the surface temperature. The radiant brightness \(B(T_S)\) of a blackbody at temperature \(T\) in the thermal infrared band was:

\[
B(T_S) = \left[ L_\lambda - L_\uparrow - \tau \cdot (1 - \varepsilon) L_\downarrow \right] / \tau \cdot \varepsilon
\]  

(2)

In the equation: \(\tau\) was the atmosphere transmittance in the thermal infrared band; \(\varepsilon\) was the surface emissivity; \(T_S\) was the surface temperature; \(B(T_S)\) was the thermal radiance of the black body in \(T_S\) obtained by deducing Planck's law; \(L_\uparrow\) represented the upward radiance of the atmosphere; \(L_\downarrow\) represented the downward radiance of the atmosphere. We got \(\tau, L_\uparrow\) and \(L_\downarrow\) by inputting the imaging time, longitude, latitude of Shenyang City Center, and other corresponding parameters into the website published by NASA.

According to the inverse function of Planck's equation, the true surface temperature \(T_S[11]\) was obtained with the radiance of a black body with a temperature of \(T_S\) in the thermal infrared band,
The diversity index $P$ was calculated as:

$$P = \frac{1}{\ln(K_1/ B(T_s)) + 1}$$  \hspace{1cm} (3)

In the equation, $T_s$ was the surface temperature; for OIL sensor, $K_1 = 666.09 \text{W/(m}^2\cdot \text{s} \cdot \text{r} \cdot \text{μm})$, $K_2 = 1282.71 \text{K}$.

2.4.2. Surface Emissivity ($\varepsilon$). Based on the normalized vegetation difference index (NDVI) and vegetation coverage FVC proposed by Qin Zhihao and others, the specific emissivity was calculated [12]. First, the supervised classification was used to divide the surface into three categories: water surface, urban artificial surface, and natural surface. The structure of the water surface was relatively simple. In the application, the part of the water body pixel could be separated first and assigned with a typical water body specific emissivity value of 0.995. Urban artificial surfaces were mainly composed of roads, buildings, and houses; natural surfaces mainly referred to various natural land surfaces, woodland, and farmland, etc. For each surface, the specific emissivity estimates of natural surfaces and urban artificial surfaces were calculated according to the following equations (4) and (5):

$$\varepsilon_s = 0.9625 + 0.0614 FVC - 0.0461 FVC^2$$  \hspace{1cm} (4)

$$\varepsilon_h = 0.9589 + 0.086 FVC - 0.0671 FVC^2$$  \hspace{1cm} (5)

In the equations, $\varepsilon_s$ and $\varepsilon_h$ represented the specific emissivity of natural surface pixels and urban artificial surface pixels, respectively; FVC was the vegetation coverage, which could be calculated by NDVI. There were many calculation equations, and the equation (6) was used to calculate [13]:

$$FVC = \left[ (NDVI - NDVI_{\text{min}}) / (NDVI_{\text{max}} - NDVI_{\text{min}}) \right]^2$$  \hspace{1cm} (6)

$NDVI$ was the normalized vegetation index, calculated according to equation (1); $NDVI_{\text{min}}$ and $NDVI_{\text{max}}$ were assigned according to the statistics of NDVI images in the study area, respectively. $NDVI_{\text{max}}=0.70$, $NDVI_{\text{min}}=0.00$.

2.5 Diversity Index

The landscape diversity index was introduced for characterization for the spatial structure characteristics of different land use types. The diversity index was the response to different types of richness and complexity based on the information theory. Refer to Shannon-Wiener index, it expressed as [14]:

$$SHDI = \sum_{i=1}^{m} P_i \times \log_2 P_i$$  \hspace{1cm} (7)

In the equation, $SHDI$ was the Shannon diversity index, $P_i$ was the area proportion of type i, $m$ was the number of types. The size of diversity depended on two factors: the number of types and the uniformity of area combinations. The diversity index was a comprehensive manifestation of type richness and combination complexity.

3. Results and Discussion

3.1. Comparative Analysis of LST and NDVI Calculation Results and Profile Changes

According to figure 2, LST and NDVI in Shenyang had opposite spatial patterns. The distribution of urban land surface temperature had obvious regional characteristics. In the first ring of the city center, the distribution high temperature was very dense but the low temperature area was small because of the severe heat island effect. The corresponding NDVI values were generally low. The high temperature areas in the second and third ring areas were mainly distributed in the northeast ceramic city-brilliance automobile group area in the southeast of the city and the Tiexi industrial zone in the west. These two parts belonged to the new industrial area in the process of urbanization, and the NDVI values were also very low. A large area of low temperature LST area appeared in the urban fringe area near the third ring, corresponding to a large area of vegetation coverage. The water surface was a special part. Its LST and NDVI values were low.
In order to show the difference in the changing trends of LST and NDVI in different directions, the values of each pixel of LST and NDVI in the east-west and north-south directions were extracted to get the east-west and north-south sections (figure 3-figure 4).

In the east-west and north-south directions, LST and NDVI values showed opposite trends. Macroscopically, LST formed a high-value area in the center of the city. That was the extent of the urban heat island. The results showed that Shenyang had a significant heat island effect in summer. This interval was the low value area of NDVI, forming a trough effect. On the microscopic level, the low value of LST corresponds to the high value of NDVI. The Beiling Park in the north-south direction had this characteristic. The LST peak on the north side of Beiling and the corresponding NDVI low valley were the industrial areas. This showed that for LST and NDVI, the richer or poorer the vegetation was, the stronger contrast between them. The water body was an exception: its LST and NDVI values were low. Both of them were in the "lowest" when passing the Hunhe River in both directions. Compared with the city center, the symmetry of the LSD and NDVI sections in the east-west direction was obviously better than that in the north-south direction. This showed that the symmetry of land use types in the east-west direction of Shenyang city was better than that in the north-south direction.

Figure 2. Spatial pattern of LST And NDVI in study area.

Figure 3. Comparison of LST and NDVI changes in west-east section.
Figure 4. Comparison of LST and NDVI changes in north-south section.

3.2. Statistical Analysis and Multiple Comparison of LST and NDVI

3.2.1. Statistical Analysis Based on Land Use Types. There were significant differences between LST and NDVI in different land use types (figure 5, P = 0.00). The LST values of public land and commercial land were the highest, followed by residential land, industrial land, traffic land and unused land. The NDVI values of these land were relatively low. This showed that these land types had less vegetation coverage and more hard ground in the Third Ring Road area, releasing a lot of artificial heat which leads to a higher LST values. Green land had a large number of vegetation coverage. The NDVI values were high with low LST. The lowest LST values were in the agricultural and forestry land. It was due to the fact that the agricultural and forestry land in the Third Ring Road of Shenyang had high plant coverage. At the same time, most of the agricultural and forestry land located in the edge of the study area, which is less affected by the heat island effect of urban center.

Figure 5. Distribution of mean and standard deviation of LST and NDVI corresponding to different land use types
3.2.2. **Multiple Comparative Analysis.** Tamhance T2 test was used to compare the differences between LST and NDVI in different land use types (tables 1 and 2). There were 13 pairs of LST with no significant difference, mainly concentrated in industrial land, residential land, public land, commercial land, traffic land and unused land. The industrial land and unused land had no significant difference with other land use types. These land types were construction land, and the surface materials are mostly composed of impervious materials such as asphalt and cement. The difference of specific emissivity of ground was small, which lead to the insignificant difference of LST. Only two pairs of NDVI had no significant difference, which were public land and traffic land, agricultural and forestry land and unused land. The vegetation coverage of green land and agricultural and forestry land was very high. But the differences between them and other land types in LST and NDVI were not the same. There were also significant differences between them. This showed that urban surface temperature was affected not only by the nature of underlying surface (land use type), but also by the spatial distribution and quantity combination of various underlying surface types (land use pattern).

**Table 1.** Multiple comparisons of the Tamhane T2 test for LST values on different land use types.

|                      | Green space | Residential land | Public land | Industrial and storage land | Commercial land | Traffic land | Agriculture and forestry land |
|----------------------|-------------|------------------|------------|-----------------------------|----------------|-------------|-------------------------------|
| Residential land     | -0.79*      |                  |            |                             |                |             |                               |
| Public land          | -1.33*      | -0.54*           |            |                             |                |             |                               |
| Industrial and storage land | -0.82      | -0.03            | 0.51       |                             |                |             |                               |
| Commercial land      | -1.23*      | -0.44*           | 0.10       | -0.41                       |                |             |                               |
| Traffic land         | -0.75*      | 0.04             | 0.58*      | 0.07                        | 0.48           |             |                               |
| Agriculture and Forestry Land | 1.89*      | 2.67*            | 3.22*      | 2.70*                       | 3.11*          | 2.63*       |                               |
| Unused land          | -0.88*      | -0.09            | 0.45       | -0.06                       | 0.35           | -0.13       | -2.76*                        |

**Table 2.** Multiple comparisons of Tamhane T2 test for DNVI values on different land use types.

|                      | Green space | Residential land | Public land | Industrial and storage land | Commercial land | Traffic land | Agriculture and forestry land |
|----------------------|-------------|------------------|------------|-----------------------------|----------------|-------------|-------------------------------|
| Residential land     | 0.10*       |                  |            |                             |                |             |                               |
| Public land          | 0.07*       | -0.03*           |            |                             |                |             |                               |
| Industrial and storage land | 0.04*      | -0.06*           | -0.04*     |                             |                |             |                               |
| Commercial land      | 0.11*       | 0.01*            | 0.04*      | 0.07*                       |                |             |                               |
| Traffic land         | 0.08*       | -0.02*           | 0.00       | 0.04*                       | -0.04*         |             |                               |
| Agriculture and Forestry Land | -0.02*    | -0.12*           | -0.09*     | -0.05*                      | -0.13*         | -0.09*      |                               |
| Unused land          | 0.00*       | -0.10*           | -0.07*     | -0.03*                      | -0.11*         | -0.07*      | 0.02                           |

3.3. **Quantitative Relationship between Land Use Types and LST, NDVI**

From the above analysis, LST and NDVI were closely related to urban land use types. LST and NDVI on different land use types were significantly different. The LST and NDVI values of each land use type patch were linear regression. Due to the particularity of LST and NDVI of water body, it was treated by masking. Regression results (figure 6) showed that LST and NDVI had a significant negative correlation at the patch scale of land use types with $R^2$ of 0.478 ($P=0.00$). This indicated that the higher the vegetation coverage, the higher the transpiration rate, and the more frequent the latent
and sensible heat exchange between the land surface and the atmosphere, what resulted in lower surface temperature.

![Figure 6](image.png)

**Figure 6.** Scatter plot and regression fitting line of LST and NDVI at plaque level.

The quantitative relationship between LST and NDVI was studied at the level of land use types (Table 3). All results showed that LST and NDVI were significantly correlated (P≤0.01). In the regression function, the largest coefficient of the first term was the unused land, and the smallest was the agricultural and forestry land. That was, with the increase of NDVI, the surface temperature of unused land decreased the slowest, while that of agricultural and forestry land decreased the fastest. With the expansion of built-up area, the surface temperature of other urban land was more sensitive than that of unused land.

| Land use types          | Regression model          | Number of samples | Correlation | R²   | Significance |
|-------------------------|---------------------------|-------------------|-------------|------|--------------|
| Green space             | Y=-9.756X+310.363         | 1194              | -0.72       | 0.52 | 0.00         |
| Residential land        | Y=-9.397X+310.049         | 1359              | -0.60       | 0.37 | 0.00         |
| Public land             | Y=-8.064X+310.087         | 496               | -0.65       | 0.42 | 0.00         |
| Industrial and storage land | Y=-14.835X+313.073    | 134               | -0.85       | 0.72 | 0.00         |
| Commercial land         | Y=-6.128X+309.374         | 539               | -0.51       | 0.26 | 0.00         |
| Traffic land            | Y=-8.755X+310.104         | 165               | -0.69       | 0.47 | 0.00         |
| Agriculture and Forestry Land | Y=-15.522X+312.542   | 92                | -0.94       | 0.88 | 0.00         |
| Unused land             | Y=-6.004X+309.461         | 36                | -0.51       | 0.26 | 0.01         |

Regression analysis with the land use showed that LST and NDVI had significant negative correlation at both patch level and land use type level. By comparison, it was found that the temperatures of agricultural and forestry land, industrial land, green space and residential land were more affected by vegetation than other types. In this way, the vegetation distributed in these land use types was more effective in mitigating the urban heat island effect and improving the urban thermal environment.

### 3.4. Correlation between Land Use Pattern and LST and NDVI

Diversity index was an indicator of land use type and area combination within a certain spatial range. Generally, the more complex the land use type and the greater the fragmentation, the greater the diversity [15].
In order to measure the relationship between land use pattern and LST, NDVI in the Third Ring Road of Shenyang, the landscape statistical software FRAGSTATS 3.4 was used to calculate the SHDI, LST and NDVI values in the moving window by the 1km × 1km moving window overlapped with Shenyang urban land use. The mobile window was taken as the basic spatial samples (355 valid samples) to study the relationship between them.

The spatial distribution of SHDI was significantly different from LST and NDVI (figure 7). The high value window of SHDI was mainly distributed in two areas: one was along Hunhe River, which was mainly due to the complexity of natural and cultural landscape types in this area; the other was northeast Ceramic City brilliance automobile group region, which was caused by the drastic change of new and old land use types in the process of urban expansion.

![Image](image_url)

**Figure 7.** Spatial distribution pattern of LST, NDVI and SHDI based on 1km × 1km moving window.

The correlation between SHDI, LST and NDVI was analyzed. There was a weak negative correlation between SHDI and LST in 1km amplitude moving window. Pearson correlation coefficient was 0.35 (P = 0.00). This showed that LST was not only affected by land type itself, but also by the spatial combination of land use types. The greater the diversity, the lower LST. There was a weak positive correlation between SHDI and NDVI with Pearson correlation coefficient of 0.21 (P=0.00), and the correlation between SHDI and NDVI was significantly lower than that of the former. The results showed that the vegetation index tended to be higher and the surface temperature tended to be low in areas with high diversity (low aggregation of land use types).

SHDI was classified by quartile method. The linear regression model of LST and NDVI was established on each SHDI class (table 4). The change characteristics of the relationship between LST and NDVI with different diversity conditions were analyzed. Considering the particularity of water surface, the samples containing water surface were removed. The results were shown in the table. All the correlations were highly significant (P = 0.00).

| Quartile | Regression model | Number of samples | Correlation | R² | Significance |
|----------|------------------|-------------------|-------------|----|-------------|
| ≤0.5334  | Y=-11.140X+310.406 | 89                | -0.781      | 0.611 | 0.00        |
| 0.5334-0.7082 | Y=-11.505X+310.423 | 89                | -0.679      | 0.444 | 0.00        |
| 0.7082-0.8799 | Y=-12.662X+310.911 | 87                | -0.657      | 0.432 | 0.00        |
| ≥0.8799  | Y=-12.897X+311.163 | 69                | -0.632      | 0.430 | 0.00        |
The constant terms of the regression model reflect the background values of LST at different levels of diversity. With the increase of diversity, the constant term increased, which indicated that the contribution of diversity to LST was positive. In urban areas with higher diversity, the intensity of human activities was higher. The basic level of LST was also higher. The first-order coefficient determined the sensitivity of surface temperature to the change of vegetation cover. It could be shown in the table that the absolute value of coefficient increased with the increase of diversity, indicating that the response of land surface temperature to vegetation cover change was more sensitive in the area with greater diversity.

4. Conclusion
Based on Landsat remote sensing image and GIS spatial analysis method, this paper studied the ecological environment of the built-up area in the Third Ring Road of Shenyang City. The spatial pattern of LST and NDVI and their relationship with urban land use types were analyzed. It was found that the heat island effect was obvious in the Third Ring Road of Shenyang. In the urban ecosystem, there were significant differences in urban surface temperature and vegetation index among different land use types. The results showed that LST had a weak positive correlation with SHDI, while NDVI had a negative correlation with SHDI at the scale of 1km. LST increased with the increase of land use type diversity, while NDVI decreased with the increase of land use type diversity. Therefore, in order to alleviate the heat island effect and improve the urban thermal environment from the perspective of land use, it is necessary to carry out reasonable spatial combination and optimal layout design among various land use types. For the traditional industrial cities, reducing the diversity of urban landscape and increasing the degree of aggregation play an important role in restraining the urban heat island effect and improving the urban ecological environment.

LST, NDVI and SHDI can be used as three basic indicators to quantitatively evaluate the urban land use structure and its impact on the ecological environment, which can be used as a reference for the evaluation of the ecological environment impact of urban land use types.

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