Mapping and Assessment of the Urban Heat Island in Zhengzhou City

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Abstract

The rapid urbanization of Chinese cities has resulted in significant effects to the urban environment and to urban ecological networks. Zhengzhou city, the capital city of Henan province in central China, is characterized by a warm climate and four distinctive seasons, with a dry spring, and a hot and rainy summer. Based on satellite images, we analyzed land surface temperature (LST) and prepared a further assessment. Using LST data, we analyzed the urban heat island (UHI) and its relationship to green space, in order to make suggestions for future urban planning. The results show that urban heat island exists in Zhengzhou city Central Urban area. The mean land surface temperature (MLST) difference between urban and non-urban is significant. In addition, the urban green space reveals a negative relationship with LST. To conclude, we discuss the role of green space in mitigating urban heat island, and propose some greenway related strategies for urban landscape planning in Zhengzhou city.

Introduction

The increase in the urban heat island problem has been a common phenomenon in China, due to the rapid urbanization in the past decades. This so-called urban heat island (UHI) effect has caused serious environmental issues in cities. It has been proven that the changes of urban environment result in both social and economic problems, also adverse impacts on urban ecological environment and growth of diseases (Estoque et al.2017). However, many studies were focused on mitigation of the urban heat island effect, for example, green spaces have been used as strategies to adapt to climate change to reduce temperatures in many cities (Gago et al. 2013). In this study, we take Zhengzhou city as our study area. Zhengzhou is now facing a series of environmental problems like urban heat island because of the high speed of urbanization in the past years, growth of population, and conversion of land use. Although we have actions and measures to focus on urban landscape planning activities, we still need further research and practice. Therefore, this research was conducted to analyze the relationship between urban green space and LST to help the project "Regulation and landscape ecological planning of urban & rural green space resources", as well as in developing an urban landscape planning strategy to address UHI.

Background and Literature Review

Urbanization is happening at a rapid rate all over the world, especially with the development of and economic investment in developing countries. Taking China as an example, in 2017 almost 58% of China's total population lived in urban areas and cities, but this number was only about 33 % in 1997 (Word Bank 2018). Rapid urban expansion has caused land surface structure changes in the urban area, which also means the replacement of natural and semi-natural land cover types with sealed, impervious surfaces, changes in the biophysical environment and changes in surface energy processes (Voogt & Oke, 2003). This consequence influenced the environment and climate regulation at the local and regional levels, one of the key phenomena in the urban heat island (UHI). UHI is defined as a microclimatic phenomenon that occurs in metropolitan areas (Rizwan, Dennis, & Liu, 2008). It consists of a significant increase of the temperature in the urban area with respect to the surrounding peri-urban and rural neighborhoods (ERDF 2014), while urban climate is influenced by the land cover types, vegetation cover and urban structure (Voogt & Oke, 2003). During the past decades, a great number of studies have investigated this phenomenon, which provides important solutions for decision makers and urban planners (Deilami & Liu, 2018). Apart from air temperature, the land surface temperature (LST) has also been employed as a parameter of study for the urban heat island and it has been largely used to detect UHI for regional scale research, such as province level and state level.

Concerning how to mitigate the effect of urban heat island (UHI), many studies have shown the use of green spaces in cities, which form the green network that has significant ecological and social benefit as well and makes the urban area more resilient. These kinds of green spaces together with the other types of green areas often are regarded as green infrastructure (GI), consisting of multiple types of activities such as the forestry, water area, agriculture land, nature protection site and other various examples in different scales (parks, gardens, green roof etc.) (Park et al. 2017; Sun & Chen, 2017). GI is widely understood to decrease the temperature and reduce pollution in the urban area, as well as to increase the environmental quality and resilience of the city in developing countries. For examples, Li found that urban green space can lower temperature compared to other land cover types. Especially linear green spaces, like greenways along the rivers and channels, have been proven to reduce temperature in cities due to evapotranspiration of plants, albedo effects of objects and plant shadows (Gago et al. 2013). Developing green infrastructure in urban areas has been a strategy to mitigate the urban climate change. Vegetation surfaces such as green walls and roof gardens, gardens, parks, lawns and water can ultimately reduce UHI to varying degrees.

Goals and Objectives

Zhengzhou city in central China has experienced rapid urbanization in the past decades. Currently, Zhengzhou is facing serious UHI problems in summer and air pollution problems in winter. Therefore, the aim of this study is to map and assess the effect of urban heat island caused by urban expansion in Zhengzhou city. Based on the Landsat TM and ETM+ images from 2013 to 2017, we applied GIS technology for the analysis of Land Surface Temperature (LST) and prepared a further assessment. The research framework can be found in Fig 1.

The research steps were:

(1) Mapping the Land Surface Temperature of the study area from 2013 to 2017;
(2) Analysis of Land Surface Temperature difference between central urban area and green area, through study sites
(3) Analysis of Land Surface Temperature related to vegetation index (NDVI) in the Central Urban area of Zhengzhou
(4) Discussion of results and ideas how to mitigate the urban heat island effect in Zhengzhou

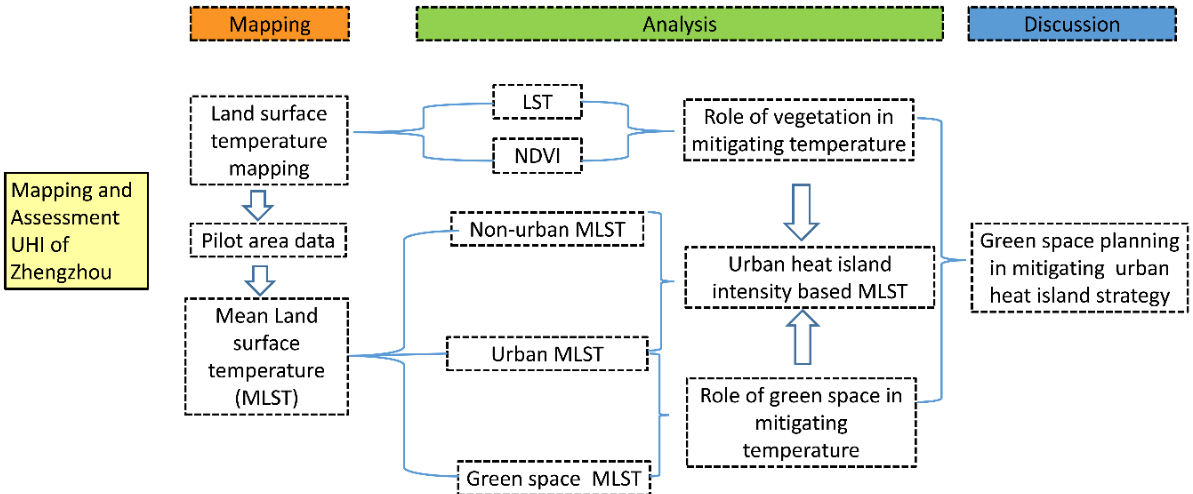

Fig. 1. Research framework

Location, Tools and Methods

Zhengzhou (34◦160 N–34◦580 N, 112◦420 E–114◦140 E) is the capital city of Henan Province in Central China and has four distinctive seasons. It is south of the North China Plain and the Yellow River (Figure 2). It is one of the largest transportation hubs in China. The population of the city was approximately 9.56 million according to the 2017 census (Henan Bureau of Statistics). The population density is the second highest in China. Zhengzhou lies in the north warm-temperate zone, characterized by a warm climate and four distinctive seasons, with a dry spring (March-May), and a hot and rainy summer (June–September).

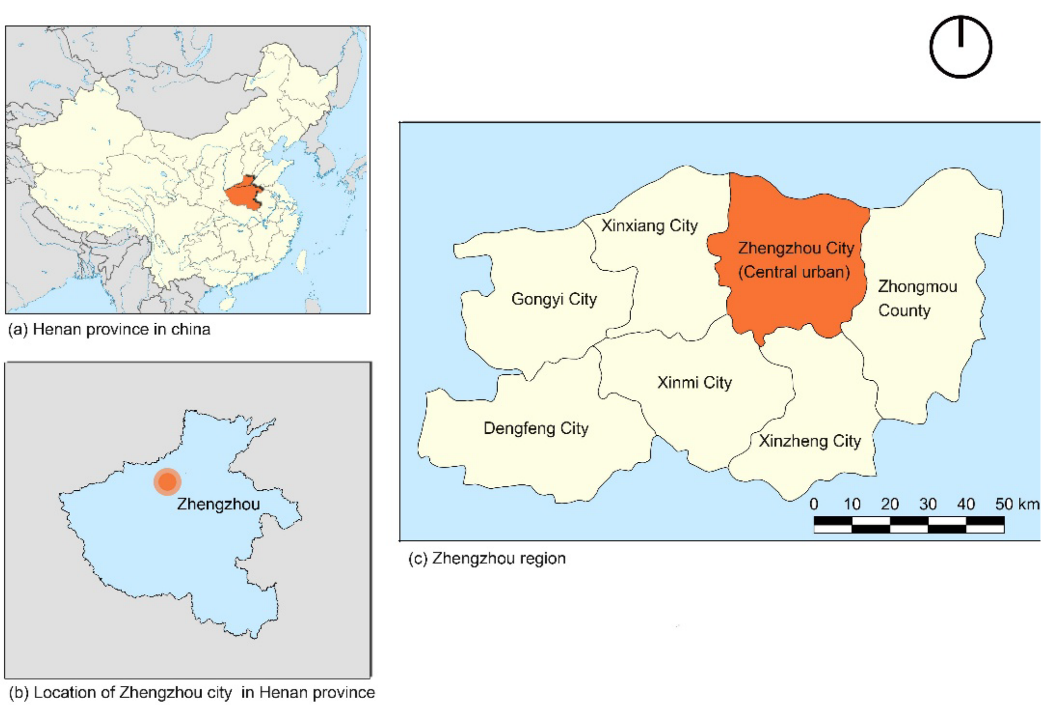

Fig. 2. Location of the Zhengzhou region.

Urbanization has taken place at a rapid rate in the past few decades in Zhengzhou city. Population and government level development policy is the main driver for the dramatic urban expansion. For example, the population of Zhengzhou increased from 4.2 Million in 1978 to 9.9 million in 2017, more than 100% growth (Mu, Mayer, He, & Tian, 2016). At the same time, Zhengzhou was selected as the core city of "Central Plain Economic Zone" and "Central Plains Urban Agglomeration". In 2016, Zhengzhou was officially named as the eighth National Central City in 2017 by the central government in China, this state-level policy provides a great number of opportunities for the development of Zhengzhou.

In this study, a total of 5 images from USGS (earthexplorer.usgs.gov; Table 1) were used to classify land use and land cover in Zhengzhou city. Those 5 satellite images were selected with cloud-free and high radiometric conditions. As the thermal infrared and sensors are different between Landsat 8 OLI-TIRS and Landsat 7 ETM+ with a spatial resolution of 100m and 60m. In method paragraphs below the paper presents the details of the formula.

Table 1. Multi-spectral Landsat images (Resolution: 30m * 30m) images used to estimate land surface temperature

Date	Satellite types	Path	Row
04/06/2013	Landsat 8 OLI-TIRS	124	36
10/08/2014	Landsat 8 OLI-TIRS	124	36
28/07/2015	Landsat 8 OLI-TIRS	124	36
11/05/2016	Landsat 8 OLI-TIRS	124	36
28/07/2017	Landsat 7ETM	124	36

The inversion method of land surface temperature (LST) has been widely recognized and generally divided into five steps (Di Leo et al., 2016; Jin, 2012; Bokaie et al., 2016):

1) Conversion to top of atmosphere Radiance;
2) Conversion to Top of Atmosphere Brightness Temperature;
3) Calculation of Proportion of Vegetation;
4) Calculation of estimate land surface emissivity (LSE);
5) Retrieval of land surface temperature (LST).

Mean land surface temperature intensity (MLSTI) is the temperature difference between the urban core area and its surrounding in rural area (Bokaie et al., 2016), here temperature is the average temperature, in this paper we choose the land surface temperature in Zhengzhou region, from the satellite images we can get the temperature at the same time both in urban and rural places. The formula as below:

$$MLSTI = T_s^u - T_s^n$$

Where T_s^u stands the average temperature in urban area, T_s^n is the surface temperature averaged from all "non-urban" pixels in the region for a specific land cover.

Results

First, we interpret the results in the whole Zhengzhou Central Urban area, comparing the MLST value based on the three rings in Central Urban area (Fig.2,Table 3), and with dot sampling of NDVI and LST data (Fig 3.). For the MLST intensity calculation we chose sample areas in non-urban landscapes, and green spaces to compare with urban areas (Table 4,5,6,7).

LST in Zhengzhou Central Urban area

The average LST spatial characteristic shows the scale and pattern of urbanization from 2013 to 2017. In Fig 2, it can be seen that the comparison of LST spatial distribution from urban center to urban edge. The three different rings are the administration boundary in Zhengzhou city (Fig.3).

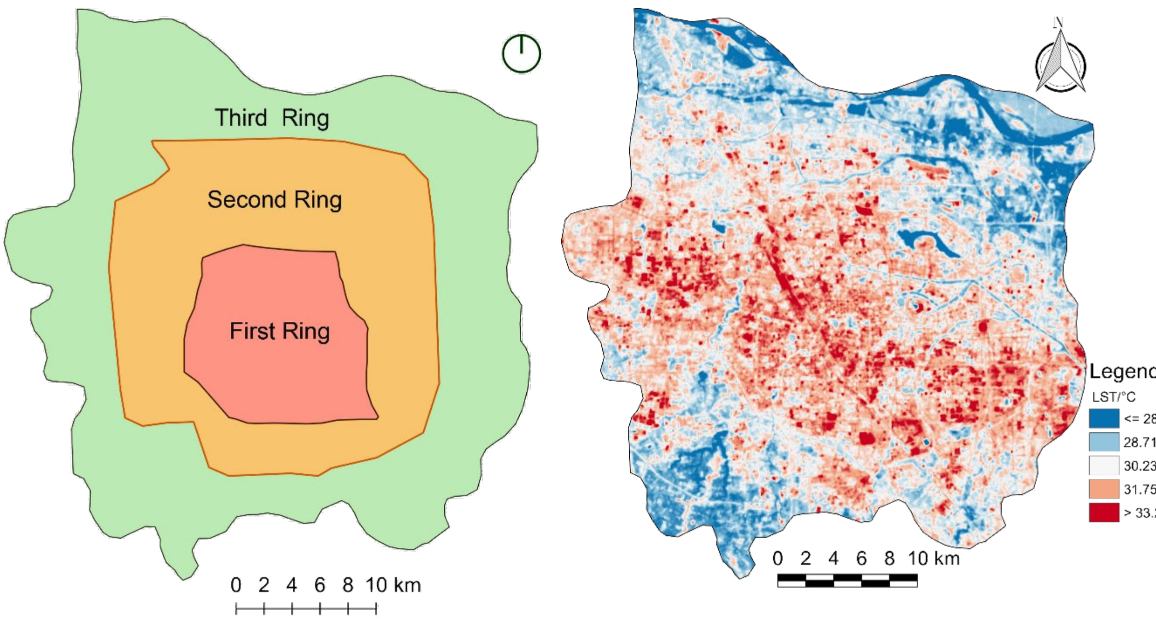

Fig. 3. Urban model of Zhengzhou Central Urban (Left); Average Land Surface Temperature (LST) from 2013-2017 of Zhengzhou Central Urban (Right)

We divided the main city area into 3 parts by the official administration boundary (Fig.3 left), the first ring is the earliest city boundary and the third is latest. From the first to the third ring, we can realize the way of urban expansion. While the spatial distribution of LST Zhengzhou central city area can be characterized by rings, from center diverging outward. As shown in table 3, we can find the mean LST value difference between the first ring and the third ring is 1.98℃, while the difference between first and second is 0.85℃. Overall, the core urban area has a higher temperature than the other parts.

Table 3. The mean Land Surface Temperature (LST) and details in three rings in Zhengzhou main city

Ring	Area (km^2)	Mean LST(℃)	Min LST (℃)	Max LST(℃)
First ring	140.31	32.49	26.95	39.16
The second ring	347.02	31.64	24.09	43.76
The third ring	571.13	30.51	22.43	42.23
All three rings	1058.54	31.05	22.43	43.76

Mean land surface temperature (MLST) intensity

For the surface temperature intensity of the land, we choose the land types of 9 non-urban areas as the reference (Table 4). These types mainly include forests, traditional villages, arable land, and waters among others, while the MLST in urban central area is mainly selected as the core area according to the spatial structure of the city. Based on the boundary of the ring segment, the core region of the first ring is selected as a temperature sample. Finally, the difference of the surface temperature of the land is obtained as the intensity value. The results (Table 4) of the 9 chosen areas reveals that the temperature of the village is the highest because of its built-up land, while the mountain is the lowest due to the mass coverage of vegetation.

Table 4. Mean, standard deviation (SD), and differences in value of Land Surface Temperature (LST) in Zhengzhou of remote sensing images in 8 non-urban pilot area

Pilot areas	Land use in rural	Area (km^2)	Mean LST(℃)	SD	Min LST(℃)	Max LST(℃)
1	Farmland	5.99	30.99	0.48	29.63	33.04
2	Cropland	2.30	27.95	1.03	24.99	30.03
3	Village	2.87	31.90	1.34	28.34	35.79
4	Forest	53.00	26.47	1.05	23.08	30.83
5	Mountain	56.84	24.84	0.93	20.46	30.65
6	Farmland & forest	37.30	27.83	1.12	24.31	31.82
7	Wilderness	32.71	30.56	0.61	27.29	32.33
8	Arable land	33.42	30.18	0.88	27.17	32.72
9	Non-urban area	10.11	29.23	0.94	27.58	33.13
	All the pilot areas	234.34	28.88	0.93	25.87	32.26

From the comparison result (Table 5) between urban and non-urban mean LST, the average temperature value reveals a big difference, it can be concluded that the spatial structure of the urban area and non-urban area was influenced by urbanization process, in which the mean LST of the urban core area increases to 32.49℃, while the suburbs and rural areas is 28.88℃. Collectively, these findings confirm the results of our literature review in the previous chapters.

Table. 5 Comparison of mean, standard deviation (SD), and differences in LST in Zhengzhou of satellite images between urban and 8 non-urban areas

	Urban	**Non-urban**
Mean LST (℃)	32.49	28.88
Stand Deviation (SD)	1.22	0.93
Range	12.21	6.39
MLSTI (℃)	3.61	

The MLSTI results show the urban heat island phenomenon exists in Zhengzhou city, which also reveals the temperature difference between urban and "non-urban" area is quite evident.

Relationship between LST and NDVI in urban

Green space can effectively reduce the UHI effect. In essence, it is due to the photosynthesis and transpiration of plants, and the leaves of plants can play a physiological role in reducing ambient temperature and air temperature. This is the principle of microscopic interpretation of green vegetation to alleviate surface temperature and thus reduce the urban heat island effect. In order to quantitatively calculate the linear relationship between vegetation coverage and urban surface temperature at the urban scale, we use the spatial analysis data and statistical tools of ArcGIS to convert the NDVI value and LST value of the study area, and then perform linear regression analysis to graph the NDVI and LST relationship (Fig. 4). The results show that the vegetation has a negative correlation with the LST.

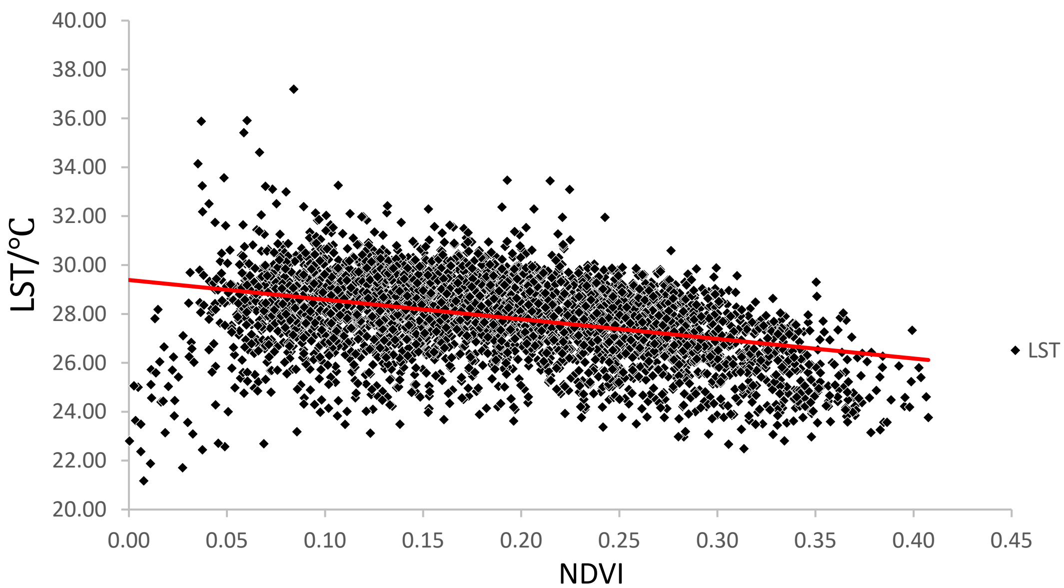

Fig. 4. Linear regression of average NDVI and LST in Zhengzhou central city

The effects of green space on LST

The role of green space in mitigating the land surface temperature can be described as temperature differences (T_d), which were estimated as the mean temperature difference between urban core area and green space ($T_d = T_s^u - T_s^g$), Where T_s^u stands the average temperature in the urban area, T_s^r is the surface temperature averaged from all green space pixels in the region for a specific land cover.

Table. 6 Mean, Standard Deviation (SD), and Range of Land Surface Temperature (LST) in the total urban area and the green spaces

	Total urban	Green spaces
Mean LST (℃)	32.49	29.54
Stand Deviation (SD)	1.22	0.89
Range	12.21	5
MLSTI (℃)	2.95	

It can be seen from the map (Fig. 3) that the shape of urban green space is irregular, so the green infrastructure signal is mixed with the adjacent urban land pixels. We also found that in these green infrastructure areas, the average LST during the 5-year period was always colder (2.95 °C) than the urban construction area, as shown in Table 6, the green infrastructure area (Table 7) in the 2013-2017 average LST image shows LST lower than the adjacent city area. However, thermal images show the effects of climate seasons and seasonal phenological differences on green infrastructure vegetation.

Table. 7 Mean, Standard Deviation (SD), and differences in value of Land Surface temperature (LST) in Zhengzhou of remote sensing images in green space

Id	Name	Land use	Area (km^2)	Mean LST(℃)	S D	Min LST(℃)	Max LST(℃)	Range
1	Renmin Park	City park	0.30	30.13	0.80	28.86	32.32	3.46
2	Ruyihu Park	District park	0.36	29.58	0.63	28.69	32.02	3.33
3	Jiangang reservoir	Water area	19.41	28.77	1.43	25.67	33.66	7.98
4	Zhengzhou city zoo	Special Park	0.20	29.79	0.89	28.12	32.43	4.31
5	Xiongerhe Park	park	1.02	29.57	0.85	28.09	32.69	4.60
6	Nursery	nursery	1.84	28.43	1.04	26.59	31.09	4.50
7	Zijingshan Park	City park	0.16	30.43	0.86	28.92	32.21	3.29
8	Dragon lake	New CBD	8.29	29.67	0.89	25.00	34.52	9.52
9	Yellow river basin area	Forest	6.40	29.53	0.66	27.62	31.60	3.99
Average				29.54	0.89	27.51	32.50	5.00

The negative correlation between LST and the Vegetation Index (NDVI) supports our hypothesis that the intensity of vegetation can significantly reduce LST. At the same time, the sample areas of green spaces also proved that higher vegetation coverage reflect lower LST, from Table 7, we can find the MLST of city parks (Renmin Park, Zijingshan Park. Fig. 5) about 2.95℃ lower than the whole MLST in the urban area due to their water surface and vegetation rate in parks. Especially, the Jiangang reservoir has the lowest LST among all the samples, for its water area percentage almost over 90%. The second lowest one is the nursery part for its 100% vegetation coverage. Therefore, we can use green space to reduce the UHI effect.

Fig .5. Renmin Park (Right) and Zijingshan Park (Left) in Zhengzhou Central Urban

Discussion

Urban heat island and land use changes

Land use change in the region is the result of a combination of urbanization and economic development. These changes are characterized by a reduction in farmland area, a decline in forests and water bodies, and an expansion of urban areas, which have become important factors affecting land surface characteristics. The urban thermal environment is also affected by changes in urban surface characteristics. The cause of land use and land cover (LULC) changes has been studied by scholars (Mu et al., 2016). The land surface structure changes due to the process of urbanization, the conversion of non-urban into urban, the cropland, forest, arable land and other coverage types transform into built-up land, and finally, the conversion of permeable surface into impervious surface material. Which, all together, results in the land surface temperature and air temperature increase in the urban area. We found higher temperature in urban built-up areas and lower temperature in green spaces, even in these located in the urban center.

Using green space (green network) to mitigate land surface temperatures

In our study, we selected a large range of green spaces patches as research sites, such as large green parks in cities, waters and special parks, and other specific green infrastructure areas. From the land surface temperature (LST) results, it is obvious that in the whole research area, the average LST of these green infrastructure areas is lower compared to the adjacent land (Table 4). Although the waterfront greenway is a linear green space, other land types in the immediate vicinity of the city, such as building pixels, are mixed together. However, it can still be seen that the linear green space forms a linear low-temperature region. Overall, we also found that, in these green infrastructure areas, the average LST during the five-year period was always cooler than the adjacent building area, as shown in Table 4. The green infrastructure area in the LST image (Fig. 6) shows that the LST is lower than the adjacent urban area. In Central Urban area of Zhengzhou city, the high LST areas, like the airport, factory, railway station (Fig. 6) have less vegetation cover and water inside, on the contrary, the impervious surface (covered with concrete, asphalt etc.) areas reveals more heat storage. However, the green space, especially the linear greenway, like Dongfeng greenway and Qili river greenway, have more effect in reducing the LST (Fig. 6). The negative correlation between LST and green areas (ie. greenway, parks, water etc.) supports our hypothesis that green space occurrence can significantly reduce LST. Specifically, our LST-NDVI analysis also showed a significant negative correlation (Table 5, Fig. 4) and explained that the variance of the best fit on the image.

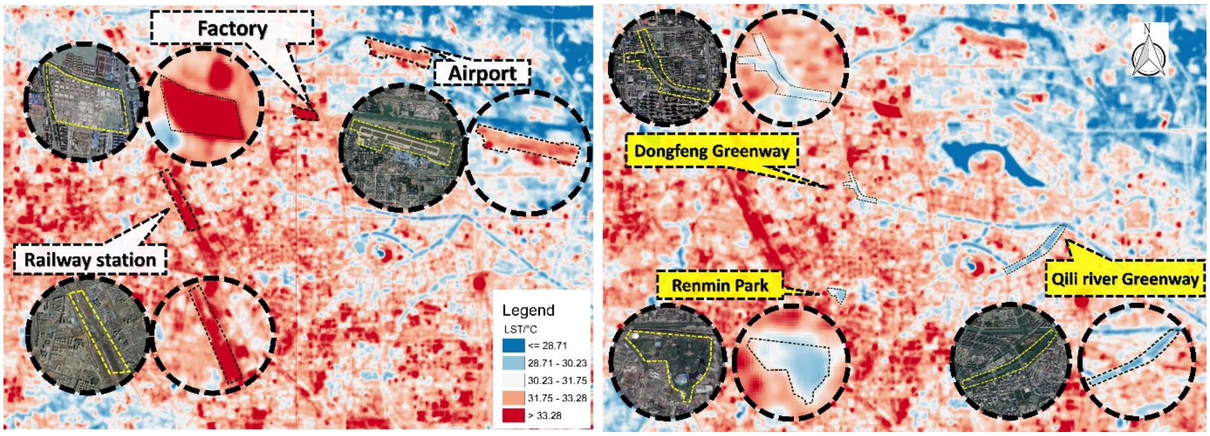

Fig. 6. Critical situations and proposals in Zhengzhou to mitigate UHI

Implications for urban landscape planning

The relationship between land surface temperature (LST) and urban landscape indicators is of great significance for urban planning and land use management and the mitigation of urban heat islands. The previous study (Gago et al. 2013) and our study all show the positive effect of vegetation and other types of green infrastructure on reducing the temperature in city area. At the city scale, the landscape metrics, such as the distribution of land surface coverage types and the impervious surface, contributes the most higher temperature to urban heat island according to the study (Li et al. 2011). Although we need residential land, transportation land, buildings and other impervious surface areas for the urban system, we still can mitigate the LST by increasing the service of green space system in high-density city center. We can use this to develop a vision to influence urban landscape planning, and inform how to make the urban environment more comfortable and healthy for residents to work and live.

Urban green infrastructure has been used as a mitigating strategy to lower the land surface temperatures in cities all over the world. It was proved that the size of green space in urban area plays an important factor in this cooling effect, but the spatial structure can affect the green space itself as well. The related studies showed that, from the city scale, LST was influenced by the area, shape, and density of green space and impervious surface area (Sun & Chen, 2017). These findings suggest that spreading the green space into high density areas has stronger mitigation of LST than the concentrated form.

Fig. 7. Green coverage in the old town and in the new Central Business District

Based on our studies, we can give recommendations for urban renewal and development of new districts: In Zhengzhou old town the future steps should:

- preserve the total area and green coverage of existing parks (e.g. Renmin Park)
- increase the significance of green spaces in block renewal (e.g. Dongfeng greenway)
- support renewal and replantation of old wood and old trees
- enhance planning of parks as linear green spaces, along the old or abandoned grey infrastructure elements to fulfil social recreational needs and ecological networks as well (Fig. 7)
- increase green area coverage in the old town, such as green roofs and roof gardens
- use vacant land for green site development
- construct water surface (e.g. lakes, fountains, channels, reservoirs).

For the new districts of Zhengzhou the futures steps should:

- develop low-density built-up areas with high rate of green spaces
- continue the construction of water channel system simultaneous with build-up area growth
- construct more water surface and forest connected with or integrated in green spaces (Table 7)
- support planning of linear green spaces of linear green spaces along the channels, especially in the direction of ruling wind to have more effects in mitigating UHI effect (Fig. 6)
- enhance greenway system planning place and green network connectivity to increase ecological and benefits of green spaces (Fig. 7).

Conclusion

This study uses satellite images to illustrate the land surface temperature (LST) characteristics of the Central Urban area of Zhengzhou city, revealing the characteristics of urban LST from different scales and types. Firstly, the magnitude of LST intensity in Zhengzhou Central Urban area is analyzed from the regional scale. The results show that the Mean Land Surface Temperature Intensity (MLSTI) value is 3.6 °C, indicating that the urban heat island effect exists in Zhengzhou. Secondly, the surface temperature in the center is higher than in the adjacent area. The MLST results indicate that the urban spatial distribution, ranked from the largest to the smallest is: first ring; second ring; third ring. Third, by comparing the average LST of the green space and the MLST value of the urban area, the mitigation effect of the green space on the urban heat island effect is revealed. The quantification results show that the urban green space MLST is 2.95 °C lower than the whole urban area, so the green space cooling effect is proven in the city. This is consistent with the relationship between NDVI and LST linear regression. The findings of the study quantify the heat island effect of Zhengzhou City and also provide useful information for green space planning to alleviate the urban heat island effect. At last, we give proposals to urban landscape planning and urban renewal, both in old town and newly built districts, and green spaces including city parks, greenways, green roofs, and other types of green corridors, to build an integrated ecological network in urban areas and make the city more sustainable in the future.

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