Spatial and temporal variation of heat islands in the main urban area of Zhengzhou under the two-way influence of urbanization and urban forestry

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Abstract

Urban heat islands are major factors hindering the quality of present-day urban habitats. The ongoing acceleration of the worldwide urbanization process is leading to an exacerbation of the urban heat island effect; however, urban forestry can mitigate it. For a sustainable urban development, it is particularly important to evaluate the dual effect of both factors on the urban heat island phenomenon. In this study, we focused on Zhengzhou City (China), at the center of the Central Plains Forest City Cluster. The spatial and temporal evolutions of the local urban heat island and vegetation coverage were measured from Landsat 5 and Landsat 8 remote sensing images taken between 2006–2020 and the effects of urban construction and urban forestry on the urban heat island effect were evaluated. The results showed that, in the past 15 years, the high-temperature zone in the urban area of Zhengzhou City has gradually spread from its center to surrounding areas. Within the same period, the whole urban heat island has deteriorated and gradually improved: its area increased by 138.72 km² between 2006–2014 and decreased by 135.66 km² between 2014–2020. Notably, the development of vegetation coverage occurred consistently with the improvement of the heat island. A quantitative analysis of the relationship between urban construction, the urban forest, and the urban heat island has shown that factors like population density (representing urban construction), urban planning, and vegetation cover (representing the urban forest) all have an impact on the urban heat island. Based on the dynamic changes of the urban heat island in the urban area of Zhengzhou City between 2006–2020, we conclude that urban forest construction strategies are beginning to bear fruit. Overall, the findings of this study provide a theoretical basis for future urban construction and urban forest construction plans; moreover, they can support landscape pattern optimization and urban heat island mitigation.
Introduction

With the acceleration of the urbanization process, the urban population has increased dramatically worldwide and a large number of impervious surfaces (e.g., buildings and roads) have replaced the original natural open land and vegetation [1, 2]. The most significant impact of urbanization on climate is the urban heat island (UHI) effect [3]. This relationship has long been of wide interest to the research community: the impact of urbanization factors (e.g., urban built-up areas, population, and ground surface impermeability) on UHIs have all been studied. Rizwan AM et al pointed out that the large amount of heat generated by urban structures (due to energy consumption and the reflection of solar radiation) and human activities are the main causes of UHI [4]. Urban areas are characterized by a very high degree of soil enclosure and continuous built-up areas. For instance, Italy is the European country with the highest artificial land coverage: a temporal increase of built-up coverage has been identified by Morabito M et al as the main cause of urban thermal environment deterioration [5]. The thermal performance of the asphalt concrete used in urban environments strongly regulates the urban UHI effect. Mohajerani A et al have suggested that the ongoing worldwide increase of man-made materials over land and that of anthropogenic heat production exacerbate the UHI effect [6]. He, B et al revealed that the degree of urbanization influences the synergistic effect between heat waves and urban heat islands [7]. Moreover, in another study, they found that the urban heat island effect is stronger in larger cities and that areal agglomeration weakens the surface urban heat island effect: areal expansion worsens the thermal environment of the region [8]. This effect is becoming increasingly significant and is causing a growth of energy consumption, thermal risks, air pollution, and pollution-related mortality [9], while lowering the quality of the living environment [10, 11]. In addition to environmental and ecosystem, social and health impacts, heat-induced economic impacts should be concerned for significant economic losses related to the impacts on labours, capital, goods and services and the possible influences on population migration [8]. The urban thermal environment has become a research hotspot in the fields of urban ecology, environment, and climate: there is an urgent need for approaches capable of mitigating the risks and negative consequences of the UHI effect.

Numerous studies have shown that vegetation can reduce temperature and increase humidity by shading long- and short-wave radiation and through transpiration [12–14]. As an important part of the urban ecosystem, urban forests can effectively improve the urban substrate and have a primary role in regulating temperature and in mitigating the UHI effect [15]. Due to urban land constraints, it is impossible to rely on the increase of urban forests alone to mitigate the UHI effect: besides expanding (in a limited way) the number and scale of urban forests, it will be fundamental to maximize the efficiency of urban forest vegetation to mitigate the UHI effect and improve the ecological benefits of urban forests. Cui, Y characterized the spatial distribution characteristics of urban forests in terms of vegetation coverage, patch characteristics, and spatial patterns, exploring the relationship between the spatial layout of urban forests and the UHI effect [16]. Wang, X et al conducted a comprehensive study on the thermal environmental effects of urban forests along the horizontal and vertical directions to explain the role of urban forest structure in thermal environment regulation [17]. Li, X et al studied the effect of forest patch landscape and community structure on the cooling effect of urban forest patches. The size, shape, and spatial distribution of vegetation patches were found to have significant effects on the urban thermal environment: increasing the area and density of patches can effectively reduce the surface temperature [18]. In fact, the higher the vegetation coverage, the larger will be the cooling effect [19–21]. Therefore, building urban forests has become an important approach to mitigate the UHI effect [22]. Further analyzing the
relationship between urban forests and the UHI effect can lead to new ideas and solutions for solving urban development problems.

The urbanization of Zhengzhou City (capital of the Henan Province, China) is progressing rapidly. In the past 40 years, the urban built-up area in the central part of the city has increased by more than six times; as a result, the land use pattern has changed significantly. The UHI effect in the city has hence attracted the attention of many scholars [23–29]. At present, Zhengzhou has a forested area of 2483.13 km², with a forest coverage of 35% and a forest accumulation of 9.3 million m³. The ecological benefits brought by an increase of the forested area, the “green core” of the urban cluster, cannot be underestimated. Therefore, it is worth studying whether Zhengzhou’s urban forest construction has achieved significant results over the years and whether it is effective in alleviating the UHI effect during a rapid urbanization process.

Being one of China’s central cities and an important national comprehensive transportation hub, Zhengzhou has a macro-regional role (i.e., it represents a connection point between eastern and western China, as well as between northern and southern China); moreover, it is fundamental for the internal and external linkage development and communication of the Central Plains City Cluster: the city has a meso-regional location, being at the core node of the cluster’s “Grand Cross” spatial skeleton.

Rao was the first to propose the use of satellite remote sensing technology to study the heat island effect. Since then, many scholars have conducted in-depth studies on this effect in different cities based on thermal infrared remote sensing data: satellite remote sensing technology provides data with a higher spatial resolution than conventional meteorological data [27]. The urban heat island effect in Zhengzhou City has been studied from different perspectives: some scholars have explored the impact of urbanization on urban heat islands, while others have studied the impact of vegetation change and forestry development countermeasures on urban heat islands; however, none of them have considered the two-way impact of urbanization and urban forestry on urban heat islands.

In this study, based on Landsat data collected in three periods (from 2006 to 2020), we studied the usefulness of night lighting data to determine the level urbanization, as well as that of the inverse vegetation index and of the vegetation cover to quantify the urban forest. The spatial and temporal dynamics of all these aspects were considered to clarify the effects of 15 years of urbanization and urban forest construction on urban heat islands, in order to provide a basis for future urban and urban forest construction.

Overall, the objectives of this study were to: (1) analyze the spatial and temporal evolutionary characteristics of the urban heat island effect and of the vegetation cover in Zhengzhou City; (2) quantitatively analyze the relationship between night lighting data, vegetation cover, and the urban heat island effect; (3) evaluate the bidirectional effects of urbanization and urban forestry on the urban heat island effect in Zhengzhou City during 15 years (from 2006 to 2020). The results were expected to provide a scientific basis for the optimization of landscape patterns and for the mitigation of the urban heat island effect.

### Study area and data

#### Study area

Zhengzhou is the capital of the Henan Province (China), located in its central-northern part (112°42’–114°14’E, 34°16’–34°58’N). It is bordered by the Yellow River to the north, the Song Mountains to the west, and the Yellow–Huai Plain to the southeast. Zhengzhou is characterized by a warm temperate continental climate with four distinct seasons and an average annual temperature of 14.4°C. The area includes a total of 35 large and small rivers, which belong to two major water systems (i.e., the Yellow River and the Huai River) and of which 150.4 km
flow through the Zhengzhou section of the Yellow River. The natural vegetation zone of Zhengzhou is occupied by a mixed coniferous and broad-leaved forest with a large number of sycamore and pine trees; however, due to unreasonable urban construction, trees have been cut down and land coverage types have been forcibly changed, leading to increasingly serious environmental problems, including persistent hazy weather. These problems explain the urgency of mitigating the UHI effect in Zhengzhou.

In this study we focused on the main urban area of Zhengzhou City (Fig 1), which includes five administrative districts: the Jinshui District (located in the north-eastern part of the city), the Guancheng Huizu District (located in the south-eastern part of the city), the Huiji District (located in the northern part of the city), the Zhongyuan District (located in the western part of the city), and the Erqi District (located in the south-western part of the city).

The main urban area of Zhengzhou covers a total of 1017 km²; here, the population amounts to 5.225 million people and the urbanization rate is ~ 74.6%. In 2014, Zhengzhou City was awarded the title of China’s national forest city; moreover, in 2018, the “Forest Henan Ecological Construction Plan (2018–2027)” proposed the creation of the Central Plains Forest City Cluster by involving national and provincial forest cities. Zhengzhou, represents the “green core” of this cluster and its ecological security is guaranteed as a node city of the “One

Fig 1. Location map of the study area.

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Belt and One Road” initiative. This initiative involves the construction of logistics channel hubs that connect eastern and western countries.

Data source
The digital elevation model (DEM) data used in this study are shown in Fig 1. The satellite image strip number of Zhengzhou City in the study area was 124, the row number 36, and the projected coordinate system WGS84. Landsat 5 TM, Landsat 8 OLI, and TIRS images were chosen as data sources for the study. Based on the acquisition time and the almost complete absence of clouds, three images were selected. They were on May 16, 2006 (TM), May 6, 2014 (OLI/TIRS), and May 22, 2020 (OLI/TIRS), respectively. These data were obtained from the Geospatial Data Cloud Platform of the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn).

Methods
Night-lighting data
The ArcGIS software was used to pre-process (including cropping, mosaic, mask extraction, and radiation calibration) the “Luo Jia No.1” night-lighting image data. The radiation calibration formula of the “Luo Jia No.1” product was as follows [30]:

\[ L = \text{DN}^{3/2} \times 10^{-10} \]

where L is the absolute radiation correction after the radiation brightness value and DN is the image grayscale value.

The UHI effect
Regional thermal field studies are usually based on two main indicators: the absolute bright temperature and the relative bright temperature (TR).

Here, we used a single-window algorithm to calculate the absolute bright surface temperature and used the remote sensing radiation value of a satellite’s thermal infrared channel to determine the temperature inversion [31, 32]; then, we produced a thematic map of the absolute bright temperature distribution in Zhengzhou City and related statistics. Zhengzhou City’s historical meteorological data were obtained from tianqi.com (http://www.tianqi.com/): three Landsat remote sensing images were acquired on May 16, 2006, May 6, 2014, and May 22, 2020, respectively. No precipitation occurred within three days before and after each acquisition date. The stable atmosphere and the dry air characterizing the area those days were extremely favorable to the formation of urban heat islands [24].

Concerning the thermal infrared band of TM data, the higher the brightness value of the image element, the higher will be the land surface temperature, and vice versa. The luminance temperature was calculated using TM thermal data (TM6): first, the image grayscale values

| Heat Island Class | Green Island | Weak heat island | moderate heat island | Strong Heat Island | Extremely strong heat island |
|------------------|--------------|------------------|----------------------|--------------------|-----------------------------|
| Relative bright temperature | <0 | 0–0.1 | 0.1–0.2 | 0.2–0.4 | >0.4 |

Table 1. Classification of the relative brightness temperature.

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(DN value) were converted into thermal radiation intensity values; then, the thermal radiation intensity values were used to obtain luminance temperature values [31]:

\[ L_{(\lambda)} = 0.1238 + 0.005632156Q_{DN} \]  

(2)

where \( L_{(\lambda)} \) is the radiation intensity received by the TM sensor (mW cm\(^{-2}\) sr\(^{-1}\) μm\(^{-1}\)) and \( Q_{DN} \) is the DN value of the image element.

\[ T_6 = K_1 \ln(1 + K_2/L_{(\lambda)}) \]  

(3)

where \( T_6 \) is the image brightness temperature (K) of TM6, while \( K_1 \) and \( K_2 \) are constants (\( K_1 = 60.776 \) mW cm\(^{-2}\) sr\(^{-1}\) μm\(^{-1}\) and \( K_2 = 1260.56 \) K). In the case of Landsat 5:

\[ T_6 = 1260.56/\ln(1 + 60.776/(0.1238 + 0.005632156 \times Q_{DN})) \]  

(4)

The radiant bright temperature of \( T_6 \) was obtained under the assumption that the features were all black bodies, and that they did not reflect the real surface temperature. Previous studies have shown that the real surface temperature can be calculated from the radiance of surface features according to the following equation:

\[ St = T_6/[1 + (\lambda \times T_6/\rho)/In\varepsilon]. \]  

(5)

where \( St \) represents the uncorrected ground temperature (K), \( \lambda \) the thermal infrared broken short central wavelength (11.5 μm; \( \rho = 0.014387 \) m K), and \( \varepsilon \) is the specific emissivity of the ground material. Since the urban subsurface is very complex, according to Griend et al. [33], \( \varepsilon \) correlates well with the normalized difference vegetation index (NDVI).

\[ \varepsilon = 1.0094 + 0.047\ln(NDVI). \]  

(6)

When the NDVI > 0, Eq (6) can be used to obtain \( \varepsilon \); when NDVI < 0, the empirical value of 0.92 proposed by Weng et al. is instead assigned to \( \varepsilon \) [34].

\( St \) represents the absolute bright temperature value of the ground in a certain quadrant. This value needs to be converted to Celsius degrees before relating it to the daily temperature experienced by the city population:

\[ T({}^\circ C) = St - 273.15 \]  

(7)

For years 2015 and 2020, we considered also Landsat 8 data, which include two thermal infrared bands (i.e., Band10 and Band11). In this case, the thermal field temperature inversion is basically the same as the that for Landsat 5 data. Since there is almost no difference in the spatial layout distribution of the regional thermal field in the inversion of the two infrared bands, but only a slight difference in the degree, we used the average of the two bands in the actual analysis.

The ground bright temperature is the temperature value for each ground image element and can be used to obtain a macroscopic spatial layout of the UHI effect; however, it does not allow a detailed quantitative regional analysis. TR represents the absolute difference of the UHI effect in the study area over time and space. Here, we applied the concept of relative heat island intensity to urban heat island classification [35, 36]. The corresponding calculation equation is as follows:

\[ TR = (Ti - Ta)/Ta \]  

(8)

where \( Ti \) is the bright temperature at the i-th point in the study region and \( Ta \) is the average bright temperature of the study area. The criteria used for the UHI classification (based TR) are shown in Table 1 [37].
Vegetation index and vegetation coverage

NDVI and FVC are considered as two key biophysical parameters in thermal remote sensing analysis. Many parameters can be employed to characterize the condition of vegetation based on remote sensing. Among them, the normalized difference vegetation index (NDVI) can be reliably used to estimate the cooling capacity of urban forests [38], which is defined as the ratio of the difference between the near infrared and visible red band values and the sum of these two bands. Since this index is the best indicator of vegetation growth and coverage, it is often used to determine the quantitative characteristics of vegetation, seasonal changes, and land coverage. In case of Landsat 5 data, the NDVI is calculated as follows:

$$NDVI = \frac{(B4 - B3)}{(B4 + B3)}$$

where \(B4\) and \(B3\) represent the digital number (DN) values of the TM3 and TM4 bands, respectively. The NDVI values vary within the range \([-1, 1]\). In the case of Landsat 8 data, due to the necessity of band adjustments, the following formula should be used to calculate the NDVI:

$$NDVI = \frac{(B5 - B4)}{(B5 + B4)}$$

where \(B5\) and \(B4\) represent the DN values of bands 5 and 4, respectively.

FVC is often used as a proxy for vegetation abundance. The vegetation coverage can be calculated based on the NDVI as follows:

$$FVC = \frac{NDVI - NDVI_{MIN}}{NDVI_{MAX} - NDVI_{MIN}}$$

where \(NDVI\) is the actual value of the NDVI of a certain image element; while \(NDVI_{MAX}\) and \(NDVI_{MIN}\) are the maximum and minimum values of the NDVI in the study area, respectively. Four levels of vegetation coverage were considered: (1) low coverage, fractional vegetation coverage (FVC) < 45%; (2) medium coverage, 45% ≤ FVC < 60%; (3) medium–high coverage, 60% ≤ FVC < 75%; (4) high coverage, 75% ≤ FVC < 100% [39].

Landscape pattern index

Landscape patterns are reflect the landscape heterogeneity, but also result from the combined action of human activities and various ecological processes at different scales [40]. To analyze the evolution characteristics of the thermal landscape pattern in Zhengzhou City between 2006–2020, we selected two indicators (i.e., the total number of patches (NP) and the largest patch index (LPI)), from both patch and landscape levels [41]. The TR maps were exported to the TIFF format using the ArcGIS software; then, the landscape analysis software FRAGSTATS 4.2 was used to calculate the landscape indices for different periods.

Results

Absolute bright temperature changes in Zhengzhou City

From the distribution of the absolute bright temperature in Zhengzhou City between 2006–2020 (Fig 2), it can be seen that the overall spatial pattern has changed greatly over the past 15 years: a high-temperature area has gradually spread from the center of the city in 2006 to the surrounding areas, and the high temperature range has expanded significantly in all administrative districts except the Erqi District (notably, the high-temperature area in the northern part of the city, near the Yellow River, has shown a change from none to something). Meanwhile, the heat increase in the central part of the city has slowed down over time. Only the Erqi District has shown a decreasing thermal trend in the past 15 years. High-temperature areas
were generally concentrated as they shifted to the built-up areas: large industrial clusters and industrial parks have become the main sources of heat over the past 15 years, while lakes and wetlands have been characterized by relatively low temperatures.

Between 2006–2020, the average surface temperature in the urban areas of Zhengzhou City first decreased and then increased, both in the study area as a whole and in the single administrative districts (Fig 3): the city's average temperature increased by 4.65˚C during this period. The average temperature increase in Huiji and Zhongyuan districts was of 4.88˚C and 5.83˚C, respectively; higher than that in the other administrative districts.

In terms of temperature extremes, the overall regional minimum temperature showed a gradual increase (Fig 4A) between 2006–2020: it increased by 4.44˚C. The trend observed in the Jinshui District was consistent with the overall trend for all administrative regions; however, some of these other regions showed a decline followed by an increase. The maximum temperature in the study area initially decreased over the 15-year study period (Fig 4B), but then increased: the overall increase was of 3.26˚C. The highest temperatures reached in the single administrative regions were generally consistent with the overall trend. The highest increase was observed in the Erqi District, where the maximum temperature reached was 7.38˚C.

Changes in the UHI effect in the urban areas of Zhengzhou

The TR results indicate the green islands in the urban area of Zhengzhou gradually moved southwards from the northern part of the city during the 15-year period: their coverage increased; moreover, their distribution changed from concentrated to scattered (Fig 5). Meanwhile, weak heat islands expanded northward, moderate heat islands expanded from a continuous patch in the central part of the city to a more scattered distribution in all districts, and strong–extremely strong heat islands became more scattered. Concerning the spatial
distribution of the heat field in 2020, strong–extremely strong heat islands were mainly concentrated in the central Guancheng Huizu District and in the northwestern part of the Zhongyuan District. Notably, between 2006–2020 (Fig 6), the total area of weak heat islands increased by 93.89 km\(^2\) (9.23%). The total area of green islands first decreased and then increased during the 15-year period; however, in 2020, it was the same as in 2006. Moderate and strong–extremely strong heat islands decreased by 85.96 km\(^2\), 3.74 km\(^2\), and 0.13 km\(^2\), respectively, between 2006–2020. Overall, there was a significant difference in the TR of each class of “island”: weak heat island > green island > moderate heat island > strong heat island > extremely strong heat island.

Fig 3. Plot of the average absolute bright temperature in Zhengzhou as a whole an in each district (between 2006–2020).

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Fig 4. Plot of the absolute bright temperature extremes in Zhengzhou as a whole and in each district (between 2006–2020). (A) Minimum temperature, (B) maximum temperature.

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The TR data for different districts in the urban area of Zhengzhou (Table 2) show that, between 2006–2020, there was a larger proportion of green island areas in the Huiji and Jinshui districts compared to other districts. This was especially true for the Huiji District, where

![Distribution map of the relative brightness temperature in the main urban area of Zhengzhou in 2006 (A), 2014 (B), and 2020 (C).](https://doi.org/10.1371/journal.pone.0272626.g005)

![Increase and decrease of the relative brightness temperature area in the main urban area of Zhengzhou from 2006 to 2020.](https://doi.org/10.1371/journal.pone.0272626.g006)
no extremely strong heat islands were registered. Except for the Erqi District, the areas of green islands in all regions first decreased and then increased during the 15-year period. In general, except for the Erqi District, the area of weak heat islands increased: the largest increase (of 42.41 km$^2$, or 21.42%) was observed in the Zhongyuan District. The area of moderate heat islands increased trend in the Huiji and Zhongyuan districts, while it significantly decreased in the remaining regions: the largest decrease (of 43.81 km$^2$, or 21.96%) was observed in the Guancheng Huizu District. The area of strong heat islands decreased in all regions except for the Zhongyuan District: the largest decrease (1.62 km$^2$, or 0.81%) was observed in the Guancheng Huizu District, followed by the Erqi District (decrease of 1.61 km$^2$, or 1.02%). Although the relative area increase of strong heat islands in all regions did not exceed 2%, the increase over the 15-year period is still worth of notice and should be considered a cause of concern: the areas of extremely strong heat islands in the Guancheng Huizu and Zhongyuan districts decreased over time (especially in the latter district, where extremely strong heat islands ultimately disappeared). Notably, the Erqi District was characterized by an opposite trend: the area of extremely strong heat islands increased over time.

**Vegetation coverage changes in the urban areas of Zhengzhou City**

Fig 7 shows how an area of low NDVI values spread from the middle of Zhengzhou City to the surrounding areas over the 15-year period. The minimum NDVI values first increased and then decreased, and their distribution changed from concentrated to scattered, while the range increased. Meanwhile, the maximum NDVI values first decreased and then increased, and their distribution was relatively fragmented.

The mean NDVI value slightly fluctuated in all administrative districts of Zhengzhou City (Fig 8): in the Erqi District it steadily increased over the 15-year period, indicating that the ecological background and maintenance of this area were good; however, the mean NDVI values in all other districts first decreased and then increased. The average NDVI value reached its maximum in 2020 in all administrative districts, indicating that vegetation growth changed to a certain extent in the whole urban area during the 15-year period, and that urban forest construction developed well in Zhengzhou City.

The vegetation coverage inversion results indicated that the low-coverage area spread from the center of the city to the surrounding areas during the 15-year period (Fig 9): it first increased significantly and then decreased, and its distribution changed from concentrated to
dispersed. Between 2006–2014, there was an obvious negative change in vegetation coverage (Fig 10), highlighted by a 44.92% increase in the area of low-coverage vegetation, while the areas of all other levels of coverage decreased. However, between 2014–2020, the area of low

![Distribution map of the NDVI in the main urban area of Zhengzhou in 2006 (A), 2014(B), and 2020 (C).](https://doi.org/10.1371/journal.pone.0272626.g007)

![Changes in the average value of the NDVI in various urban areas of Zhengzhou from 2006 to 2020.](https://doi.org/10.1371/journal.pone.0272626.g008)
coverage decreased by 20.03 km$^2$, while the area of all other levels of coverage increased. Overall, the areal distribution of different levels of coverage reflected the following relationships: low coverage > medium coverage > medium-high coverage > high coverage.

Fig 9. Distribution map of the vegetation coverage in the main urban area of Zhengzhou in 2006 (A), 2014 (B), and 2020 (C).

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Fig 10. Increase and decrease of the vegetation coverage area in the main urban area of Zhengzhou City.

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Table 3 shows the changes in vegetation coverage that occurred in different areas of Zhengzhou City between 2006–2020. Based on these data, the vegetation coverage of the Erqi District was clearly higher than that of other districts: here, we observed the smallest area of low coverage and the largest area of high coverage. Except for the Zhongyuan District (where the low-coverage area gradually and continuously increased), the low-coverage area generally first increased and then decreased. Among all areas of the city, the Zhongyuan District showed the largest increase (105 km$^2$, or 53%). The medium-coverage area decreased instead in all regions: the largest decrease (30.75 km$^2$, or 15.42%) was observed in the Guancheng Huizu District. The medium–high-coverage area also decreased in all regions: the largest decrease (47.05 km$^2$, or 21.17%) was observed in the Huiji District. The area of high coverage in all regions showed a decreasing trend, followed by a small increase: the largest decrease (42.34 km$^2$, or 21.39%) was observed in the Zhongyuan District, followed by Huiji District (decrease of 42.7 km$^2$, or 19.21%).

Changes in the Zhengzhou urban landscape pattern index

The landscape indices obtained from two indicators (i.e., the total NP, representing the patch level, and the LPI, representing the landscape level) for different periods between 2006–2020 (Table 4) indicate that the number of patches on green and moderate heat islands increased, while their maximum patch index decreased. Also, the number of patches on weak heat islands decreased, while their maximum patch index increased. Finally, the number of patches on strong and extremely strong heat islands decreased while the maximum patch index decreased.

Spatial distribution characteristics of urban night lighting data

In the center of cities with a human population size of 500,000–1,000,000, temperature is generally 1.1–1.2˚C higher than in the suburbs. The difference can even reach 1.2–1.5˚C for cities with a population size $>1,000,000$ [42]. Intensity information, based on night lighting data,
can be used to visualize the distribution of a population in real life and reflect its spatial density within a region [43]. We produced a night lighting image map of Zhengzhou City for October 30, 2018 (Fig 11A). This map shows that the central area of Zhengzhou City had a significantly higher population density than its surrounding areas. We considered the range of light and dark areas in the night lighting image map and compared the relative light temperature of Zhengzhou’s urban area between 2006–2020 in these two types of areas, finding that the intensity of the UHI effect in the light areas (presenting a larger distribution of strong–extremely strong heat islands, a high intensity of green space construction, and a higher amount of green islands) was higher than in the dark areas. After grading the night lighting data for five areas of the main urban area, we also found that the night lighting intensities of the administrative districts reflected the following relationships: Jinshui District > Guancheng Huizu District > Zhongyuan District > Erqi District > Huiji District (Fig 11B).

**Correlation analysis between FVC, the night lighting data, and the urban heat island effect in the study area**

The obtained vegetation cover FVC, the night lighting images, and the relative bright temperature images of the urban heat islands in the main urban area of Zhengzhou City were normalized and 240 sample points were randomly selected from the three images; then, FVC, the night lighting data, and the relative bright temperature values of each sample were counted. The correlations among them were hence determined (results shown in Table 5): the correlation between FVC and the relevant bright temperature was extremely strong in 2006, 2014, and 2020, while the correlations between the night lighting data in 2018 and the relative bright temperature values in 2014 and 2020 were weak. This indicates that urban heat island intensity is more strictly correlated with the vegetation quality of the urban forest than to urban construction.

**Analysis and discussion**

The first study on Zhengzhou’s UHI is dated 1997 [44]. The authors of that study concluded that the occurrence of a UHI in Zhengzhou was mainly due to the difference between the
thermodynamic properties of the urban substrate and those of the suburbs. Obvious daily, seasonal, and annual variations were observed in the intensity of the UHI effect; however, the intensity changes related to height are less apparent. Here, we compare our results with those of five previous studies: Chen, Y’s Landsat satellite remote sensing images (collected in 2000, 2004, 2008, and 2015) [25], Zhang F et al’s MODIS surface temperature data (collected between 2007–2016) [27], Min M’s Landsat images (collected in May 1996, 2000, 2006, 2010, and 2014) [26], Zhang, X’s Landsat images (collected in April–May 2000, 2008, and 2017) [28].

All of the above works concluded that the surface temperature in Zhengzhou City increased during the respective study periods and that the UHI effect became increasingly serious over time. Thich is consistent with our idea that, between 2006–2014, the overall urban thermal environment of Zhengzhou City deteriorated and the UHI effect became more serious. Since the authors of those previous studies did not consider images collected after 2017, they could not observe the reduction of the UHI effect that occurred in Zhengzhou after that time. Meanwhile, Geng, L (who selected Landsat images collected in July–August 2000, 2004, 2009, 2013, and 2019) found that, under continuous urbanization, the expansion and spreading of built-up areas, and the decrease of the green space scale, the UHI effect in Zhengzhou City did not intensify, but rather slowed down and diminished in intensity [29]. This is consistent with our idea that the urban heat environment improved between 2014–2020: urban forest construction began to bear fruit before 2020; moreover, the area of medium–high and high-vegetation coverage increased.

### Impact of urbanization construction on the UHI effect

Rapid urbanization is the main cause of the UHI effect [45–47]. We explored this relationship from two perspectives: population density and urban planning. The spatial distribution characteristics of night lights (Fig 11) suggest that: (i) a high population density may promote urban construction, including urban forestry; furthermore, population density correlates with

| Table 5. Correlation between FVC, the night lighting data, and the urban heat island effect in the study area. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | 2006 FVC        | 2014 FVC        | 2020 FVC        |
| 2006 FVC        | 1.000**         | 1.000**         | 1.000**         |
| 2014 FVC        | 1.000**         | 1.000**         | 1.000**         |
| 2020 FVC        | 1.000**         | 1.000**         | 1.000**         |
| 2018 Night Lighting Data | 0.035 | 0.035 | 1.000** |

Note
** means that, at the 0.01 level (two-tailed), the correlation was significant.

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the presence of impermeable surfaces that, in turn, correlates with the extent and intensity of heat islands; (ii) an increased emphasis on green space is key to the urbanization process; (iii) the higher the population density, the more urbanized will be a certain area, and the more funding and capacity there will be for green space development. These findings are in line with those of Xu, Y et al: a high population density would sustain an increase of the urban green space construction scale; additionally, a larger population would promote investments in green space construction by the local government [48, 49].

Reasonable urban planning can effectively mitigate the UHI effect, improve the urban thermal environment, enhance human comfort, and lead to a reduction of building energy consumption [50, 51]. The Zhengzhou City Master Plan (2010–2020) (revised in 2017) proposes to build a regional-urban center system with the Erqi Square commercial center, the Zhengdong New District CBD, the Zhengzhou East Station transport hub center, and the Zhengzhou Airport transport hub center as the core, while Zhengzhou actively builds industrial clusters in the context of industrial transfer. The main areas include: the High-tech Development Zone in Zhongyuan District, Erqi Mazhai Industrial Cluster, Guancheng Yutong Industrial Park, Jin Dai Industrial Park, and Huiji District Economic Development Zone (Fig 12). An analysis of the evolution of the heat landscape pattern in Zhengzhou City over the 15-year period.
(2006–2020) shows that the number of weak and moderate heat island patches increased significantly between 2006–2014, while their maximum patch index decreased, indicating that the weak and moderate heat island patches gradually tended to become fragmented and complex, which is consistent with the start of large-scale construction in the city during this time period. The maximum patch index of the strong and extremely strong heat islands shows an overall decreasing trend over the 15-year period, and the number of patches is also gradually decreasing, which indicates that the urban construction of Zhengzhou City is accelerating, and the strong and extremely strong heat island patches are gradually decreasing through reasonable design and planning, increasing greenery and water area and other related measures. The layout of industrial parks is closely related to the heat island effect, and the spatial distribution of heat island patches matches the spatial distribution of industrial clusters to a high degree: the two extremely strong heat island patches are the Zhengzhou Luyuan Kitchen Waste Treatment Plant in Erqi District and the Dongfeng Nissan Zhengzhou Engine Plant in Guancheng Huizu District. The strong heat island patches are mainly located in the vicinity of the car repair center in Jinshui District, the Gree Industrial Park in Zhengzhou High-tech Zone, Zhong Yuan District, Zongye Da Intelligent Manufacturing Industrial Park, and Hengtian Heavy Industry Co Ltd, and industrial clusters and industrial parks, such as Zhengzhou Coal Mining Machinery Group Co Ltd, Henan Bonded Logistics Centre, and Economic Development Zone in Guancheng Huizu District.

**Impact of urban forest construction on UHI**

Building urban forests is an important means of promoting urban ecosystem restoration and improving the human environment in China [52]. Policy guidance is important to reduce the heat island effect and influence vegetation coverage [53–55]. From the results of the study, it is clear that 2014 was an important point of change in the construction of urban forests in Zhengzhou. Previously, although NDVI was on the increase, the significant increase was only in the area of low vegetation coverage, with a decrease in the area of medium-high and high vegetation coverage, which did not provide effective relief to the UHI. after 2014, due to the increasing emphasis on ecological civilization in China, Zhengzhou was awarded the Chinese “National Forest City” for its urban forestry achievements, the construction of the Central Plains Forest City Cluster proposed in the “Forest Henan Ecological Construction Plan (2018–2027)”; the “Zhengzhou National Central City Forest Ecosystem Plan (2019–2025)” proposed that Zhengzhou will focus on creating a forest isolation circle around the city’s suburbs and vigorously promote tree planting and greening projects on the periphery of the main urban area; the “Forest Zhengzhou Ecological Construction Plan (2020–2035)” promotes Zhengzhou to leapfrog from a “green city” to a “green capital”. It is clear that, between 2014–2020, the area of medium to high vegetation coverage in the urban areas of Zhengzhou increased, and the UHI effect improved and developed for the better. This shows that in the process of urban forestry, we should not only focus on the increase of the vegetation area, but also on the quality of planting and vegetation density.

The Zhengzhou City Master Plan (2010–2020) proposed the construction of new parks and green areas: large comprehensive parks and special parks, strip parks along city roads and waterways, parks and green areas in residential areas (according to the national standards), and small gardens and street green areas (according to the 500-m service radius rule). According to Table 4, the number of green islands in the urban area of Zhengzhou increased between 2006–2020 (by a total of 393 patches). By combining these data with the distribution of green islands in the urban area of Zhengzhou (Fig 5), we determined the changes in NP between
2006–2020: the number of green island patches increased over time and their distribution became more dispersed from the periphery to the center, reflecting a “greening at the seams” development. Green islands showing obvious changes were those near the Longhu in Jinshui District, the Zhengzhou West University City, the Economic and Technological Development Zone in Guancheng Huizu District, and the South Water North Transfer Ecological and Cultural Park in Zhujiang Shangjing (Erqi District) (Fig 13). The fragmentation of green islands in the main urban area of Zhengzhou has led to the creation of many small discrete patches: large dominant patches have been constantly replaced and impacted by expanding discrete urban construction sites. Studies have shown that an increase of the urban green space area can effectively mitigate the UHI effect [56, 57]. Our analyses of the spatial and temporal changes in the heat field and vegetation coverage of the urban area of Zhengzhou City showed that the vegetation condition in the study area gradually deteriorated and the intensity of the UHI effect increased between 2006–2014. In the subsequent seven-year period, the vegetation condition in the study area began to improve: the total green island area increased, while the overall intensity of the UHI effect decreased. Based on these observations, we suggest to implement a combination of greening means (according to the local conditions of Zhengzhou City) to increase the green coverage of the city and effectively mitigate the UHI effect.
Typical point change analysis

By considering the NDVI values obtained for 2020 and 2006 (Fig 14), we found that the area with the smallest difference was characterized by both strong-heat and extremely strong heat island patches. However, some areas with high amounts of vegetation also presented some heat island patches; this is because urban construction is typically faster than urban forest construction. According to the green island area, the strong-heat and extremely strong heat island areas identified from Figs 12 and 13, and the urban planning of recent years, we selected the Long Lake Recreation Center, the Zhengzhou West University Town, the New Zhengzhou Station Comprehensive Transportation Hub, and the Zhengzhou Luyuan Kitchen Waste Treatment Company as typical change points and further analyzed the local changes in the UHI and in the urban forest.

Located in the Jinhui District, the Long Lake Recreation Centre has a water area of ~ 5.6 km² and was officially impounded in 2012 by the Long Lake Transfer Project. Changes in TR during the study period are shown in Fig 15. Notably, the ecology of the Long Lake Recreation Centre had not yet been destroyed in 2006. According to the Zhengzhou Urban Master Plan (2010–2020), the Long Lake area transformed into a key construction area in Zhengzhou and landscape design started along the Long Lake in 2013. Hence, the green island area around the Long Lake decreased from 2014 onwards, moderate heat island areas increased and some strong heat islands appeared. By 2020, the ecological environment of the Long Lake’s
recreational center had recovered, the green island area had rebounded significantly, and the area of strong heat islands had significantly reduced. This indicates that, even though the Long Lake area is still under construction and development, an urban forest has vigorously developed: vegetation and water bodies have mitigated the heat island effect. Therefore, the ecological environment of the Long Lake has not been greatly affected and extremely strong heat islands have never appeared.

The Zhengzhou West University Town is located in the Zhongyuan District. A park was created at this location in 2001 to promote the Zhengzhou National High-Tech Development Zone. As shown in Fig 16, heat island changes were consistent between 2006–2014: weak heat islands dominated, green islands decreased yearly, and moderate heat islands increased yearly. By 2020, the West University Town’s heat island and vegetation coverage had changed dramatically: the green island area was almost equal to the whole area, and the areas of weak, moderate, and strong heat islands had decreased, indicating that urbanization construction in this area had stopped, while the construction and development of urban forest had started. As a result of these measures, the green island area had increased significantly and the ecological environment had improved greatly.

The New Zhengzhou Station Comprehensive Transportation Hub, whose foundation stone was officially laid in 2007, is located in the Guancheng Huizu District. As shown in Fig 17, the
TR at this location in 2006 was dominated by green islands. According to the Zhengzhou City Master Plan (2010–2020) (revised in 2017), the Zhengzhou Station Comprehensive Transportation Hub transformed into a key construction area. The largest moderate heat island area was observed in 2014; moreover, a strong heat island of 0.21 km$^2$ was observed at that time. This indicates that the ecology of the new Zhengzhou Station integrated transport hub was severely damaged in 2014. By 2020, the green island area had increased, the area of the weak heat islands had decreased, and the area of strong heat islands had also decreased as a result of effective mitigation measures.

The Zhengzhou Luyuan Kitchen Waste Treatment Company, shown in Fig 18, is located in the Erqi District. Between 2006–2014, this area was dominated by weak heat islands, green islands appeared and increased, and both moderate and strong heat islands decreased, indicating an improvement of the ecological environment over time. However, in 2020, the Luyuan Kitchen Waste Treatment Company coincided with one of the two extremely strong heat island patches of Zhengzhou City, the green island disappeared, and the area of strong heat islands increased, indicating that the ecological environment faced unprecedented challenges at this location in 2020. Therefore, mitigation measures are urgently needed here to improve the thermal environment.
Limitations

This innovative study on the impact of urban heat island by both urbanization and urban forestry presents limitations. 1) Since we considered Landsat images, whose data accuracy is not high, the results are suitable for macroscopic research (large scale studies) only: the resolution is not sufficient for considerations at the administrative or neighborhood scales. 2) Remote sensing data should be combined with actual surface observation data (e.g., forest structure, vegetation type, and actual surface temperature) to improve the applicability of the research results and the operability of future planning.

Conclusion

Based on Landsat remote sensing images collected between 2006–2020, we calculated the surface temperature and the vegetation index for the urban area of Zhengzhou City. Geospatial analysis and landscape pattern analysis techniques were integrated to assess the impact of urban construction and urban forestry on the UHI effect in Zhengzhou City, which has been considered a national forest city and the “green core” of the Central Plains Forest City Cluster for the past 15 years. The results showed that, between 2006–2014, Zhengzhou’s UHI
deteriorated due to the continuous expansion of urban construction land, changes in land coverage of the urban substrate, landscape fragmentation, and negative changes in vegetation coverage. In this context, strong and very strong heat island patches coincided with industrial agglomerations, indicating the latter had a certain influence on the intensification of the UHI effect. However, between 2014–2020, the UHI effect was mitigated due to reasonable urban planning and construction. In this context, vegetation coverage increased, suggesting that urban forest construction can significantly reduce the UHI effect. Urban forest construction is influenced by vegetation coverage and policy guidance; notably, if urban forest construction preponderates over urbanization construction, the UHI effect will be weakened. We can hence conclude that urbanization construction and urban forestry construction deeply influence the UHI effect. We did not only analyze the spatial and temporal evolutionary characteristics of the urban heat island effect and of vegetation cover in Zhengzhou City, but also quantitatively analyzed the relationship between urbanization, the urban forest, and the urban heat effect. In particular, our results on the two-way effects of urbanization and urban forest on the urban heat island effect in Zhengzhou City during the past 15 years will support the implementation of new solutions for urban heat island mitigation and landscape pattern design. Although we only evaluated construction effectiveness of urbanization and urban forestry, analyzing its...

Fig 18. Relative brightness temperature distribution map and area change map of the Zhengzhou Luyuan Kitchen Waste Treatment Company in 2006 (A), 2014 (B), and 2020 (C).

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causes would provide important references for future urban construction, planning, and decision making.

Supporting information

S1 Data.

Author Contributions

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