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Carbon saving potential of urban parks due to heat mitigation in Yangtze River Economic Belt

Mo Chen [a], Wenxiao Jia [a,*], Chunlei Du [a], Manqing Shi [a], Geoffrey M. Henebry [b], Kai Wang [a]

[a] College of Landscape Architecture & Arts, Northwest A&F University, Yangling, 712100, China
[b] Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI, USA

A R T I C L E   I N F O

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A B S T R A C T

Urban parks are considered as an effective, sustainable, and affordable heat mitigation strategy. At present, there is a lack of understanding of the carbon saving potential of urban parks in the context of urban warming. Here we provide a simple approach to estimate the potential carbon savings due to heat mitigation based on analysis of 1510 parks in 26 major urban areas of the years 2017–2021 within the Yangtze River Economic Belt (YREB), China's largest sustainability experiment. On average, an urban park with 26.9 ± 1.5 ha in the YREB could avoid 23.7 ± 1.6 t CO_2 (1.08 ± 0.03 t CO_2/ha) in emissions due to heat mitigation per summer day. Considered altogether, the 1510 urban parks can offset 5.37% of the daily fossil fuel emissions in the YREB. To boost carbon saving efficiency, lush vegetation should be first considered and the coupled green and blue infrastructures are always advocated. The total parks carbon saving of cities gradually improved along the Yangtze River from west to east, among which Shanghai city (in the east of the YREB) is with the largest amount (4341 t CO_2). The strategies using exquisite landscape design for improving carbon saving may differ across different climate zones. These findings can inform decision-making for urban sustainable development and climate change mitigation, which may benefit China's movement toward carbon neutrality.

1. Introduction

In recent decades, rapid urbanization has caused multiple undesirable environmental consequences(Grimm et al., 2008), including intense urban heat islands(Ebi et al., 2021; Maggiotto et al., 2021; Manoli et al., 2019), extreme precipitation events and urban flooding (Liu and Niyogi, 2019; Pour et al., 2020) etc. The urban heating problems are more complicated in the context of human-induced global warming, accompanied by more frequent, intense and long-lasting hot extremes across most land regions (IPCC, 2021). To alleviate the effect of urban heating, a series of heat mitigation measures have been explored, including individual cooling and urban green infrastructure as nature-based solution (Alajmi and Zedan, 2020; Cuthbert et al., 2022; Teotonio et al., 2018). The use of air conditioners and electric fans to stay cool in buildings comprises nearly 20% of total building electricity use and this trend is set to grow(Birol, 2018). The electricity cooling intervention not only further exacerbates climate change and urban heat island by driving up greenhouse gas emissions, but also widens inequality in hot extremes(Hsu et al., 2021; Jay et al., 2021). More sustainable, affordable, and decentralize measures need to be sought to cope with heat-related health risks and climate change issues. As blue-green infrastructures inside the urban parks can offer cooling service via shading, evapotranspiration, and large heat capacity, urban parks are considered as effective sustainable nature-based solutions, thereby potentially saving energy and reducing carbon emissions through heat mitigation(Bao et al., 2016; Cheng et al., 2015; Li et al., 2019; Sugawara et al., 2021; Zhao et al., 2017). Identifying the value of energy or carbon savings from urban parks from the perspective of heat mitigation, could lead to better regional planning, urban sustainability, and decision-making under increasing urban warming context.

Many studies have verified urban parks' significant cooling effects (Du et al., 2022; Wong et al., 2021). In contrast, the contribution of urban parks to carbon emission reduction through heat mitigation has been less understood. Numerous previous researches have addressed the contribution of urban parks in carbon balance due to direct fixation by photosynthesis (Gratani et al., 2016; Jo et al., 2019; Shadman et al., 2022; Wang et al., 2021), but ignored the indirect reduction of carbon emissions through reducing thermal environmental pressure (Lin et al., 2011; Zhang et al., 2014). The heat mitigation by urban parks can result in considerable reductions in carbon emissions. A scenario analysis in Adelaide, South Australia, estimated that greener public spaces could

* Corresponding author.
E-mail address: wxjia@nwafu.edu.cn (W. Jia).

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Nomenclature

CSI	Carbon Savings Intensity
CSE	Carbon Savings Efficiency
YREB	Yangtze River Economic Belt
Cwa	Köppen's subtropical monsoon humid climate
Cfa	Köppen's subtropical humid climate
CY	Cheng-Yu urban agglomeration
MRYR	Middle-Reach Yangtze River urban agglomeration
YRD	Yangtze River Delta urban agglomeration
LST	Land Surface Temperature
LSI	Landscape Shape Index
NDVI	Normalized Difference Vegetation Index

avoid 140,000 tons of CO_2 emission annually compared to the business as usual scenario (Sharifi et al., 2020). A case study in Beijing showed 14,315 tons CO_2 could be saved and the amount was related to the biomass, size, and shape of urban green areas (Lin et al., 2011). However, few studies have attempted to calculate carbon savings potential resulting from urban parks' cooling effect. Extant studies were carried out in a single city or in certain area within a city; thus, the carbon saving potential resulting from urban parks' cooling effect on regional scale remains unclear (Morakinyo et al., 2018; Xu et al., 2019).

Established in 2016, the Yangtze River Economic Belt (YREB) is China's largest cross-province sustainability experiment, which could have important implications for global governance of climate and sustainable development (Bai and Wang, 2020; Kuhn, 2019; Peng et al., 2021b). It is the most flourishing and densely populated region of China, including three major urban agglomerations: Cheng-Yu urban agglomeration (CY), the Middle-Reach Yangtze River urban agglomeration (MRYR), and the Yangtze River Delta urban agglomeration (YRD) (Liu et al., 2021). China's economic and demographic growth has become more focused in YREB(Li et al., 2021; Yu et al., 2020). According to the statistics of the Ministry of Ecology and Environment of the People's Republic of China, the urban area of the YREB increased by 84.1% from 2000 to 2015, with an average annual growth rate of 5.6%. However, YREB faces increasing threats from heat: frequent occurrence of extreme heat waves and severe urban heat islands have affected the productivity and health of urban inhabitants(Shi and Ye, 2021; Zhong et al., 2017). Seven of the China's top ten "furnace cities" are located within the YREB: Chongqing, Hangzhou, Nanchang, Changsha, Wuhan, Nanjing, and Hefei. The YREB's development plan emphasizes a green development path to cope with the heating issue, aiming to bring benefits to human development, health and well-being.

Here we analyzed data from 1510 urban parks across 26 cities throughout the YREB to quantify their potential carbon savings during hot summer days. Our study had three objectives: 1) to quantify the spatial distribution of carbon savings due to urban parks; 2) to analyze the factors influencing urban carbon savings and propose actionable solutions for maximizing carbon savings; 3) compare the carbon savings of urban parks across different urban agglomerations.

2. Materials and methods

2.1. Study area

The YREB stretches across the western, central, and eastern of China, covering 11 provinces with an area of 2.05 million km^2. The three urban agglomerations, i.e., CY, MRYR, and YRD, constitute the "three growth poles", located in the upper, middle, and lower reach, respectively (Fig. 1). The CY urban agglomeration is an important platform for the development of western China. The MRYR urban agglomeration promotes the rise of the central region. The YRD urban agglomeration is the leader of YREB with the most prosperous, densely urbanized performance in China (Gu et al., 2011; Huang and Lu, 2015). Our study area is within the urban boundary of 26 cities of the three urban agglomerations in YREB, mapped from the global artificial impervious area data (Li et al., 2020). According to the Köppen climate classification system, these cities are located in subtropical monsoon humid climate (Cwa) and subtropical humid climate (Cfa) (Peel et al., 2007). According to the World Urbanization Prospects 2018, we cluster the 26 cities into four mega cities (more than 10 million urban inhabitants), nine large cities (more than 5 million urban inhabitants), and 13 medium-sized cities (more than 1 million urban inhabitants)(WUP, 2018).

A total of 1510 urban parks in 26 cities of the three urban agglomerations were analyzed. Urban parks are major component of the green infrastructure in cities and support myriad environmental and health benefits for urban dwellers. We have obtained the urban parks' locations from AutoNavi map, and digitized their boundary through artificial visual interpretation based on high-spatial-resolution Google Earth

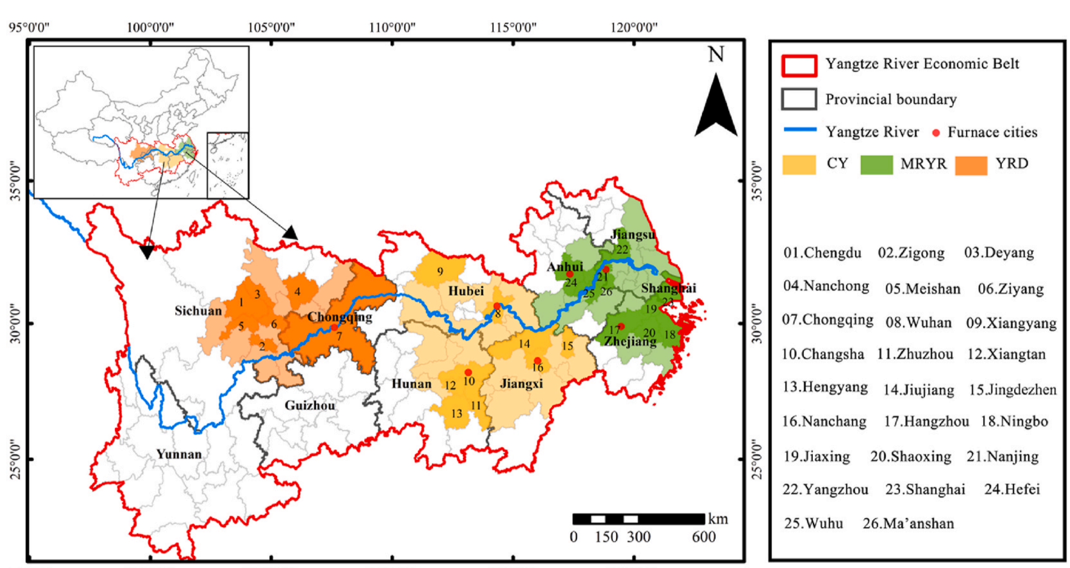

Fig. 1. The location of study area. Note: CY denotes the Cheng-Yu urban agglomeration; MRYR denotes the Middle-Reach Yangtze River urban agglomeration; and YRD denotes the Yangtze River Delta urban agglomeration. The cities selected are with darker color.

images.

2.2. Land surface temperature retrieval

Landsat-8 images (https://glovis.usgs.gov) were used to retrieve land surface temperature (LST) in this study. Our study selected 16 images from summers of 2017–2021 (Supplementary Table 1). The specific dates of remote sensing image acquisition were sunny without cloud or wind. A practical split window algorithm was used to obtain the spatial pattern of LST, and the LST accuracy of this algorithm was better than 1.0 K (Chen et al., 2015; Ren et al., 2015). The equation for temperature retrieval was as follows:

$$\mathrm{LST} = a_0 + \left(a_1 + a_2\frac{1-\varepsilon}{\varepsilon} + a_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_1+T_2}{2} + \left(a_4 + a_5\frac{1-\varepsilon}{\varepsilon} + a_6\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_1-T_2}{2} + a_7(T_1-T_2)^2 \tag{1}$$

where T_1 and T_2 are top of atmosphere brightness temperatures of the two thermal bands in Landsat 8. $a_0, a_1, \ldots, a_7$ are coefficients from water vapor simulated dataset (Chen et al., 2015). ε is the average emissivity of the two channels and $\Delta\varepsilon$ is the differenced emissivity.

2.3. Estimation of urban parks' carbon savings potential

The carbon savings from urban parks due to heat mitigation were estimated as the carbon emissions to achieve the same cooling effect in the absence of the parks. We proposed a sliced carbon saving model based on each park's cooling curve as follows (Fig. 2). Starting from the center of one urban park, LST gradually increases outwards and then reaches its turning point. We divided each park's cooling volume into100 frustums. Usually, the more frustums are divided, the more accurate the calculation results are, but more computing resources are required (Fig. 2d). The sum of 100 frustums method is an efficient and accurate balance, considering the large number of irregular shapes. The accumulated carbon savings intensity (CSI) from cooling the same air mass is estimated by the following equation:

$$CSI = k\cdot\rho\cdot a\cdot\int_0^H \sum_{i=0}^{N}\frac{1}{3}\left(S_i + S_{i+1} + \sqrt{S_iS_{i+1}}\right)\Delta T dh \tag{2}$$

where k stands for the specific heat under constant air pressure with value 1004.68 J kg^{-1} °C^{-1}, ρ stands for air density (1.2923 kg m^{-3}), and a is the transformation coefficient of energy consumption to carbon emission via coal-fired power (841g/3,600,000 J) in the year of 2018, according to the statistical analysis of China Electricity Council (https://www.cec.org.cn/). h stands for the vertical influence sphere (H = 70 m)(Lin et al., 2011). ΔT is the temperature difference between two adjacent buffers, S_i and S_{i+1} is the base area. We then calculated carbon savings efficiency (CSE) as the accumulated carbon savings intensity (CSI) divided by park area.

Based on the Open-Data Inventory for Anthropogenic Carbon dioxide (http://db.cger.nies.go.jp/dataset/ODIAC/. Reference date: 2019)(Oda and Maksyutov, 2011; Oda et al., 2018), we derived the daily average CO_2 emissions from fossil fuel combustion (from Jun. to Sep.) in each city. We then calculated the offset percentage of carbon savings by the urban parks.

2.4. Potential factors analysis

The potential factors influencing the heat mitigation effect include the park area, the park perimeter, the park landscape shape index (LSI, Equation (3) (Wu, 2004);), the vegetation status inside park as indicated by the normalized difference vegetation index (NDVI), and the water

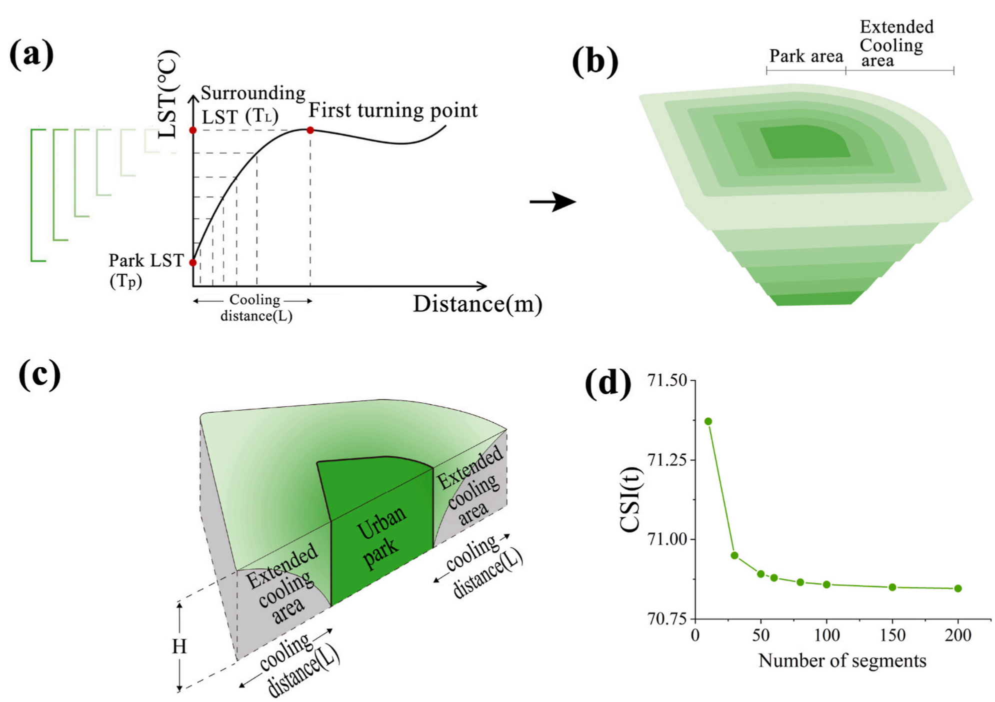

Fig. 2. The schematic diagram of a park's (a) cooling curve, (b–c) carbon savings intensity (CSI) model and (d) the influence of frustum' number on irregular-shaped parks' CSI.

area ratio inside the park.

$$LSI = \frac{L}{2\sqrt{\pi \times A}} \quad (3)$$

where L is the park perimeter, and A is the park area. A larger LSI indicates a more complicated or irregular shape (Yu et al., 2017).

The differential reflectance of the near-infrared and red bands of Landsat 8 imagery was used to calculated the NDVI. Water area ratio was derived from Bigemap. Pearson correlation analysis was used to examine the relationship between parks' carbon savings and their influencing factors. Furthermore, variable's importance was calculated using Random Forest model to evaluate the relative importance of potential drivers. The Random Forest algorithm has been widely used to evaluate the relative importance roles in ecological studies in recent years (Gao et al., 2022; Wang et al., 2022). Repeated ten-fold cross-validation was conducted to evaluate the robustness of our Random Forest model.

3. Results

3.1. Carbon saving potential of urban parks due to heat mitigation

The urban parks were averaged 2.01 °C cooler than the surrounding urban area. Among the 1510 parks, 88.5% (1336) of parks showed significant cooling effect, equivalent to that from anthropogenic cooling equipment by 3.8×10^7 kW h, saving carbon emissions of 31,722.5 t CO_2. On average, one park in the YREB could save 23.7 ± 1.6 t CO_2 in emissions due to heat mitigation, and the averaged CSE is 1.08 ± 0.03 t CO_2/ha. Xuanwu Lake Park located in Nanjing city had the highest CSI (up to 1107.8 t CO_2). The spatial distribution of parks' carbon savings for representative cities from different urban agglomerations appears in Fig. 3. For each city, there was a positive relationship between parks' area and CSI. However, some small parks showed a relatively high CSE, indicating the large efficiency for carbon savings from these small urban parks. Sport Park (4.4 ha) located in Yangzhou city from YRD exhibited the highest CSE (11.4 t/ha).

The carbon savings of urban parks differed by Köppen climate classification. In Cfa, 89.4% of urban parks had a significant cooling effect;

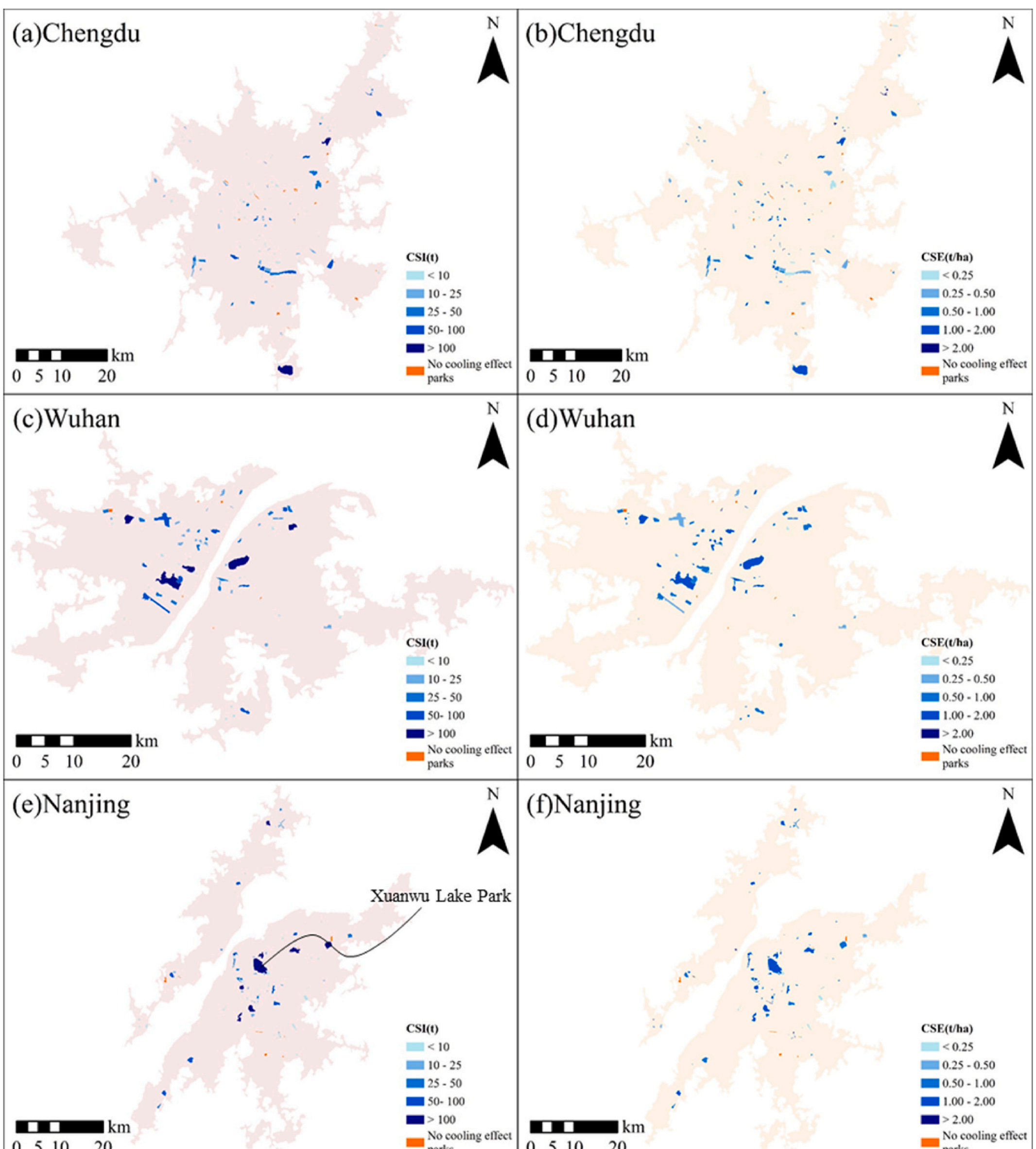

Fig. 3. Spatial distributions of CSI (a, c, e) and CSE (b, d, f). Note: the figures show example cities in the YREB. More can be seen in Fig. S1.

whereas, in Cwa, 80.7% of urban parks had significant cooling effect. CSI of the urban parks in Cfa ranged from 0.01 t CO_2 (Children Park located in Nanchang city) to 1107.8 t CO_2 (Xuanwu Lake Park located in Nanjing city), with an average value of 24.1 ± 1.7 t CO_2. The mean CSE of parks in Cfa was 1.09 ± 0.03 t CO_2/ha, significantly ($p < 0.05$) higher than the mean CSE in Cwa (0.91 ± 0.08 t CO_2/ha). CSI of parks within Cwa ranged within 0.3 t CO_2 (Automotive theme park located in Ziyang city) to 603.8 t CO_2 (Xinglong Lake wetland park located in Chengdu city). The average CSI of parks in Cwa was 21.1 ± 4.8 t CO_2, lower than that from parks in Cfa. It indicated that the urban parks located in Cfa had greater carbon savings.

In addition to the two local background climates, the discrepancies between "furnace cities" and ordinary cities were also noteworthy. The furnace cities' average CSI amount was 2306.8 t CO_2 per city, significantly ($p < 0.01$) higher than ordinary cities (819.7 t CO_2 per city). The average CSI of urban parks in "furnace cities" was 30.9 ± 3.3 t CO_2, higher than the average ordinary city (19.1 ± 1.4 t CO_2). However, the difference between the average CSE of "furnace cities" (1.08 ± 0.04 t CO_2/ha) and ordinary cities (1.06 ± 0.03 t CO_2/ha) was only marginal.

3.2. Analysis of influencing factors

CSI was positively correlated with parks' area, perimeter, and water area ratio, suggesting that larger park and more blue infrastructure could boost carbon savings across both climate zones (Fig. 4a). These three factors, however, had little effect on CSE, suggesting that smaller parks could be as efficient as larger ones for each unit park area. In addition, LSI showed significantly ($p < 0.01$) positive influence on the CSI and CSE only in Cfa, suggesting that parks with irregular shapes enhanced the interactions between the park and the surroundings. Moreover, parks with higher NDVI had better CSE. To boost carbon savings efficiency, lush vegetation should be first considered. Therefore, a better urban park design and management could be a more effective way to improve the carbon saving efficiency than expanding park area.

The Random Forest model can explain more than 90% of the CSI variation (Fig. 4b). Overall, park area was found to be the variable explaining the most variation in the CSI, with 87.5% and 51.3% relative importance in Cfa and Cwa climates, respectively. Water area ratio also had relatively high importance in Cwa (32.0%). For CSE, NDVI and LSI showed relatively high importance both in Cfa and Cwa. LSI appeared more important than the NDVI in Cfa, while NDVI was the more important factor in Cwa. These results indicated that strategies for using urban parks to reduce carbon emission may differ due to the local climate background.

3.3. Carbon savings of urban parks in different cities from three agglomerations

From the perspective of three urban agglomerations, the average city' s CSI amount in YRD urban agglomeration was the highest (1906.8 t CO_2 per city), significantly higher than the MRYR urban agglomeration (806.9 t CO_2 per city) and CY urban agglomeration (770.3 t CO_2 per city), showing a spatial pattern of high in the east and low in the west (Fig. 5a). This was related to the large disparity in the park areas across these cities, the average park area with potential carbon saving of cities in YRD urban agglomeration was the largest (2105.9 ha), followed by the MRYR urban agglomeration (927.7 ha) and CY urban agglomeration (926.6 ha). Specifically, urban parks in Shanghai city (the city with the largest total park area of 5362.1 ha) from YRD urban agglomeration had the potential to save more carbon emissions by total value 4341.4 t CO_2; whereas, the limited urban park area (52.1ha) in Meishan city from CY urban agglomeration could potentially save only 16.21 t CO_2.

The average CSI of urban parks in MRYR urban agglomeration was the highest (33.2 ± 4.5t CO_2), followed by the CY (23.1 ± 3.7t CO_2), while the YRD urban agglomeration was the lowest (21.6 ± 1.8 t CO_2) (Fig. 5b). On average, one urban park in Wuhu city from YRD urban agglomeration, could save the most carbon emission with value 64.6 ± 19.8 t CO_2/park, whereas one park in Meishan city (CY) from CY urban agglomeration was with the smallest value (3.2 ± 0.9 t CO_2/park). The high average CSI in Wuhu was probably due to that average park area in Wuhu was the highest (60.2 ha/park).

From the efficiency perspective, CSE in YRD urban agglomeration was the highest (1.2 ± 0.04 t CO_2/ha), followed by CY (0.95 ± 0.06 t CO_2/ha) and MRYR urban agglomeration (0.89 ± 0.06 t CO_2/ha) (Fig. 5c). The average CSE for each city showed that Shaoxing city from YRD urban agglomeration had the highest average CSE of 1.6 ± 0.2 t CO_2/ha, while Meishan city from CY urban agglomeration was the lowest (0.26 ± 0.07 t CO_2/ha). In 2015, the State Forestry Administration awarded Shaoxing city the title of "National Forest City". The top-down greening policy is an important support and driving force for urban greening (Fan et al., 2017; Liu et al., 2020), which has improved both the quantity and quality of urban parks and thus enhance the potential carbon saving efficiency.

To provide a more intuitive insight on the contribution of urban parks for carbon emission, Fig. 5d represented carbon offset value by the parks. Overall, the urban parks can totally offset 5.37% of the daily fossil fuel carbon emissions in study area. The carbon offset provided by urban parks in CY urban agglomeration was the highest (10.1%), followed by MRYR urban agglomeration (8.5%) and YRD urban agglomeration (4.2%), exhibited a descending west-east gradient. The urban parks of Ziyang city from CY urban agglomeration, which can potentially offset 22.3% of daily carbon emissions, are highest. By contrast, only 1.4% of the daily carbon emissions can be offset by urban parks in Deyang city from CY urban agglomeration.

4. Discussion

4.1. Carbon saving potential of urban parks due to heat mitigation

The urban parks composed of blue-green landscape is an important

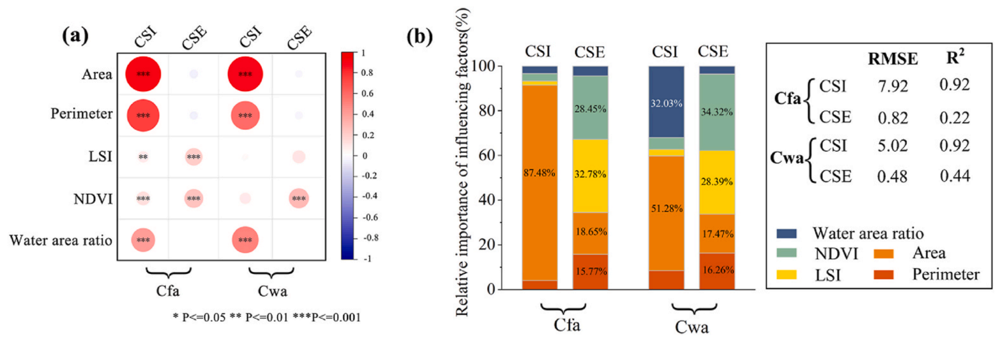

Fig. 4. Analysis of carbon savings influencing factors: (a) Heat map of Pearson correlations; (b) Relative importance of factors. Note: CSI denotes Carbon Savings Intensity; CSE denotes Carbon Savings Efficiency; Cwa denotes Köppen's subtropical monsoon humid climate; Cfa denotes Köppen's subtropical humid climate.

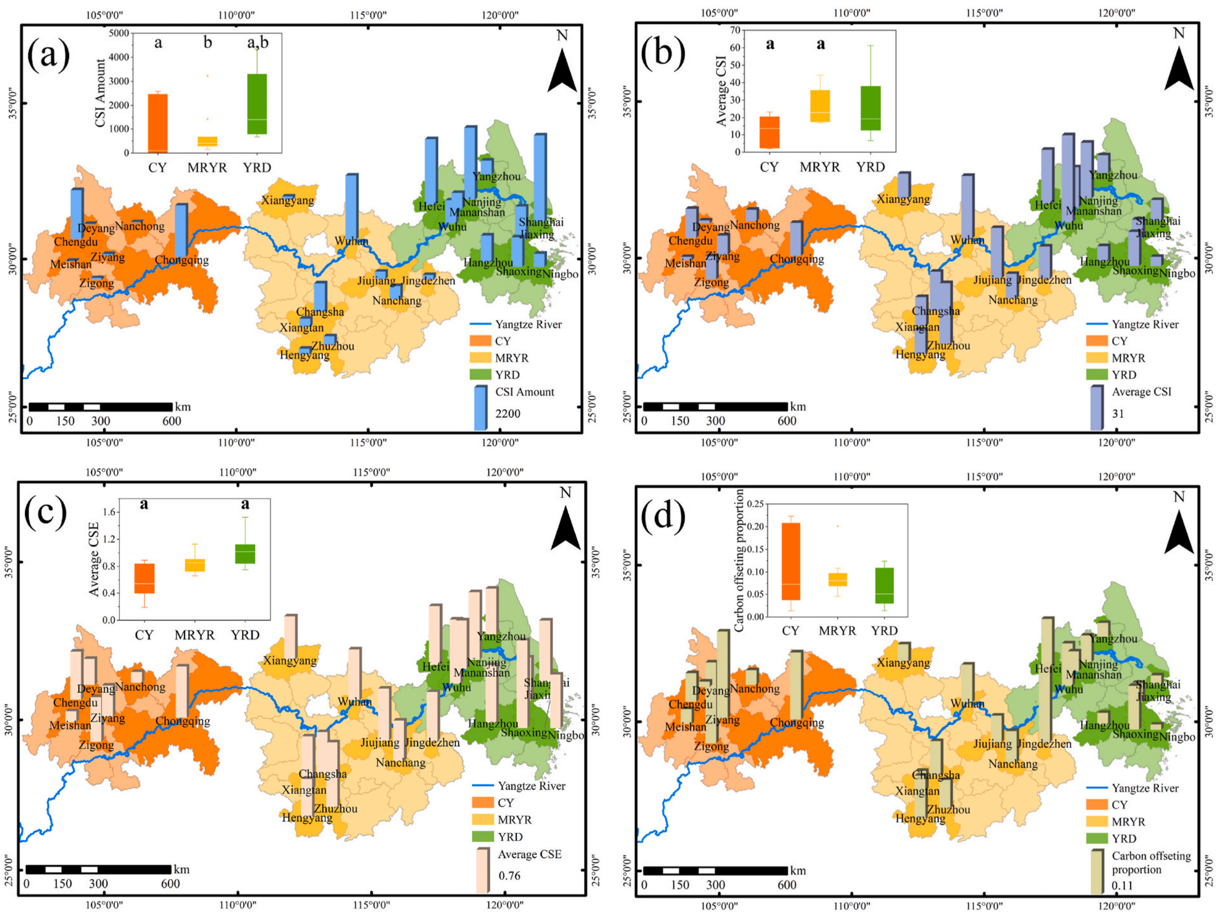

Fig. 5. Spatial distributions of (a) amount of CSI for each city, (b) average CSI, (c) average CSE and (d) Carbon offset in three urban agglomerations in the Yangtze River Economic Belt. Note: Significant ($p < 0.05$) differences (Mann-Whitney *U* test) are indicated by the same letters; Box plots show the IQR (box), the median (horizontal line in box) and 1.5 IQR (whiskers).

mitigation measure against urban heat and can generate a three-dimensional cooling intervention in hot summers(Kong et al., 2016). Our study applied accumulation perspectives to estimate the carbon savings of urban parks based on a sliced three-dimensional model. Lin et al. (2011) proposed a cylindrical model for calculating green area's heat absorption to estimate the possible energy conservation to maintain the temperature difference between green area and their surroundings in Beijing. However, Lin et al. (2011) assumed the green area as a round-shaped zone, which might result in the uncertainty of the findings. Our proposed sliced model is suitable for irregularly shaped parks. Furthermore, the method can be easily applied to other cities with different local climates. The potential carbon savings of urban parks can be quantified based on the cooling effect, which highlighted a new idea to understand the contribution of urban parks to the urban carbon budget.

On average, a park in the YREB could potentially save carbon emissions of 23.7 ± 1.6 t CO_2 due to heat mitigation effects. On a smaller scale, Kong et al. (2016) found that the cooling benefits of green space on Nanjing Gulou Campus could save totally 1.3×10^4 kW h (10.9 t CO_2) during a hot summer day. Previous studies in Beijing reported the cooling effect by a traditional garden to be 694.1 kW h (0.6 t CO_2) (Xu et al., 2019), consistent with our results. CSE averaged at 1.08 t CO_2/ha, ranging from 0.01 to 11.4 t CO_2/ha. However, there has been little work on the CSE of urban parks. The carbon savings per unit of park area play significant roles in land investment per unit area.

The magnitude of carbon saving provided by the urban parks of each city ranged from a minimum of 16.2 t CO_2 in Meishan city from CY urban agglomeration to a maximum of 4341.4 t CO_2 in Shanghai city from YRD urban agglomeration. That is to say, urban parks in one city saves averagely 1220.1 t of CO_2 emissions. If using electric facilities to cool the same air mass, it will require 1.5×10^6 kW h to generate this amount of cooling capacities. This result was significantly lower than Lin et al. (2011) with 14,315.4 t CO_2 in Beijing. This difference could be related the divergence of method and land coverage. Lin et al. (2011) calculated all urban green spaces in Beijing while we only study the urban parks. Moreover, Zhou et al. (2022) found that approximately 42% of urban parks in China could face degradation in heat mitigation due to climate change. Accordingly, it is important to explore how to "future-proof" the cooling capacities of urban parks as regional temperatures increase.

Most previous studies focused on a single city; whereas, few studies were at the regional scale. With the emergence of urban agglomerations, the mitigation strategy of urban heat island effect needs to be implemented at regional scale (Geng et al., 2022; Hsu et al., 2021; Sun et al., 2019). Our work provides an initial investigation of the urban parks' potential for carbon savings in YREB, which is China's largest sustainability experiment, thus would have unprecedented implications for global governance of climate and sustainable development. Our approach is not only conducive to summarize some general trends beyond the study of a single city, but also to reflect differences in potential energy conservation of urban parks in different climatic regions. In the context of global warming, our study provides useful insights for future studies of regional heat island mitigation, and the method proposed in this study are generic and easily portable for application to other cities.

4.2. Implications for urban park design

Due to the shortage of urban land resources caused by rapid urbanization, how to maximize the cooling effect of park and achieve high benefits of carbon saving has become one of the ecological problems to be solved urgently (Chen et al., 2022; Peng et al., 2021a). This study aims to provide guidance for urban park design on a regional scale. Urban park area is significantly correlated with CSI, consistent with previous results (Lin et al., 2011). NDVI was a significant influential factor serving positive impacts on both CSE and CSI, suggesting that parks with higher NDVI could have a better potential for carbon saving, consistent with previous studies in the field of thermal environment(Liu et al., 2022; Peng et al., 2021a; Yan et al., 2021). Water bodies inside parks were also significantly correlated to CSI owing to their large specific heat capacity, consistent with previous findings (Chen et al., 2022). In both Köppen climate zones, a higher area of water inside parks was related to enhanced CSI. However, the water body area showed non-significant influence on CSE. Landscape and regional planning of urban parks should consider the water area of an urban park as a key design factor.

The strategies using subtle landscape design for maximizing carbon saving may differ across different climate zones. In Cfa climate, the LSI of urban parks had a significant effect on CSI and CSE. The increase of the interaction near boundary between parks and the external environment provides opportunities for heat and energy exchange, thus enhancing park's cooling effect. Therefore, more complex parks could provide more cooling effect for carbon savings(Lu et al., 2012; Qiu and Jia, 2020). Vegetation growth showed a strong and significant positive correlation with CSE. For cities in Cwa climate, the blue infrastructures inside urban parks are relatively more important, suggesting that combining both blue and green infrastructures inside urban parks may increase potential carbon savings.

4.3. Urban parks carbon saving ratio relative to the urban carbon emissions

The potential carbon savings by parks of the cities in the lower reaches of the Yangtze River is higher than that in the upper reaches. As one of the core areas with highly developed economies in China, the YRD local governments should pay more attention to the design and construction of urban parks. Some cities in YRD have implemented green development measures such as "ecological city", "National Healthy City", and "National Forest City", focusing on the greening of core urban areas (Li et al., 2017; Wu et al. 2019, 2021). The entire YREB should make more effort to build low-carbon city and greening city to counteract with urban heat island and help achieve carbon neutrality (Bian et al., 2021; Chen et al., 2021; Tian et al., 2021).

The discrepancies of the carbon offset percentage by the parks among cities exhibited a descending west-east tendency. Some cities with low total amount of CSI also have lower population density and lower fossil fuel carbon emissions, thus the offset proportion by parks is relatively higher. In contrast, some cities with larger CSI values showed lower carbon offset proportion, e.g., Shanghai is with the largest total CSI but offset just 2.3% of the daily carbon emissions. Construction of urban parks in these cities might be relatively mature, thus limits the potential carbon saving capacity of parks and only a decrease in CO_2 emissions from fossil fuel combustion will enable an approach to carbon neutrality(Zhang et al., 2022).

4.4. Limitations and future research directions

Our research has various limitations. Firstly, it should be acknowledged, that this research was based on a controlled simulation, assuming the cooling effect of urban parks and its extended cooling area does not change in the vertical direction. The upper limit of the influence of park cooling area need to be investigated in future studies to improve the accuracy of estimating the energy savings under real conditions. In addition, the limited image numbers could bring some uncertainties for the evaluation. Also, there are multi-temporal remote sensing images and some of images were selected after the outbreak of COVID-19. During the COVID-19 lockdown period, the reduced transportation and industrial activity may have ameliorated intensity of urban heat island (Roshan et al., 2022). However, since we calculated the carbon savings benefits brought by the relative cooling effect between the park and the surroundings, the impact of the background temperature on the results should be marginal. Due to the polar-orbiting nature of Landsat, our study quantified the park's potential energy saving at the same time of day (i.e., ~03:33 UTC). The daily dynamic change of parks' carbon saving due to cooling effect should be further studied comprehensively, e.g., more observations acquired at different time of day with high temporal resolution should be investigated in the future, perhaps using the ECOSTRESS LST product (Hulley et al., 2019) together with temporally dense observations of the urban land surface from geostationary sensor. Additional potential influence on the cooling effect should be investigated, including shade fraction, leaf area index, actual evapotranspiration, vertical structures inside and nearby parks, and eco-physiological characteristics of plant species.

5. Conclusions

Although many studies have proved that urban parks can effectively alleviate the urban heat, few studies have quantified the heat reduction and carbon savings potential of urban parks, which are crucial to understand the value of the cooling services provided by urban parks. Our study estimated the potential carbon saving of 1, 510 parks across 26 major urban areas in three urban agglomerations in the YREB. Significant cooling was observed in 1336 of 1510 (88%) of urban parks with average CSI of 23.74 $\pm$ 1.56 t CO_2, CSE of 1.08 $\pm$ 0.03 t CO_2/ha, and a total accumulated savings of 31,722.5 t CO_2. Park area and blue infrastructure inside parks played a significant role in CSI in Cwa climate. Coupled both blue and green infrastructures inside urban parks should be advocated in park planning and design. The amount of CSI in YRD urban agglomeration was the highest, followed by MRYR and CY urban agglomeration, meaning that uneven public green infrastructure existed in the YREB. This study provides theoretical support and practical reference for rational planning and exquisite design of urban parks on a regional scale, with the potential to help regional climate mitigation, sustainable development, and low-carbon city construction, thereby benefiting China's movement towards carbon neutrality.

CRediT authorship contribution statement

Mo Chen: Conceptualization, Methodology, Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Wenxiao Jia:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision. **Chunlei Du:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Manqing Shi:** Investigation, Visualization. **Geoffrey M. Henebry:** Revising, Supervision. **Kai Wang:** Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135713.

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