Sustainable Cities and Society 74 (2021) 103135

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

How to build a heat network to alleviate surface heat island effect?

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ARTICLE INFO

Keywords:
Surface heat island
Morphological spatial pattern analysis
Circuit theory
Reverse thinking
Climate mitigation

ABSTRACT

Numerous studies have proposed cooling measures to mitigate surface urban heat island (SUHI) effect from the perspective of landscape pattern. However, rare studies have considered to alleviate the SUHI from a network perspective, which was demonstrated by first building a SUHI network to identify the key nodes and links of a SUHI network and subsequently breaking this network to effectively mitigate SUHI. Here, a new approach to build SUHI network is proposed, which integrates morphological spatial pattern analysis and circuit theory. It includes: i) identification of stable and high-risk SUHI patches, ii) extraction of the "core" type, iii) evaluation of "core" importance, iv) construction of a friction map, and v) generation of links and pinch-points. Dongguan city was selected as case and the results showed: 1) 42 links were identified with 31 pinch points located in these links; 2) Most of these links and pinch-points were distributed in the southwestern and northwestern regions; 3) Cooling measures (patch-based) should be implemented in these specific areas to avoid connections between the links and nodes that could seriously aggravate the thermal environment of entire region. The method and reverse thinking process adopted could provide new insights for climate adaption planning and urban sustainability.

1. Introduction

Urbanization has changed the earth's surface significantly from natural and semi-natural to impervious urban settings, which has led to higher temperatures in the urban areas compared with the surrounding rural areas, resulting in the well-known urban heat island (UHI) phenomenon (Oke, Mills, Christen & Voogt, 2017). The UHI effect has caused negative impacts, such as altering species composition and abundance, enhancing water and energy consumption, exerting heat stress on organisms and increasing heat morbidity and mortality (Forman, 2014; Grimm et al., 2008; M. Santamouris, 2015). In general, UHIs can be classified into two categories, namely, atmospheric UHI (AUHI) and surface UHI (SUHI) (Oke et al., 2017). Owing to the feasibility of consistent and repeatable observations, Land surface temperature (LST) is widely used to investigate the spatiotemporal patterns of the SUHI and associated thermal environment consequences (Deilami, Kamruzzaman & Liu, 2018; Estoque, Murayama & Myint, 2017; Gao, Yu, Wang, & Vejre, 2019; Luan et al., 2020; J. Yang et al., 2021), which is also a focus of this study.

Previous studies have revealed that landscape composition and spatial configuration (or arrangement) can influence the surface UHI effect, and urban green space (UGS) is considered a promising method because it is a cost-effective, environmentally friendly, and politically acceptable method (S. Chen, Yu, Liu, Da, & Faiz ul Hassan, 2021; Martins et al., 2016; G. Yang, Yu, Jørgensen & Vejre, 2020; Z. Yu et al., 2020). However, although UGS has a positive effect on mitigating UHI effect, UGS cannot be limitlessly increased due to land restrictions or funding shortages. Hence, these effective cooling measures should be firstly considered and implemented where they are most needed (as well as the place we can intervene) (Yu, Zhang, Yang, & Schlaberg, 2021).

On the other hand, existing studies have mainly explored the mitigation of UHI from the perspective of landscape patches, such as the effect of the size, shape, composition, configuration, and type of green and blue patch (Bowler, Buyung-Ali, Knight & Pullin, 2010; Fan et al., 2019; Lai, Liu, Gan, Liu, & Chen, 2019; Mat Santamouris et al., 2018). For example, Cao, Onishi, Chen and Imura (2010) found the cooling effect to be more significant in large-sized UGS patches, while Yu, Guo, Jørgensen and Vejre (2017) revealed that the optimal patch size of UGS that achieved the maximum cooling efficiency had a threshold value of efficiency (TVoE). Fan et al. (2019) further revealed that the TVoE of UGS in low latitude Asian cities ranged from 0.60 ha to 0.95 ha. Furthermore, the spatial relationship between the UGS patches has been

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https://doi.org/10.1016/j.scs.2021.103135
Received 4 April 2021; Received in revised form 28 June 2021; Accepted 30 June 2021
Available online 6 July 2021

proposed to address the correlations between the green-blue spaces and cooling effect. For example, closely spaced and well-connected green spaces provide better cooling effect for adjacent urban areas compared with large individual green spaces (Shih, 2017; Zupancic, Westmacott & Bulthuis, 2015). Xie et al. (2014) used morphological spatial pattern analysis (MSPA) to explore the influence of UGS connectivity on UHI mitigation and found that increasing the edge, branch, and bridge areas was the most effective strategy for cooling urban thermal environments.

However, the above-mentioned cooling measures are primarily based on a simple Patch-Mosaic Model concept, and it is difficult to describe the overall pattern and connectivity of the UHI effect (L. Chen, Sun, & Lu, 2019; Yu, Zhang, Yang, & Schlaberg, 2021). Besides, studies have revealed that the increased regional connectivity of UHI patches enhances UHI intensity, but related studies on the mitigation of SUHI from the perspective of the network (graph) and overall connectivity is still lacking (D. Zhou, Bonafoni, Zhang & Wang, 2018). Further, the most crucial step prior to the implementation of cooling measures is to accurately identify the most critical location (in the network) of the SUHI patches. Yu, Zhang, Yang, & Schlaberg, 2021 proposed a new methodology from the graph perspective for evaluating and mitigating regional surface heat islands. However, the proposed methodology is a conceptual framework which still lacks appropriate methods for building SUHI networks, resulting it difficult for urban planners and decision makers to accurately identify the key nodes and links of SUHI network to implement effective heat alleviate measures.

Therefore, an appropriate method for building the SUHI network should be proposed to target the key nodes and links of the SUHI patches. Previous studies have suggested that SUHI patches can be regarded as a "thermal" landscape (Yu, Yao, Yang, Wang & Vejre, 2019a), at the same time graph-based approach (e.g., MSPA) can be applied to segment a raster "thermal" landscape binary map (i.e., UHI versus non-UHI areas) into different landscape pattern categories to further identify the crucial SUHI patches (Yu, Zhang, Yang, & Schlaberg, 2021). Moreover, circuit theory, originating from physics (Brad H. McRae & Beier, 2007), can be introduced to identify the important SUHI links and key nodes associated with thermal flow which are analogous to electric currents by virtue of sharing the random “walk” property. Therefore, movement patterns across complex landscapes can be predicted to identify important landscape patches, links, and sites of the SUHI spatial patterns. More importantly, as a reverse thinking process, if we block the links and pinch points, the SUHI effect can be accurately and effectively mitigated. These “blocks” could potentially prevent the intensification of SUHI groups and have a positive impact on climate mitigation (Yu, Zhang, Yang, & Schlaberg, 2021; Yue, Qiu, Xu, Xu & Zhang, 2019). To verify the validity of this method, Dongguan city, one of the most rapidly urbanizing cities in Guangdong province, China, was selected to address the following specific research questions: 1) why and how to build an SUHI network; 2) where are the most critical location (i. e., links and nodes) of SUHI network in the case; and 3) how to effectively mitigate the SUHI effect based on the SUHI network theoretically?

2. Methodology

Fig. 1 shows the proposed framework for building surface heat network to alleviate surface heat island effect. First, the LST was calculated during a specific time interval, and subsequently the relative land surface temperature (RLST) was calculated to identify the consistent high-risk positions of SUHI effects during this period. We considered these consistent high-risk positions as SUHI areas, and thus a binary map that suggests UHI versus non-UHI areas can be generated. Second, the MSPA-based SUHI patterns were calculated using the Guidos Toolbox 2.8 software (Saura & Pascual-Hortal, 2007). Third, the “core” type

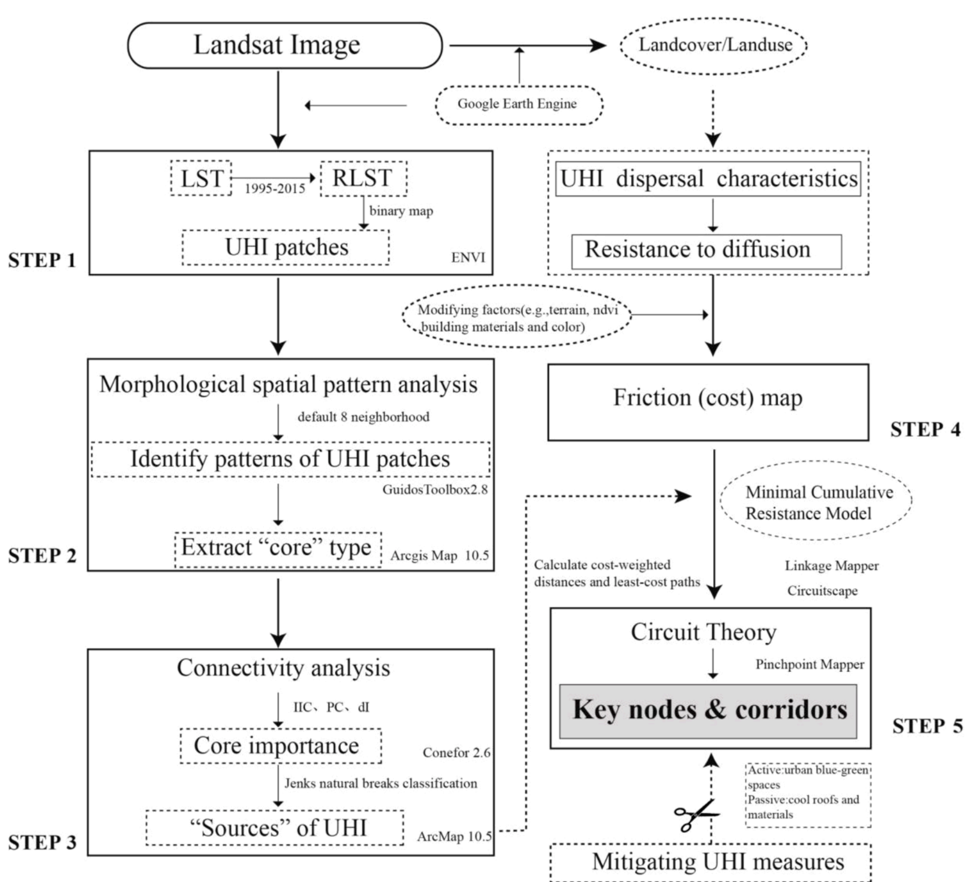

Fig. 1. Framework for building surface heat network to alleviate surface heat island effect.

SUHI patches (Table 1), extracted from MSPA, were selected for connectivity analysis using the Conefor 2.6 software. In this step, the importance of the "core" type was evaluated, with the highly important patches regarded as the "source" of the SUHI patches. Fourth, a friction (cost) map was constructed based on the SUHI dispersal characteristics, which are mainly influenced by the land cover and other modifying factors (e.g., terrain, vegetation cover, building materials, and colors). Finally, circuit theory was proposed to identify the links (corridors), which represent the cumulative resistance of the least-cost path connecting the SUHI "sources," using the Linkage Mapper software. In addition, key nodes (pinch points) were also identified using the Circuitscape software. Subsequently, theoretically, the SUHI effect would be significantly mitigated if these key nodes or links are blocked (by implementing active and passive cooling measures in these specific areas) (Shih, 2017; Yu, Zhang, Yang, & Schlaberg, 2021). Next is the explanation of the specific calculation method.

2.1. LST and relative LST calculations

An algorithm solving the radiative transfer equation (RTE) was selected to calculate the LST (Jiménez-Muñoz, Sobrino, Skoković, Mattar & Cristóbal, 2014). The RTE can achieve the highest LST accuracy in environments with high atmospheric water vapor (Fan et al., 2019; Yu et al., 2017). The corresponding equation is given by:

$$L_\lambda = [\varepsilon B(T_s) + (1-\varepsilon)L\downarrow]\tau + L\uparrow \tag{1}$$

where ε is the surface emissivity, T_s is the real surface temperature (Kelvin), $B(T_s)$ is the brightness temperature, and τ is the atmospheric transmittance in the thermal infrared band. Using Eq. (2) below, the LST can be calculated as:

$$T_s = \frac{K_2}{ln\left(\frac{K_1}{B(T_s)+1}\right)}, \tag{2}$$

where $K_1 = 774.89$ (mWm^{-2}s•r^{-1}μm^{-1}) and $K_2 = 1321.08$ K in the Landsat images.

The LST can be used to characterize SUHIs on a particular date; however, in principle, it is not an appropriate measure for comparing the SUHI spatial patterns over time. SUHI trends cannot be optimally quantified from a spatiotemporal perspective by comparing the LST values acquired on different dates and under different atmospheric conditions. Hence, to identify the consistent high-risk areas of SUHI effects during different years, we proposed the RLST as the reference value. The RLST can be computed as follows:

Table 1
Definition of MSPA classes and their meaning in the UHI context.

Class	Meaning in the SUHI context
Core	***Core*** is defined as those UHI pixels whose distance to the non-UHI areas is greater than the given edge width.
Bridge	***Bridge*** is defined as the sets of contiguous non-core SUHI pixels that connect the ends of at least two different core areas. Bridges correspond to structural connectors or corridors that link different SUHI core areas.
Islet	***Islet*** is defined as the isolated SUHI patches that are too small to contain core pixels.
Loop	***Loop*** is similar to bridges but with the ends of the element connected to different parts of the same core (SUHI) area.
Edge	***Edge*** is defined as a set of SUHI pixels whose distance to the patch edge is lower than or equal to the given edge width and corresponds to the outer boundary of a core area.
Perforation	***Perforation*** is similar to an edge but corresponds to the inner boundary of a core (SUHI) area.
Branch	***Branch*** is defined as the pixels that do not correspond to any of the previous six categories. It typically corresponds to an elongated set of consecutive SUHI pixels that emanate from a SUHI area and do not reach any other SUHI area at the other end.

$$RLST_j^i = LST_j^i - \overline{LST_j}, \tag{3}$$

where i represents each of the five years, LST_{ij} represents the remotely sensed LST of the pixels in year j, and $\overline{LST_j}$ represents the average LST of the entire area.

2.2. Morphological spatial pattern analysis

MSPA is a type of mathematical morphology method that detects image pixel patterns (binary patterns) in the landscape and automatically classifies the pixel data of the focus feature (foreground) class into a new structural connectivity feature class (Carlier & Moran, 2019). Moreover, MSPA can detect the structural connection reliably, which is a key feature used to quantify the important individual landscape map elements in network analysis (Saura & Torné, 2009). MSPA classifications can be performed using either 4 or 8 neighborhood rules. In this study, the default 8 neighborhood rule was used to classify the SUHI patterns (UHI versus non-UHI areas) into seven basic pattern classes (Table 1), namely, core, bridge, islet, loop, edge, perforation, and branch, of which "core" is the most important type/class in the dominant SUHI spatial patterns.

2.3. Connectivity analysis

Landscape connectivity is defined as the degree to which the landscape facilitates or impedes movement among resource patches (Taylor, Fahrig, Henein, & Merriam, 1993), with the maintenance of good connectivity being conducive to the stability of the ecosystem (Pascual-Hortal & Saura, 2008). Furthermore, connectivity analysis is also an important factor in the evaluation of SUHI patterns. The node importance of the "thermal" landscape was primarily determined by the patch area, connectivity, and diversity; thus, it can be used to identify the important node (Benedict & McMahon, 2012). Graph theory-based integral index of connectivity (*IIC*) and probability of connectivity (*PC*) index in the Conefor 2.6 software were adopted to reflect the connectivity of landscapes and important values of patches (*dI*) (Pascual-Hortal & Saura, 2006; Saura & Pascual-Hortal, 2007; Saura & Torné, 2009). The equations governing the *IIC, PC*, and *dI* are given by:

$$\mathrm{IIC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left(a_i a_j / 1 + nI_{ij}\right)}{A_L^2}, \tag{4}$$

$$\mathrm{PC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^*}{A_L^2}, \tag{5}$$

$$\mathrm{d}I\ (\%) = \frac{I - I_{remove}}{I} \times\ 100\%, \tag{6}$$

where n is the total number of SUHI patches, a_i and a_j are the areas of the SUHI patches, nI_{ij} is the number of links in the shortest path between patches i and j, p_{ij}^* is the maximum product probability of all possible paths between patches i and j, and I_{remove} is the index value obtained after the removal of that landscape element.

Subsequently, the results corresponding to the important values of the SUHI patches were divided into five levels (not important, less important, generally important, important, and highly important) based on the method of natural breaks in the ArcGIS platform, with the patches having the highest level (extreme importance) selected as the SUHI "sources".

2.4. Construction of the friction map

The friction (cost) map describes the difficulty faced by a "thermal environment" when moving through complicated landscape patterns, while also reflecting the horizontal resistance to diffusion. This map (also called resistance surface) can characterize the influence of landscape heterogeneity on the flow of the SUHI process. The value of resistance to diffusion is closely related to the distance of the different SUHI patches. In addition, land cover is also an important factor, as the intensified expansion of the SUHI effect and frequency of heatwaves are mainly caused by the loss of natural spaces (land cover changes) in the process of rapid urbanization. The ability of the natural elements (e.g., forest, water, and grassland) to lower temperatures has been well documented (Buyantuyev & Wu, 2010; G. Yang et al., 2020); hence, the forestland, water, and grassland have a poorer heat dispersal capacity than bare land and constructed land. Based on previous research, the cooling effects of land cover are sorted into forests, water, grasslands, built-up areas, and bare land (Yu et al., 2019a). Based on the coefficients of SUHI resistance surfaces, forestland was assigned the highest value of 100 as it has the highest vegetation cover and least human disturbance, with water ranked second with 50 and followed by grassland with 25. Considering that the built-up areas and bare land in Dongguan City are highly affected by human interference with low greenness, which can easily exacerbate the SUHI effect and promote heat flow, their corresponding resistance coefficients were assigned the lowest values of 5 and 1, respectively.

Furthermore, a V-I-S (vegetation–impervious surface–soil) model (Ridd, 1995) based on linear spectral separation technology was used to extract the built-up area (impervious surface area, *ISA*) in Dongguan City in 2015. The following equation was used to modify the resistance of the patches:

$$R_i^{'} = \frac{ISA_i}{ISA_a} \times R \tag{7}$$

where $R_i^{'}$ refers to the revised resistance of patch *i* based on the *ISA*, ISA_i is the impervious surface percentage of patch *i*, and ISA_a is the average impervious surface percentage of the same land use type as patch i.

2.5. Identification of key nodes and links

Key nodes and links are vital elements of a thermal landscape network. The link (corridor) is a narrow strip in landscape patterns, which represents the main channels for gene flow, meta-population dynamics, infectious disease spread, and heat dispersal. The connectivity of the thermal landscape (SUHI patches) will significantly decrease when these links are blocked, leading to the accurate and effective mitigation of the thermal environment. A pinch point is a high flow key node, which represents the specific area with the most concentrated high current flow in the corridor. The removal of the pinch point would have a serious impact on the overall connectivity of the SUHI network.

Circuit theory and Ohm's law were adopted to construct the SUHI network and identify the key nodes and links. In this model, thermal resistance surfaces were represented as electric conduction surfaces; furthermore, each grid with a finite resistance was represented as a node in two-dimensional space, which was connected to either its four first-order neighboring grids or eight first-order or second-order neighboring grids. The low resistances were assigned to the landscape components that best promoted heat flow, with the high resistances assigned to the landscape components impeding thermal movement. In addition, each SUHI "source" was regarded as an electric circuit node, and the cumulative resistance of each link between two nodes was calculated in terms of the least-cost distance retrieved from the thermal resistance surface. The cumulative resistance was assigned as the electric resistance of the link. Subsequently, for each pair of electric circuit nodes, one node was arbitrarily connected to a 1 A current, while the other node was linked to the ground. The effective resistances between multiple paired electric circuit nodes were calculated iteratively (Fig. 2) (Leonard et al., 2017). The accumulated current value, which represented the net migration by random walk to the destination node, could be used to identify the importance of the corridor (higher values resulted in increasing importance). Furthermore, specific areas with the highest current density values were considered as pinch points (B. H. McRae & Kavanagh, 2011; B. H. McRae, Shah & Mohapatra, 2013).

The Linkage Mapper toolbox and Circuitspace software based on circuit theory were used to identify the links and pinch points. In particular, *Build Network and Map Linkages,* a toolkit of Linkage Mapper in ArcGIS, was used to map the corridor. The *Drop Corridors that Intersect Core Areas* box was checked, which enabled links that were too long in the cost-weighted distance to be dropped automatically. *Pinchpoint Mapper* in the Linkage Mapper Toolbox was used to calculate the current density values. This tool runs the Circuitscape software, injecting current into one node (SUHI "source") and allowing it to flow through the corridor to the other node area. The current tends to concentrate in the narrow areas of the corridors, suggesting that most corridors are constricted in such areas (pinch points).

3. Case study

3.1. Study areas

Dongguan city (located between 22°39′N and 23°09′N, 113°31′E and 114°15′E), part of the Pearl River Delta urban agglomeration, is in the south of Guangdong province, southern China. Dongguan has a humid subtropical climate with abundant sunshine and rainfall throughout the year. The average temperature is 22.7 °C throughout the year *(Appendix A)*. The city is spread over 4 sub-districts and 28 towns, covering a land area of 2542 km^2 in 2018. The topography of Dongguan is largely heterogeneous, comprising of hills in the southeast to alluvial plains in the northwest. It has been one of the most rapidly expanding cities of China over the last two decades, with an urbanization rate of 88.82% and 91.02% in 2015 and 2018, respectively (http://www.dg.gov.cn/). Many ecological lands (e.g., forests, grasslands, and water) were converted to constructed land during this period (Fig. 3). In particular, forests and grasslands decreased from 1906 km^2 in 1995 to 762 km^2 in 2015. The decrease in vegetation cover and increment/increase in the built-up land have significantly exacerbated the frequency of urban storms, air pollution, and particularly extreme heatwaves (UHI effects) (Hoag, 2015). The residents of Dongguan have frequently experienced high temperatures in recent years (http://gd.cma.gov.cn/dgsqxj/index.html). Therefore, effective cooling measures are necessary to assist urban planners and decision-makers in effectively mitigating the SUHI effect in Dongguan.

3.2. Data collection and preprocessing

A Landsat image series (1995–2015, July or August) was obtained

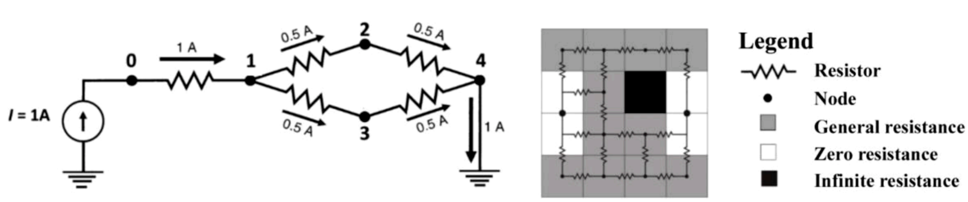

Fig. 2. Landscape raster data structure representation based on circuit theory (B. H. McRae et al., 2013).

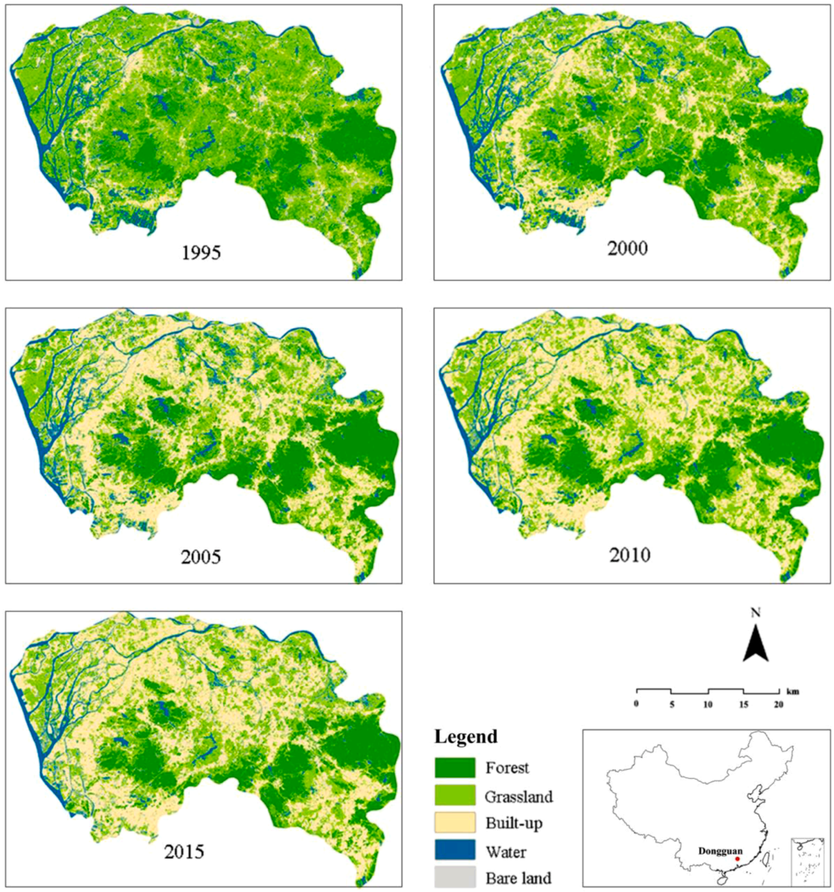

Fig. 3. Land cover map of Dongguan city from 1995 to 2015.

from the USGS Earth Explorer to map the LST of Dongguan city *(Appendix B)*. Google Earth Engine (GEE) is a cloud-based computing platform that provides quick access to a large number of geospatial datasets and analysis functions on a planetary-scale (Gorelick et al., 2017). In this study, a simple cloud-free algorithm was used to filter the images from the Landsat series.

In this case study, based on our previous findings of the pilot study on the Pearl River Delta urban agglomeration region, the area with a RLST >4 °C was considered a stable and high-risk area during 1995–2015 (Yu, Yao, Yang, Wang & Vejre, 2019b). Hence, areas with a RLST >4 °C in Dongguan city were defined as SUHI patches (Fig. 4).

4. Results

4.1. Results of MSPA-based classification: where is the "core" type?

The seven MSPA classes exhibited different distribution characteristics (Fig. 5b). In general, the core constitutes the major MSPA class, and 3377 cores were identified, which accounted for 67.08% of the total SUHI patch area and 19.61% of the entire study area. In graph theory, the core type is an important element determining the stability of the network. The core generally covers large-scale impervious areas (e.g., residential areas) where the SUHI effect is most severe. This is followed by the edge type/class, which is external to the core and accounted for 22.08% and 6.45% of the seven MSPA classes and entire study area, respectively. The third and fourth major MSPA categories were branch and perforation, respectively, which approximately accounted for 3.66% and 3.55% of the total SUHI patch areas, respectively. The MSPA classes had a lower proportion of the bridge and islet categories, a majority of which was less than 2% of the seven MSPA areas. The loop class constituted the lowest proportion of the MSPA categories, accounting for only 0.82% of the total SUHI patch area and 0.24% of the total study area (Table 2).

4.2. Results of connectivity analysis: which are the important "core" patches?

Based on the values of the habitat availability indices (Table 3), the core importance of the SUHI patches was visualized using the ArcGIS platform (Fig. 5c). Five grades, namely, highly important, important, generally important, less important, and not important, were classified based on the method of natural breaks classification, which accounted for 35.05%, 22.21%, 4.70%, 3.64%, and 1.51% of the total SUHI patches, respectively. Considering the spatial distribution in Dongguan city, a majority of the extremely important core areas were found to be distributed in the western part of the city, which also contained the urban core built-up areas. These areas have a significantly higher density of commercial or residential land with few natural settings. In contrast, in the eastern part of Dongguan city, only a few important core areas were identified owing to the natural reserves and lower human disturbance. In addition, the distribution pattern showed diffused characteristics around large-scale natural areas. For example, cores 1 and 2 were found distributed around the Dalingshan forest park, which is one of the largest natural settings in the southwestern part of Dongguan city (Fig. 5d).

4.3. Corridors and pinch points of the thermal landscape network: where to "block" or "break"?

As shown in Fig. 6b, the thermal resistance ranged from 0 to 57.54, which was determined based on the minimum cumulative resistance (MCR) model. The areas with high resistance values mainly

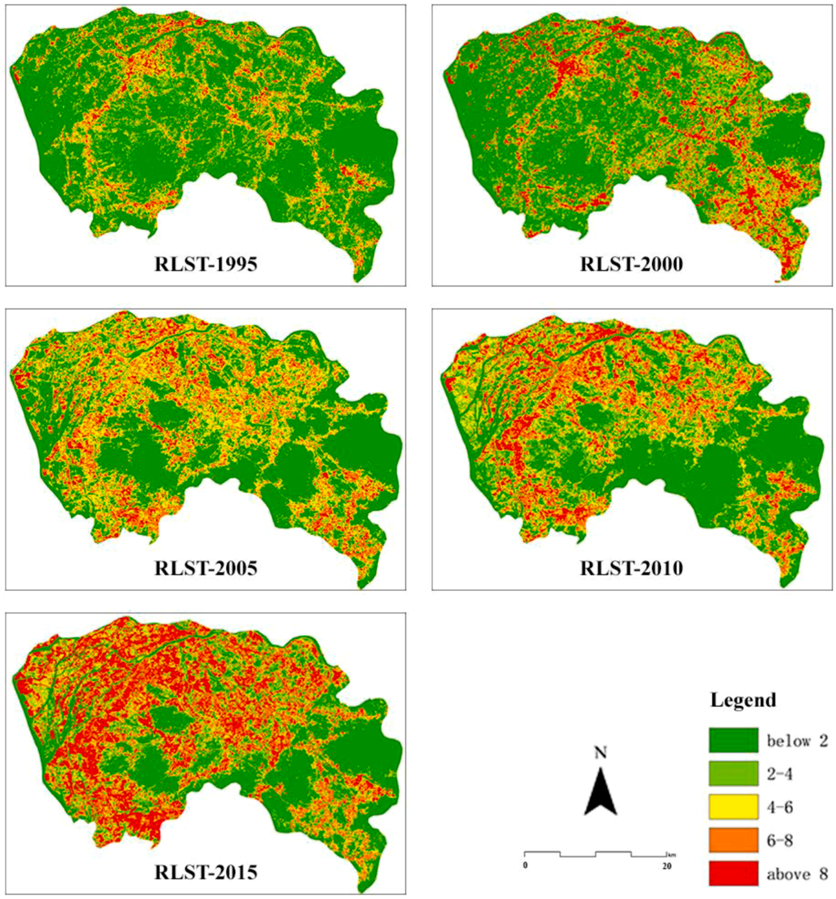

Fig. 4. Spatial distribution of the relative land surface temperature (RLST) from 1995 to 2015.

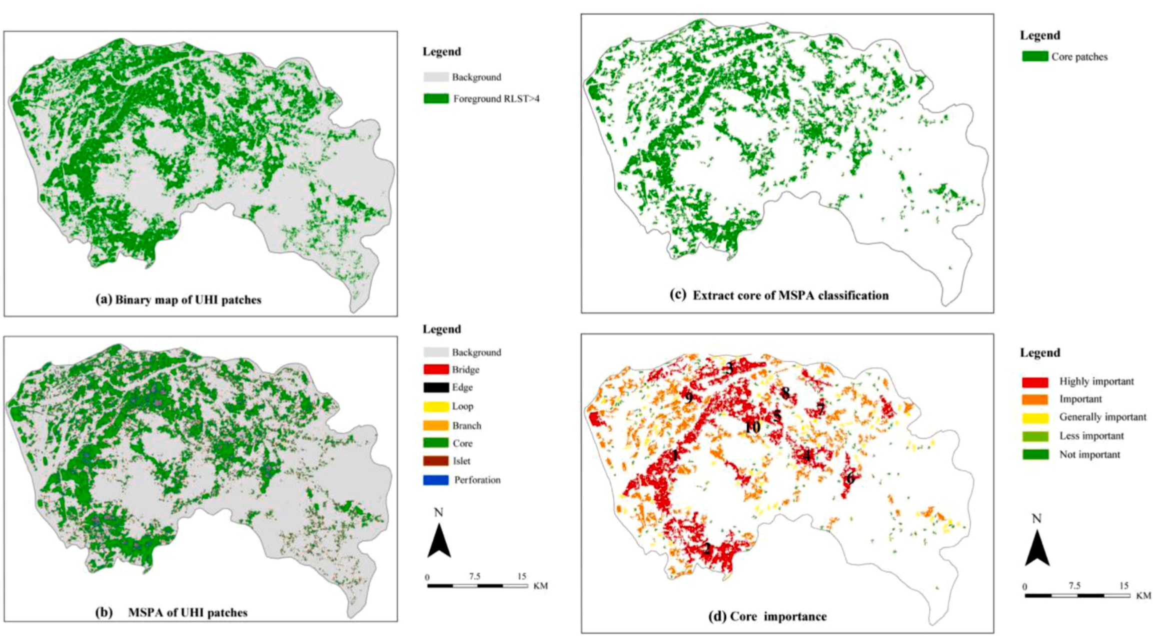

Fig. 5. Process used to identify the node importance: (a) binary map of the SUHI patches; (b) classification of the SUHI patches based on MSPA; (c) spatial distribution of the "core" type; and (d) core importance result in Dongguan City based on connectivity analysis using the Conefor 2.6 software.

corresponded to forestland in the south and east of Dongguan City. The corridors were extracted subsequently based on the friction map (i.e., resistance surface) and the above-mentioned SUHI "source". In this study, corridors that were too long in the cost-weighted distance were dropped automatically, as the heat diffusion process tends to be affected by various uncontrollable factors (e.g., wind direction); this would result

Table 2
MSPA-based classification and statistics of the SUHI patches.

Type	Amount (number)	Area (km^2)	Total area of the SUHI patches (%)	Total study area (%)
Core	3577	470.64	67.08	19.61
Bridge	4951	8.98	1.34	0.37
Branch	11,179	25.64	3.66	1.07
Edge	7038	154.85	22.08	6.45
Islet	2666	10.29	1.47	0.43
Loop	3399	5.72	0.82	0.24
Perforation	1543	24.86	3.55	1.04

in errors when extracting the long-distance corridors. Finally, 42 corridors were identified (Appendix C) with most of them distributed in the northwestern areas of Dongguan city (Fig. 6c). These areas had relatively fragmented SUHI patches with smaller distances between these patches, thus resulting in a lower resistance surface value (mainly built-up area). The following were found distributed in the southwestern areas of Dongguan city, which housed the highly important core with many bare lands.

Considering the current density distribution shown in Fig. 5d, many of the areas with higher current densities were in the corridors. Finally, we targeted a total of 31 pinch points in 42 thermal corridors. Most of these key nodes were in the southwestern and northwestern areas of Dongguan city where are mainly the built-up area.

5. Discussion

5.1. Applicability of the framework employed to build the SUHI network

The framework proposed in this study addresses a reverse thinking process, which first requires the construction of a SUHI network followed by the destruction of the key links and nodes of this network to alleviate the SUHI effect. Specifically, the SUHI was measured by remote sensing-based LST and the RLST was subsequently calculated to identify the stable and high-risk SUHI areas (RLST > 4) that could be regarded as consistent SUHI patches (i.e., thermal landscape) (Yu et al., 2019a, Yu, Zhang, Yang, & Schlaberg, 2021). Subsequently, a framework combining graph theory and circuit theory was applied to build the SUHI network, identify the SUHI "sources" (i.e., important SUHI patches), and generate corridors connected to these "sources", thereby identifying the critical location of the SUHI network (i.e., pinch points) for mitigating the SUHI effect.

Graph-based theory is an effective method for describing the landscape pattern as a network and implementing complex analysis on the landscape connectivity (Matos, Petrovan, Wheeler & Ward, 2019; Saura, Estreguil, Mouton, & Rodríguez-Freire, 2011). It has been widely applied in fields such as green infrastructure, biological conservation, and biodiversity assessment (Santos, Cagnolo, Roslin, Marrero, & Vázquez, 2019; Saura, Estreguil, Mouton, & Rodríguez-Freire, 2011; Zhao, Ma, Wang & You, 2019). Similarly, the morphological image processing method based on graph theory, which was initially introduced for analyzing the structure and shape of objects (Soille & Vogt, 2009), can be employed to identify the "core" area by analyzing the pattern of the SUHI patches. Hence, in this study, MSPA-based

Table 3
Ranking of the top 10 cores in terms of their importance index.

Sort	dA	dIIC	dPC	Sort	dA	dIIC	dPC
1	22.55145	61.01003	40.01723	6	2.705229	0.8779306	5.337275
2	13.02534	20.35308	24.35408	7	2.372	0.6749657	4.687737
3	7.273609	6.346761	14.01816	8	1.797294	0.3875167	3.562285
4	4.936226	2.923091	9.628789	9	1.753389	0.3688151	3.476034
5	3.841413	1.770249	7.535262	10	1.661357	0.3311145	3.295113

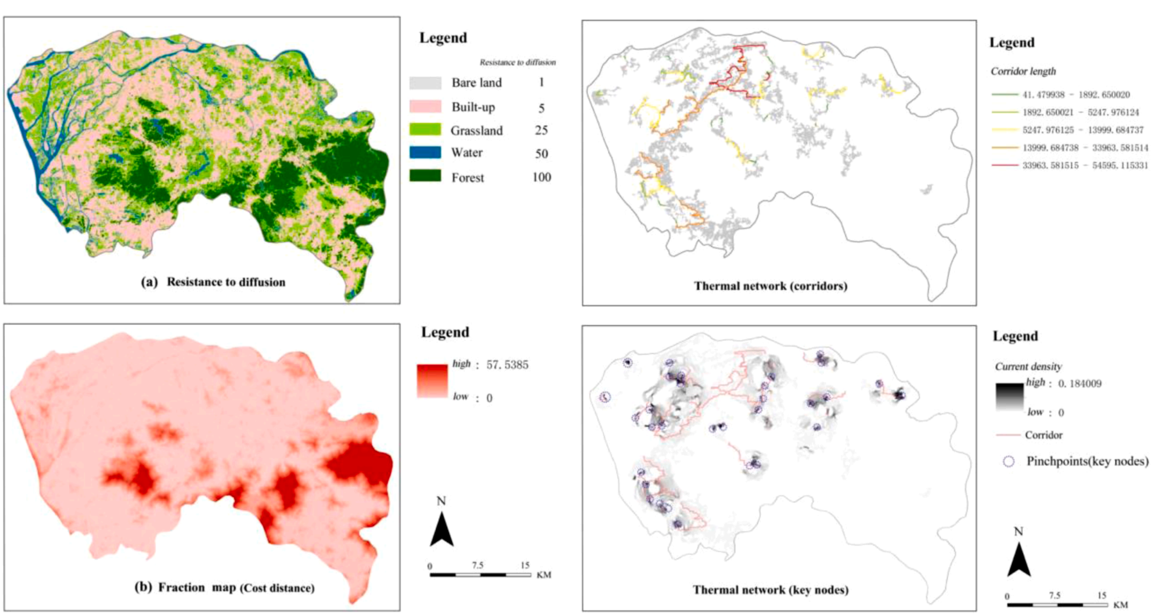

Fig. 6. The process to identify the corridors and key nodes by ArcGIS and Linkage Mapper toolbox and Circuitspace software: (a) spatial distribution map of resistance to diffusion; (b) fraction map based on the minimum cumulative resistance (MCR); (c) spatial distribution of the thermal corridors; and (d) location of the key nodes and pinch points of the thermal (SUHI) network based on circuit theory.

classification was adopted for exploring thermal landscape morphological pattern to identify the core types, which might significantly increase SUHI effects in an urban environment. Furthermore, the importance of these core types should be calculated to accurately identify the UHI "sources." In this study, connectivity analysis was applied to evaluate the core importance (i.e., identify SUHI "sources"), as landscape connectivity is a vital element of landscape structure (Taylor, Fahrig, Henein, & Merriam, 1993) that might reflect the stability of the SUHI patches.

In addition to identifying the SUHI "sources," generating corridors connected to the "sources" is another principal step in the building/construction of a SUHI network. To generate the SUHI corridors, a friction map should be constructed, which represents the resistance to diffusion of thermal flow. An urban thermal environment is evidently a dynamic condition that tends to flow, spread, and intensify randomly (Kikumoto, Ooka & Arima, 2016). However, this process will heavily be affected by the land cover and land use to a certain extent due to differences in the reflection and absorption of radiant energy (Oke et al., 2017). The ecological landscapes in the city, such as forests, grasslands, and water bodies, generally absorb more solar radiation and release less sensible heat, thus lowering the temperature (Forman, 2014; Peng, Xie, Liu & Ma, 2016). In contrast, urban landscape elements, such as built-up areas and barren lands, exhibit high temperatures in a thermal environment (Gilbert, Mandel & Levinson, 2016). Therefore, in this study, land cover information was mainly considered when constructing the friction map. In addition, due to the random "walk" property of thermal flow that is analogous to electric current, circuit theory originating from physics was applied to evaluate the important SUHI corridors and particularly identify pinch points. In summary, the proposed method is a promising approach for the effective and accurate mitigation of SUHIs on a city or region (urban agglomeration) scale.

5.2. Implications for urban climate adaption planning

Many SUHI mitigation studies are conducted from a patch perspective, which subsequently propose corresponding measures, such as optimal patch sizes and shape of the UGS, to mitigate the UHI effect (Bowler et al., 2010; G. Yang et al., 2020) and an optimal composition and configuration of UGS to achieve the maximum cooling efficiency (Peng et al., 2016; W. Zhou, Wang, & Cadenasso). However, it is evident that the most important step before the implementation of these measures is to accurately identify the most critical location (Yu, Zhang, Yang, & Schlaberg, 2021); otherwise, the proposed SUHI mitigation measures cannot be well integrated with urban design and planning. Hence, this study proposed a promising framework that integrated graph theories and circuit model to build a SUHI network to identify the key links and nodes. Subsequently, a network perspective was employed to mitigate the SUHI effect, which enabled us to accurately target the spatial pattern and crucial nodes and links of the SUHI, along with the formulation of effective mitigation and adaption strategies. In the reverse thinking process, SUHI connectivity decreases when the links and pinch points are blocked to break the networks, thus significantly alleviating the SUHI effect. Therefore, the new methodology to mitigate the SUHI effect should (1) first identify the key nodes and links from a network perspective, and (2) implement effective mitigation measures from a landscape patch perspective that have been proposed and applied extensively (Akbari & Kolokotsa, 2016; Gilbert et al., 2016; Mattheos Santamouris, 2014).

For example, in the study, 31 pinch points were identified in the 42 thermal corridors, which mainly distributed in the southwestern and northwestern areas of Dongguan city. It clearly indicates that planners and policymakers should be concerned about these areas when implement the planning of climate adaption and the measures of SUHI mitigation. Besides, effective cooling measures should be implemented in high-risk and key areas to prevent the corridors from being connected, which could seriously aggravate the thermal environment of the entire region. In the northwestern part of Dongguan, it is difficult to alleviate SUHI effects by increasing urban green spaces (e.g., urban parks) due to the high construction density in these areas. Therefore, passive mitigation measures, such as cool roofs or cool building materials, can be implemented on the pinch points to mitigate the SUHI effects. Bare lands present in the southwestern part of Dongguan can be used for development of greening to alleviate the SUHI effects. Hence, active mitigation measures such as urban green spaces can be constructed near the pinch points, and street trees (i.e., tree cover) can be increased on both sides of the corridor to "block" the heat flow. Overall, the proposed framework advances the patch to a combined network and patch perspective, resulting in implications for climate adaption planning.

5.3. Limitations and future studies

Some limitations should be addressed. First, although the aim of this study was to propose a framework to build SUHI network, the land cover could have been categorized with greater detail to obtain more reliable results. For example, a core step of the proposed method was the construction of the friction map; however, only five types of land cover were considered in this study. In future studies, more accurate results can be obtained by a more detailed classification of land cover maps, such as built-up areas that can be further classified in terms of land use (residential, commercial, and industrial land). In addition, different materials used for the roofs and facades of buildings have different thermal diffusions (Oke et al., 2017; Z. Yu et al., 2020). Materials with high solar reflectance and infrared emittance can increase the albedo of areas, thus decreasing the ambient temperature (Akbari & Kolokotsa, 2016). Hence, the resistance to diffusion of heterogeneous built-up areas should be further assigned different resistance values. Second, the construction of the thermal network was considered at a two-dimensional level, ignoring the influence of three-dimensional parameters. Three-dimensional factors such as topography, height of buildings, and vegetation cover also significantly affect thermal diffusion, which should be considered when constructing the friction map. For example, areas with low-to-middle-rise buildings and low vegetation cover have higher temperatures than those with high-rise buildings or high vegetation covers (Li et al., 2011). Third, the urban thermal environment is in a state of continuous flow and might be affected by uncontrollable factors such as wind direction and wind speed (He, Ding, & Prasad, 2020). Although the wind speed in Dongguan city is relatively low in summer (*Appendix A*) and the long-distance corridors are automatically removed when generating the thermal corridors, the results still exhibit some errors.

The major objective of the study is to address the importance of mitigating the SUHI effect from the network perspective, and further integrate the implementation of patch-based cooling measures from a reverse thinking process. To improve the accuracy of this framework, future studies should build a refined SUHI network considering more accurate land cover classification, building height, building colors and materials, vegetation cover, and topography and wind direction. Besides, in the future research, it is also important to apply the method in specific cities, implement the cooling measures (patch-based), and finally evaluate the effectiveness of the method.

6. Conclusions

Many SUHI mitigation measures have been suggested from the perspective of the landscape patch, while few studies have attempted to identify key SUHI nodes and links from a connectivity and network perspective, which could assistant urban planners and decision-makers to accurate alleviate the SUHI effect in these specific high-risk areas. Based on graph and circuit theory, in this study, we proposed a framework to establish a surface heat network to mitigate surface heat island effect. Specifically, the new proposed method include as follows: i) identification of stable and high-risk SUHI patches, ii) extraction of the "core" type, iii) evaluation of "core" importance, iv) construction of a friction map, and v) generation of links and pinch-points. This framework can provide new insights for climate adaption and urban sustainability, and the method can be effectively applied to other cities and regions (Yu et al., 2020b; Yu et al., 2020).

Declaration of Competing Interest

The authors declare that there is not conflict of interest.

Acknowledgements

The study was supported by the Shanghai Science and technology Innovation Action Plan (grand no. 21ZR1408500), National Science Fundation of China (grand no. 4217010227), and Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration (grant no. SHUES2021A02); We thanks anonymous reviewers and academic editor for their constructive comments and suggestions.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2021.103135.

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