Landscape Ecol (2021) 36:2165–2174
https://doi.org/10.1007/s10980-020-00982-1

RESEARCH ARTICLE

Where and how to cool? An idealized urban thermal security pattern model

Zhaowu Yu · Ole Fryd · Ranhao Sun · Gertrud Jørgensen · Gaoyuan Yang · Nevruz Cinar Özdil · Henrik Vejre

Received: 1 November 2019 / Accepted: 3 February 2020 / Published online: 15 February 2020

Abstract
Contexts Urban green infrastructure (UGI) has been recognized as a promising approach to mitigating urban heat island (UHI); however, most of the previous studies are case-based and explore the effects of the existent landscape and its spatial configuration on UHI mitigation rather than modeling an optimized spatial pattern.
Objectives We aimed to transcend the existing research logic (from case studies to obtain the patterns of the cooling effect of UGI, then propose implications for UHI mitigation) and established a hypothetical idealized urban thermal security pattern model (TSP_{urban}).
Methods Based on two basic concepts deduced from the physical property of UGI—(threshold) size and cooling distance, as well as the simplifying assumptions we defined. Then, three proposed conceptual UGI types (ecological, efficient, and elementary—3E) and subtypes were used to frame the model.
Results We deduced that the idealized TSP_{urban} model conforms to a hierarchical hexagonal structure in theory and it can be calculated and applied, although it generally cannot be seen in the real world.
Conclusions The idealized TSP_{urban} model can help us better-understanding UGI cooling effects when considering climate adaption planning and decision-making; it also serves as a novel pathway to study the cooling effects of UGI and mitigate the UHI effect.

Keywords Urban heat island · Urban green infrastructure · Urban thermal security pattern · Hierarchical hexagonal structure · Climate adaption planning

Z. Yu (✉) · O. Fryd · G. Jørgensen · G. Yang · N. C. Özdil · H. Vejre
Department of Geosciences and Natural Resource Management, Faculty of Science, University of Copenhagen, 1958 Copenhagen, Denmark
e-mail: zhyu@ign.ku.dk

Z. Yu · R. Sun
State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

Z. Yu
Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, Shanghai, China

Introduction

The urban heat island (UHI) is a climatic phenomenon that is characterized by temperatures being higher in urban areas compared to the surrounding rural areas (Oke 2002). Many studies have shown that rapid urbanization and climate change are considered major factors aggravating the UHI effect (Coumou and Robinson 2013; Forman 2014; Norton et al. 2015; Yu et al. 2019b). UHI effect is believed to be one of the most significant urban environmental problems related to public health and urban sustainability (Grimm et al. 2008; Wu 2014; Akbari and Kolokotsa 2016; Liu et al. 2018; Gao et al. 2019). Generally, the UHI effect increases energy consumption and intensifies carbon dioxide emissions (Santamouris 2014). It also increases heat stress on humans and increases exposure to air pollutants, thereby compromising urban residents' health and comfort (Forman 2014; Akbari and Kolokotsa 2016; Sun and Chen 2017).

In response to these challenges, growing attention has been paid to the role of blue and green spaces, summarized as urban green infrastructure (UGI) (Derkzen et al. 2017; Jiao et al. 2017; Shih 2017; Fan et al. 2019; Luan et al. 2020). Through careful planning and implementation, the effects of UGI might actively be employed in future climate mitigation efforts (Kong et al. 2014; Gillner et al. 2015; Solcerova et al. 2017). Physically, UGIs can influence the urban climate due to evapotranspiration and the shading effects of trees, which alter the urban environment by selective absorption and reflection of incident radiation and regulation of latent and sensible heat exchange (Oke 2002; Bowler et al. 2010; Forman 2014; Zhou et al. 2017). Many studies report that UGIs can significantly reduce the UHI effect. The effect depends on the composition (type and vertical structure of land cover), configuration (pattern and shape), and the UGI greenness measured by the normalized difference vegetation index (Santamouris 2014; Gillner et al. 2015; Norton et al. 2015; Yu et al. 2015; Akbari and Kolokotsa 2016). Previous studies also revealed that the spatial distribution of the land surface temperature (LST) matches the land cover pattern and is correlated with the UHI and urban cooling effect (Gillner et al. 2015; Jaganmohan et al. 2016; Shih 2017; Yu et al. 2019c). Further studies have shown that UGI cooling effects are not restricted to just the specific blue-green spaces themselves but also affect their surrounding areas. The efficacy of the UGI cooling distance decreases with the distance from the boundary and eventually vanishes (Lin et al. 2015; Monteiro et al. 2016; Yu et al. 2017; Fan et al. 2019).

The UGI **cooling capacity** and **cooling distance** have been gaining increasing attention (Sun and Chen 2012; Santamouris 2014; Akbari and Kolokotsa 2016). The cooling capacity is often considered as the cooling potential of a specific UGI, also referred to as the UGI cooling intensity. For instance, in a meta-analysis, Bowler et al. (2010) concluded that the mean reduction in urban temperature by green spaces was 0.94 °C during the day and 1.15 °C at night. If the area of green space exceeds threshold size, the cooling intensity will not increase (Yang et al. 2020). The cooling distance is often defined as the distance from the boundary of the UGI within which significant cooling caused by the UGI is still traceable (Lin et al. 2015). For instance, a study by Hamada and Ohta (2010) indicated that the cooling distance of green space could extend horizontally 300 m and 200–300 m during the daytime and nighttime, respectively, while the largest distance did not exceed 500 m.

Due to the spatial dependence of UGI, the landscape composition and spatial configuration of UGI are two of the essential determining aspects of cooling capacity and cooling distance (Wu 2014; Zhou et al. 2011; Li et al. 2017; Sun and Chen 2017). The landscape composition is readily quantified and is typically described by the proportion of each landscape type in the total surface area (Gustafson 1998; Wu 2014; Peng et al. 2016). The spatial configuration of system properties is much more difficult to quantify. Attempts have focused on describing the spatial characteristics of the individual patch and the spatial relationships among the landscapes' constituent patches (Gustafson 1998; Forman 2016). The critical size and shape of UGIs on the cooling effect have also been calculated (Kong et al. 2014; Žuvela-Aloise et al. 2016). For instance, Sun and Chen (2012) found that for water bodies, the mean cooling intensity and efficiency are 0.54 °C/hm and 1.76 °C/hm/ha, respectively. In a subtropical city, Yu et al. (2017) revealed that the green spaces connected with waterbodies intensified the cooling effects, whereas the grass-based green space showed weaker cooling effects. Meanwhile, the large-sized and compact-shaped green spaces produced a stronger cooling effect, yet there is a threshold value of the patch size on the cooling effect (or threshold value of efficiency, TVoE). Le et al. (2019) found the TVoE in Hanoi City is 1 ha. Fan et al. (2019) also found that the TVoE in hot-humid (Asian) cities are ranged from 0.6 to 0.9 ha, and the TVoE is highly correlated with the Normalized Difference Vegetation Index (NDVI) and background temperature. Other studies revealed that the UGI spatial configuration influences the cooling intensity and distance. For instance, studies have shown that the spatial pattern contributed more to the cooling effect than the total area of green space (Zhou et al. 2011; Monteiro et al. 2016; Peng et al. 2016; Sun and Chen 2017).

However, these studies have primarily focused on a discrete patch within the landscape matrix and identified the cooling effects as being dependent on the sizes and shapes of UGIs, rather than modeling or proposing the optimized spatial arrangement (Peng et al. 2016). Besides, it has been reported that the relative location of a UGI in an urban area is important when designing a cooling intervention to preserve the largest and most important UGIs, in addition to identifying the means to connect existing cool islands (Demuzere et al. 2014; Gunawardena et al. 2017; Shih 2017). For instance, Debbage and Shepherd (2015) found that planting smaller networks of vegetation could be a significant part of the mitigation of UHI intensity. The European Environment Agency (2016) also stated that "a network of green features that are interconnected and therefore, bring added benefits, are more resilient than if they remained isolated". These findings indicate that an optimized spatial pattern of blue-green space is needed in order to most effectively mitigate the UHI effect. Moreover, there is a need for studies that take both landscape composition and spatial configuration into account and quantitatively explore their combined impacts on the cooling effect (Zhou et al. 2011; Akbari and Kolokotsa 2016; Peng et al. 2016). Due to variations in urban areas are dependent on natural and socio-economic conditions, most of the cooling effect related studies are case-based and seek to explore the UGI effects within the existent landscape composition and spatial configuration. Nevertheless, some questions remain to be addressed. For instance, it is unclear whether the case-based studies are of sufficient extent, coverage, and quality to synthesize general models and theories regarding the UGI role in urban cooling. Considering these limitations in the previous research, here we aim to (1) transcend the existing research logic and propose an idealized spatial pattern of UGI for UHI control; (2) build a quantifiable and applicable idealized hierarchical structure; and (3) discuss the availability and limitations of such a model.

Idealized urban thermal security pattern model

Fundamental premise

It has been widely acknowledged that the size of a UGI is one of the most critical and positively correlated factors in the cooling effect (Bowler et al. 2010; Jaganmohan et al. 2016; Zhou et al. 2017; Fan et al. 2019). As stated above, UGI not only lowers its own temperature but also lowers the surrounding ambient temperature. However, the UGI cooling effect decreases with distance from the boundary and eventually vanishes (Lin et al. 2015; Yu et al. 2018a). Accordingly, two basic concepts on the cooling effect of UGI can be deduced-threshold size and cooling distance (Fig. 1a).

As defined previously (Yu et al. 2018a; Fan et al. 2019), the UGI cooling effect is defined as the temperature difference between the UGI and the surrounding urban area. The maximum UGI cooling distance is defined as the distance between the edge of the UGI and the first turning point of temperature change compared to the UGI temperature. This turning point is the maximum ΔT (T = temperature) and is defined as the cooling intensity. The cooling efficiency (in terms of the size of UGI) is defined as a curve between the area of each UGI and its maximum ΔT (Fig. 1b). The cooling efficiency curve shows that the ΔT will increase rapidly with increasing UGI size, before reaching a stable ΔT maximum. This point is the threshold value of efficiency (TVoE) and is similar to the 'Law of Diminishing Marginal Utility' in economics (Fig. 1b). The cooling efficiency curve can be approximated by a logarithmic function, which means calculating the reciprocal of the logarithmic function can get the TVoE point of a given UGI (x:y equals 1:1 in this reciprocal function; when $x > y$, it means the cooling efficiency of UGI is decreasing). Accordingly, we can calculate the TVoE value to achieve the maximum cooling effect while using the smallest UGI area.

It has been widely proved that the UGI cooling effect efficiency curve exists (Santamouris et al. 2018; Yu et al. 2018a; Fan et al. 2019; Le et al. 2019; Yang et al. 2020). Previous studies also identified that if the UGI is large, under many conditions (such as the ecological type described below), there would also be a significant cooling effect (Yu et al. 2017; Zhou et al. 2019).

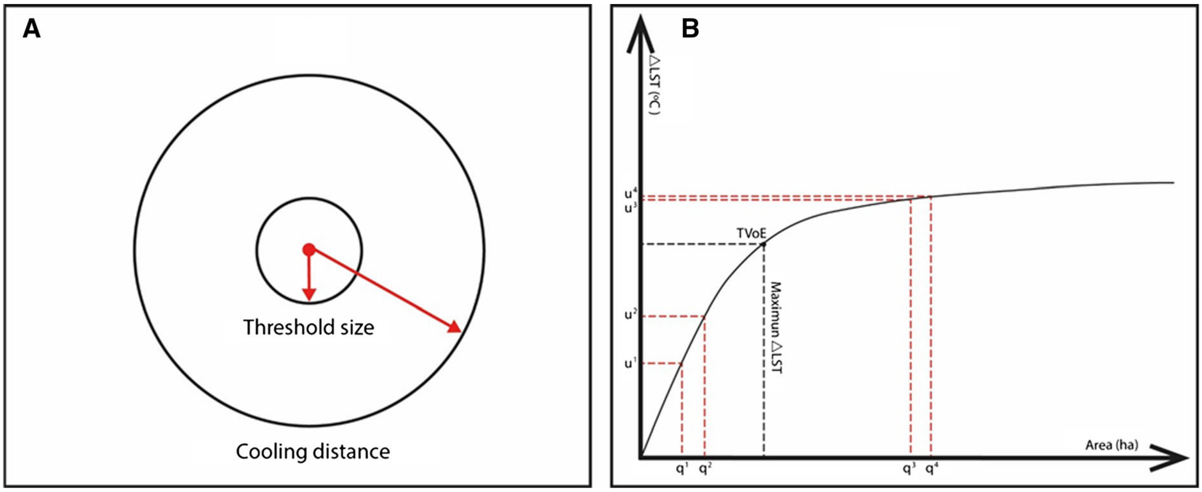

Fig. 1 **a** Two basic concepts derived from the physical properties of UGI– threshold size and cooling distance. **b** The cooling efficiency curve of UGI. An increase in UGI size from q^1 to q^2 leads to a large ΔT ($u^2 - u^1$), while an increase in UGI size from q^3 to q^4 leads to a small ΔT ($u^4 - u^3$). The size of $q^2 - q^1$ is equal to $q^4 - q^3$

Conceptual schematic

Based on the above reasoning, three conceptual UGI types are proposed and defined (Fig. 2). Specifically, the **Efficient Type** (Fig. 2b) is defined as the most efficient size of UGI to achieve the cooling effect, which can be calculated and expressed as the TVoE (as stated above). The efficient type is the key control node for urban cooling and climate adaption. Additionally, the efficient type is also the most effective size for balancing urban development and UHI mitigation, a critical need for decision-makers and urban planners (Yu et al. 2017; Fan et al. 2019). In short, the efficient type of UGI can use the smallest area to achieve the maximum cooling effect. Hence, it is the most important category of UGI for the cooling effect.

The **Ecological Type** (Fig. 2c) denotes a sufficiently large UGI where the cooling efficiency is kept stable within a certain range (Fig. 1b), but at the same time it has a strong cooling intensity and provides a variety of ecosystem services (i.e. regulates urban microclimate, reduces urban floods and provides plant and animal habitat) (Fig. 1b). Within a city, the

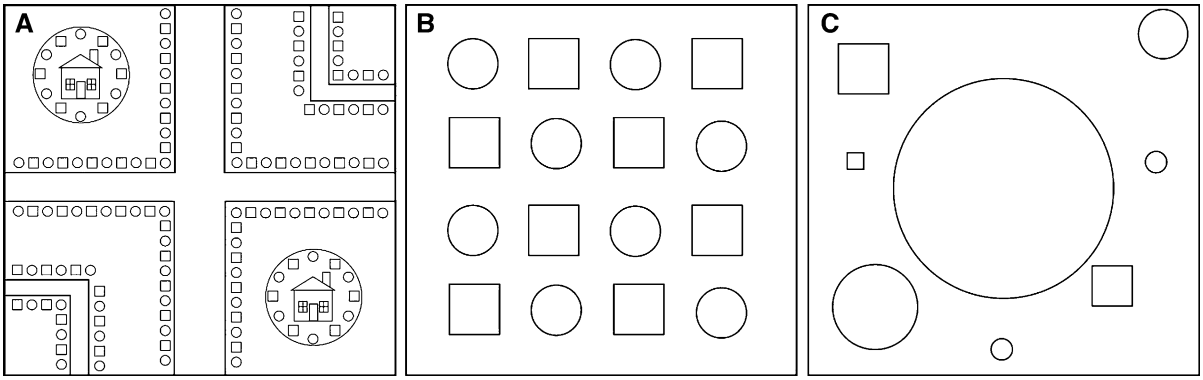

Fig. 2 Three basic types of UGI deduced from the size and cooling distance of each. The circle and square represent water bodies and green spaces. **a** This pattern represents the conceptual elementary UGI type. It can be such as the backyard garden, tree-lined streets of a certain width, etc. **b** This arrangement represents the conceptual efficient UGI type. This type is the most critical and calculable type in the TSP_{urban} model. **c** The largest circle in **c** represents the conceptual ecological UGI type. It is rare to see ecological UGI in the city however, it has comprehensive ecosystem services associated with rich species diversity

ecological type is usually rare and often occupies a large area of blue-green space (e.g. New York's Central Park and Beijing's Olympic Park) and has a rather independent ecosystem. This type is comparable to the mainland-island distribution pattern of island biogeography. The large "island" offers the most comprehensive ecosystem services associated with rich species diversity (to be discussed below). The small "islands"—efficient and elementary types, around the large "island" would probably conform to the island biogeography principle. The ecological type of UGI is usually rare and hard to plan because of the lack of land resources within a city (the size ratio between the ecological and efficient type is 1:6 in theory, see Fig. 3e). However, this type is an indispensable part of providing a variety of ecosystem services and forming an optimized urban thermal security pattern.

The **Elementary Type** (Fig. 2a) represents a pattern of small and scattered UGI, including pocket garden, backyard gardens, and small ponds. The size, shape, and surrounding environment can significantly influence the cooling effect of these UGI types (Bowler et al. 2010; Norton et al. 2015; Zhou et al. 2017). Generally, the elementary types are small, scattered, with low cooling intensity and short (or no) cooling distance, and might contain nothing more than a single simple ecosystem service (Demuzere et al. 2014).

Hypothetical build and apply

Most previous urban planning practices design the developed area (and population growth predictions) as a priority (Pickett et al. 2016). In this research, we try to build a hypothetical model from the opposite perspective, which is a strategy to prioritize the UGI (Norton et al. 2015). Drawing from the ***Central Place Theory***, five simplifying assumptions were proposed to develop the hypothetical model:

(1) A homogeneous, unbounded, and isotropic abstract space (all flat),
(2) An evenly distributed developed area (the same height and density of buildings) and population,
(3) Uniform incident solar radiation and reflectance,
(4) A static area with no wind or air movement,

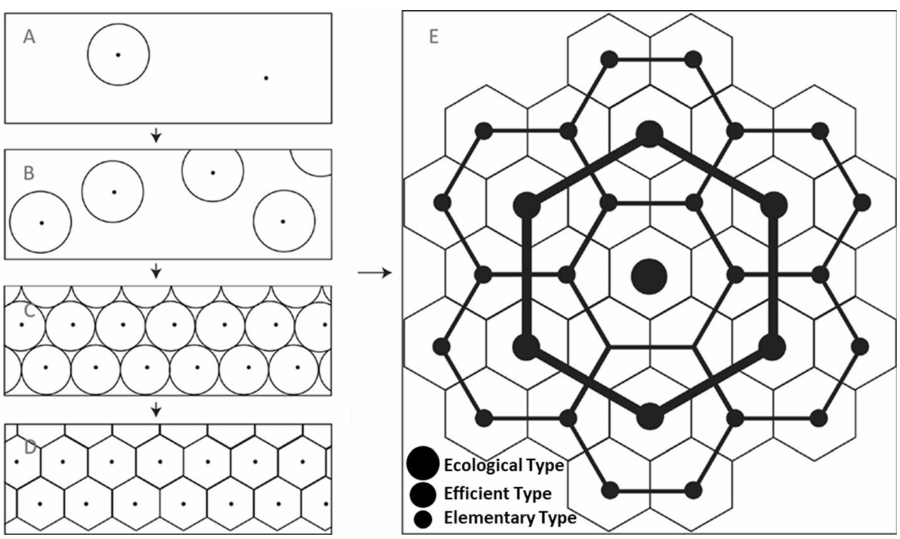

Fig. 3 **a–c** From single UGI to multiples, the circular shape of UGI cooling distances leads to either unserved or overserved cooling areas. To avoid this deficiency, we suggest hexagonal-shaped cooling ranges, as shown in **d**. Within a given area, there must be fewer high-order ecological types relative to the efficient types and much lower order-elementary types, as shown in **d**. For any given order, theoretically, the UGIs will be equidistant from each other. The higher-order UGIs needs to be placed further apart than the lower order UGIs. **e** One ecological type plus six efficient types and some elementary types within a hexagonal pixel frame the hypothetical idealized TSP_{urban} model. The blank spaces are for other land uses within a city, such as developed areas. In theory, this pattern could be the idealized model to cool the urban areas most effectively or the so-called TSP_{urban}

(5) All UGI exists in an equidistant triangular lattice pattern.

Following these assumptions, the cooling effect depends on UGI physical properties. Theoretically, the best UGI spatial pattern for the most effective cooling is determined by the specific UGI size (if the sizes of UGIs are equal), which then determines available land to develop within a city. However, when UGI sizes are not equal, the logarithm function of cooling intensity (Fig. 1b) becomes important. Thus, combining the three UGI types (elementary, efficient, and ecological), we hypothesize that these three basic types of UGI frame the hypothetical idealized urban thermal security pattern model (TSP_{urban}). Each high-ranked UGI could offer a stronger cooling effect than lower-ranked UGI. According to this logic, a hypothetical idealized TSP_{urban} is prioritizing the size of the corresponding green space, forming the (hierarchical) network, and then designing other land use types in urban planning (Fig. 3e). Finally, TSP_{urban} can be framed as a heat-control-based urban geometry. Figure 4 shows the simple abstract 3D model of TSP_{urban}.

In summary, the principle of the TSP_{urban} model is based on the physical properties of UGI and deduced from the two important concepts of size (threshold) and cooling distance, as well as the concept of the threshold value of efficiency (TVoE) to quantify the efficient type. Theoretically, the size-based spatial (hierarchical) pattern of UGI can be designed and applied to frame a hypothetical idealized TSP_{urban} model (Fig. 3). However, this topology likely cannot be found in the real world. Although, the application to the real world is the calculable size of different (efficient and ecological) types (Yu et al. 2017; Yu et al. 2018b) and physical properties of UGIs (Akbari and Kolokotsa 2016). The reflection hence is that the "real world" should be consistent with the model when planning a city for heat island mitigation purposes.

Further discussion

Applicability of the model

Although the TSP_{urban} model usually cannot be found in the real world, the model still can be framed (built) in a specific city by the following steps. Firstly, calculate the size of the efficient type is the most important (calculable) step to frame this model. As we stated above, the efficient type is the key control node for urban cooling and can be calculated by quantifying

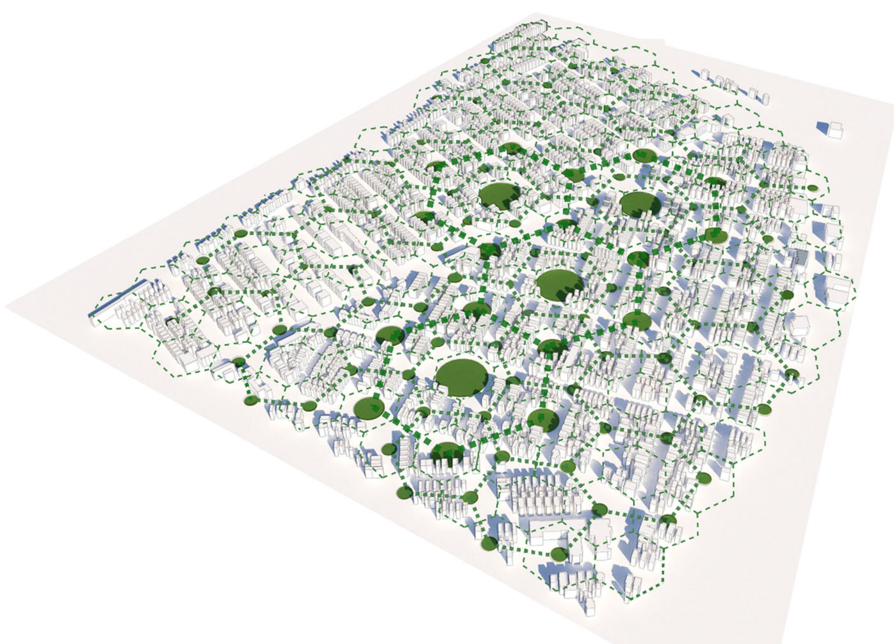

Fig. 4 The simple abstract 3D model of TSP_{urban}

the threshold value of efficiency (TVoE) of UGI (Yu 2018). In fact, many previous studies in different climatic zone cities have revealed some general rules and influencing factors for the value of TVoE (Yu et al. 2018b, 2019a; Yang et al. 2020), such as the TVoE in low latitude (tropic and subtropic Asian) city is around 0.6 to 0.95 ha (Fan et al. 2019; Le et al. 2019). Moreover, in the future, more specific-case-based and climate-zone-based studies are needed to determine the TVoE and potential influencing factors on a global scale.

Secondly, determine the size of the Ecological type, but it still no clear conclusion. As we defined above, the ecological type is a sufficiently large UGI where the cooling efficiency is kept stable within a certain range, but the threshold-size of the ecological type is still discussable. For instance, Zhou et al. (2019) found that an increase in the area can enhance the cooling intensity of a greenspace when it is smaller than a certain threshold (i.e., 10 ha). Jaganmohan et al. (2016) revealed that the size of the green space will be the primary factor in influencing the cooling intensity when the size of green space exceeds 14 ha. Mikami and Sekita (2009) reported that the cooling intensity of an urban forest will not increase when the area exceeds 20 ha. It is clear that the ecological type exists and offers the most comprehensive ecosystem services and more studies are required to determine the sufficient size of UGI, although we predict that about 10 ha may a threshold based on the previous studies.

Thirdly, when we calculated the efficient type and determined ecological type, the final step is to place the elementary type, such as pocket garden and street trees as stated above. It also needs to be mentioned that, a compact shape (circle or square) of UGI is generally recommended due to its better cooling effect than complexity shape (Sun and Chen 2012; Santamouris et al. 2018; Yang et al. 2020). These three basic steps are the general guideline to frame the model; and further, despite this model still have uncertainties, this deductive analysis thinking-way (transcend the existing research logic) would provide a new pathway to climate adaption planning.

Potential influencing factors

Based on the three proposed types of UGI (elementary, efficient, and ecological), the hypothetical idealized TSP_{urban} model (hierarchical hexagonal structure) was established based on UGI size (**size-based**). However, many factors will lead to deviations from this ideal model due to different cooling effects. For instance, the cooling effect dependence on different species of trees, shrubs, and grasses, wind speed and direction, blue and green space differences, as well as seasonal and diurnal variations of UGIs (Santamouris 2014; Gillner et al. 2015; Akbari and Kolokotsa 2016; Derkzen et al. 2017; Zhou et al. 2017). These variations lead to the subdivision of the three main UGI types in the TSP_{urban} model. For instance, Kong et al. (2014) and Demuzere et al. (2014) summarized the cooling effects of green vegetation and found that trees had the strongest cooling effect, followed by bushes, and grasses (**type-based**). O'Malley et al. (2015) found that green space has a stronger cooling effect than water bodies, while other studies have shown the opposite result (Yu et al. 2015; Yang et al. 2020). Zhao et al. (2014) and Yu et al. (2018b) identified that the local background climate strongly contributes to the UGI cooling effect (**climate-based**). In addition, social factors and planning practices may also influence the idealized model. Complicating factors could include anthropogenic heat, the shape of UGIs, building density and height, direction of streets, and air conditioner usage (Akbari and Kolokotsa 2016; Jaganmohan et al. 2016; Li et al. 2017; Martins et al. 2016; Sun et al. 2017, 2018; Santamouris et al. 2018).

These influencing factors cannot be ignored in the real world, and all of these factors complicate the idealized hierarchical hexagonal structure (the structure may not be a regular six-sided polygon if we consider potential influencing factors). Nevertheless, the value and the purpose of this hypothetical ideal model lie in the use of abstract models to explain complex concepts, which will give us a deeper understanding of this issue and become part of the climate adaption planning and decision-making process.

Certainty and uncertainty

One of the hotspots of related research is what urban spatial structure has the greatest impact on the urban thermal environment. In 2018, ***Physical Review Letters*** reported a study showed that the arrangement of a city's streets and buildings plays a crucial role in the local UHI effect (Sobstyl et al. 2018). Specifically, the study investigated more than 50 cities worldwide and demonstrated that cities with an orderly street pattern (i.e., New York and Chicago)—laid out on a precise grid, such as the atoms in a crystal, have a much greater UHI effect than those with a more disorderly pattern (like the disordered atoms in a liquid or glass). This finding inspired us that an orderly UGI pattern may produce a significant cooling effect. In fact, Zhang et al. (2017) have demonstrated that clustered green space (in Phoenix) enhances local cooling because of the agglomeration effect, while dispersed patterns of green space lead to greater overall regional cooling. Shih (2017) found that the relative location and connectivity of urban green spaces are very important when planning green space cooling. The European Environment Agency also suggested that a green space network contributes to more resilient than an isolated pattern as we stated above. Besides, many studies have demonstrated that the spatial structure of green spaces contributed more to the temperature variation than the total area of green spaces (Chen et al. 2014; Debbage and Shepherd 2015; Monteiro et al. 2016; Sun and Chen 2017). Kong et al. (2014) revealed that a large size of green space could extend its cooling effect beyond its boundaries and enhance the cooling effect of the nearby small green spaces. They called it the mainland-island spatial pattern and recommended the use of multiple small green spaces as a landscape planning strategy designed to alleviate the UHI effect. Generally, the mainland-island pattern can be regarded as the ecological type in the hypothetical TSP_{urban} model. Hence, a critical issue is how to design the specific pattern of an isolated ecological type and surrounding other UGI types to maximize the cooling effect.

From the perspective of ***Island Biogeography Theory***, the size of the island and the distance from the mainland determine the species richness, as well as the extinction and colonization rate. Accordingly, the spatial pattern and use of land cover around an ecological type become a critical issue, i.e. what size UGI and how far away from the ecological type should it be to generate a significant synergy cooling effect between the ecological type and surroundings UGI types? Furthermore, the discussion should address whether or not the interconnected small-sized UGI form a network corridor that intensifies the cooling effect within an ecological type. Additionally, how does the height of buildings alter the cooling effect between the ecological type and the surrounding UGI? These questions all need further study in specific cases.

Besides, in this study, we have only considered the transpiration effect of urban blue-green space. However, another uncertainty is the cooling effect of shading by tree-covered UGIs (Martins et al. 2016; Zhou et al. 2017). The study by Jiao et al. (2017) found that with a fixed area of tree cover, a number of small patches could provide more shade than a single large patch. Moreover, considering the joint effects of shading and transpiration, an optimal size of tree patch might occur at which the joint effects of shading and transpiration are maximized. Further, it is widely acknowledged that the public health risks of the UHI and heatwaves are highly correlated, as well as the effects of UGI (Ward et al. 2016; Liu et al. 2018). However, the uncertain part needing to be investigated is the contribution of the TSP_{urban} model to public health management.

Conclusion remarks

There is a large body of research exploring the UHI effect and related mitigation strategies. However, most of the studies on the UGI cooling effect are case-based and seek to explore the effects of the existent landscape composition and spatial configuration of UGI, rather than modeling the optimized spatial pattern in an urban area. Therefore, in this research, we expand upon the existing research logic and framework. We extracted the most critical impact factors from the existing research and came up with three basic UGI types (ecological, efficient, and elementary), which are both calculable and applicable. Subsequently, we proposed a hypothetical idealized TSP_{urban} model, but due to the potential influencing factors and uncertainties discussed, the ideal TSP_{urban} model generally cannot be found in the real world.

Admittedly, the UGI cooling effects based on physical properties (threshold size and cooling distance) and framed in the TSP_{urban} model is almost impossible to find in the real world. It needs to be mentioned is that this model also inspired by the *Central Place Theory*. However, the advanced step in the TSP_{urban} model is that we only consider the physical property of UGIs, yet the hypothetical premise of the *Central Place Theory* includes many psychologies and human behaviors which make the model more complex. Cities are an open, complex mega-system in which various factors can influence the cooling effects of UGIs and the TSP_{urban} model. Yet, the meaning of the TSP_{urban} model is that this hypothetical ideal model lies in the use of abstract models to explain complex concepts; and it can help us better understand the cooling effects of UGI and consider it when decision-making for climate adaption. Further, this model also can be extended to a regional scale, it can be called the regional thermal security pattern model. Therefore, it is clear that this model (research logic) served as a novel pathway to study the cooling effects of UGI and mitigate the UHI effect.

Acknowledgements This work was financially supported by Open Foundation of the State Key Laboratory of Urban and Regional Ecology of China (Grant No. SKLURE2019-2-6); National Natural Science Foundation of China (Grant No. 41922007); Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration (Grant No. SHUES2019A01); WEL Visiting Fellowship Program; China Scholarship Council (Grant No. 201504910797). We also thank anonymous reviewers for their constructive comments and suggestions.

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