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REVIEW ARTICLE

The Role of Urban Trees in Reducing Land Surface Temperature

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ABSTRACT

Increasing urbanization in the world in recent years has resulted in the replacement of areas covered with plants by buildings. Because of this change, urban areas are warmer than rural areas (urban heat island). In this investigation, the urban heat island (UHI) effect, the methods of combating this effect and notably the role of urban trees are exhaustively elaborated by considering the relevant literature. In addition, suggestions were made on which species should be selected and how tree species should be positioned to reduce UHI effect. There are solid evidences that trees, urban green spaces and wider green infrastructure can bring significant reductions in urban temperatures. Urban planners and decision makers can help combat UHI and increase urban resilience to the effects of climate change, primarily by planting the urban environment with extensive shade-providing species and harnessing the most of the opportunities afforded by restoration activities. Trees and other vegetation can cool the surrounding air by evapotranspiration thanks to both transpiration from plant leaves and evaporation of water from irrigated soil. The tree canopy can considerably improve outdoor thermal comfort by preventing a pedestrian from being exposed to solar radiation, and also by protecting floors and building coverings from UHI effect. Furthermore, if a roadside afforestation is to be established to combat UHI effect, a proper plan based on the character of the road will be beneficial in terms of achieving the determined goals. Eventually, the adaptation to UHI should be achieved to plan short-, medium- and long-term changes.

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1. Introduction

Since the industrial revolution, the population of cities, developing economically and technologically, has gradually increased and thus expanded (Begen, 2020). It has been envisaged that the world population will be about 8 and 10 billion and urbanization will be 60.4% and 68.4% in 2030 and 2050, respectively (United Nations, 2018). These increases will lead to urban expansion notably in developing countries, and tropical and subtropical regions (Oke et al., 2017).

Urban sprawl can be seen since ecological factors such as sunshine status, daylight, prevailing wind direction, air currents, green areas, groundwater levels and geophysical characteristics are ruled out in the urbanization process (Kırzıoğlu et al., 1999). Changes such as urban sprawl, industrialization and deforestation resulted in various environmental problems (Kaplan et al., 2018; Ersoy Tonyaloğlu, 2019).

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With urbanization, the number of urban building has increased and lands with vegetation are covered with buildings, roads and other utilities. Hence, lands that were once permeable and moist often become impervious and dry (EPA, 2012). This situation affects the aerodynamic properties of the earth's surface, and have significant effects on the local and regional climate by changing the land-air exchange and meteorological conditions (Harman, 2003; Zhang et al., 2019). One of these effects is the fact that urban areas are exposed to higher temperatures than rural areas, called as the urban heat island (EPA, 2012).

The purpose of this review study is to explain urban heat island (UHI) effect elaborately, to reveal the methods of combating UHI in urban areas within the framework of the discipline of landscape architecture, and especially the role of urban trees in the fight against UHI based on the related national and international literature. In addition, it is aimed to present suggestions on which tree species will select against UHI and how they should be positioned in landscape designs.

1.1. Urban Heat Island

Other facilities such as buildings, roads and infrastructure increased by urbanization absorb and re-radiate more solar heat than natural land covers such as forests and water bodies. In addition, urban areas have less moisture content than rural areas due to impermeable surfaces that make urban areas dry (Figure 1). Consequently, the natural cooling processes such as evaporation and evapotranspiration occur restricted in urban areas and cannot control the increasing of urban temperature (Imran et al., 2021). Urban areas, where buildings are concentrated and green areas are limited, happen to islands with higher temperatures compared to the surrounding rural areas. This is defined as the urban heat island (EPA, 2021; Orhan, 2021).

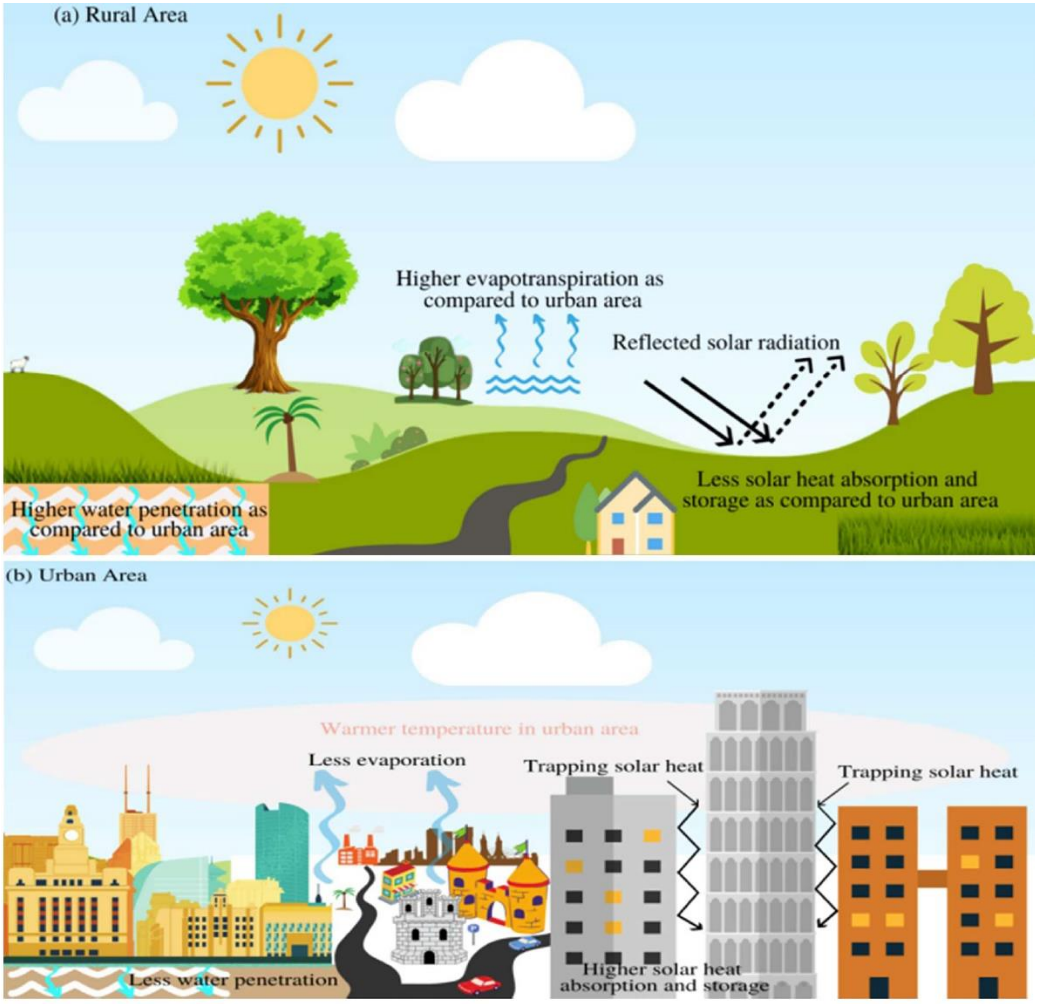

Figure 1. An illustration of rural (pervious) and urban (impervious) areas (Imran et al., 2021).

The urban heat island was firstly explored and described by Luke Howard in the 1810s (Howard, 2012). The study of the urban atmosphere continued throughout the nineteenth century. Between the 1920s and 1940s, researchers in local climatology or micrometeorology in Europe, Mexico, India, Japan, and the United States pursued new methods of understanding this problem. In 1929, Albert Peppler coined the term "*Staedtischen*

Waermeinsel" as the first word equivalent to the urban heat island (Stewart, 2019).

The urban heat island has been the focus of many scientific studies since 1990 (Masson et al., 2020).

Some studies have suggested that UHI has a non-significant effect on global temperature averages due to urban areas that make up only 1% of the earth's surface (Hansen et al., 2010; Hartmann et al., 2013; Wang et al., 2015; Wang & Yan, 2016). However, some studies have reported that UHI has a more negative impact on climate change than greenhouse gas in urban areas (Stone, 2007; Fujibe, 2009; McCarthy et al., 2010; Yan et al., 2016; Wang & Yan, 2016; Kachenchart et al., 2021).

1.2. Urban Heat Island Effect

The urban heat island effect is examined at micro (subsurface and surface), local (urban canopy layer) and mezzo (urban boundary layer) scales owing to urban biophysical nature and the multi-layered structure of the atmosphere (Erell et al., 2011; Roth, 2013). The urban temperature extends to the urban boundary layer through the entrainments of sensible heat clouds from micro-scale areas (bottom-up) and warmer air from local scale areas (top-down) and the boundary layer forms UHI (Figure 2). As examined underground and surface heat islands at the micro scale (1-100s m), it is observed that rainwater runoff affects the temperature, groundwater properties, the health of aquatic ecosystems, and carbon exchange between soil and atmosphere (Roth, 2013).

Researches exploring the canopy layer of the atmosphere under buildings and trees at a local scale (1≤10 km) (Figure 2) have reported the existence of cool islands due to shading from tall buildings during the day (Chow & Roth, 2006; Roth, 2013).

Besides, UHI at the local scale is affected by solar radiation, so the largest temperature differences are most evident during the day (Roth et al., 1989) especially in open areas exposed to direct sunlight. Norton et al. (2013) also stated that solar radiation is one of the key factors in determining human thermal comfort under hot conditions. UHI at the local scale has far-reaching effects on building energy use, water use for irrigation, thermal circulation, air quality and urban ecology, as well as affecting the thermal comfort of urban residents (Roth, 2013).

The urban boundary layer covers the area above urban canopy layer that is affected by the urban surface below (Voogt & Oke, 2003). A cross-section from the air above the city shows a simple dome (in calm conditions) or a cloud of warm air directed downwind of the city (in windy conditions) and usually extends for tens of kilometres (Figure 2). UHI at the mezzo scale exhibits a flow from local to medium scale and its density is less (~1.5-2 °C) compared to local scale. In the urban boundary layer at the mezzo scale, it was reported only weak heat islands decreasing as moved further away from the urban area. In addition, UHI in the boundary layer can potentially affect local circulation, regional climate patterns, precipitation, thunderstorm activity downwind and plant cultivating season (Kotharkar et al., 2018).

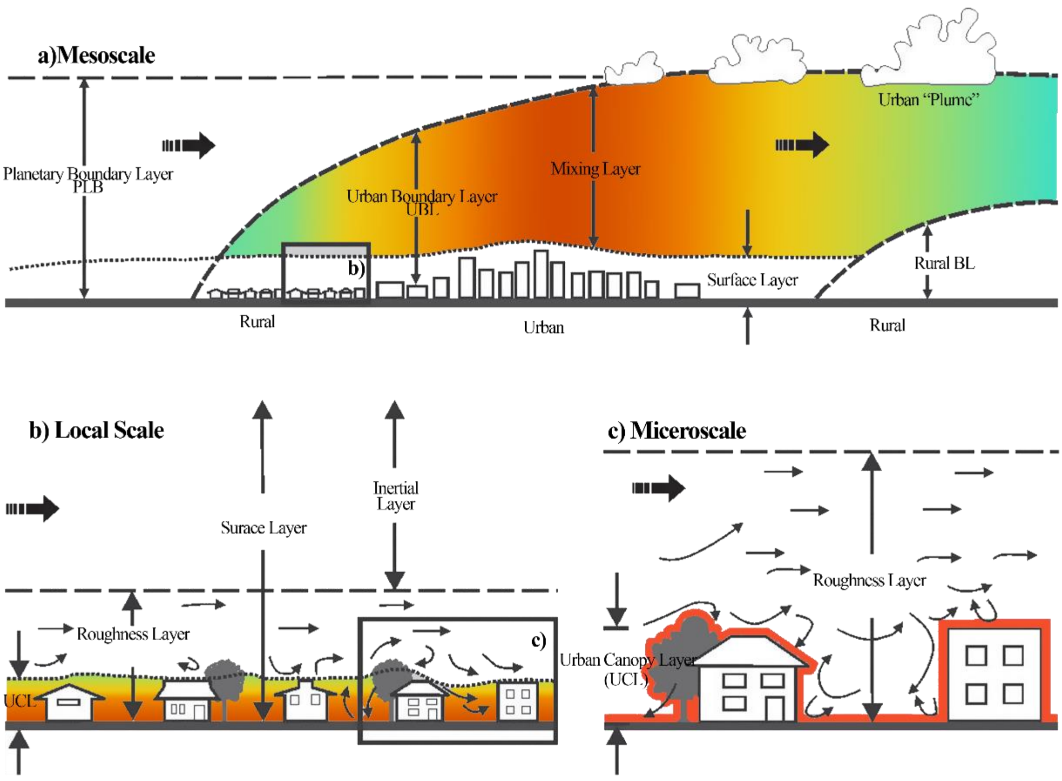

Figure 2. Climatic scales and vertical layers in urban areas. PBL: planetary boundary layer, UBL: urban boundary layer, UCL: urban canopy layer; (a) Mezzo scale, (b) local scale, and (c) micro scale - grey parts (Oke, 2006).

The negative effects of UHI were widely accepted, and these effects cause to the increase in cooling requirements, energy consumption, water demand, and disease and mortality from heat stress and the decrease in air quality (Bhargava et al., 2017; Heaviside et al., 2017; Balany et al., 2020; Peng et al., 2020; Yao et al., 2022).

2. Methods of Combating Urban Heat Island

Although urban climatologists have studied urban heat islands for decades, public interest and concerns regarding the subject have recently begun to emerge. This interest in heat-related environmental and health issues has contributed to the development of heat island combating methods, particularly trees and vegetation, green roofs and cool roofs.

Urban heat island effects need to be combated notably in line with climate change. Besides building designs, urban planning and strategic use of water features, vegetation and green areas within the landscape should be considered. The urban climate can be effectively changed by varying the amounts of heat energy absorbed, stored and transferred and by adopting cooling strategies. The methods of combating urban heat island were discussed in the following subheadings.

2.1. Vegetation

Most studies have been found to be consistent about the ability of trees to lower temperatures and improve human thermal comfort. Shade areas generated by trees reduce direct solar radiation. Through evapotranspiration, trees can give water vapor to the atmosphere, increase the relative humidity, lower the temperature and eventually improve thermal comfort conditions (Doick & Hutchings, 2013). It was reported that the increase in the number of trees decreased the air temperature by around 0.2 °C (Jamei et al., 2014), 0.35-0.6 °C (Tsoka, 2017), 0.3-1.5 °C (Duarte et al., 2015), 1 °C (Skelhorn et al., 2014), 1.49 °C (Salata et al., 2017), 1.87 °C (Herath et al., 2018), 2.27 °C (Srivanit & Hokao, 2013). These results are in line with those from previous literature revealing that adding trees and fences to an urban area can reduce the peak ambient temperature by 0.2 to 5.0 °C (Santamouris et al., 2017; Soltani & Sharifi, 2017; Tsoka et al., 2018).

2.2. Reflection

The extent to which solar energy warms the urban area is associated with the surface albedo or reflection of radiation. Less reflection means more absorbed and stored energy to heat the local environment. A lower urban albedo (usually a rural albedo of 20-25% versus 15%) culminates relatively greater absorption than in the rural area (Doick & Hutchings, 2013). Some studies suggested that reflective surfaces can help reduce UHI and mitigate the microclimate within the city (Zhu & Mai, 2019; Helletsgruber et al., 2020; Cheela et al., 2021).

2.3. Evaporative Cooling and Evapotranspiration

Conducted investigations have shown that the temperature difference (ΔT) between urban and rural areas increases in dry weather compared to humid weather (Fischer & Schar, 2010; Zhao et al., 2014; Amorim, 2020; Feinberg, 2021). Since impervious surfaces such as pavement, adjacent and bare building surfaces, etc. prevent evaporative cooling, solar absorption turns into sensible heat rather than latent heat (Qin, 2020). As hot air traps more water vapor and creates a local greenhouse gas, UHI causes an increase in humidity on impermeable surfaces and thus a decrease in convection cooling. Many studies determined that evaporative pavements could be reduced by the use of roof and vertical gardens (Zhao et al, 2014; Kubilay et al., 2019; Manteghi & Mostofa, 2019; Qin, 2020).

2.4. Shading

Vegetation of surfaces with high evaporation rates and shading artificial materials, that especially have low albedo, are effective strategies to lower surface temperatures and reduce the effect of UHI (Gago et al., 2013; Rahman et al., 2020a; Park et al., 2021; Tan et al., 2021). Shading combats UHI in three complementary ways. First, it restricts energy storage and subsequent heating of the local environment by limiting solar penetration. Second, it reduces the direct energy absorption from the openings and the resulting internal greenhouse effect. Reducing the air conditioning demand saves energy and costs, and reduces the emission of waste heat energy. Third, shading protects people from direct sun exposure (Emmanuel, 2005; Doick & Hutchings, 2013).

3. Spatial Scales of Cooling

The importance of urban vegetation as a “natural capital” is indisputable and it is known to be important in reducing heat stress at the neighbourhood scale (Gunawardena et al., 2017; Willis & Petrokofsky, 2017). Besides, unpredictable climatic conditions adversely affect the efficiency of urban vegetation as heat reduction solution at a city-scale. Because urban-rural differences in evaporative cooling and evapotranspiration increase with precipitation, virtually the entire urban area needs to be replaced with green surfaces to dramatically decrease these differences under wet conditions. In addition, although vegetation reduces thermal comfort by increasing air humidity in hot tropical regions, it can significantly increase pedestrian comfort by providing shade (Manoli et al., 2019).

The surface temperature in a green area can be 15–20 °C lower than that of the surrounding urban area, resulting in 2–8 °C cooler temperatures and a diffuse cooling effect (Taha et al., 1988; Saito et al., 1991).

A study (Monteiro et al., 2016) conducted on the cooling effect of green areas in cities showed that 3-5 hectares of green areas would provide about 70-120 m of cooling effect. Cai et al. (2018) focused on water bodies and reported that the cooling effect of water bodies was effective at a distance of less than 500 m. The study (Hou & Estoque, 2020) carried out in the city of Hangzhou dwelt on the concept of minimum benefit scale in order to determine how far, how much green space or water body should be planned for the target UHI areas. In the same study, it was detected that afforestation and water bodies should be made at distances shorter than 120 m and 150 m to the target area, respectively, and that the cooling effect of the forest (more than 690 m) was considerably higher than the water bodies (less than 210 m).

4. The Right Tree in the Right Place

Although urban trees differ in humid and arid climates, they can reduce heat in urban areas and its negative effects on human health, energy consumption and urban infrastructure (Manoli et al., 2019; Wang et al., 2019). As the urban area and barren surfaces expand, the increase in land surface temperature adversely affects the living conditions of the urban population (Yelsiz & Yücedağ, 2022). In many studies investigating the climatic effects, the effects of different vegetation types (urban trees, urban forests, treeless green areas, etc.) on temperature have been attested (Li et al., 2015; Takács et al., 2016; Duveiller et al., 2018). According to Schwaab et al. (2021), it was confirmed that trees have a high potential to reduce urban heat in Europe (Figure 3).

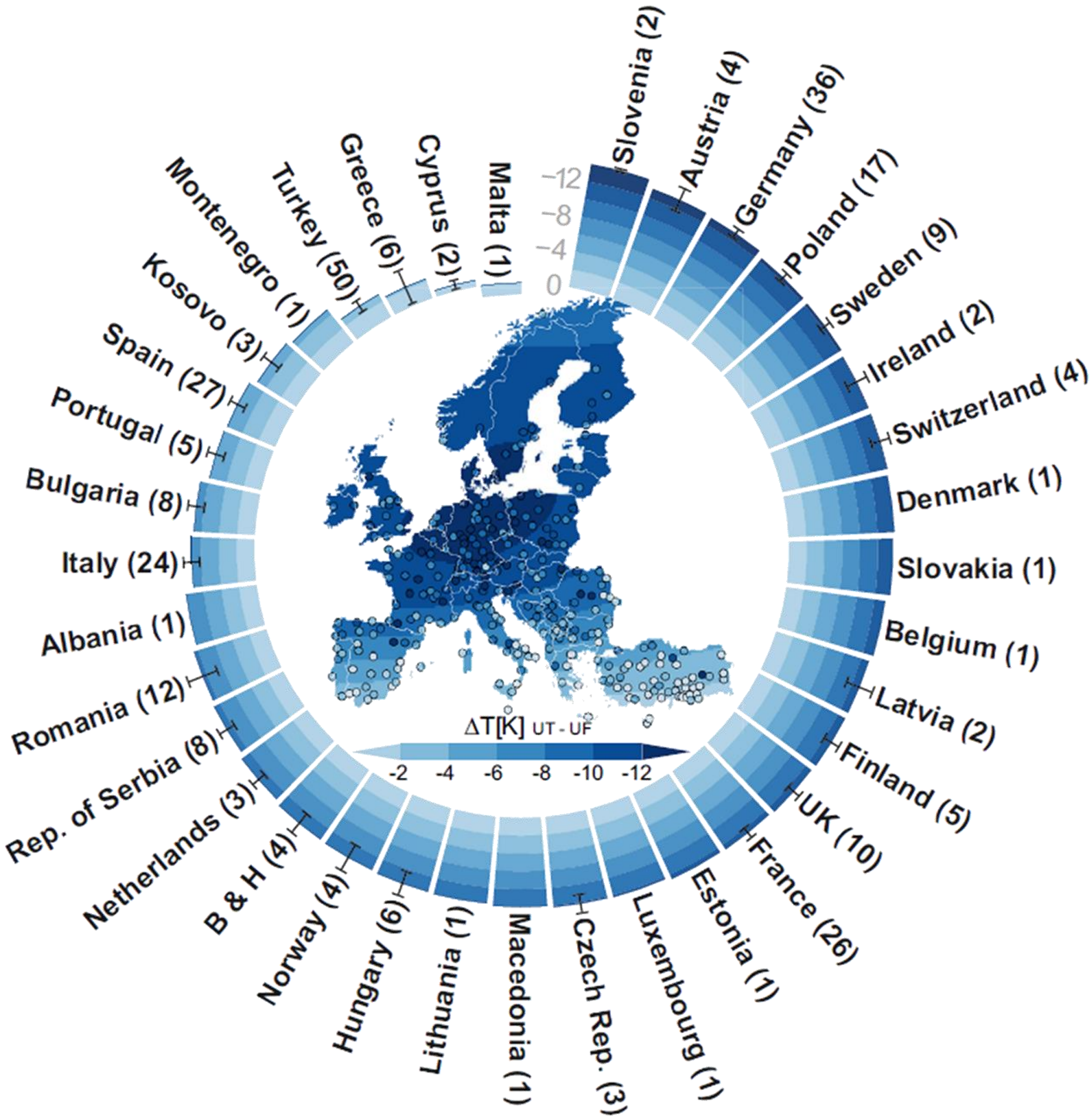

Figure 3. Regional temperature differences (ΔT) during hot extremes between areas covered with 100% urban trees (UT) and with 100% continuous urban fabric (UF). Each dot represents the temperature difference in a specific city. The number of cities for each country is indicated in brackets after the country name (Schwaab et al., 2021).

Urban environmental conditions can increase or decrease the temperature decline provided by trees (Winbourne et al., 2020). For example, higher nutrient availability (Decina et al., 2017), higher temperatures (Aykır, 2017) and higher irrigation levels (Reyes-Paecke et al., 2019) were regularly observed in urban areas compared to rural areas. These can increase transpiration and cooling (Melaas et al., 2016). On the other hand, high temperatures in cities can increase water stress (Meineke et al., 2016), insufficient soil volumes and soil compaction can limit root growth (Jim, 2019), and increased air pollution in cities can have many negative effects on trees. These factors, which may adversely affect the growth of urban trees and the cooling effect, should be considered in urban areas (Chen et al., 2015; Schwaab et al., 2021).

4.1. Tree Selection

There are two main factors leading the cooling property of trees (Rahman et al., 2020b). First, the canopy closure of trees provides shade and shields more than 90% of the shortwave radiation to which the surface is exposed (Massetti et al., 2019). A surface temperature difference of up to 40 °C was reported between asphalt surfaces under the dense canopy of trees and directly exposed to the sun (Armson et al., 2012). Another factor that allows trees to cool is to reduce the amount of available heat (sensible heat) by absorbing the energy (latent heat) around the trees with evapotranspiration. Therefore, air temperatures in the shade of trees can be significantly lower than in the shade of buildings (Charalampopoulos et al., 2013). Consequently, the shading and/or evapotranspiration capacities of the tree species selected in the combating UHI effect should be considered.

Not all tree species have the same cooling effect (Scholz et al., 2018; Chen et al., 2019; Rahman et al., 2020b). The cooling provided by shade and evapotranspiration depends on many sub-factors such as size and temperature of leaf, structure, size and density of shade and water condition of the plant. As the leaf size increases, the variation between latent heat and sensible heat decreases. Therefore, trees with smaller leaf size have higher cooling rates. In case of low leaf density, more leaf surface is exposed to higher solar radiation throughout the entire plant, and thus resulting in higher air temperature and transpiration rate is not sufficient to cool the leaves (Manickathan et al., 2018). As the leaf temperature, that is, the stomatal resistance, increases, the plant performs less cooling, which is directly related to the water status of the plant (Urban et al., 2017). In addition, the health and vitality of the plant is critical to the constant supply of the cooling advantage. Therefore, temperature, drought, disease and pollution tolerance, availability of rooting medium and sensitivity to compression should be considered in the selection of tree species (Doick & Hutchings, 2013).

Like all plants, if trees cannot quickly adapt to adverse conditions during extreme heat waves, heat tolerance is exceeded and the plant may suffer direct thermal damage or death (Drake et al., 2018). Drought tolerance includes mechanisms that limit the damage caused by prolonged drought and allow plants to maintain their metabolism (Courtois et al., 2000; İlhan, 2016). Pathogens and pests are more likely to adapt to adverse environmental conditions (air pollution, lack of humidity, extreme temperatures, etc.) and survive due to their much shorter life span than trees. It should be ensured that the selected tree species gain resistance by various methods to have long-lived (Jactel et al., 2017; Iason et al., 2018; Pike et al., 2021). Root media compatibility is critical to make a young tree long-lived, and in particular, when they inhabit urban green spaces (Shotaroska et. al., 2019). In dense urban environments, sufficient soil for growth, the existing rooting area, availability of moisture, oxygen and nutrient largely determine the size of a tree over its lifetime (Urban, 2008).

All these factors mentioned above will also be affected by future climatic changes. Therefore, tree species may differ in their suitability to cool the local environment under different conditions. For this reason, the selection of tree species should be performed by considering both present and future environmental conditions.

4.2. Tree Position

As considered the positive effects of afforested areas in cities, the size of green areas, plant selection, landscape design and continuity are of great importance in terms of increasing the quality of life (Kuşçu Şimşek, 2016). Furthermore, main aspects and functions of the plant design in parks and gardens (Sandeva et al., 2013) in urban environment need to be carefully met (Despot et al., 2013). In landscape areas serving a specific purpose, the correct positioning of species is as important as their selection (Fazio, 2017). Before determining the tree species and position to be used for cooling cities, the spatial distribution of temperature and climatic differences in the city should be considered (Tan et al., 2016; Morakinyo et al., 2020; Rakoto et al., 2021).

According to a study (Adıgüzel et al., 2022) carried out for various surfaces (soil, parquet, asphalt, turf), the highest and the lowest surface temperatures were determined at the soil surface and on the parquet surface under the tree shade based on tree shade-sun exposure conditions, respectively. This study also revealed that hard surfaces had more absorption rates than grass surfaces throughout the day.

It is a fact that the street canyons, building form and layout, which are formed by increasing urbanization, direct the afforestation activities and tree positioning (O'Malley et al., 2014). In this direction, both urban and tree morphology as well as the afforestation rules determined by the countries (*e.g.*, TS 8146, 1990) should be considered when determining the position of trees in the strategies to reduce UHI effects (Tan et al., 2016). It was determined that trees cool the hot air more in deep and wide canyons than in narrow and shallow canyons, depending on the amount of heat storage, the movement area of the wind, and the shaded and unshaded total surface area in cities (Loughner et al., 2012; Yang et al., 2017; Morakinyo et al., 2020).

In a case study (Langenheim et al., 2020) considering the highest summer temperatures and the time zone corresponding to UV levels for a region in western Australia, the shadows formed by trees of various forms were simulated (Figure 4). This simulation suggested that pedestrians on east-west oriented streets felt the need for wider canopy trees to shade, and that taller tree forms on north-south oriented streets obtained more pedestrian shade especially when closely located during the target time period. Further studies should consider the shadow direction, i.e. the location and the sun angle of the city on the world.

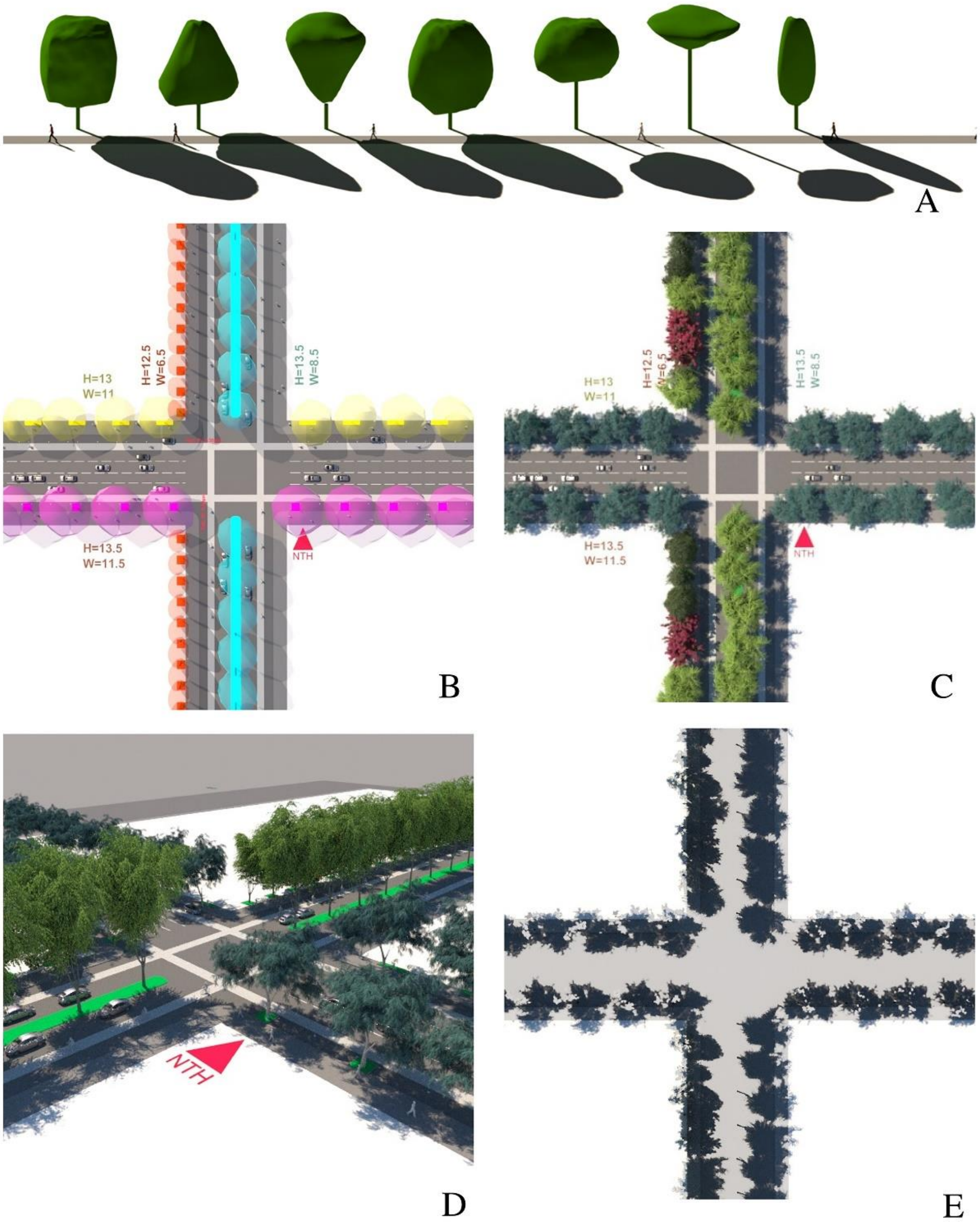

Figure 4. Typical tree form models (A), Optimal geometry and placement model with height width output (B), Fitted recursive 3-D polygon-dense models of species on preferred council list (C), Perspective view of intersection demonstrating visual impact of tree-scape design (D), Texture baked tree shade (E) (Langenheim et al., 2020).

Zhao et al. (2017) displayed a simulation to make the trees around the building optimum cooling and to maximize the shading of the façade, doors and windows. This study, which can serve as an example for cities in the northern hemisphere, showed that the best place for a single tree is at location 4, which is 3 m from the south side and 9 m from the west and east sides of the building (Figure 5).

To locate a second tree with our heuristic method, the best near-optimal solution is at location 3 and 5 (Figure 6).

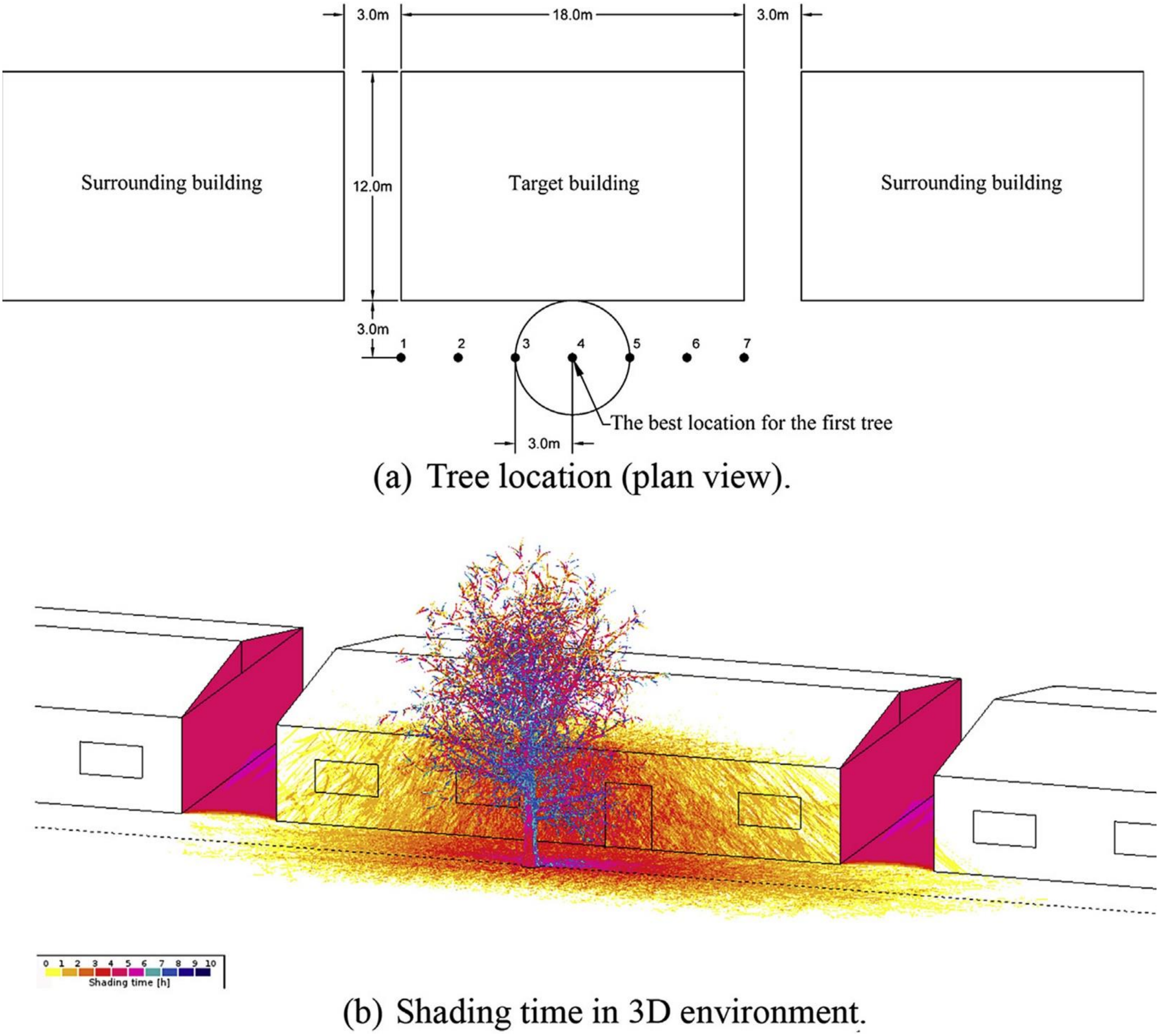

Figure 5. Optimal shading from one tree (August 15th, at location 4) (Zhao et al., 2017).

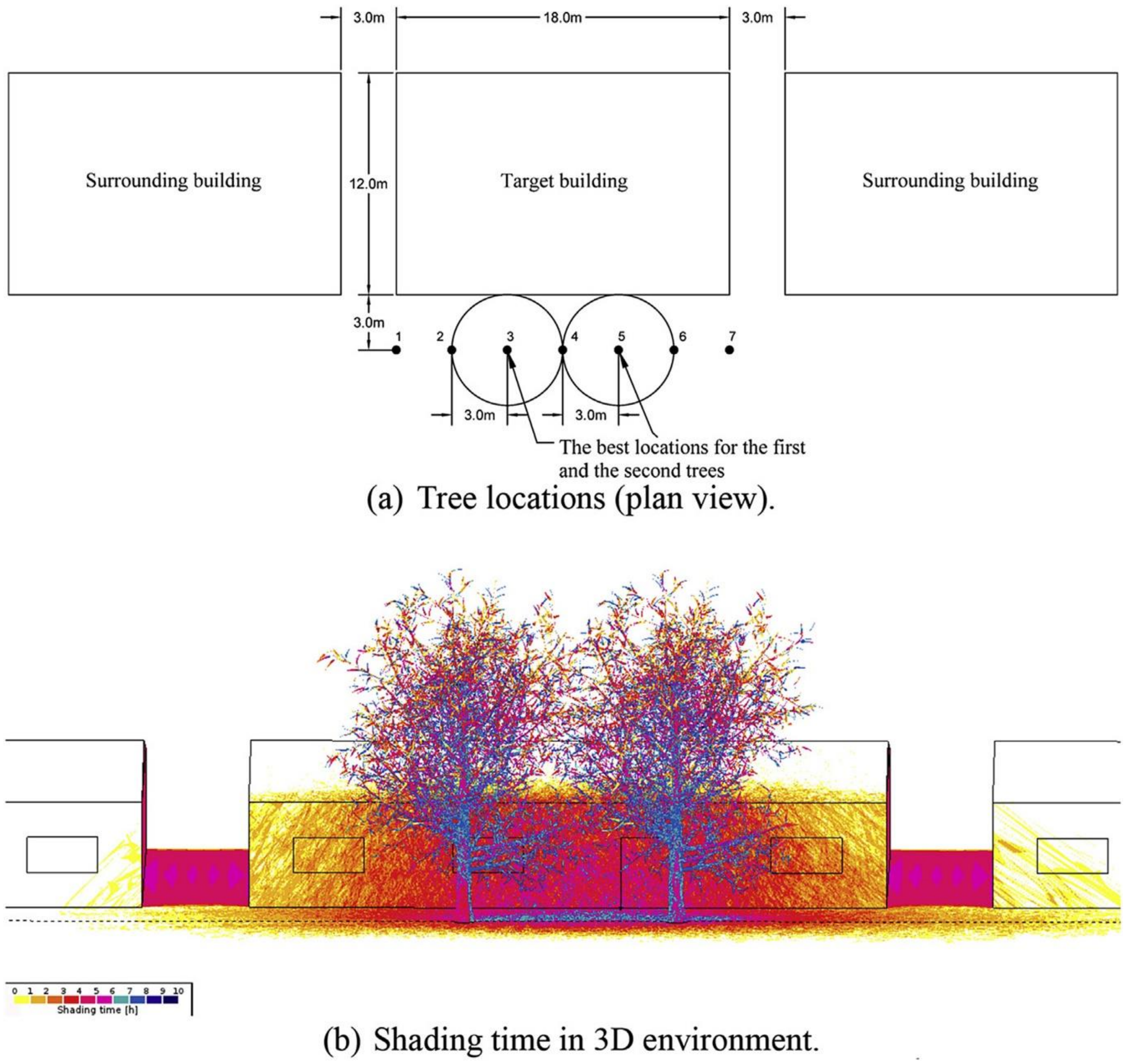

Figure 6. The best near-optimal shading from two trees (August 15th, at locations 3 and 5) (Zhao et al., 2017).

5. Conclusion

With the UHI effect, cities typically show higher average temperatures than the surrounding rural areas. The density of UHI may vary relying on the city and time. While the temperature difference is 6 °C in Istanbul, it reaches 9 °C in Antalya. Projections regarding climate change foresee an increase in temperatures and extreme heat events that will exacerbate the UHI effect. Prolonged high temperatures can have serious effects on human health. Therefore, adaptation to UHI should be achieved to plan short-, medium- and long-term changes. There are solid evidences that trees, urban green spaces and wider green infrastructure can bring significant reductions in urban temperatures and help prevent health problems caused by heat waves.

Urban planners and decision makers can help combat UHI and increase urban resilience to the effects of climate change, primarily by planting the urban environment with extensive shade-providing species and harnessing the most of the opportunities afforded by restoration activities. Trees and other vegetation can cool the surrounding air by evapotranspiration thanks to both transpiration from plant leaves and evaporation of water from irrigated soil. It was figured out that tree canopy can considerably improve outdoor thermal comfort by preventing a pedestrian from being exposed to solar radiation, and also by protecting floors and building coverings from UHI effect.

In the selection of tree species to combat UHI effect, their shading and/or evapotranspiration capacities should be evaluated, and heat, drought, disease and pollution tolerance, availability of rooting medium, and sensitivity to compression should also be considered. It is ideal to plant the southwest facades of the building in order to cool the building and ground surfaces and to provide human thermal comfort but neighbour relations and optimum utilization of solar energy by neighbours should not be neglected. In addition, if a roadside afforestation is to be established to combat UHI effect, a proper plan based on the character of the road will be beneficial in terms of achieving the determined goals.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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