Cooling Strategies for Thermal Comfort in Cities: A Review of Key Methods in Landscape Design

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Research Article

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Abstract

Under the climate change scenario, the negative impacts of urban heat island (UHI) will exacerbate due to unsustainable urban planning and human activities. Thermal comfort has close relationships with UHI in urban areas. This paper is based on the studies of urban heat island, thermal comfort, microclimate and urban planning in cities in the recent decade, combined with cross-analysis research method. The key topics include vegetation and water conditions, the albedo of materials, urban morphology and more. By the comparative case studies in landscape projects, the results further reveal that the density of tree canopies, the natural structure and density of ground cover, the form of water features, the colour and texture of materials, and the scale of shading structures have different cooling effect and performance in outdoor thermal comfort improvement with specific features in the landscape design. It is also found that there are some external conditions that can influence design determinations in real practices. The purpose of this study is to provide theoretical research methods and evaluation of thermal comfort landscape design elements, and to provide guidance for future sustainable city research and landscape design.

1. Introduction

In the contemporary world, around half of the human population lives in urban areas. It is expected that the number of urban residents will increase by 70% of the present world urban population by 2030 (Urban Heat Islands, 2019). Population growth and the shortage of urban land supply have led to increased pressures on transportation and the environment, which are extremely unsustainable for cities (Rehan, 2016). Gradually, the unsustainable urban sprawl, the removal of vegetation, the increasing numbers of cars, the large amounts of energy consumption, impervious surfaces, and air pollution, etc. have contributed to the urban heat island (UHI) effect. This negative effect creates warmer and drier conditions in urban areas than in their surrounding rural areas and decreases the level of thermal comfort and quality of life (Grilo et al., 2020). To prevent and adapt to the rising temperature in the future, to balance the urban ecosystem and maintain the high quality of the living environment with more acceptable and comfortable temperature for urban citizens, numbers of studies in urban planning and landscape have started to explored and tested solutions to alleviate urban heat island and improve thermal comfort in cities.

The purpose of this paper is to provide suggestions for outdoor thermal comfort improvement in landscape designs with specific strategies and effective elements that are explored from thematic research. In this paper, the relationship between urban heat islands and thermal comfort are identified, and the key factors that mainly affect outdoor thermal comfort are classified into 5 aspects from previous theoretical research and methods. The comparative analysis of three precedents aims to further evaluate the overall cooling performance based on the key factors with different design features. From theoretical research and landscape practices, this paper tries to find out the effective and adaptable strategies as well as recommendations for thermal comfort improvement in the outdoor environment through landscape designs.

2. The Definition And Relationship-uhi And Thermal Comfort

2.1 Urban Heat Island (UHI)

The urban heat island (UHI) is defined as those urban areas or metropolitan areas that are significantly warmer than their surrounding rural areas mainly due to human activities, especially the anthropogenic heat produced mainly through the actions of heating and cooling plants and buildings, industrial activities, as well as the heat mainly produced by CO_2 emission from vehicles (Rehan, 2016). Additionally, this effect is also caused by impervious surfaces, such as concrete and asphalt instead of natural evaporative surfaces (vegetation), which absorb a large amount of solar heat from radiation during the day (Ahmed et al., 2008).

2.2 Thermal comfort

Thermal comfort was defined as people's satisfaction with the thermal environment of the space between buildings (Watkins et al., 2007). There are many urban conditions and factors that could affect thermal environment, including air temperature, air humidity, wind speed, urban form, urban space configuration, human activities, etc. Psychological emotions could also influence people's perceptions and subjective feelings to the environment.

2.3 Causal relationship and future trend

Many studies and evidence have proved and predicted that among the world's cities, the first and most serious impact of climate change will be the increasing temperature in the future. The worry is that the negative impacts of UHI will be exacerbated because of the worldwide increasing temperature under the climate change scenario.

The constant high temperature in cities during the summer will directly lead to some negative effects, threatening public health, well-being and quality of life. The persistent summer heat can cause health problems for urban residents, such as heatwaves that have led to increased morbidity and mortality (Gabriel and Endlicher, 2011). However, in fact, high temperature conditions are predicted to deteriorate in many cities. Over-reliance on refrigeration devices and increased demand for irrigation by plants in high-temperature conditions has accelerated energy consumption. This situation is particularly serious in dry and hot tropical cities as well as in developing countries because the continuous long-term high temperature, water shortage, and the use of traditional fuels (such as coal and petrol) have brought greater environmental burdens.

From these causal relationships, it could be found that there is a close connection between these negative effects. At the same time, it provides opportunities for scholars and experts to further consider and explore mitigation measures that could benefit in many aspects because of interactions. For example, improving the thermal comfort of the public open spaces not only enables the outdoor temperature to maintain an acceptable level in summer, but also encourages urban citizens to touch the nature or conduct social activities in the public domain with a comfortable environment at any time instead of relying on the constant indoor environment maintained by air conditioners. To some extent, this is also beneficial in the reduction of energy consumption. Therefore, from a long-term perspective, improving the urban thermal environment is one of the important steps in the near future to deal with climate change, to prevent and mitigate the negative impact of UHI, to maintain a healthy urban ecology, and to improve people's wellbeing and the quality of life.

3. Key Factors In Thermal Comfort

Based on the urban context, the microclimate conditions and anthropogenic activities that affect thermal comfort contain lots of elements. Among the urban microclimate conditions, the key factors that are related to the urban thermal environment mainly include air temperature, humidity, and wind conditions. The anthropogenic activities dominated by urban planning and design can be identified as one of the key factors.

3.1 Air temperature

Air temperature is the most direct factor affecting thermal comfort because the human body's perception of the ambient temperature is most obvious than other factors. Air temperature is the simplest factor to easily measure and understand (Watkins et al., 2007). In general, people would feel uncomfortable and hot in an environment where the temperature exceeds 25°C. While in an environment where the temperature exceeds 37°C, people would feel extremely uncomfortable and hot. Brager and de Dear also pointed out that even under the climate change scenario, the temperature preferences of people are relatively consistent and similar (Brager and de Dear, 1998).

3.2 Humidity

The relative humidity of the environment is negatively correlated to the intensity of the urban heat island. A higher relative humidity corresponds to a lower UHI intensity (Santamouris, 2015). The influence of air humidity on thermal comfort is mainly related to evaporative cooling. Humidity as a kind of invisible phenomenon can be manipulated by devices through technology or can be promoted by blue and green infrastructure.

3.3 Wind condition

The speed at which air moves over the surface of the body is highly influential in the heat balance and therefore the sensation of thermal comfort (Watkins et al., 2007). This is because the wind could remove the heat released by the human body through the moves. Therefore, properly increasing the wind speed allows heat to be quickly removed, making it easier to create a cooler environment. Santamouris had proved this point of view by analyzing and comparing the characteristics and magnitude of the heat island effect in different regions. One of his findings shows that in the same area, the increase in wind speed makes UHI intensity lower. Strong winds can change the cooling rate of urban and rural areas (Santamouris, 2015).

3.4 Urban planning and urban design

The influence of urban planning and urban design on thermal comfort lies mainly in the reflectivity of urban structures to solar radiation. The temperature of the air mainly comes from solar radiation. In cities, due to impervious surfaces and dense urban buildings, solar radiation is reflected multiple times. The total amount of solar radiation absorbed by these urban structures during the day increases, at the same time, the heat released at night also meets an increase (Doulos et al., 2004). This is one of the reasons why city temperatures are generally higher than surrounding rural areas. Besides, urban configuration which focuses on the H/W (height/width) ratio has a great influence on the temperature distribution in the urban area (Jamei et al., 2017).

4. How To Improve Thermal Comfort In Cities

4.1 Cross-analysis Method

The cool city is one of the sustainable urban solutions for the city of tomorrow that depends on the application of the principles of urban heat management. It is the key factor to diminishing the urban heat release, creating solutions of future climate change by reducing the volume of global emissions, and creating smart growth and cool community scenarios (Rehan, 2016).

How to reduce heat accumulation in urban areas? Rehan proposed corresponding strategies in the framework of a cool city, and emphasized that cities can alleviate the UHI effect through a series of planning actions. This cool city framework can help improve the urban thermal comfort, the air and water quality, reduce energy consumption, and prepare a sustainable and resilient urban environment for combating future climate change.

The cross-analysis method is based on Rehan's cool city framework as horizontal guidance of thermal comfort improvement in urban planning and landscape design (see Fig. 1). The vertical theoretical lens in this paper comes from landscape theories mentioned in Herrington's book, including forming, material matters, and system logic (Herrington, 2017). From a landscape perspective, tree canopy and ground cover are usually used as the design process of green infrastructure, water features are a kind of engineering infrastructure. The colour and form of materials reflect the design formalism. The selection of material texture and consideration of essential performance is a kind of tectonic expression revealing the truth of materiality.

4.2 Cooling strategies

Based on the methodology mentioned above, cooling strategies with detailed actions need to be further classified and differentiated in combination with key factors related to thermal comfort. Therefore, the strategies will be divided into five parts to further illustrate each strategy with different urban elements and effective planning and design actions.

4.2.1 Urban Greening - Vegetation

Increasing urban green space and vegetation coverage is a common and effective method to improve pedestrian thermal comfort and reduce heat islands based on a natural solution. The tree canopy increases the relative humidity of the environment through shades and evapotranspiration to avoid heat accumulation. Green spaces can regulate the microclimate, helping to reduce urban temperatures and increase humidity. Moreover, with higher tree density green spaces can provide a better cooling effect. In terms of the effective range of green spaces, they can affect the air temperature and humidity within 60m at the farthest (Grilo et al., 2020) (see Fig. 2). In addition, the natural evaporative surfaces (vegetation) could absorb a large amount of solar heat from radiation during the day (Vieira et al., 2018). The more complex vegetation types have a higher ability to adjust the microclimate. Multi-layer plant communities are one of the most effective approaches in cooling and humidifying (Zhang et al., 2013).

4.2.2 Urban Greening - Water

The impact of urban water bodies on human comfort is seldom evaluated, but water bodies can effectively improve human comfort in coastal areas, especially during the hot and hot summer months. Area 10–20 m from the water edge showed the greatest improvement in thermal comfort (Xu et al., 2010). In addition, appropriate planting of vegetation can produce a synergistic effect and make the water body have a more positive and efficient impact on human comfort. Flowing water has a larger cooling effect than stagnant water. Moreover, dispersed water like from a fountain has the biggest cooling effect (Rehan, 2016).

4.2.3 Albedo - Materials

Materials with high reflectivity obtain less solar heat during the day, and therefore have a significant effect on reducing urban heat islands and improving the thermal environment. The reflectivity of the material to solar radiation during the day will affect the thermal balance of the material surface. This depends on the color, construction, and surface texture of materials. The outdoor paving materials characterized by smooth, light-colored, and flat have a more significant cooling effect on improving thermal comfort (Doulos t al., 2004) (see Fig. 3).

4.2.4 Ventilation - Urban morphology

The size of the city, the width of the street, the spatial layout, the geometry of buildings and the materials of the facade which are related to urban planning and design could affect the intensity of UHI and the thermal environment in urban regions. The cooling effect is mainly achieved by establishing urban ventilation corridors and street canyons. Wind penetration in deep canyons can significantly improve pedestrian thermal comfort (Jamei et al., 2017). However, the establishment of urban ventilation corridors needs to consider many planning factors and environmental impacts, such as the aspect ratio of buildings, the sky view factor of public open spaces, the width of streets, the materials of outdoor spaces, and the interaction of these factors with microclimate conditions (Hsieh and Huang, 2016).

4.2.5 Other aspects

The methods to improve thermal comfort also include technology, policy, engineering, and energy strategies. Strategies such as new clean energy replace traditional energy, green roof and green wall engineering facilities; artificial shade structures are useful in thermal comfort improvement. However, all the strategies require related planning and policy support to mitigate the UHI effect.

5. Landscape Practices - Comparative Precedents

In real projects, thermal comfort improvement will not be served as the only design goal or intention in any project; therefore, it is often used as an additional benefit in sustainable design. It is especially in tropical cities or cities with extreme atmospheric conditions, improving the urban thermal environment may be considered as one of the initial design goals.

The analysis of precedent studies will compare the design features that are conducive to improving thermal comfort in landscape projects. It aims to find out the application of key factors in thermal comfort improvement and the determinations of design features in different project contexts. Corresponding to the cooling strategies mentioned above, these three precedents will be analyzed in four factors that are related to thermal comfort improvement: vegetation, water, materials, structure. Because there is no obvious ventilation corridor design in these three projects, the strategy of ventilation will not be analyzed further.

5.1 “The Park” in Las Vegas, Nevada

“The Park” is located in Las Vegas in America, designed by !MELK in 2014 (see Fig. 4). Las Vegas exists in extremely challenging arid regions, exposed to sunlight, high temperatures, heat, dust storms and water shortages. One of the design goals is claimed to mitigate these extreme situations and to create an enjoyable urban experience for the publics (The !Melk Team, 2016).

Overall, most areas of the site can be shaded by the canopy or shading structure at a certain time of the day (see Fig. 5). But there are still some areas exposed to the sun basically all day long. When looking into these exposed areas, it can be found that water features are distributed in a part of these areas. These potential hot areas are alleviated and cooled to a certain extent due to the presence of water bodies. In addition, it is noticeable that the centralized large-scale art structure provides a large area of shade for the park from 5 AM to 8 PM during the day.

5.2 Darling Quarter in Sydney

This project is located in Sydney in Australia. The design goal of this project claimed by ASPECT Studios is to create premium quality and highly sustainable public realm by upgrading the plane materials, lighting, furniture, and plants (ASPECT studio, 2011). The landscape design focuses on the playground, providing a safe and cool public space for children and their parents. Different types of play experiences provide children with a rich play environment (including interaction with nature, water, and safe play facilities). Therefore, some of the sustainable design methods which are related to thermal comfort improvement can be found in this area (see Fig. 6).

It can be seen from the analysis map (see Fig. 7) that almost all the visible design features that can effectively improve thermal comfort are concentrated in the playground, making this area the coolest place in the whole project. The street between the buildings is the second comfortable area because of the small water pool and tree canopies along the street, the shadows provided by the buildings are beneficial to cool the environment. However, in other public open spaces on the south the building where are not covered by the shadow from buildings and without water that benefits these areas, the shading zones are inadequate for the daytime in summer. Although large areas of the surface are paved by turf, the direct solar radiation making these areas received more heats than the playground.

5.3 Gubei Gold Street in Shanghai

The promenade is 700 meters long and 50–80 meters wide, which consists of three different blocks (SWA Group, 2009) (see Fig. 8). The project area is blocked by two large open parks perpendicular to the promenade. These parks connect the promenade to adjacent communities. Create an "urban nature" landscape through plants and water features. Due to the exhaust from heating, air-conditioning and motor vehicles, as well as the sharp rise in the ambient temperature in Shanghai in the past decade, the urban environment is being threatened. Based on this reason, SWA Group claimed that they take the sustainable strategy as a method to improve the urban ecological environment and thermal environment, aiming to provide a safe, multi-functional and sustainable continuous walking space for people of all ages.

From the analysis map (see Fig. 9), the canopies on the west side of the promenade are larger and denser, and there is a large area of water features. Therefore, compared to the smaller and sparser canopies cover on the east side, the west side of the promenade is cooler. Except for the three intersections, the middle section of the promenade has a large area of hard paving and no shades coverage. The original intention of this part of the design is to provide a public place for people to conduct social activities. However, the thermal environment here is not satisfactory because there is no direct shade to avoid sun radiation, even though the design team added fountain facilities in the area. Therefore, it is recommended to increase green land or ground coverage instead of large areas of hard paving to improve the thermal comfort of the central area which accommodates main activities in the promenade. In general, in the scope of vegetation, water, materials, this landscape project had relatively good considerations in thermal comfort improvement in landscape design.

5.4 Comparative results

Table.1 Comparison of three precedents with design features in vegetation, water, materials, and structure

Landscape project	*Location*	*Designer*	*Vegetation conditions*	*Water condition*	*Materials (paving)*	*Structure (shading)*
"The Park"	Las Vegas, NV, USA	!Melk	- high density of tree canopies; - medium density of shrubs and herbs; - simple plant structure on the ground;	- fountain; - micro-waterfall;	- mixed light coloured paving; - smooth & flat surface; - mosaic texture with small pieces; - natural stone, paving stone;	- iconic shading structure (10-15m height)
Darling Quarter	Sydney, NSW, Australia	ASPECT Studios	- high density of tree canopies around the playground; - medium density of shrubs and herbs cover; - simple plant structure on the ground;	- fountain; - water play facilities; - static small pools;	- light grey paving on the playground; - smooth & flat surface; - paving stone, cement, concrete, wood, rubber;	- open wooden shelter (2.5m height); - movable awnings
Gubei Gold Street	Shanghai, China	SWA Group	- high density of tree canopies; - high density of shrubs and herbs; - complex plant structure on the ground;	- fountain; - cascading water feature;	- large areas of light coloured paving; - dark coloured paving surround the water feature; - smooth & flat surface; - paving stone, concrete, wood;	NO structure for shading

By comparing the design features and performance of these three precedents in materials, vegetation, water features, and artificial structures (see Table.1), it shows similar as well as different design features in determination in different public open spaces in three cities. The result shows that vegetation coverage (especially the tree canopy), artificial shading structures, and water features settings are commonly used in improving thermal comfort and combating urban heat island in landscape design. Due to the differences in tree canopy density, natural ground coverage, structure size, and the form of water features, the cooling effect shows a difference. The high canopy density, tall and big size of shading structures, and the moving or dispersed waterscape has a better cooling performance. The commonly used method in paving materials is light-colored stone with mosaic texture to prevent the site from absorbing excessive heat during the day.

In general, tree canopies play an important role in thermal comfort improvement. Different density of tree canopies in these three precedents might results from the different height of the surrounding buildings and the distribution and allocation of other artificial shading structures. While the selection of plant species always prefer local and ornamental at priority, for the purpose of better cooling effect, the species, scale and height of plants should be decided with more care.

The design of the water features has two main purposes, one is to provide viewing and interactive functions, and the other is to provide some cooling effects in hot summer or as a design element to create a cool outdoor environment. Therefore, the demand for water features mainly depends on the microclimate conditions of the site, the site context, and the design goals of the project. These are also the prerequisites for evaluating whether there is a demand for additional artificial shading structures. Once artificial structures are decided to use for shading pedestrian, appropriate scales and forms need to be considered in the shading structure.

Since there are many features that can affect the thermal balance of the material, the selection of materials is more flexible, because each feature can be selected individually or matched together. The superposition of multiple advantageous features can achieve the best cooling effect in terms of materials, but in actual projects, different degrees of thermal balance considerations are often reflected in the use and selection of materials. This could be attributed to differences in project budgets, design goals and local resources.

6. Discussion &recommendations

The effectiveness and adaptability of different strategies for improving thermal comfort have occurred some consensus and controversy. A few studies starting from the two key factors of microclimate conditions and urban planning are often presented in two experimental models. One is to study the relationship and changes of local microclimate conditions and heat intensity under the same scenario (single or unique urban context) by manipulating atmospheric parameters. The other is to observe and deduce the general relationship between microclimate conditions and heat intensity through the manipulation of atmospheric parameters under different scenarios (multiple urban contexts). The former aims to formulate the most effective strategies for certain specific areas or regions, while the latter aims to summarize and develop more adaptable methods in cities. In order to cope with the climate change crisis soon, the effectiveness of thermal comfort improvement has received more attention and development. However, in the face of potential crises in the far future, the applicability of the strategy requires more support and longer-term research to repeatedly test, modified, and update.

Based on the discussion about the effectiveness of related strategies for improving urban thermal comfort, the consensus is that natural-based solutions (such as green spaces dominated by trees) should be given priority because they have a more effective cooling intensity and wider cooling range. However, plant strategy as one of the key strategies to improve thermal comfort, need to be carefully considered and selected, because the changes in the shade from artificial structures might affect the growth of plants. Another effective method is to use reflective materials to replace impervious outdoor paving to avoid solar heat storage and release. Additionally, "shade plays an important role in designing pedestrian-friendly spaces in cities because it has a major impact in improving the thermal comfort and that artificial and natural shades are equally efficient." (Klok et al., 2018). Based on the microclimate conditions and built form of the target site, it is necessary to further test and simulate the summer sunshine time and shadow coverage area of the site in order to obtain a more accurate assessment and identification of areas that need to improve thermal comfort.

On the other hand, due to the subjectivity of thermal comfort, it is necessary to comprehensively consider human physiological comfort and psychological needs, and further study other factors that can affect human perception, such as acoustic environment, air quality, and urban landscape appreciation (Jusuf et al., 2018).

It is also worth noting that in some of the practical research, strategies are complementary and have a synergistic effect (see Table.2). On the opposite side, some of the authors show that there are also negative results when overlapping these strategies. Therefore, in general, comprehensively considerate the microclimate in urban planning and the selection of design technology to achieve a better cooling effect. When adopting multiple measures, it is necessary to further consider the geographical and atmospheric conditions, the built forms, resources, policies in the unique urban context at a local level with professionals when developing urban planning or landscape design proposals.

Table.2 Synergy between reducing the urban heat island and increasing thermal comfort (Watkins et al., 2007)

Thermal Comfort Parameter	*Relationship to the Urban Heat Island*
Air temperature	Reducing the UHI increases thermal comfort in summer
Radiant temperature field	Reducing surface temperatures reduces the UHI and increases thermal comfort
Solar radiation	Reduced solar penetration limits the UHI and improves thermal comfort
Air speed	Increased air speed removes heat from the urban environment and improve thermal comfort
Humidity	Use of evaporative cooling from lakes may increase humidity and decrease thermal comfort

7. Conclusions

This research is based on the "cool city" concept proposed by Rehan, combined with the theoretical basis proposed by Herrington, S. Expanded and studied the landscape elements that affect the thermal comfort of the urban environment mentioned in the cool city concept. Vertical research based on landscape theory contains more comprehensive and coherent elements to match the horizontal development that includes specific landscape elements. The research framework is relatively comprehensive, systematic, and targeted in the landscape field. Furthermore, the analysis of the three successful precedents reflects the practicality of theoretical knowledge in the thematic scope of thermal comfort, and reveals a visible application and transformation of theoretical strategies in design features in landscape projects. Finally, this study further discussed the problem of effectiveness and adaptability of different strategies for improving thermal comfort from a critical point of view.

The significance of this research is to provide theoretical research methods and practical applications as efficient guidance for future thermal comfort landscape design. In theory, the cross-analysis of vertical and horizontal theories will help improve the accuracy, breadth and systematicity of future related research. In terms of practicality, it also gives clear guidance for the future urban thermal comfort landscape design; that is, through the combined planning of materials, vegetation, water features, and artificial structures, and other considerations to achieve a better cooling effect.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Mo Zou: Designed and performed the experiments, analyzed the data and prepared the paper.

Heng Zhang: Participated to collect the materials related to the experiment.

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Figures

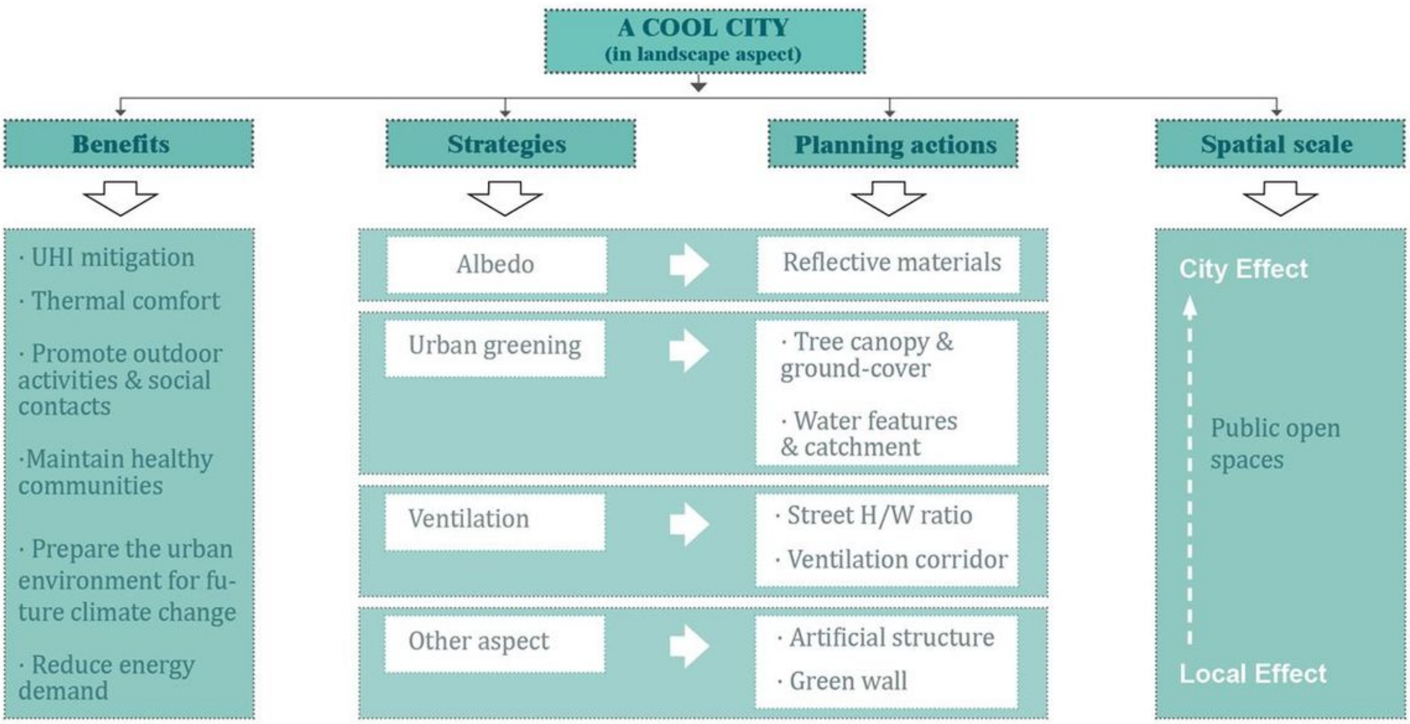

Figure 1

A cool city framework in landscape (Rehan, 2016)

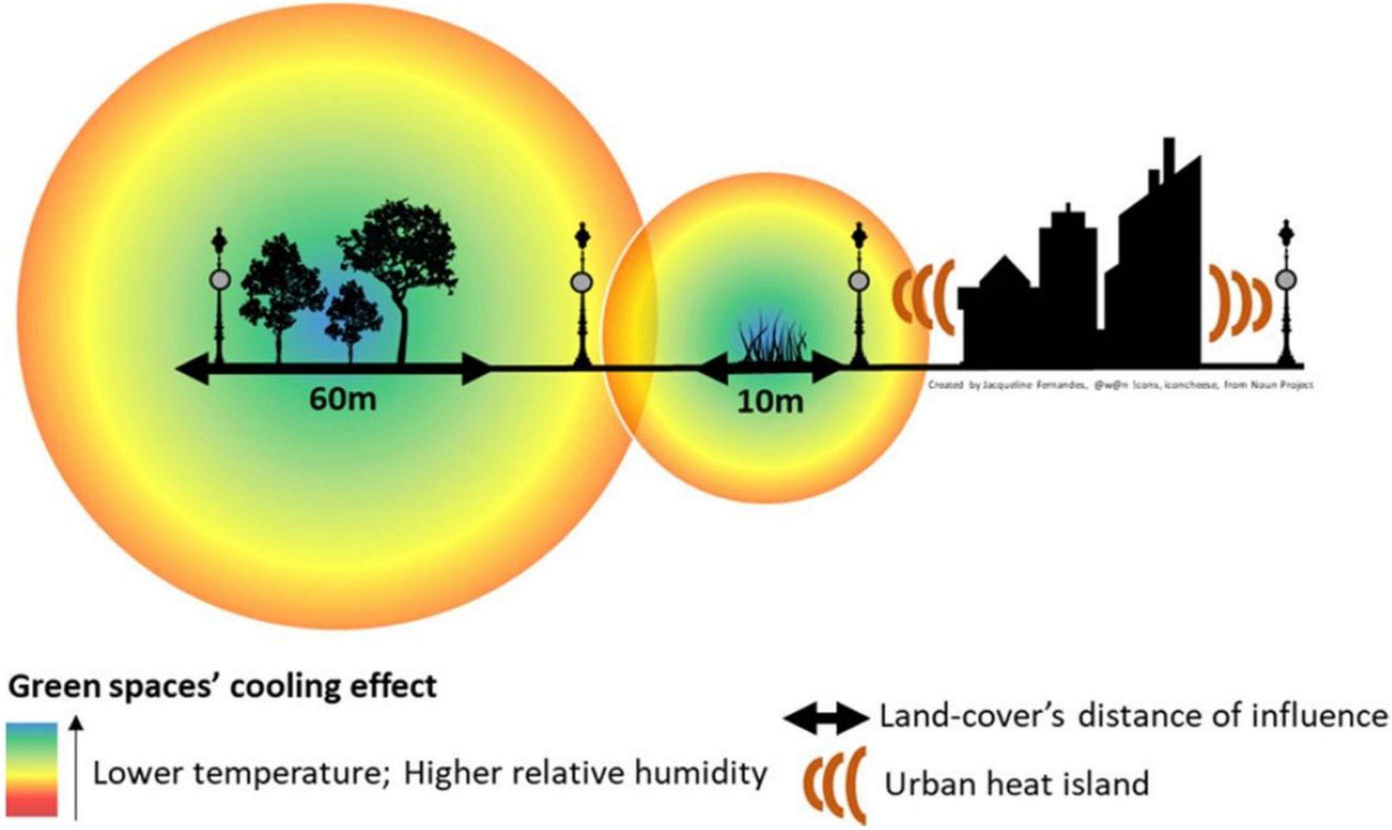

Figure 2

Green space cooling effect (Grilo et al., 2020)

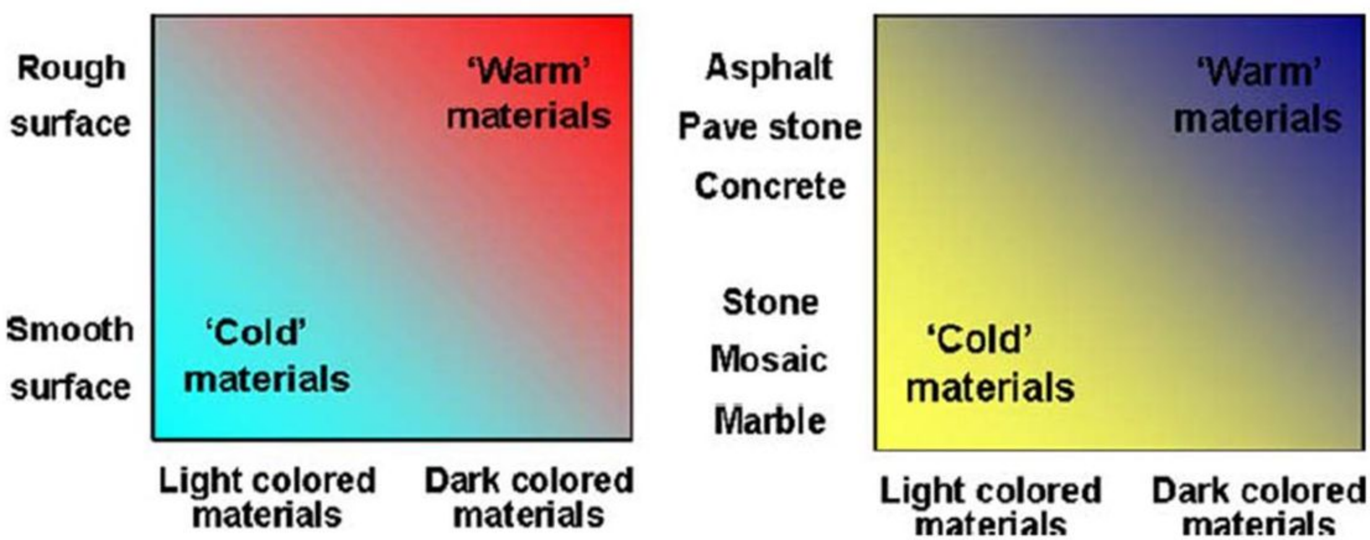

Figure 3

Comparison of materials (Doulos et al., 2004)

Figure 4

Aerial View of the park (The !Melk Team, 2016)

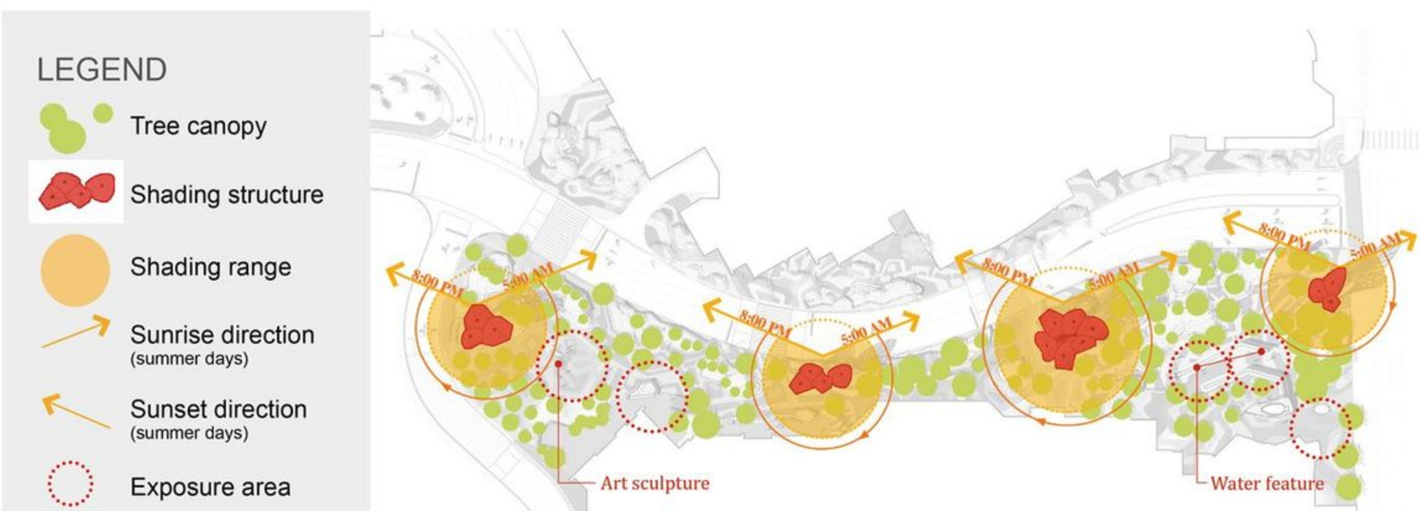

Figure 5

Shading conditions and locations of the water features and structures in the park

Figure 6

Aerial View of the playground in Darling Quarter (ASPECT studio, 2011)

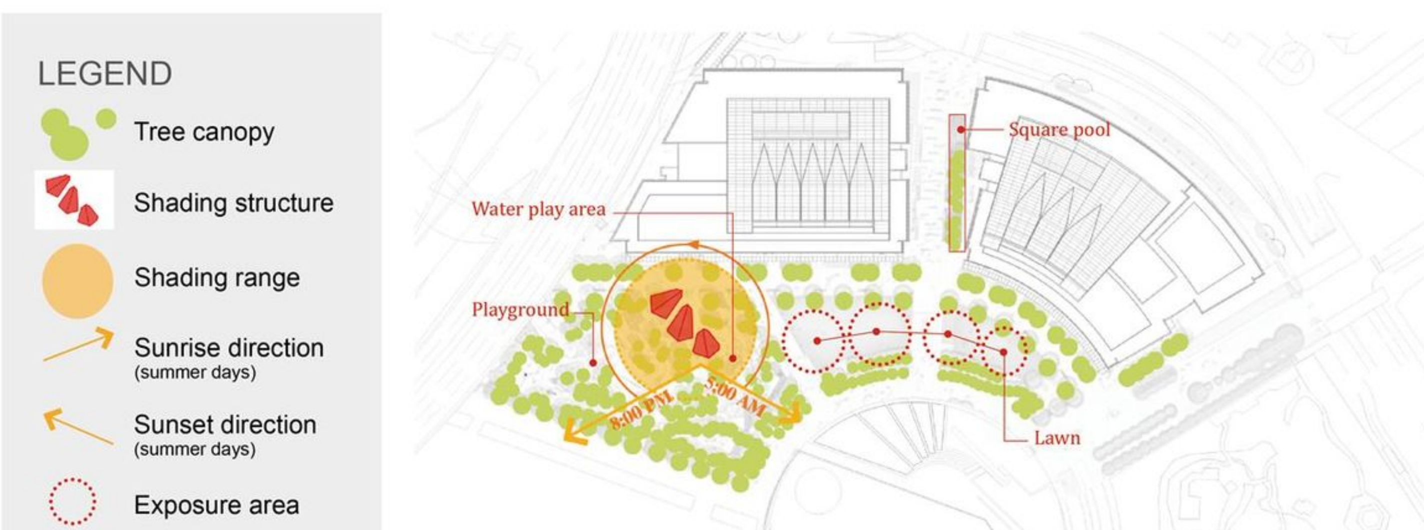

Figure 7

Shading conditions and locations of the water features and structures in Darling Quarter

Figure 8

Aerial View of the playground in Darling Quarter (SWA Group, 2009)

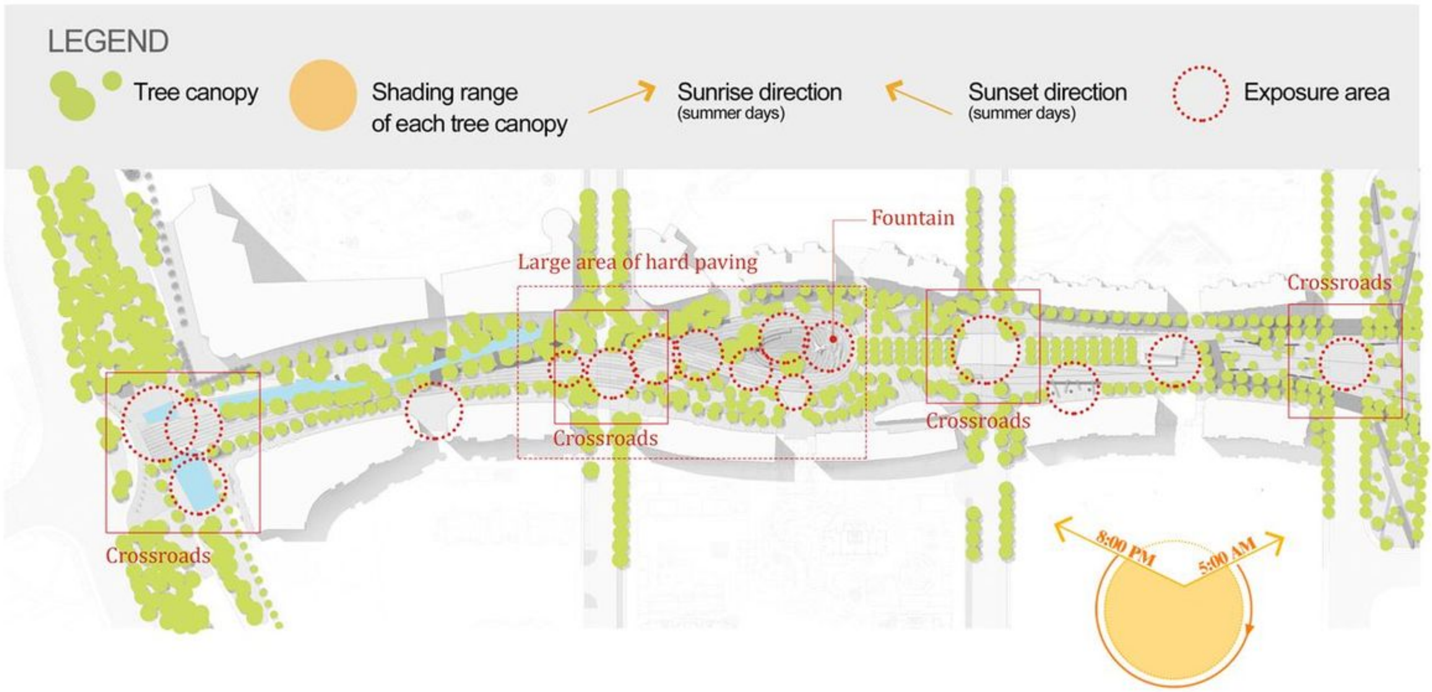

Figure 9

Shading conditions and locations of the water features in Gubei Gold Street