Chapter 17
Plant Selection and Placement Criteria for Landscape Design

Chun Liang Tan, Nyuk Hien Wong, and Steve Kardinal Jusuf

Abstract This study explores how landscape design can be optimized by considering specific plant traits and their corresponding temperature reduction potential. An initial study was conducted with the aim of quantifying the impact of rooftop greenery on mean radiant temperature (T_{mrt}). Results show that under clear sky conditions, plots with vegetation can reduce surrounding T_{mrt} by up to 6.0 °C. The effect in temperature reduction is evident for a distance up to 3.0 m away from the center of the green plots. Thereafter, a second set of measurements was made to identify specific plant traits that contribute to temperature reduction. Results indicate that the temperature reduction potential of different types of vegetation varies according to their physical characteristics as well as physiological attributes such as plant evapotranspiration rate and shrub albedo. An empirical model was developed to establish the relationship between T_{mrt} reduction, plant evapotranspiration and shrub albedo. Findings from these studies are used as a basis to formulate a framework for landscape planning and design. In the proposed framework, vegetation as well as building information are superimposed using a Geographical Information Systems (GIS) platform. A hypothetical scenario is used to illustrate the efficacy of the proposed landscape planning framework.

Keywords Mean radiant temperature • Outdoor thermal comfort • Rooftop greenery • Vertical greenery

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1 Introduction

The cooling effect of greenery has been well documented worldwide (Gao 1993; Ca et al. 1998; Shashua-Bar and Hoffman 2000; Jonsson 2004; Wong and Chen 2005). Recognising the positive impacts of urban vegetation, many governments have initiated policies aiming to improve the condition of the city through the addition of greenery (Beatley 2000; Ra 2006; Zhao 2011). Provision of Urban Green Spaces (UGS) acts as urban lungs, helping to absorb pollutants and releasing oxygen, providing clean air, water and soil and cleansing the city's environment (Hough 1984).

Many studies have been conducted to quantify the benefits of urban greenery. As ground level space is a limiting factor for most urbanized areas, rooftop greenery and sky terraces have gradually become more prominent in the urban landscape. Research into green roofs often focuses on the reduction of roof surface temperature due to the presence of greenery (Wong et al. 2003; Cheng et al. 2010; Perini et al. 2011). Vegetation can reduce the impact of the Urban Heat Island (UHI) effect by shading heat-absorbing surfaces and cooling the air through evapotranspiration (McPherson 1994). The reduction in temperature can lead to lower cooling loads for the building interior (Wong et al. 2009; Pérez et al. 2011). There are also studies into various aspects of rooftop greenery such as the types of plants used, growth substrates, acoustic performance, air quality and maintainability (Akbari 2002; Parizotto and Lamberts 2011; Baik et al. 2012; Saadatian et al. 2013). Various feasibility studies have also been conducted to determine structural and logistical considerations for green roof implementation (Castleton et al. 2010).

The cooling effect exhibited by plants is a result of their metabolic processes, such as photosynthesis and evapotranspiration. The extent to which plants engage in these processes is directly related to the amount of green matter, usually found in the leaves of the plant (Jones 1992). However, this knowledge is not being utilized to its full potential in the current landscape design and planning processes. More often than not, designers assume the cooling effect of plants to be homogenous, resulting in indiscriminate selection and allocation of plants to the landscaped area.

This study seeks to assess the effects of rooftop greenery on mean radiant temperature, as well as to explore the possibility of formulating objective landscape design principles based on the cooling potential of specific plant traits in the tropical urban environment.

2 Methodology

2.1 Rooftop Greenery Measurement

In the initial study, a total of 28 points were set up for mean radiant temperature (T_{mrt}) measurement. Each measurement point, which consisted of a customized globe thermometer fixed at 1.3 m above ground (Fig. 17.1.) and an air temperature

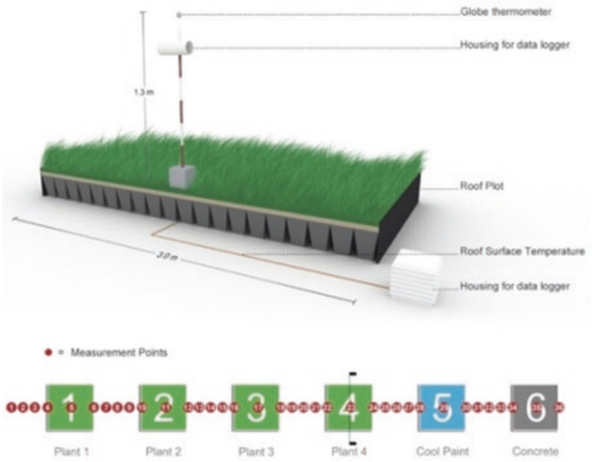

Fig. 17.1 Measurement points and sectional perspective of roof garden setup

Table 17.1 Plot characteristics for rooftop garden

Plot	Characteristic	Specification
1	Shrub	Phyllanthus cochinchinensis
2	Shrub	Heliconia 'American Dwarf'
3	Shrub	*Sphagneticola trilobata*
4	Turf	*Axonopus compressus*
5	Cool Paint	*JOTUN* Jotashield extreme
6	Concrete	Control

sensor housed in a PVC pipe, was secured with a concrete footing. Measurement points were aligned and named as shown in Fig. 17.1. The experiment was conducted at the National University of Singapore SDE1 rooftop. The T_{mrt} of six plots were measured. Each plot had a dimension of 3.0 m by 3.0 m. The first four plots were plots with vegetation. The fifth plot was covered with an acrylic sheet painted with cool paint. The sixth plot was bare concrete, used as a control for the measurement. Characteristics of each plot are shown in Table 17.1. Leaf reflectivity was measured for all plant species used in this study. Leaf total reflectance was measured using a Spectrophotometer (Shimadzu UV-3150 UV-VIS-NIR) for the range of 190–3200 nm.

Each plot was placed at regular intervals of 3.0 m to minimize interference from neighbouring plots. Roof surface temperature was measured underneath Plots 1–4, as well as on Plots 5 and 6 using a Yokogawa multi-logger. Sensors were deployed to measure T_{mrt} of all plots. Measurement was made at 1 min intervals. A total of 42 sensors were deployed. Each globe temperature sensor was attached to a survey pole and measured T_{globe} at 1.3 m above the plots. Six sensors were placed underneath each plot to measure the roof surface temperature. Estimation of T_{mrt} can be done using the globe thermometer (Vernon 1932). Initially developed for indoor usage, the globe thermometer has since been adapted for outdoor use (Nikolopoulou and Lykoudis 2006). The Vernon globe is a 150 mm diameter copper sphere painted black with a thermometer positioned in the middle of the sphere. For outdoor measurement, the 38 mm globe thermometer is a common option as the globe used is a table tennis ball, which can be readily purchased and conveniently replaced (Humphreys 1977). Accuracy of the 38 mm globe thermometer can be adjusted to cater for outdoor conditions by recalibrating the mean convection coefficient (Thorsson et al. 2007). In this study, T_{mrt} was estimated using the following formula specifically calibrated for tropical outdoor use (Tan et al. 2013):

$$Tmrt = \left[\left(Tg + 273.15 \right)^4 + \frac{2.20 \times 10^8\, Va^{0.119}}{\varepsilon D^{0.4}} \times \left(Tg - Ta \right) \right]^{0.25} - 273.15 \quad (17.1)$$

Where,

T_g = Globe temperature (°C)
V_a = Air velocity (ms^{-1})
T_a= Air temperature (°C)
D = Globe diameter (m)
ε = Globe emissivity

3 Results and Discussion

Diurnal T_{mrt} profile for measurement points at the center of the plots are shown in Fig. 17.2. The maximum and minimum values of T_{mrt} recorded were 63.0 °C and 24.9 °C respectively. The maximum difference during the hottest time (14:00 h) was

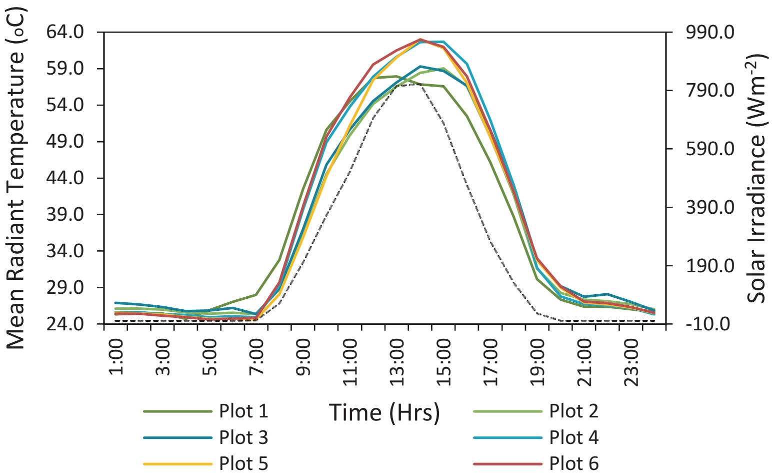

Fig. 17.2 Diurnal T_{mrt} profile for clear sky conditions

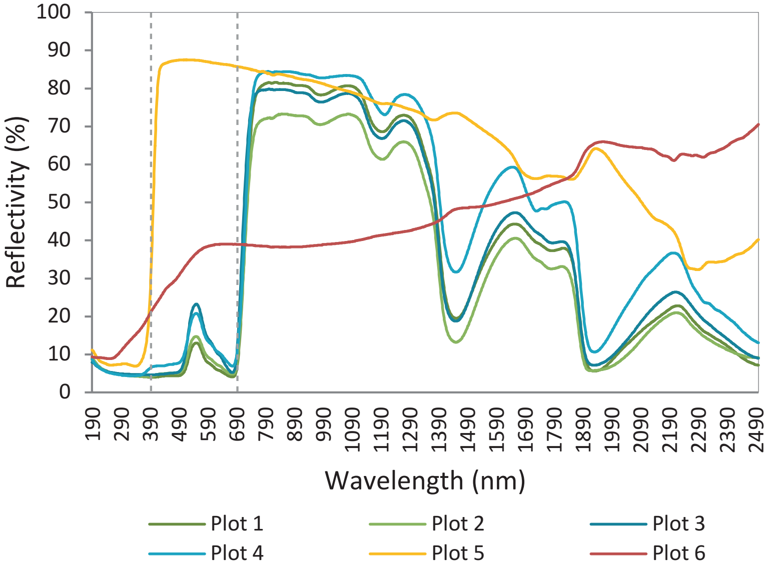

Fig. 17.3 Spectrometer test results

approximately 6.0 °C. It is observed that Plots 4, 5 and 6 exhibit similar T_{mrt} profiles, peaking at approximately 63.0 °C. Of the six plots, Plot 1 (Phyllanthus cochinchinensis), had the lowest diurnal T_{mrt} profile, followed by Plot 2 (Heliconia American Dwarf) and Plot 3 (Sphagneticola trilobata). In the absence of sunlight (01:00–07:00 h and 19:00–00:00 h), the T_{mrt} profile for all six plots remained stable without much fluctuation.

Material reflectivity was measured using a spectrophotometer and results are shown in Fig. 17.3.

Under the visible light spectrum, which spans from approximately 380 to 700 nm, cool paint exhibits the highest reflectivity of more than 80.0%. This is followed by concrete with a peak reflectivity of 40.4%. Vegetation under visible light displays relatively lower reflectivity, peaking at 25.2% (Plot 4), 21.6% (Plot 3), 14.5% (Plot 1) and 13.8% (Plot 2) at around 550 nm. For wavelengths in the near-infrared range (700–2500 nm), the reflectivity of cool paint reduces gradually, while the reflectivity of concrete increases at a similar pace. Reflectivity of the plants increases significantly from 700 to 1400 nm and undergoes a series of fluctuations, rising again from 1600 nm to 1800 nm and 2200 nm. It can be seen that the reflectivity of plants from the range of 701 to 1300 nm can equal that of cool paint.

The diurnal roof surface temperature (T_s) profile is shown in Fig. 17.4. The solar irradiance peaked at 1004.4 Wm^{-2} at 14:00 h. The surface temperature under Plots 1–4 was significantly lower than Plots 5 and 6 during daytime. The maximum difference between Plot 6 and Plot 3 was approximately 14.4 °C. The surface temperature of Plots 1–4 was maintained at between 26.0 and 29.0 °C throughout the day. In contrast, the surface temperature of Plots 5 and 6 increased greatly during the

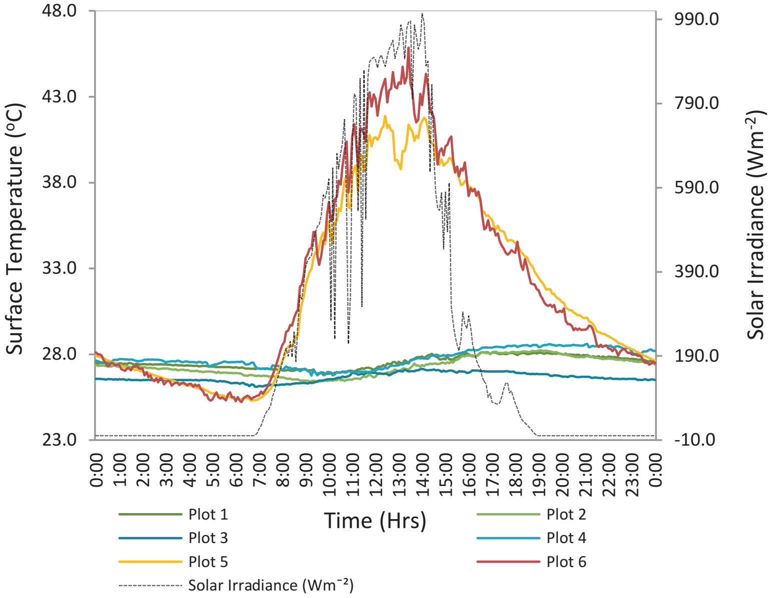

Fig. 17.4 Roof surface temperature – 9th October 2012

day. A peak of 45.9 °C was observed at 13:25 h for Plot 6, while the corresponding temperature of Plots 1–4 is only in the range of 27.0–27.5 °C. It can be observed that the diurnal surface temperature profiles for Plots 5 and 6 were similar for large parts of the day, except for periods of high solar irradiance (11:00–14:00 h), where temperature readings for Plot 5 were slightly lower than those of Plot 6. From 03:00 to 07:00 h, it can be observed that Plots 5 and 6 (Cool paint and concrete roof) had a slightly lower temperature compared to the other plots.

Infrared thermal images were taken on separate days with clear sky conditions. A total of three readings are obtained and averaged. Figure 17.5 shows that when the roof is exposed to direct solar irradiance, the surface temperature of the bare roof can reach up to 63.5 °C. With the exception of Plot 4, all plots with vegetation displayed temperatures lower than the cool roof and concrete roof.

Results show that when cool roofs and green roofs are exposed to direct solar irradiance, the surface temperature is significantly lower compared to the exposed concrete roof. However, only green roofs provide a substantial reduction in mean radiant temperature. At peak solar irradiance, T_{mrt} at 1.3 m above the green roof plots can be up to 6.0 °C lower than above the concrete surface. Besides lowering T_{mrt}, the introduction of green roofs can also help to minimize temperature fluctuations. Fluctuations in radiant temperature will drastically change the radiation absorbed by an individual and the energy budget of the individual, affecting the overall thermal comfort.

Results from the reflectivity test show that for the visible light range (380–700 nm), the cool roof can have a reflectivity of more than 80%. In comparison, the

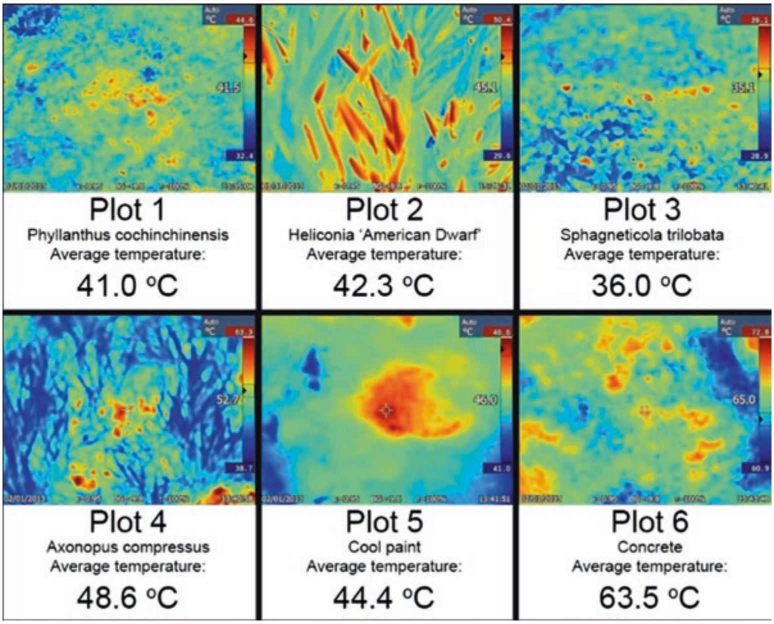

Fig. 17.5 Average roof surface temperature.

reflectivity of plants is in the range of 20%, which is rather low. However, at the near-infrared range, especially from the range of 700 to 1400 nm, the reflectivity of plants can almost equal that of cool paint (Fig. 17.3).

Since up to 50% of the solar irradiance distribution is in the near-infrared zone, this attribute may be crucial for reflecting heat back to the atmosphere. The high reflectivity of plants, in addition to the inherent cooling potential through evapotranspiration, may be the main factors leading to significantly lower T_s, T_a and T_{mrt} values.

3.1 Landscape Planning Framework

Numerous studies have highlighted the significance of strategic plant placement in landscape design (Gómez-Muñoz et al. 2010; Simpson and McPherson 1996). Cameron et al. (2014) showed that different plant species varied distinctively in their cooling capacity and the mechanisms for cooling varied between species.

With the benefits of greenery widely acknowledged, the next challenge is to translate this knowledge into industry practice. While there are existing frameworks to objectify landscape planning processes such as maintainability and irrigation (CTLA 1992), methodologies for assessing landscape proposals in terms of plant cooling potential have yet to be formalized in a comprehensive manner. The problem of visualizing the thermal impact of any landscape design is exacerbated by the inclusion of alternate forms of vegetation such as vertical and rooftop greenery.

Recent developments in modeling the outdoor thermal environment have enabled scientists to understand the impact of vegetation in landscape planning. Climatic maps are able to serve as visualization aids from micro to macro level. Through the Geographical Information Systems (GIS) platform, multiple layers of spatial information can be analyzed simultaneously. The use of climatic mapping has become a prominent feature in studies of the outdoor climate (Katzschner et al. 2004; Katzschner and Mülder 2008; Koster 1998; Stocks and Wise 2000). In particular, there has been extensive usage of GIS for the mapping of green spaces (Kamishima et al. 2002; Laing et al. 2006), providing opportunities to propose landscape solutions via GIS mapping techniques. The following section discusses the potential of this methodology through a hypothetical landscape design exercise.

3.2 Plant Selection via Functional Traits

Results from the initial study showed that rooftop greenery can significantly reduce T_{mrt} above the plant canopy. Consequently, a second set of measurements was conducted, this time with the intention of quantifying specific plant traits and their impact on T_{mrt}.

Measurements of T_{mrt} above three rooftop greenery plots were conducted at the same location (Rooftop of the National University of Singapore SDE1). The plants used were Phyllanthus cochinchinensis, Heliconia 'American Dwarf' and Sphagneticola trilobata. Concurrent measurements of plant evapotranspiration rate and shrub albedo were made for a period of 5 months. A detailed description of the study is outlined in Tan et al. (2015). The empirically derived prediction model based on relevant measurement data is as follows:

$$Tmrt_{Plant} = 0.782 Tmrt_{ref} - 200.111 ET - 61.011 SA + 26.937 \quad (17.2)$$

Where,

$Tmrt_{Plant}$ = Mean radiant temperature above rooftop greenery (°C)
$Tmrt_{Ref}$ = Mean radiant temperature above concrete (°C)
ET = Plant evapotranspiration rate ($mm{\cdot}min^{-1}$)
SA = Shrub Albedo

The model can be used to determine the cooling potential of shrubs by assessing their respective evapotranspiration and albedo traits. This enables the landscape designer to select plants based on their ability to reduce temperature. Usage of plants with higher evapotranspiration rates or albedo may be favored in light of their corresponding cooling potential. Since there is lesser chance of reducing T_{mrt} through shade provision by large canopy trees on roof gardens and sky terraces due to structural loading issues, it is important that the shrubs used can help reduce T_{mrt} as much as possible.

4 Landscape Planning Framework Based on Plant Cooling Potential

The proposed landscape design framework is intended to enable landscape designers to evaluate the thermal impact of their design proposals. The workflow is outlined in Fig. 17.6. Digital Elevation Models (DEMs) are the basic spatial layers used for thermal simulation. Raster arithmetic is subsequently employed to deduce the cooling impact of shrubbery. Mean radiant temperature (T_{mrt}) is used to measure plant cooling potential, as this quantity plays a crucial role not only in indoor situations but also outdoors as indicated in several studies which have stressed that outdoor thermal comfort is highly dependent on the short wave and long wave radiation fluxes from the surroundings (Mayer 1993; Mayer and Höppe 1987).

In the hypothetical urban model, four design iterations have been conducted for an area slated to be park space. Simulation is conducted with SOLWEIG (Lindberg and Grimmond 2011) and ARCGis software. In Iteration 1, trees with small canopies (5 m diameter) are placed at locations designated by the landscape planner. In Iteration 2, trees with larger canopies are assumed (15 m diameter) at the same spots. The T_{mrt} reduces drastically near the trees. In Iteration 3, more trees (20 m diameter canopy) are added to areas that are anticipating larger pedestrian flow. As a result, thermal conditions of these areas are shown to have improved significantly. In Iteration 4, thermal effects of shrubbery are factored into the T_{mrt} map via an empirical model based on the cooling effects of plants due to their evapotranspiration rates and albedo values (Eq. 17.2).

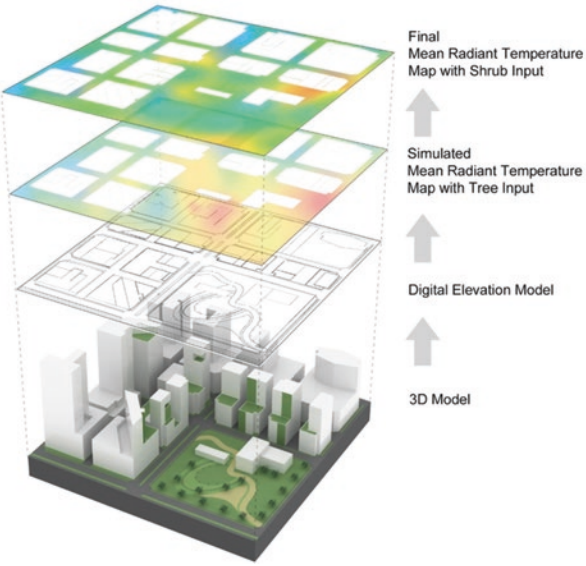

Fig. 17.6 Landscape planning T_{mrt} modelling hierarchy.

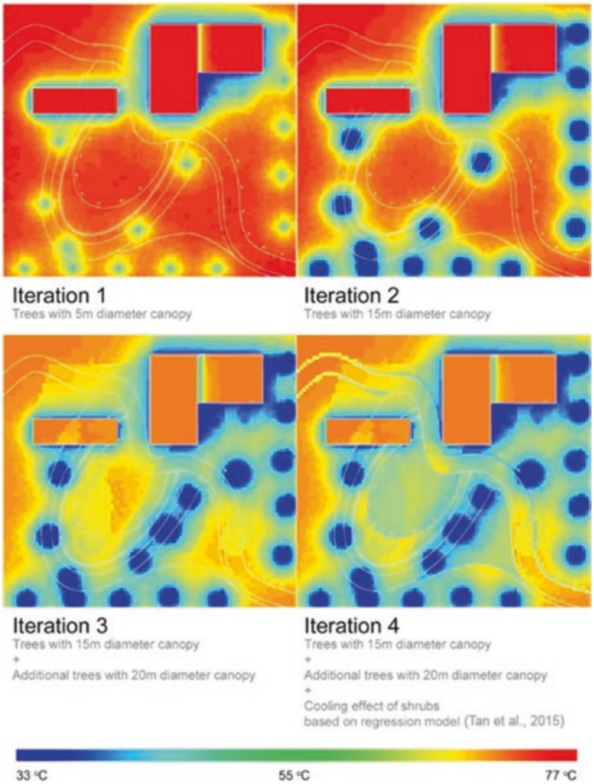

Fig. 17.7 Comparison of T_{mrt} simulation results

Comparison of all four iterations reveals the immense positive impact of tree and shrub allocation using the proposed landscape planning framework (Fig. 17.7).

The proposed landscape design framework allows designers to understand the impact of their choice of plant selection and allocation before eventually committing to a final decision. This can help to minimize undesirable outcomes such as lack of shading provision at prominent locations as well as inadequate light provision for plants due to excessive overshadowing from adjacent buildings.

5 Conclusion

Objective plant selection and placement are important factors in landscape planning. In the above example, scientific objectives are proposed to lend sophistication to the landscape design process. Introduction of thermal simulation in this study has highlighted the importance of context and locality. Adjacent buildings can affect solar exposure significantly, thereby influencing the plant placement process, dispelling the common myth that plants can improve the environment by cooling temperature indiscriminately.

The proposed framework for landscape planning seeks to more effectively realize the cooling effects of greenery as an urban heat mitigation technique and to optimize urban greenery as an ecosystem resource.

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