Landscape and Urban Planning 92 (2009) 179–186

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

The cooling efficiency of urban landscape strategies in a hot dry climate

Limor Shashua-Bar, David Pearlmutter, Evyatar Erell*

Desert Architecture and Urban Planning, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sde Boqer Campus, Midreshet Ben Gurion 84990, Israel

ARTICLE INFO

Article history:
Received 11 February 2009
Accepted 27 April 2009
Available online 27 May 2009

Keywords:
Urban microclimate
Cooling
Efficient water use
Hot-arid regions
Shading

ABSTRACT

This paper describes a climatic analysis of landscape strategies for outdoor cooling in a hot-arid region, considering the efficiency of water use. Six landscape strategies were studied, using different combinations of trees, lawn, and an overhead shade mesh. The effects of these treatments were tested during the summer season in two semi-enclosed courtyards located at an urban settlement in the arid Negev Highlands of southern Israel. Compared to a non-vegetated exposed courtyard, which on average reached a maximum air temperature of 34 °C in mid-afternoon, a similar courtyard treated with shade trees and grass yielded a daytime temperature depression of up to 2.5 K, while shading the courtyard with a fabric shading mesh, counter-intuitively, caused a relative increase of nearly 1 K. Unshaded grass was found to cause only a small air temperature depression and had the highest water requirement. However when the grass was shaded, either by the trees or by the shade mesh, a synergic effect produced greater cooling as well as a reduction of more than 50% in total water use. The "cooling efficiency" of these strategies was calculated as the ratio between the sensible heat removed from the space and the latent heat of evaporation, with the latter representing the amount of water required for landscape irrigation. This measure is proposed as a criterion for evaluating landscape strategies in arid regions, where water resources are scarce.

1. Introduction

Many studies have discussed the importance of climatic knowledge in the process of urban design and planning (e.g., Paparelli et al., 1996; Eliasson, 2000; Svensson and Eliasson, 2002). Appropriate measures may moderate the urban heat island, reduce building energy demand and improve pedestrian comfort (Steemers, 2003; Grimmond, 2007). Measures such as shading and judicious use of vegetation are of special importance in hot-arid regions, where intense solar radiation and high air temperatures may have detrimental impacts on even the most basic human activities.

Vegetation in parks and streets may generate localized cooling, a phenomenon sometimes referred to as the "park cool island", which stands in contrast to the more commonly discussed "urban heat island" effect. Temperature reductions of up to 3–4 K have been observed in urban parks at mid-day during summer (e.g., Bernatzky, 1982; Oke, 1989; Shashua-Bar and Hoffman, 2000; Dimoudi and Nikolopoulou, 2003; Chen and Wong, 2006). However, as Spronken-Smith and Oke (1998) showed, the actual extent of this cooling may vary significantly, depending on the attributes of the park—such as the vegetation and irrigation regime, the adjacent urban fabric, and the aridity of the location. This finding was enhanced in other comparative studies on parks located in the same vicinity (i.e. Potchter et al., 2006; Chang et al., 2007).

Evaluating the cooling effects of vegetation within an urban context is further complicated because they are interrelated with other building effects (Stabler et al., 2005; Shashua-Bar et al., 2006). The microclimate in an urban space is influenced by the adjacent buildings and landscape elements, and by the complex interactions between them (Erell and Williamson, 2006). Thus, conditions at different points within the urban canopy layer may differ significantly even in the same overall climatic context, and they can be affected by a variety of factors relating to geometry and surface properties (Pearlmutter et al., 2006) as well as by anthropogenic heat release. It is therefore important to investigate the impact of vegetation within the context of planning strategies appropriate to the climatic region and to the related urban environment.

Vegetation has the potential to moderate air temperature not only through shading and the reduction of surface temperatures, but also through evaporative cooling (McPherson et al., 1994). The relative importance of each of these mechanisms may vary with climate, the characteristics of the plants involved and their response to environmental conditions. Conversely, elevated external air temperatures increase the irrigation requirements of urban vegetation (Guhathakurta and Gober, 2007).

The presence of trees in the urban matrix may affect air temperature at a variety of spatial scales, from individual streets to the larger urban boundary layer. However, the magnitude of this effect may depend on a variety of factors, due to the complex interaction

* Corresponding author. Tel.: +972 8 6596878; fax: +972 8 6596881.
E-mail addresses: shashual@bgu.ac.il (L. Shashua-Bar), davidp@bgu.ac.il (D. Pearlmutter), erell@bgu.ac.il (E. Erell).

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doi:10.1016/j.landurbplan.2009.04.005

between trees and other constituents of the urban environment. Trees intercept not only incoming solar radiation, but also reflect short wave radiation from their surroundings, long wave radiation from the ground, building surfaces and the sky—and in some cases there is significant sensible heat exchange between the warm urban air and the cooler leaves. The dissipation of this heat load by transpiration cooling depends on the water balance, the wind climate and the tree species (Oke, 1989). Species from hot dry habitats can dissipate heat and conserve water by regulating the opening of leaf stomata, or in small leaves by minimizing the density of stomata (Hemsely and Poole, 2004). The transpiration rates from such trees may accordingly be lower than those of broadleaf trees, and thus may have a smaller effect on the air temperature in their surroundings. Recent studies of the microclimate of vegetated areas in desert environments report substantially different cooling effects (Saaroni et al., 2004; Potchter et al., 2008). The inconsistent results might be due to differences in the behavior of the plant species of the study areas or in the variability of the surrounding locales.

Unlike trees, grass reduces temperatures mainly through evapotranspiration at ground level, in urban lawns (Bonan, 2000) as well as in green walls and roofs (Onmura et al., 2001; Takebayashi and Moriyama, 2007; Alexandri and Jones, 2008). The ultimate contribution of lawns to thermal comfort may in fact be limited since it does not affect the direct incoming radiation, which has such a dominant impact on the daytime thermal stress in hot dry urban spaces (Pearlmutter et al., 2006). The maximum cool island intensity found in a large irrigated lawn park in Mexico City was 2 K (Spronken-Smith et al., 2000).

Concerns over scarcity of water have focused attention on irrigation, which is the primary use of water world-wide (Perry, 2007). In arid regions, where the mean annual precipitation (P) is significantly less than the characteristic potential evapotranspiration (PET) (Bruins and Berliner, 1998), appropriate selection of plants and efficient watering systems can conserve a large amount of urban irrigation water (Ferguson, 2007). Differences in irrigation needs may be substantial. For example, in Israel a well-irrigated lawn in the Mediterranean coastal region consumes just over 3 l/m^2 of water on a summer day, while in the arid Negev region the daily requirement is as much as 6 l/m^2 (Kremmer and Galon, 1996). In addition to such objectively high water requirements in arid regions, waste of water in many sectors of agriculture and landscaping, is further aggravating water scarcity and emphasizing the need for developing ways to improve irrigation efficiency (Lankford, 2006).

Shading can be achieved not only by trees but also by shading devices such as a lightweight mesh. Recently, shade mesh fabrics have been used extensively for agricultural crops in greenhouses. Such a mesh has been found to act as an effective means for regulating the solar radiation as well as the evapotranspiration rate of the crops in its shade, thus leading to significant water savings (Moller et al., 2004). While the use of fabric shading is also fairly common in open spaces of some arid zone cities, its effect on urban microclimate has not yet been explored in relation to other environmental strategies.

As this brief overview indicates, the cooling effect of vegetation in urban open spaces is well-documented. However, the extent of this effect has not been analyzed in a systematic manner with respect to the water resources required to achieve it. In hot-arid regions, water availability is a limiting factor and must be considered. This study addresses this shortcoming by focusing on the water consumption of several combinations of shade and vegetation in relation to the cooling effect they produce in an urban context.

2. Methodology

2.1. Sites and observations

As mentioned above, the microclimatic conditions within urban open spaces are affected by adjacent buildings as well as by vegetation. Due to the complex interactions between these elements, it is difficult to identify comparable urban sites in which the effects of individual parameters such as landscape treatments may be analyzed empirically. The methodology used in the present study addresses this problem by establishing a controlled experiment in two adjacent courtyard spaces, which are similar in their geometry and material attributes but differ in their landscape treatments (Fig. 1). Both are oriented along an approximately N–S axis and have an H/W ratio of about 0.5 (Figs. 1 and 2), giving similar exposure to the environment (Meir et al., 1995).

The courtyards are located at the Sde-Boqer campus in the arid Negev Highlands region of southern Israel (30.8°N latitude, 475 m altitude). The region is characterized by hot dry summers and cool winters. Diurnal temperatures and relative humidity fluctuations are wide, with summer daily maxima and minima well above and below the thermal comfort zone, respectively (Bitan and Rubin, 1994).

Six different landscape strategies were studied in the courtyards, using different combinations of trees, grass, and shade mesh. The six study cases are summarized in Table 1, and two cases, "Mesh-bare" and "Trees-grass", are illustrated in Fig. 2. The ground surface in the two courtyards initially consisted of light gray concrete paving tiles (covering about 70% of the area) and exposed soil (occupying the remaining 30%). One of the courts had three trees planted along its center line, two of which were *Prosopis juliflora* and the third *Tipuana typu*. Both species are common in hot-arid regions

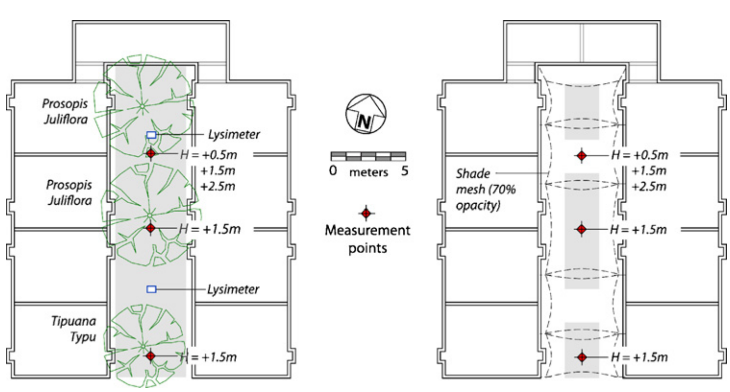

Fig. 1. Plan showing location of measurement points (in both courtyards), of trees in west courtyard (left) and of shading mesh in east courtyard (right). The grey area drawn for convenience only in west courtyard shows extent of grass cover in both courtyards, once it was applied. The grey areas shown in the east courtyard indicate the extent of bare soil in both courtyards; the rest of the ground surface was paved.