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Urban Green Infrastructure as a tool for urban heat mitigation: Survey of research methodologies and findings across different climatic regions

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ABSTRACT

The combined trends of urban heat island intensification and global warming are focusing attention on greening of cities as a tool for urban heat mitigation. Our study examines the range of research approaches and findings regarding the role of urban green infrastructure (UGI) in mitigating urban heat and enhancing human comfort. It provides an overview based on 89 studies, carried out in a range of geographic and climatic regions.

We surveyed the distribution of methodologies employed, spatio-temporal scales considered, type and extent of UGI, climatic variables studied and contribution of UGI to ambient air cooling and enhancement of human comfort. It was found that neither the differences in geographic location or in climate conditions had a significant impact on the choice of research approach. The studies, mostly done on limited spatio-temporal scales, have focused on the rate of air cooling by UGI, and to a lesser extent on its impact on thermal comfort. Maximum observed intensities of park cool island (PCI) effects typically ranged between 1.5 °C–3.5 °C, with no apparent correlation to climatic region. However, there is a tendency seen for larger green sites to induce a stronger PCI, whereas well-shading street trees also have a significant cooling and relieving effect.

1. Introduction

1.1. The urban heat island (UHI) and its relation with climate change

The majority of humanity is now urbanized, with the proportion of global population living in cities reaching 54% in 2014 and projected to grow further over the coming decades. Urban dwellers already comprise about three quarters of the population in Europe, and the number of urban agglomerations with over 5 million inhabitants is rising around the world – including over 30 “megacities” whose population exceeds 10 million (United Nations, 2014).

As the urban population continues to grow, the challenges of life in densely populated cities are intensifying as well. One of the most prominent environmental features of urban areas is the localized climatic phenomenon known as the urban heat island (UHI), characterized by higher temperatures within the city than in the rural surroundings (Oke, 1982). The magnitude of this urban-rural

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temperature difference is influenced not only by the city's population size but also by its physical attributes, including the density of the built-up area, the materials comprising its buildings and ground surfaces, and the distribution of anthropogenic activities (Oke, 1987; Arnfield, 2003). While the UHI tends to be most pronounced on calm clear nights, when its intensity is typically in the range of 1–3 °C (Oke, 1987) but in extreme cases can reach as high as 12 °C (Voogt, 2004), localized heat islands can develop during daytime as well. Urban heating can exacerbate human discomfort and lead to acute thermal stress, impairing the functionality and even the health of the urban population, especially the elderly and the chronically ill (Barata et al., 2011).

Because of design features such as the geometry and material makeup of "urban canyons", heat is often trapped within streets and other non-vegetated outdoor spaces – intensifying pedestrian thermal stress in the daytime and adversely affecting nighttime cooling as well (Pearlmutter et al., 2009; Erell et al., 2011). For many cities facing conditions which are already warm and humid, such as in the Mediterranean region, warmer nights are a growing problem (Ziv and Saaroni, 2011). The most intensive UHIs have been observed in mid-latitude cities (Wienert and Kuttler, 2005), though significant urban warming has been observed in tropical and sub-tropical regions as well, amplifying the already severe thermal discomfort characterizing these regions (e.g., Balling and Brazel, 1987; Saaroni et al., 2000; Chow and Roth, 2006; Sofer and Potchter, 2006; Velazquez-Lozada et al., 2006; Roth, 2007; Wang et al., 2016; Matsumoto et al., 2017).

Compounding the UHI effect is the ongoing increase in temperature due to regional and global climate change. A recent report by the Urban Climate Change Research Network (Rosenzweig et al., 2015) shows that mean annual temperatures in 39 cities have increased at a rate of 0.12 to 0.45 °C per decade over the 1961 to 2010 time period, based on data from the NASA GISS GISTEMP. Moreover, projections from 35 global climate models for two representative concentration pathways (RCP4.5 and RCP8.5) show that mean annual temperatures in 100 cities are projected to increase from 0.7 to 1.5 °C by the 2020s, 1.3 to 3.0 °C by the 2050s, and 1.7 to 4.9 °C by the 2080s.

Although the projected air temperature increase caused by global warming is more gradual than the local increase due to the UHI effect (Grimmond, 2007), the combined effect of both is expected to amplify thermal stress within the urban environment (e.g., Saaroni and Ziv, 2010; Potchter and Ben-Shalom, 2013), and the two may even be synergistic (Li and Bou-Zeid, 2013). The ongoing increase in frequency, intensity and duration of heat waves (e.g., in the eastern Mediterranean and the Middle East, Lelieveld et al., 2012), and the projected increase of this trend by climate models (IPCC, 2013) will further aggravate thermal stress and discomfort.

Heat waves pose increased risk to vulnerable urban populations. For example, increased mortality rates have been reported by many countries, including France, Russia and the Netherlands, during and following the heat waves of 2003 and 2010 (Matzarakis et al., 2009; Norton et al., 2015). In the estimate by Mora et al. (2017) of the global risk of heat-related mortality, around 30% of the world's population is currently exposed to climatic conditions exceeding the deadly threshold of daily mean surface air temperature and relative humidity for at least 20 days a year. By 2100, this percentage is projected to increase to ~48% under a scenario with drastic reductions of greenhouse gas emissions (RCP2.6) and ~74% under a scenario of growing emissions (RCP8.5). Lelieveld et al. (2016) investigated projected climate change and temperature extremes specifically in the Middle East and North Africa (MENA), concluding that while at present the warmest nights are on average below 30 °C, they will surpass 34 °C by the end of the century (RCP8.5). Maximum temperature during the hottest days, 43 °C at present, is expected to increase to nearly 46 °C by the middle of the century, and to reach nearly 50 °C by the end of the century in the same scenario. The average duration of warm spells is also expected to increase.

All of these trends contribute to the urgency of developing effective UHI mitigation and adaptation strategies. Solecki et al. (2005) and Gago et al. (2013) define UHI mitigation as a transformation of urban microclimate through modifications of the physical environment, with the use of vegetation as a major tool. They defined UHI adaptation as an immediate response to thermal discomfort, e.g., by using air conditioning or by changing outdoor activity patterns. However, we argue that the term 'adaptation' can also be associated with longer-term planning.

1.2. The role of urban green infrastructure (UGI)

UGI in general, and urban trees and forests in particular, are widely considered to be the most effective strategy for urban cooling – primarily through shading and the reduction of ground surface temperatures, but in some cases through evapotranspiration as well. Several studies have indicated UGI as the number one tool for both urban heat mitigation and thermal comfort enhancement of city dwellers, both in temperate and (sub) tropical regions (Solecki et al., 2005; Gill et al., 2007; Bowler et al., 2010; Ng et al., 2012; Gago et al., 2013; Norton et al., 2015).

Many studies have attempted to quantify the intensity of Park Cool Island (PCI) effect, defined as the temperature difference between urban green spaces and their surrounding built-up terrain (Spronken-Smith and Oke, 1998; Oliveira et al., 2011), as one measure of the potential UHI mitigation rate. Bowler et al. (2010) indicated in their review that most of these studies deal with "micro-scale" PCIs, whose thermally mitigating effect is localized to the immediate vicinity of the vegetated area and may under-estimate the cooling effect beyond the green area. In fact, there is great diversity in the cooling effectiveness of PCIs, in part because urban parks are typically composed of different types of green coverage – including trees, grass, and a variety of low-growing shrubs. In particular, large tree-covered areas – sometimes referred to as 'urban forests' – are the most effective cooling agents, especially during the day (Brown et al., 2015; Yoshida et al., 2015). Parks with large grassy areas have been found to be effective cooling agents during the night (e.g., Spronken-Smith and Oke, 1998), but during the day they can potentially be warmer than the surroundings, especially if not adequately irrigated (e.g., Jauregui, 1991; Potchter et al., 2006; Saaroni et al., 2015).

The rate of air temperature reduction induced by stands of trees within the city depends firstly on the extent of shading, since shaded ground or built elements maintain lower surface temperatures than those which are exposed and therefore transfer less heat to