Urban Forestry & Urban Greening 16 (2016) 50–61

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Local impact of tree volume on nocturnal urban heat island: A case study in Amsterdam

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ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form 17 January 2016
Accepted 26 January 2016
Available online 28 January 2016

Keywords:
Geospatial information
LIDAR
Sky view factor (SVF)
Tree volume
Urbanization
Urban heat island intensity (UHI)

ABSTRACT

The aim of this research is to quantify the local impacts of tree volumes on the nocturnal urban heat island intensity (UHI). Volume of each individual tree is estimated through a 3D tree model dataset derived from LIDAR data and modelled with geospatial technology. Air temperature is measured on 103 different locations of the city on a relatively warm summer night. We tested an empirical model, using multi-linear regression analysis, to explain the contribution of tree volume to UHI while also taking into account urbanization degree and sky view factor at each location. We also explored the scale effect by testing variant radii for the aggregated tree volume to uncover the highest impact on UHI. The results of this study indicate that, in our case study area, tree volume has the highest impact on UHI within 40 m and that a one degree temperature reduction is predicted for an increase of 60,000 m^3 tree canopy volume in this 40 m buffer. In addition, we present how geospatial technology is used in automating data extraction procedures to enable scalability (data availability for large extents) for efficient analysis of the UHI relation with urban elements.

Introduction

A negative impact of urbanization is the urban heat island phenomenon which is the increase in temperature of a metropolitan area (in relation to the rural outside) due to human activities (Oke, 1995). Two instances of extreme urban heat island hazards are the heat-related deaths of 485 people during the Chicago heat-wave in 1995 (Whitman et al., 1997) and the 130% increased mortality rate in Paris and suburbs during the Western Europe heat-wave in 2003 (Grynszpan, 2003). In addition to the public health effects, urban heat island increases the demand for air-conditioning-related energy consumption (Akbari, 2005). When considering the contemporary rapid urbanization growth (McMichael, 2000), serious attempts should be dedicated to mitigate the heat island formation in urban areas. This study explores the influence of tree volume on UHI variations across the city of Amsterdam, the Netherlands.

Relevant studies

Urbanization and construction growth in cities have a direct influence on the urban heat island formation and its increase. Urbanization causes surface and atmospheric changes that lead to warmer temperatures, especially at night (Voogt and Oke, 2003). Chen et al. (2006) concluded that the urbanization in Pearl River Delta was the major contributor to the regional temperature rise in this region from 1990 to 2000. Next to the regional impact of urbanization, certain parameters have more local influence on UHI, such as different street designs and built environment configuration can lead to different UHI values across neighbourhoods (Shashua-Bar and Hoffman, 2003; Swaid and Hoffman, 1990; Bourbia and Boucheriba, 2010; Nakamura and Oke, 1988; Giridharan et al., 2005). A key urban design parameter is Sky View Factor (SVF), which is the extent of visible sky from a location. SVF relates to the ability of that location to cool down, where low SVF causes a slow rate of heat emission at night (Oke, 1982). Previous studies have demonstrated that the locations which are more open to the sky, e.g. near the top of the canyon, lose heat approximately four times faster than the points near to the floor (Oke, 1988), making SVF a very useful indicator to express the magnitude of urban heat island (Yamashita et al., 1986).

Another important parameter affecting UHI is vegetation. Vegetation influences temperature through shading as well

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http://dx.doi.org/10.1016/j.ufug.2016.01.008
1618-8667/

as evapotranspiration (Solecki et al., 2005). Previous research concluded that vegetation mitigates UHI and improves urban microclimate through reducing summer temperatures (Dimoudi and Nikolopoulou, 2003). This temperature reduction effect is not only present within the green area itself, but also beyond it. Wong and Yu (2005) observed a maximum of around 4 degree difference between the planted and the central business district in Singapore at summer midnight. Yu and Hien (2006) carried out a research on the thermal benefits of city parks in Singapore. They came to the conclusion that temperature reduction caused by vegetation was not bounded to parks, but also to the neighbouring regions based on their distances to the park. Their other observed phenomenon was the fluctuation stabilization of temperatures by vegetation (more than buildings). Benefits of urban parks on UHI mitigation in different regions have been acknowledged and quantified in various studies (Chang and Li, 2014; Jauregui, 1991; Hamada and Ohta, 2010). Vegetation impact on UHI is not limited to urban forestry and city parks. Pocket parks and local street vegetation might play an important role on UHI, depending on the environmental settings and urban configuration. While in the compact mid-rise urban area of Rotterdam, vegetation can have a dominant influence on local UHI (Heusinkveld et al., 2014), in a compact high-rise region such as Hong Kong, vegetation exclusively might not lead to considerable outdoor temperature reduction. In such an urban environment, impact of parameters like sky view factor and altitude should be fully considered, when introducing vegetation, for noticeable results (Giridharan et al., 2008). While the studies regarding vegetation impact on UHI mainly use vegetation surface in their investigations, information on vegetation volume can produce additional insights as the shading and evapotranspiration cooling characteristics are more correlated with the vegetation 3D geometry rather than its surface. However, according to Armson et al. (2012), the 3D characteristics of trees have not sufficiently being investigated in UHI studies. In this research we have used the 3D information of individual urban trees, extracted from high resolution LIDAR dataset, to estimate the spatial extent and volumetric impact of trees on nocturnal UHI in the city of Amsterdam. We believe that estimating the impact of local street trees on UHI can inform urban planners, designers and urban health practitioners on the endorsement of the urban green planning for more liveable cities.

Fig. 1. Map of Amsterdam (municipality borders in blue) depicting the built-up and green spaces in the city. *Note*: Map background source: TOP10NL, the Dutch cadastral topographic map (http://www.kadaster.nl/web/artikel/producten/TOP10NL.htm); Amsterdam municipality border source: Centraal Bureau voor de Statistiek (http://www.cbs.nl/nl-NL/menu/themas/dossiers/nederland-regionaal/publicaties/geografische-data/archief/2012/2012-wijk-en-buurtkaart-2011-art.htm); visualized using ArcGIS software. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Research objectives

This research attempts to investigate the effect of trees, in particular tree crown volume, in its capacity to mitigate UHI in the city of Amsterdam. While it is acknowledged that the presence of trees may reduce temperature, this study demonstrates a methodology that studies how many trees and of which size is necessary to plant in order to achieve significant effects. An additional contribution of this research is the demonstration of a scalable methodology to determine the impact of tree volume. The added value of geospatial information and GIS techniques in our analysis is presented through automation in information extraction from large datasets. This methodology enables the use of nation-wide datasets for trees in different extents without the need for tree field data measurements.

Methodology

Study area

Our study area is Amsterdam, the capital and the largest city of the Netherlands, with a total population of around 800,000 inhabitants and an area slightly larger than 200 km^2. This city contains diverse land uses including built-up areas, parks, forests, agricultural lands, water bodies and industrial regions which leads to diversity in population distribution in the city (Fig. 1).

The vast built-up and the densely populated areas of Amsterdam lead to urban heat island formation in the city. Measurements of the recent heat wave in 2006 revealed the maximum 7–9 degrees nocturnal air temperature difference between Amsterdam and its surrounding suburb. This categorizes Amsterdam as a city with strong urban heat island intensity compared to other European cities (Van der Hoeven and Wandl, 2015).

UHI analysis

In this study, ordinary least squares regression analysis has been used to determine the contribution of different factors to the UHI variation. Tree volume is expected to have an impact on air temperature from shadowing effects (protecting surrounding structures from direct irradiation therefore absorbing less heat) and from evapotranspiration. Nevertheless, it is still unclear how much, and at what distance, trees may influence the air temperature at a given location. In order to define the maximum impact of tree volume on UHI from a local perspective, we have studied different buffers with variant radii around each temperature observation. We defined the