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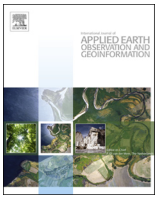

Assessing effects of urban vegetation height on land surface temperature in the City of Tampa, Florida, USA

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ABSTRACT

Urban vegetation can mitigate urban heat island (UHI) due to its ability to regulate temperature by directly or indirectly influencing water vapor transport, shading effect, and wind speed and direction. Mechanisms of effects of vegetation cover on land surface temperature (LST) have been extensively documented. Few studies, however, have examined the role of vegetation height in controlling LST. In this study, we examined the relationship between LST and vegetation height by using Light Detection and Range (LiDAR) data from the city of Tampa, Florida, USA. The results revealed that vegetation height has significant impact on LST. Additionally, we also identified the optimal height and fractional cover at which vegetation can exert the greatest influence on LST. In particular, we found that the maximum cooling effect of vegetation can only be achieved when vegetation cover is above 93.33%, an amount of which is nearly impossible to have in most of the cities. On the other hand, LST decreases at an increasing rate with vegetation height, and is optimized at 20 m. This shows that vegetation height can play an important role in regulating UHI in contributing to effect maximization with least cover possible in a city. Findings derived from this study could provide urban planners with critical insights on precise and efficient urban vegetation management in the purpose of UHI mitigation.

1. Introduction

Urban warming has become a serious problem due to global change and urbanization. One important phenomenon is the increasing urban heat island (UHI) effect, which can increase water consumption and energy use (Akbari et al., 2001; White et al., 2002), elevate environmental pollution (Stone, 2005), and compromise human health and comfort (Tan et al., 2010). With the majority of the world's population residing in cities, it is important and urgent to examine whether and how urban regions can become more sustainable under global change (Campbell, 1996). UHI affects the sustainability of urban regions and residents worldwide (Murgante et al., 2011). About 60% of the global urban population is currently experiencing twice as much warming as the world's average and the temperature in cities is projected to increase by another 2 °C by 2050 (Johnston, 2017). Any hard-won victories over climate change on a global scale could be wiped out by the effects of uncontrolled UHI (Estrada et al., 2017; Hakner, 2017). Therefore, mitigating UHI effects, especially under climate change, is necessary for the promotion of urban sustainability (Akbari et al., 2001).

City-level adaptation strategies to mitigate UHI have important economic and environmental benefits for most of the cities around the world. Planting of vegetation in urban areas is one of the most widely applied methods (Bolund and Hunhammar, 1999; Susca et al., 2011). The structure of vegetation affects temperature by directly or indirectly influencing water vapor transport, shading effect, and wind speed and direction. The two fundamental aspects of vegetation structure are horizontal and vertical structure. Attributes of the horizontal structure of vegetation such as vegetation cover, crown size, and crown shape all contribute to evaporative fraction and turbulent fluxes (Su et al., 2001). Height, as another major attribute of vegetation structure, and a primary determinant of surface roughness, has a significant influence on water vapor transport and convergence, wind speed, and shading area (Geier-Hayes et al., 1995; Maurer et al., 2015; Su et al., 2001; Sud et al.,

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1988). Therefore, understanding how vegetation height affects UHI would contribute to precise urban greenspace management approaches to alleviate UHI effects.

Considerable number of studies have demonstrated the significance of the horizontal structure of urban vegetation in decreasing temperature (Alkama and Cescatti, 2016; Declet-Barreto et al., 2016; Deilami et al., 2018; Susca et al., 2011; Weng et al., 2004; Wu et al., 2014). It is obvious that the greater the extent of vegetation cover is, the stronger the cooling effect would be. However, since cities have limited space to extend vegetation cover, reducing UHI effect by increasing vegetation cover might be impossible in many cities. Moreover, height is an attribute that is easier and less costly to manage (e.g. through pruning and selection of tree species) than vegetation cover. A better understanding in the relationship between vegetation height and LST would provide significant insight to efficient UHI mitigation. Contrary to research on the effects of vegetation cover, the impacts of height on urban temperature have rarely been studied. A recent study conducted in Chicago, Illinois found that vegetation volume affects summer nighttime temperature (Davis et al., 2016). Using the City of Tampa, Florida as an example, this study aims to investigate the effects of vegetation height on LST so that it can be used to combat UHI effects and develop precise urban greenspace management plans.

2. Study area and data

The study area is located in the City of Tampa, Florida (28 °N, 82 °W), with a total area of 350 km^2 (Fig. 1). The region is characterized by a humid, sub-tropical climate with warm, wet summers and mild, dry winters. The extent of urban land use has increased approximately sevenfold during the last century in the Tampa Bay area (Xian and Crane, 2003, 2005). Due to rapid growth of the city over the past 40 years, impervious surface has expanded extensively into exurban zones and native forests (Xian and Crane, 2005), resulting in a heterogeneous landscape of impervious surface and urban vegetation. By 2006, the City of Tampa was comprised of 36% impervious surface, 58% vegetation (of which 29% is tree canopy), 2% water, and 4% bare land/soil (Landry and Pu, 2010).

Datasets used in the study included Landsat 5 thematic mapper (TM) land surface reflectance (LSR) product, Landsat TM level-1 thermal infrared (TIR) product, Light Detection and Ranging (LiDAR), and high-resolution land cover map (Table 1). Landsat 5 T M products (both LSR and TIR) acquired on May 2, 2006 were downloaded from the USGS EarthExplorer website (https://earthexplorer.usgs.gov). The LSR images were derived after applying the atmospheric correction routines of MODIS (the Second Simulation of a Satellite Signal in the Solar Spectrum, done by U.S. Geological Survey (USGS)) to the original Landsat Thematic Mapper (TM) images. The resulting pixel value of the LSR data, ranging from 0 to 1, is a standardized reflectance factor of the land surfaces. The TIR product provides thermal infrared data at wavelengths between 10.4 μm to 12.5 μm and was used to derive LST. LiDAR data provided by Southwest Florida Water Management District were used to obtain mean vegetation height. LiDAR data was collected by Optech Gemini scanners at a maximum frequency of 167 kHz with four returns and an average point density of 1.51 points per m^2. The first and last return of LiDAR data were used to produce digital surface models (DSM) and digital elevation models (DEM), respectively, using a binning average interpolation technique (1 m cell resolution). Normalized digital surface model (nDSM), derived by subtracting the DEM form the DSM, is used to model the above ground height of vegetation (Figs. 2 and 3). Land cover was mapped using object-based artificial neural network from the pan-sharpened IKONOS 1 m panchromatic and 4 m multispectral bands) acquired in April 6, 2006 (Landry and Pu, 2010). Vegetation in the land cover map includes tree canopy and other vegetation (such as grass, lawn, and shrub). All the datasets were acquired under a clear sky condition and projected to the same coordinate system (Florida West State Plane NAD83) and subset to the study area. All remote sensing data were acquired in 2006 and the difference of months between the LiDAR data and the rest of the data would not be expected to have a meaningful impact on the analysis, as the vegetation height should not change much during this time period in Tampa.

3. Methodology

Data analysis includes two main procedures: (1) retrieving LST, vegetation fraction, and mean vegetation height, and (2) exploring the relationships between LST and mean vegetation height (Fig. 4).

3.1. LST retrieval using the radiative transfer equation (RTE) algorithm

We calculated LST using the radiative transfer equation (RTE) algorithm (Fu and Weng, 2016; Jiménez-Muñoz and Jiménez-Muñoz and Sobrino, 2006; Sobrino et al., 2004; Weng and Fu, 2014). According to the RTE algorithm, TIR radiance at wavelength λ can be expressed as (Sobrino et al., 2004):

$$L_{sensor,\lambda} = [\varepsilon_\lambda B_\lambda(T_s) + (1-\varepsilon_\lambda)L^{\downarrow}_{atm,\lambda}]\tau_\lambda + L^{\uparrow}_{atm,\lambda} \tag{1}$$

where ε_λ is land surface emissivity (LSE), $B_\lambda(T_s)$ is blackbody radiance at land surface temperature T_s (K), and $L^{\downarrow}_{atm,\lambda}$, $L^{\uparrow}_{atm,\lambda}$, and τ_λ are atmospheric parameters representing the downwelling atmospheric radiance, the upwelling atmospheric radiance, and the total atmospheric transmissivity between the surface and the sensor, respectively. The atmospheric parameters $L^{\downarrow}_{atm,\lambda}$, $L^{\uparrow}_{atm,\lambda}$, and τ_λ for each Landsat 5 T M scene were obtained from the NASA Atmospheric Correction Parameter Calculator (Barsi et al., 2003, 2005). The LST can then be derived from $B_\lambda(T_s)$ using Planck's law:

$$B_\lambda(T_s) = \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T_s}\right)-1\right]} \tag{2}$$

where C_1 and C_2 are constants ($C_1 = 1.191 \times 10^8 W\mu m^4 sr^{-1} m^{-2}$, $C_2 = 1.439 \times 10^4 \mu m{\cdot}K$).

LSE (ε_λ) was estimated using the NDVI Thresholds Method (NDVI^{THM}) proposed by Sobrino et al. (2008). NDVI was calculated from atmospherically-corrected red and near infrared bands of the Landsat 5 T M LSR product. The NDVI^{THM} method assigns different emissivity to bare soil (NDVI < 0.2), full vegetation (NDVI > 0.5), and soil-vegetation-mixed pixels (0.2 ≤ NDVI ≤ 0.5):

$$\varepsilon_\lambda = \begin{cases} 0.97, & NDVI < 0.2 \\ 0.004P_v + 0.986, & 0.2 \le NDVI \le 0.5 \\ 0.99, & NDVI > 0.5 \end{cases} \tag{3}$$

where P_v is the fraction of vegetation and according to Carlson and Ripley (1997) can be estimated as:

$$P_v = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2 \tag{4}$$

where $NDVI_{min}$ and $NDVI_{max}$ are 0.2 and 0.5, respectively.

3.2. Extraction of vegetation fraction and mean vegetation height

Vegetation fraction and mean vegetation height were extracted by zoning the vegetation cover map and the nDSM of vegetation to the same spatial resolution of the LST image (30 m). Vegetation cover map was derived by selecting tree canopy and other vegetation from the land cover map, and then vegetation fraction was assigned as the sum of all cell values in each zone divided by total number of cells in each zone. The nDSM of vegetation was obtained by extracting nDSM covered only by vegetation, and the mean vegetation height was calculated as the mean of all cell values in each zone. Zoning vegetation cover and nDSM of vegetation using the pixels of LST can ensure LST, vegetation fraction, and mean vegetation height to be geo-coregistered. Vegetation