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Effects of urban tree canopy loss on land surface temperature magnitude and timing

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ABSTRACT

Urban Tree Canopy (UTC) plays an important role in moderating the Surface Urban Heat Island (SUHI) effect, which poses threats to human health due to substantially increased temperatures relative to rural areas. UTC coverage is associated with reduced urban temperatures, and therefore benefits both human health and reducing energy use in cities. Measurement of this relationship relies on accurate, fine spatial resolution UTC mapping, and on time series analysis of Land Surface Temperatures (LST). The City of Worcester, Massachusetts underwent extensive UTC loss and gain during the relatively brief period from 2008 to 2015, providing a natural experiment to measure the UTC/LST relationship. This paper consists of two elements to this end. First, it presents methods to map UTC in urban and suburban locations at fine spatial resolution (~0.5 m) using image segmentation of a fused Lidar/WorldView-2 dataset, in order to show UTC change over time. Second, the areas of UTC change are used to explore changes in LST magnitude and seasonal variability using a time series of all available Landsat data for the study area over the eight-year period from 2007 to 2015. Fractional UTC change per unit area was determined using fine resolution UTC maps for 2008, 2010, and 2015, covering the period of large-scale tree loss and subsequent planting. LST changes were measured across a series of net UTC change bins, providing a relationship between UTC net change and LST trend. LST was analyzed for both monotonic trends over time and changes to seasonal magnitude and timing, using Theil-Sen slopes and Seasonal Trend Analysis (STA), respectively. The largest magnitudes of UTC loss occurred in residential neighborhoods, causing increased exposure of impervious (road) and pervious (grass) surfaces. Net UTC loss showed higher monotonic increases in LST than persistence and gain areas. STA indicated that net UTC loss was associated greater difference between 2008 and 2015 seasonal temperature curves than persistence areas, and also larger peak LST values, with peak increases ranging from 1 to 6 °C. Timing of summer warm period was extended in UTC loss areas by up to 15 days. UTC gain provided moderate LST mitigation, with lower monotonic trends, lower peak temperatures, and smaller seasonal curve changes than both persistence and loss locations. This study shows that urban trees mitigate the magnitude and timing of the surface urban heat island effect, even in suburban areas with less proportional impervious coverage than the dense urban areas traditionally associated with SUHI. Trees can therefore be seen as an effective means of offsetting the energy-intensive urban heat island effect.

1. Introduction

Urban areas experience elevated temperatures relative to surrounding non-urbanized areas due to alteration of land-cover, in what is known as the Urban Heat Island (UHI) (Oke, 1982; Voogt and Oke, 2003; Weng, 2001). Previous research has convincingly documented that increased temperatures are a function of proportional coverage and spatial configuration of impervious surfaces within dense urban sites (Maimaitiyiming et al., 2014; Solecki et al., 2005; Weng, 2009; Weng et al., 2007). However, less attention has been given to temperature elevations in low density residential areas, which have a comparatively greater proportional cover of grass and other non-tree vegetation. Quantification of the temperature effects of land cover in these areas is critically important due to the large amount of energy used in home cooling (Akbari, 2002; Pandit and Laband, 2010). This paper draws on a

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dense time series of eight years of thermal data to investigate local alterations to the UHI caused by Urban Tree Canopy (UTC) change.

UTC coverage is closely tied to LST, because trees provide shading, increased evaporative cooling, and lower thermal absorption and retention (McPherson and Simpson, 2003; Nowak and Dwyer, 2007; Solecki et al., 2005). Absence of UTC coverage in urban areas causes the increase in LST, causing the Surface Urban Heat Island (SUHI) effect, which is a component of the overall UHI (Voogt and Oke, 2003). Therefore, one of the major ecosystem services provided by urban forests is the reduction of the SUHI effect by reducing LST, which translates to reduced cooling energy demands and reduced risks to increased human health and comfort (Cui and De Foy, 2012; Hamada and Ohta, 2010; Nowak and Dwyer, 2007). In Worcester, Massachusetts, several state and federal government reports provide qualitative evidence suggesting that residents in the city have experienced marked thermal discomfort and increased energy bills due to tree removal, particularly during summer months of June through September, when air conditioning creates a large demand for electrical energy (Morzuch, 2013; Palmer et al., 2014). The case of Worcester is relevant to understanding SUHI/LST dynamics because the majority of tree removal and planting in the city since 2008 has occurred in lower density private residential areas, rather than in more densely urbanized areas (Hostetler et al., 2013), which contain a much larger total population of residents than dense urban areas typically investigated for heat island effects. Therefore, this study investigates the cooling benefits of trees in areas with mixed vegetation and impervious cover composition, using four scales of analysis: city, neighborhood, street, and parcel. This approach allows the exploration of the scalar nature of the UTC/LST relationship, showing the heterogeneity of UTC loss and corresponding LST change, and can therefore illustrate the importance of neighborhood-wide urban forestry efforts.

The research described in this paper analyzes the impact of Urban Tree Canopy (UTC) change on LST magnitude and seasonal timing, using a case study in Worcester, Massachusetts, USA. This study area was selected due to an extremely large amount of tree canopy change over the brief period from 2008 to 2015. This change occurred predominantly in low density residential areas (Hostetler et al., 2013), which comprise a complex patchwork of impervious surfaces, grass/lawn area, small and large trees, and exposed soils (Rogan et al., 2013). Therefore, the canopy change has exposed a mixture of impervious and pervious surfaces. Hypothetically, LST increases in these low density residential locations due to canopy loss potentially present a weaker signal compared to dense and highly built urban locations, allowing for a more nuanced quantification of this relationship, while also providing a test of the capability of remotely measured LST.

The goals of this study were to: (1) create an up-to-date, high spatial resolution UTC map of Worcester to monitor the dynamic UTC conditions; and (2) quantify the magnitude and seasonality of LST change between 2007 and 2015 within locations of UTC gain, loss, and persistence. The relationship between UTC reduction and LST increase is explored at the city, neighborhood, street, and individual property-parcel scales. Remote sensing provides an ideal basis for this analysis due to the utility of high-resolution imagery for effectively mapping fine-scale UTC changes, and the ability to investigate nuanced temperature trends and cycles using the large collection of thermal images available over the study period.

2. Study area

Worcester is located in central Massachusetts, USA (Fig. 1). With a population of 183,000 and a population density of 1808 persons/km^2, it is the second largest city in New England after Boston. Worcester covers approximately 100 km^2, and has a heterogeneous land-use pattern and composition typical of medium-sized cities in temperate climates, comprising a mixture of high- and low-density residential development, woodland areas, and impervious surfaces (Rogan et al., 2010), typical of many mid-latitude temperate urban centers. Worcester has a humid continental climate, with an average daily high of 26 °C in July and 0 °C in January. Average annual precipitation is 1220 mm, as well as 163 cm of snow per season (www.nws.noaa.gov 2015). Elevation ranges from 110 to 320 m above sea level. Worcester's urban forest consists of a mixture of hardwood and conifer species, with 51% hardwood, 11% conifer, and 38% mixed (Hall et al., 2002; Rogan et al., 2010). As of 2008, Worcester had 17,113 street trees, providing roughly $2.4 million dollars of gross ecosystem service benefits, or $980,000 of net benefits after subtracting maintenance and management (Freilicher et al., 2008). In addition to these street trees, Worcester contains a large (as-yet uncounted) number of trees on public and private property, which constitute the bulk of the UTC for the study area.

Worcester's urban forest has been greatly influenced by large climatological, biological, and anthropogenic disturbance events, culminating in the recent Asian Longhorned Beetle infestation. These disturbance events have prompted several extensive planting efforts to rebuild the urban forest, resulting in a highly dynamic urban forest (Herwitz, 2001). During the 20th century, these efforts relied heavily on just a few species of trees, especially the *Acer* (maple) genus, which was favored for its urban adaptability, and which ultimately came to constitute 80% of street trees as of 2008 (Freilicher, 2011; Freilicher et al., 2008). This near-monoculture approach has made the city vulnerable to outbreaks of invasive species, which precipitated the city's most recent UTC disturbance, caused by the invasive insect, the Asian Longhorned Beetle (*Anoplophora glabripennis*, ALB) infestation. This infestation was first identified in 2008 (Dodds and Orwig, 2011), and continues to date (2017), presenting an ongoing urban forest management problem and a large quantity of UTC change in a short time period. To exterminate ALB, roughly 30,000 mature trees have been removed, the bulk of which were removed from the Burncoat and Greendale residential neighborhoods in the north of Worcester (Santos and Cole, 2012; WTI, 2015). Approximately 65 ha of UTC was removed by 2010, a 21% decrease in UTC relative to 2008. Previous research mapped UTC at 1 m spatial resolution for the years 2008 and 2010, providing a basis for comparison, as well as further contextual knowledge of the study area (Hostetler et al., 2013). This dramatic UTC changeover provides an ideal natural experiment to investigate the temperature mitigation effect of urban tree cover.

3. Data

To determine the effect of UTC change on LST, two datasets were assembled and analyzed: the first involves high spatial resolution mapping of UTC and therefore UTC change, and the second involves LST. High resolution mapping provided the context for LST trend analysis; the data and methods for UTC mapping are described in Sections 3.1 and 4.1 below. LST time series analysis is described in Sections 3.2 and 4.2.

3.1. UTC mapping: fine spatial resolution imagery and Lidar data

The first stage of the analysis involves UTC change detection between 2008, 2010, and 2015, corresponding to the periods: (1) directly before tree removal; (2) directly after tree removal; and (3) after tree planting. Two existing 1 m UTC maps of Worcester