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Research Paper

A systematic approach to model the influence of the type and density of vegetation cover on urban heat using remote sensing

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HIGHLIGHTS

- Temperature had a negative linear correlation with tree cover and mixed cover >40%.
- Coastal proximity and urban structure influence temperature/veg cover relationship.
- A 14% tree cover increase would completely offset urban materials thermal loading.
- Novel model can calculate future temperature changes under vegetation scenarios.

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ABSTRACT

Cities around the world are pursuing increasing green or vegetation cover as a way of managing heat whilst improving beauty, biodiversity and recreational value. However, the pattern of the relationship between vegetation cover and urban temperature can be masked, controlled or exaggerated by vegetation structure, topography and other climate variables. This study examines the relationship between Sydney's urban surface temperature and vegetation cover as defined by two vegetation indices; mixed vegetation cover and tree cover exclusively. The shape of this relationship and relative influence of confounding factors are explored using penalised-likelihood criteria ranked regressions. Overall, increasing tree cover reduces average surface temperatures more dramatically than mixed vegetation cover. This study demonstrates that the extent of influence of greencover on surface temperatures is more accurately defined by identifying and incorporating site specific factors that confound the influence. Best predictor models are significantly improved when the influences of elevation, coastal effects and urban structure are added. Therefore, heat reducing urban greening strategies will be improved if based on local variables and conditions.

1. Introduction

A growing majority of the global population now resides in urban areas. In 2013 urban populations made up approximately 52.5% of the world's population, and by 2050 this urban proportion was expected to rise to over 67% or some 6.25 billion people (UN Secretariat, 2013). During the same period, global average temperatures are projected to rise by between 1.3 and 1.8 °C in response to anthropogenic atmospheric warming (Meehl et al., 2007). In addition, the well known Urban Heat Island (UHI) effect means that air temperatures in urban areas are on average 2–5 °C higher, and in some cases more than 10 °C higher, than those in surrounding non-urban areas (Ackerman, 1985; Collier, 2006; Onishia, Caob, Ito, Shia, & Imuraa, 2010; Taha, 1997). Collectively, these phenomena indicate that a significant majority of the future global population may have to endure average maximum temperatures several degrees warmer than those currently experienced in adjacent rural areas today.

Heat stress and related mortality form a major public health issue across broad regions of the globe as high or extreme temperature is known to have serious implications for human health (Vescovi, Rebetez, & Rong, 2005). In Europe, during the first 15 days of August 2003, as many as 35,000 additional deaths above the mean mortality rate were attributed to heat related illnesses as a result of an unusual heatwave (Schär & Jendritzky, 2004). The World Health Organisation estimates that on average an additional 141,000 people died each year from elevated temperatures during

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the last 30 years of the 20th century (World Health Organisation, 2009). This number is expected to increase dramatically in the future as heatwaves are expected to be more intense, more frequent and longer lasting (Meehl & Tebaldi, 2004). Additionally mortality rates will be exacerbated by the increasing urbanisation of the world population. McMichael and Bertollini (2009) estimate that annual heatwave mortality rates will double in some cities.

Warmer temperatures due to the urban heat island effect can also lead to increased ozone production (Gray & Finster, 2000) and increased energy use for air-conditioning and refrigeration and thus increased green house gas emissions. In temperate and cold climates it would be expected that the UHI has beneficial effects in winter by reducing the energy consumption for the heating of buildings (Levinson, Akbari, Konopacki, & Bretz, 2005). However, significant reductions in annual net energy consumption have occurred through the implementation of strategies to reduce the UHI effect in urban areas with extended cold periods such as Toronto, Canada (Akbari & Konopacki, 2004).

A UHI is defined by the differences in observed ambient temperatures between urban areas and surrounding non-urban areas. The increased urban temperatures are caused by the presence of urban structures and infrastructure materials. Urban structures and materials change land cover geometry and irradiative properties such as albedo and emissivity (Bowler, Buyung-Ali, Knight, & Pullin, 2010). Changes to these properties affect the proportions of solar radiation reflected, absorbed and re-emitted as long wave radiation. Therefore the simplest and most influential way to mitigate the UHI effect is by changing surface cover characteristics (Oke, 1982; Weng, Lu, & Schubring, 2004). In particular increasing the amount of vegetative cover can significantly influence regional temperatures. Simpson (1998) estimates that every 1% increase in canopy cover results in maximum mid-day air temperature reductions of 0.04–0.2 °C. Cities such as Chicago, New York and London have significant tree planting programs underway (Dunbaugh & Vabicenti, 2009; Nickson et al., 2011; Rosenzweig et al., 2009). Copenhagen's Climate Plan specifies additional green areas, pocket parks and green roofs and walls to manage heat, and slow down rainfall run-off (Climate Capital Copenhagen, 2009). London is looking to increase the green coverage in its city centre by 5% by 2030 and a further 5% by 2050 (Nickson et al., 2011), Chicago by 20% overall by 2020 (Dunbaugh & Vabicenti, 2009).

The role vegetation cover plays in influencing surface and air temperature is complex. In an urban environment, surface temperatures generally determine variations in surrounding air temperature (Kalnay & Cai, 2003; Kawashima, Tomoyuki, Mitsuo, & Tetsuhisa, 2000; Unger et al., 2009). Trees and other vegetation can reduce surface temperatures because they intercept solar radiation and shade buildings and other surfaces. Consequently, vegetation cover directly modifies surface temperature and therefore air temperature through changes to land cover geometry and radiative properties (Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010). Vegetation also tends to maintain a daytime canopy temperature close to that of surrounding air temperature via evaporative cooling. In a remote sensing study on the effect of vegetation cover on land surface temperature (LST), Mildrexler, Zhao, and Running (2011) found that globally, LSTs in forested areas (based on the global vegetation classification scheme created by the International Geosphere-Biosphere Programme http://edc2.usgs.gov/glcc/globdoc2_0.php) rarely exceeded 38 °C whilst LST in bare areas were recorded above 60 °C with air temperatures in excess of 42 °C. Also the type, structure and spatial distribution of green cover can influence the amount of cooling afforded by vegetation (Dimoudi & Nikolopoulou, 2003). For example, grass cover and green-wall structures reduce thermal transmission and increased evapotranspiration but they do not provide the shading properties of trees.

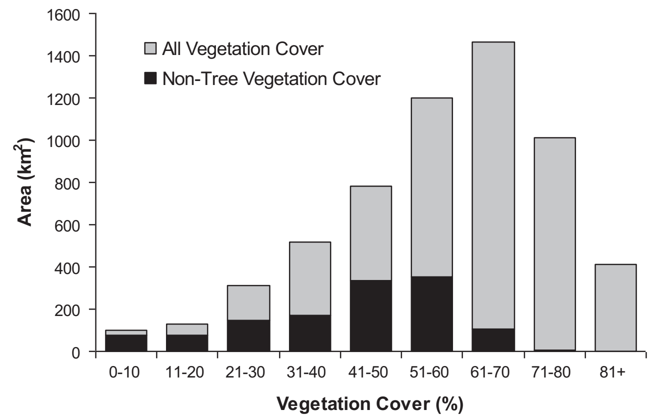

Fig. 1. Total area of vegetation cover (%) in the Sydney greater metropolitan area based on PV and FPC (see Section 2).

The effect of increasing vegetative cover on a UHI varies between cities depending on a range of factors relating to local climate, topography and other local environmental factors (Bowler et al., 2010). General factors include aspect, elevation, shape and size of the urban area and weather conditions including wind speed, cloud cover, relative humidity (Hoffmann, Krueger, & Heinke Schlünzen, 2012; McCutchan & Fox, 1986). Some cities have site-specific influences. In Oklahoma City, The Great Plains low level jet strongly influences regional temperatures. However the influence varies with urban shape and structure (Lemonsu, Belair, & Mailhot, 2009). The arrangement of buildings and their heights are two principal determinants. Assessing and accounting for these site specific factors is paramount in understanding the relationship between vegetation cover and temperature. This is particularly important considering the growth of urban greening schemes across the globe. If we are to optimise the benefits of reducing UHI from increasing vegetation cover we need a strong model of the expected benefit based on information tailored to the specific environmental and infrastructure properties relevant to the city where greening schemes are being considered.

Our study site is the greater metropolitan area of Sydney, the capital city of the State of New South Wales (NSW), Australia. The city of Sydney and its greater metropolitan area are located on the South east coast of Australia at 33.8°S latitude; the climate is temperate with mild winters and warm summers. Rainfall is fairly uniform throughout the year, although April is the wettest and September the driest month. In Sydney, climate is largely dictated by its coastal position and the temperate ocean current that surround it. Average maximum summer air temperatures in the inland suburbs (up to 30 °C) are 3–4 °C higher than the CBD (25.6 °C) (Bureau of Meteorology, 2012). Sydney's greater metropolitan area lies entirely within the Sydney Basin surrounded by deeply dissected plateaus and steep escarpments. Elevations in urban areas range from 0 to 600 m above sea level. This difference causes temperatures to be 3–4 °C cooler in upland areas.

Sydney is home to over 4.6 million people, approximately 20% of the total population of Australia (Australian Bureau of Statistics, 2012). Sydney's urbanised land covers 6000 km^2, from the coast to the Great Dividing Range. The highly variegated landscape of the Sydney greater metropolitan region has large areas of forested and rural lands interspersed with urban areas. On a global scale the urban density of Sydney is relatively low and the city already has a relatively high proportion of green or open space (Fig. 1). Of the 6000 km^2 of the greater Sydney region less than 100 sq km has a vegetation cover of less than 10% and more than 90% of the area has a vegetation cover of more than 20%. The Sydney greater metropolitan region also contains large areas of forested lands with more