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Impacts on cooling energy consumption due to the UHI and vegetation changes in Manchester, UK

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ABSTRACT

Climate change projections estimate a rise of approximately 3 °C by the 2080s for most of the UK (medium emissions scenario at 50% probability level, 1961–1990 baseline). Warming is a particular concern for urban areas due to urban densification and the Urban Heat Island (UHI) effect.

To counteract the UHI, one adaptation strategy for urban areas is increasing the proportion of greenspace, such as parks, street tree plantings, and green roofs. This research employed an interdisciplinary approach to measure and model fine-scale microclimate changes due to greenspace and explore the implications for building energy demand in Manchester, UK. Both the modelled and measured microclimate data informed development of a series of weather files for building energy modelling of three commercial building types.

For a scenario adding 5% mature trees to the urban case study, the combination of microclimate modelling and data analysis estimated a maximum hourly air temperature reduction of nearly 1.0 °C under peak UHI conditions and wind speed reductions up to 1.0 m/s. These results were used to change the weather files in the building energy modelling, which estimated a reduction of 2.7% in July chiller energy due to the combination of reduced UHI peak hours and eight additional trees shading a three-storey shallow plan building. Energy savings increased to 4.8% under a three-day period of peak UHI conditions.

1. Introduction

Climate change projections estimate a rise of approximately 3 °C by the 2080s for most of the UK (under a medium emissions scenario at 50% probability level, 1961–1990 baseline) [1]. Warming is of particular concern for urban areas due to the issues of urban densification and the Urban Heat Island (UHI) effect. This paper utilises research on the Urban Heat Island Intensity (UHII) (the temperature difference between the city centre and a rural reference location) in Manchester and Greater Manchester [2], a city and urban area in the northwest of England, UK. The research found that the UHII can reach 8 °C and is also increasing over time. Fig. 1 shows the frequency distribution based on half-hourly readings from 11 measured locations in Manchester city centre during May to August 2010 [2,3].

As an adaptation to both climate change and the UHI, one strategy that has been suggested for urban areas is increasing the proportion of greenspace [4,5], such as public parks [6,7], gardens, street trees [8–10], and green roofs. While many studies have investigated the cooling effect of greenspace in terms of park size [11,12], proximity to a park, or area covered by tree canopy (see Bowler et al. [5] for a comprehensive review), and other studies have explored the impact of the UHI or microclimate on building energy demand [13–18], relatively few studies have specifically explored the impacts of vegetation in urban environments on building energy demand.

Those that have investigated building energy demand have primarily focused on residential buildings [19–23], most frequently for humid tropical/sub-tropical or Mediterranean climates [24,25] rather than for temperate maritime climates (Koppen climate classification [26]), such as that of the UK. Of those that have included vegetation, most have analysed building energy (and/or CO_2 emissions) solely as function of one variable, either air temperature or shading effects, with a wide range of variation.

As early as 1977, research by Mattingly and Peters [27] on the sheltering and building energy effects of fences, adjacent houses, and tall evergreen trees found that a straight row of evergreen trees was the most effective scenario tested, reducing infiltration by up to 40%. Parker [28] supported this finding, stating that, for the warm, humid climate of south Florida, careful placement of

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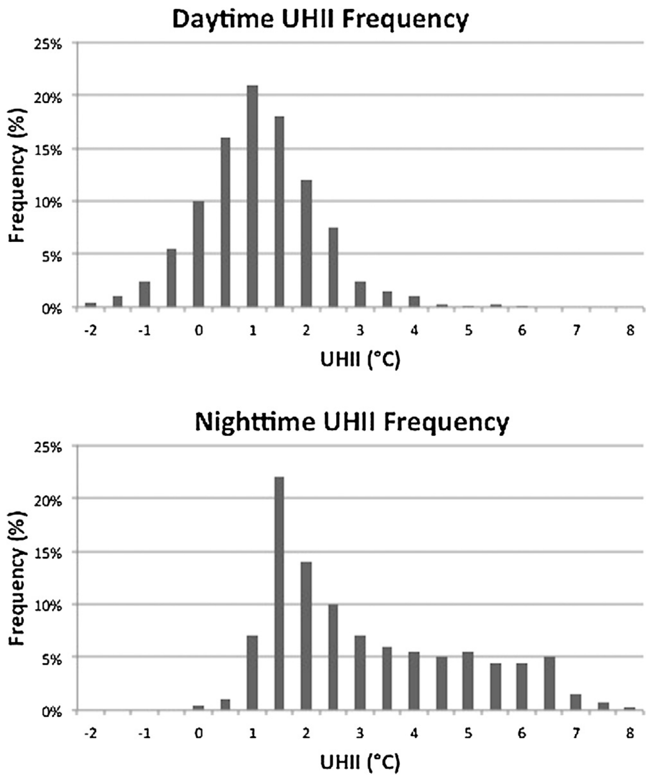

Fig. 1. Histograms of summer daytime and nighttime UHII frequency for Manchester [2].

trees and shrubs in relation to prevailing winds reduces infiltration during summer, and found a reduction of 50% cooling energy requirements on warm summer days for insulated mobile home.

Huang et al. [19] used a modelling approach to investigate meso- and micro-climates and their relationship to building energy. Using a building prototype of a single story residence of wood-frame construction, the study found that a 25% increase in tree cover can save 40% on residential cooling energy for Sacramento, CA, compared to 25% in Phoenix, AZ and Lake Charles, LA. The cooling energy savings increased to 50% and 33%, respectively, when optimising for shading.

In a study of residential buildings in Chicago, McPherson et al. [29] estimated 7.7–10.8% air-conditioning savings for one tree on the West wall of 1 and 2-storey brick buildings. In Sacramento, California, a study of two residential buildings estimated seasonal cooling energy savings of 29% solely through the use of sixteen shade trees [22]. More recently, an empirical study analysing electricity billing data in Sacramento by Donovan and Butry [30] found that trees on the South and West side of residential buildings reduced summertime energy consumption by 5.2% while trees on the North side increased consumption by 1.5%. While the study does not explicitly state the percentage of the buildings being shaded, it does perform regression modelling to correlate electricity consumption with the ground area covered by trees within set distances from the buildings. By developing an empirical model based on residential data from Auburn, Alabama, Pandit and Laband [31] found 14% savings in summer cooling energy for 50% dense shade, but also a 6% increase in winter heating energy with 20% winter shading. In comparison, a modelling study by Nikoofard et al. [32] on four Canadian cities investigated the concept of neighbouring shading structures, including buildings and trees of various sizes, distances, and orientations from a modelled two-storey residence. It found that the largest impact for tree shading was in the Vancouver model, which reduced cooling energy by up to 36% (west side of building with tree size = 12 m $H \times 8$ m W of building) while increasing heating energy by only 1.2%.

In Tokyo, Japan, Ca et al. [33] examined the influence of a nearby park during August and September by measuring air temperature, relative humidity, wind, foliage temperature and several surface temperatures. Through modelling of a four-storey building (20 m wide), the study estimated a 15% reduction in cooling energy requirements at noon with approximately 1.5 °C air temperature reduction. In a similar study, Chen and Wong [34] studied the effects of a park on air temperature and cooling energy requirements in Singapore. The study found that the cooling effect of the park extended into the areas surrounding the park with a maximum temperature difference of 1.3 °C between the park and surroundings, with savings of up to 10% on cooling energy for an 8-storey office building. The study considered energy savings due to air temperature cooling, but not the effects of shading, changes to relative humidity, or wind speed changes.

Using a numerical model, Kikegawa et al. [35] classified urban canopies (denoted as residential and office) in Tokyo, Japan according to SVF and investigated the effects of several different UHI countermeasures, including albedo increases, urban greening (ground, walls, or roof), reducing waste heat discharge, and conservation of cooling energy. In the residential canopies, the study estimated 0.7 °C reduction in air temperature and 20% reduction in building energy due to green walls, while the office canopies were shown to have the greatest reductions (0.5 °C air temperature and 5% energy savings) for the scenario that eliminated waste heat discharge from air conditioning.

In perhaps the most comprehensive study of this type, Akbari and Konopacki [36] developed summary tables of energy savings based on simulations employing a selection of UHI reduction strategies, including solar-reflective roofs, shade trees, and ambient cooling. The analysis looked at buildings that were profiled according to usage (residences, offices, and retail stores), age (pre-1980 (old) or 1980+ (new)), and fuel (natural gas or electricity). Simulations estimated cooling and heating energy use and peak power demand using the DOE-2.1E model and weather data for about 240 locations in the United States. Energy use and savings per 1000 ft^2 of roof area were integrated to provide results tables sorted by heating and cooling degree-days. Savings were greatest for residential buildings, ranging from 12% to 25%, and for office buildings, the electricity savings ranged from 5% to 18%, depending on the age and climatic location (as characterised by HDD) of the building. Shading was estimated by placing a building element (block) next to the building with the estimated height and volume of a tree and assigning a transmittance (0.1 for summer, 0.9 for winter).

Raji et al. [37] developed a recent thorough literature review that discusses the energy impacts of several types of greening systems applied directly to buildings, including green roofs, walls, and balconies, sky gardens, and indoor sky gardens. Their review with regard to energy consumption concludes with wide variations over summer heating and cooling seasons. They found more effective and efficient energy reductions in all systems during the summer, but conflicting results for winter, depending on study conditions, such as climate location, orientation of the greening system and building age.

This section has identified and discussed a range of studies on the impacts of vegetation on building energy. However, no single study addresses all aspects of vegetation modifications in urban environments and the studies demonstrate a wide range of energy reductions, from 5% up to 50%, depending on building type, area of shading, estimated air temperature reductions, and climatic location.

While the current northern UK climate may currently have a relatively low demand for cooling energy, it is anticipated that cooling demand will rise significantly under projected climate change