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Influence of evaporative cooling by urban forests on cooling demand in cities

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Abstract

Trees provide important ecosystem services to urban human society. Their absence can lead to more pronounced environmental and social consequences, for example the urban heat island effect. Evapotranspiration (E_t) from trees reduces air temperature in the urban microclimate by converting sensible heat to latent heat. Quantification and valuation of the ecosystem services provided by urban trees is important for improving cost-benefit evaluations in support of protecting tree planting and maintenance budgets and, thus, for building climate change resilience into cities. Inclusion of E_t cooling could improve ecosystem service valuation models by producing a more complete picture of the benefits that urban trees provide to society.

This study explores two approaches for evaluating climate regulation as an ecosystem service of urban trees. Firstly, an enthalpy-based approach was adopted to valuate latent heat of evaporation from tree transpiration (in three case study urban forests) by equating it to an equivalent service from an active direct evaporative cooling system. Secondly, energy savings to air-conditioned buildings was modelled using TRNSYS and TRNFLOW simulation programs with and without air precooled and humidified by urban trees.

Trees are shown to provide substantial urban cooling with an annual valuation of £84 m estimated using the enthalpy-based approach, or ranging from £2.1 m to £22 m using TRNSYS and TRNFLOW dynamic simulation programs; both for inner London case study. The latter savings arose from a modelled 1.28 – 13.4% reduction in air-conditioning unit energy consumption. Challenges around assumptions of homogeneity in both built form and urban forest canopy effects are discussed.

The case study examples highlighted differences in E_t cooling between tree species, with *Castanea sativa*, *Prunus avium*, *Quercus petraea*, *Platanus hybrida* and *Fagus sylvatica* typically providing more E_t cooling than any of the other tree species commonly found in urban forests. The research highlighted a shortage of published E_t data, particularly for urban environments.

Key Words:

Ecosystem services; Evapotranspiration; Urban cooling; Heat comfort; Bowen ratio.

Introduction

Trees provide many benefits to people (Davies et al., 2017) and these have been collectively termed as ecosystem services (ES) (Reid *et al.*, 2005). Urban environments typically have considerably fewer trees than rural environments, meaning that urban populations may have less access to the ES that trees provide. In dense urban environments these ES can be of significant importance, for example helping to mitigate the urban heat island (UHI) effect. This effect occurs where built-up areas absorb more heat energy than surrounding rural environments and together with the high density energy fluxes from human activity lead to pronounced increases in ambient surface and air temperature (Arnfield, 2003). UHIs contribute to human heat stress and the plethora of associated health problems: for example, Health Protection Agency (2012) reported that heat-related mortality already accounted for 2,000 premature deaths in the UK and forecast this to increase to around 10,800 premature deaths by 2080. Mora et al. (2017) reviewing the international literature from 1980 to 2014 found 783 cases of heat-related excess human mortality from 164 cities in 36 countries.

There is a positive correlation between locations that suffer from UHI and those that lack evapotranspiring surfaces (Ca *et al.*, 1998; Leuzinger et al., 2010) and the inclusion of green infrastructure in urban environments has been identified as an effective way to mitigate UHI through evapotranspiration (E_t) (Gill *et al.*, 2008; Ballinasa and Barradasa, 2015; Saaroni, *et al.*, 2018). E_t associated with trees results in the release of water vapour from leaves into the air (Kozlowski and Pallardy, 1997) that reduces the surrounding ambient air temperature through an evaporative cooling process (Akbari, 2002). Trees and vegetation growing on or in close proximity to buildings also provide multiple other benefits (Davies *et al.*, 2017), including supporting biodiversity and reducing air pollutant loading (Varghese *et al.*, 2015). However, while urban forests (herein defined as "all the trees in the urban realm" Davies *et al.*, 2017) in temperate climates can produce a net cooling benefit by E_t, not all trees offer the same level of cooling: canopy size and leaf amount are important determinants of species and cultivar differences in water use (Stratópoulos *et al.*, 2018), trees with high leaf area and transpiration rate are the most effective in reducing air temperatures (Gillner *et al.*, 2015; Rahman *et al.*, 2018) and urban forests vary in their size and species and age-class composition (UFWAC, 2016).

Under a changing climate, cooling loads in buildings are expected to increase in the future (Jenkins *et al.*, 2008). Mechanical cooling requirements can exacerbate the UHI effect by heat ejection to the surrounding environment, adding to cooling loads across a city (Masson *et al.*, 2014). Energy demand for cooling services can be reduced by the presence of urban trees through both shade casting (so called: shade-effect trees) and E_t cooling (so called: climate-effect trees) (Akbari *et al.*, 2001). Noting that peak urban electric demand rose by 2-4% for each 1°C rise in daily maximum temperature, Akbari (2002) reported potential cost savings of up to $200 per tree. However, the effect of E_t was not considered and the level of benefit varied by climate region. Reviewing the literature, Doick *et al*. (2013) reported that in temperate climates the role of shading and evapotranspiration are approximately equal. This study is concerned with the E_t cooling of urban trees.

i-Tree Eco is a tool within the i-Tree suite of peer-reviewed software tools (i-Tree, 2017). It is based on the UFORE (Urban Forest Effects) methods (Nowak and Crane, 1998) and has been developed to support urban forest management through the quantification of urban forest characteristics, and analysis and valuation of the ES that they provide (i-Tree, 2017). Climate regulation from E_t cooling is an ES not currently included in i-Tree Eco. However, the UFORE method has the capability to model leaf area at the species level and total canopy surface area for a given location (Nowak and Crane, 2003). Latent heat transfer across an urban forest could be calculated if appropriate E_t rates were considered. Indeed, E_t cooling is likely to be substantial on a city-wide scale (Gillner *et al.*, 2015) given maximum transpiration rates for individual trees can be many hundreds of litres per day (Hsieh et al., 2018; Stratópoulos *et al*., 2018).

The quantification and valuation of ES is of growing international interest within a context of natural capital accounting (NCA) (UN et al., 2012). Indeed, the UK government is interested in developing accounts for a broad range of UKNEA habitats including woodland and urban (Defra/ONS, 2017). A scoping study to develop an urban NCA for the UK incorporated *inter alia* the climate regulation ES, with valuation based upon both the ISO standard 7243 estimates of productivity loss at different outdoor temperatures and an i-Tree Eco based estimation of building energy use avoided due to the presence of urban trees (Eftec, 2017). The former determines the loss in productivity with and without air temperature reduction by urban green infrastructure to value the contribution of this ES in terms of maintaining productivity and notes methodological limitations of an assumed average cooling effect of parks and woodland. The latter considers the impact of tree shade and shelter on summer cooling energy (avoided use of air conditioning) as well as winter warming (reduced requirement for electrical warming). This approach is limited however by the lack of adaptation of the i-Tree module for UK building types. Both approaches excluded the saving related to the non-emission of CO_2. Indeed, a comprehensive valuation of this ES is complicated by the multiple ways that trees impact urban temperatures and, thus, the numerous savings mechanisms that could be considered.

This study aimed to evaluate the impact of urban trees on 1) mechanical cooling loads in buildings, and 2) energy cost savings associated with cooling ambient air by mechanical means. Energy saving was evaluated through a) direct comparison of E_t to evaporative cooling using an enthalpy-based approach to valuate latent heat of evaporation from tree transpiration, and b) by incorporation of E_t into established dynamic building thermal and air flow modelling programs - TRNSYS and TRNFLOW. Valuation of the climate regulation ES could provide a useful complement to tools, such as i-Tree, that show the wide range of benefits of urban trees, as well as emergent NCA methodologies.

Methodology

Evapotranspiration rate of trees

Values for E_t and stomatal conductance (g_s) were gathered from published literature for tree species relevant to urban environments within a temperate oceanic climate: namely 'Cfb' from the Koppen-Geiger Climate Classification (Kottek *et al.*, 2006) and 'Do' from the Köppen-Trewartha Climate Classification (Belda *et al.*, 2014). Where only g_s data was available, E_t rate (E_tR) was calculated using Fick's law of diffusion, after Rahman *et al.* (2011), and converted to units of $g/m^2/s$. Table 1 presents the minimum, mean and maximum E_t for the range of species and cultivars used in this study.

[Insert table 1: Evapotranspiration rates for tree species, sourced from the published literature.]

Analysis of E_tR was conducted to consider the range of values reported in the literature. Stomatal conductance, and therefore E_tR, has high temporal (especially daily) and spatial variability, affected by factors such as water vapour pressure deficit, soil moisture, plant health, position orientation and age of leaves (or needles) (Breuer *et al.*, 2003). To account for such variations as far as reasonably possible minimum, mean and maximum values from the literature were considered in this study. Figure 1 shows the mean E_tR for eight tree species and three genera where multiple records are reported; minimum and maximums are shown as vertical bars. Single E_tR values for the other 17 tree species and one genus listed in Table 1 are also shown. The average E_tR across all records was 0.058 +/- 0.012 $g/m^2/s$ (95% confidence interval; solid and dashed blue horizontal bars, respectively, in Figure 1). Three of the genus values and twelve of the tree species E_tR (minimum, mean or maximum) values fell within the 95% confidence intervals of the all-data average. E_tR has a linear relationship to the amount of cooling provided; therefore the range of E_tR for each of the species is indicative of the uncertainty associated with the cooling results.

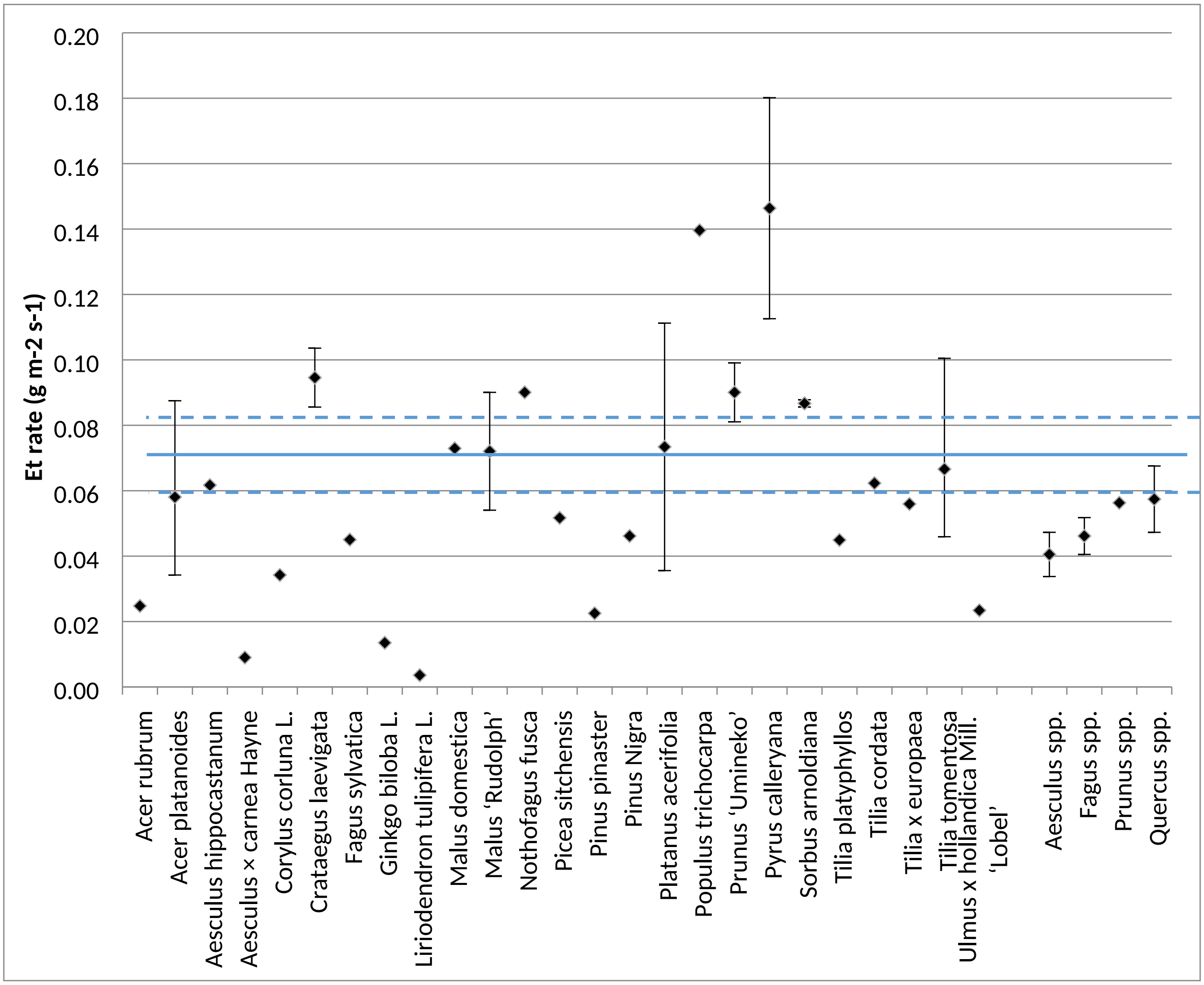

Figure 1. Mean evapotranspiration rates (E_tR; black diamonds) for all of the tree species considered; sourced from the published literature. Minimum and maximum E_tR are shown by vertical bars. For genera with multiple values in the literature, the genus average and range are shown. The mean of all the species and genera E_tR and the 95% confidence interval of this mean are presented (solid horizontal line, upper and lower intervals as dash horizontal lines).

Evapotranspiration from an urban forest

Three case studies were considered, each having a completed i-Tree Eco survey: Edinburgh (Hutchings *et al.*, 2012), Greater London (Rogers *et al.*, 2015), and Wrexham (Rumble *et al.*, 2015). For Greater London, the Outer and Inner London figures as detailed in the study are used. The species composition and total leaf area values, as reported by i-Tree Eco, were used in conjunction with Table 1 E_tR values to provide a total E_t for each case study urban forest. Total E_t was determined using the species mean E_tR where possible; where a species mean was not available, the genus average E_tR was adopted. Where neither species nor genus data were available, the all-data mean E_tR was used (Table 1). E_t was normalised across the case studies according to land surface area (E_t/km^2; assuming an even distribution of trees).

The rate of water mass transfer, $\dot{m}$ (g/m^2/s), for E_t was converted into rate of thermal energy absorbed, $\dot{q}$ (kJ/m^2/s), from the surrounding environment using Eq. 1:

$$\dot{q} = \dot{m} \times \lambda_{vH_2O} \tag{1}$$

Where $\lambda_{v_{H_2O}}$ is the latent heat of vapourisation of water ($\lambda_{v_{H_2O}} =$ 2.456 kJ/g at 292 K and atmospheric pressure; Wagner and Pruss, 2002). Calculating energy transfer rate allowed E_t to be related to cooling as a measure of power (i.e. E_t power). For modelling purposes, it was assumed that tree leaves had zero heat capacity (Ca *et al*., 1999).

The distribution of heat from E_t cooling can be generally characterised by the Bowen ratio (B) (Santamouris, 2013). Guided by Taha (1997), the Bowen ratios of ‘typical’ UK urban and wooded areas were used to apply an adjustment factor of $0.5.(B_{tree}+1/B_{urban}+1)$ to calculated E_t energy values. This generalised adjustment factor does not consider local spatial factors, but provides an estimate for the amount of energy that equates to cooling, i.e. the effective E_t cooling potential.

A common method of assigning a monetary value to ES is to use a comparative service as an economic benchmark (Defra/ONS, 2017). Following the methodology of Rahman *et al.* (2011), an economic assessment of E_t cooling from trees was made through direct comparison with the cost to provide equivalent cooling from operating an air conditioning (A/C) unit. An active direct evaporative cooling system (DEC) was used for comparison because the cooling mechanism is the same as E_t from trees (Amer *et al.*, 2015). A mid-sized evaporative cooler was selected (model ECP07, EcoCooling Ltd, www.ecocooling.org). This model provides 35 kW of cooling from 1.5 kW of electricity and a flow rate range 10-14.5 m^3/hr. The B-adjusted E_t cooling power of the trees was divided by the rated cooling capacity of the evaporative cooler (35 kW) to give the number of A/C units required to deliver an equivalent amount of cooling as the three case study urban forests. This value was then multiplied by electricity consumption of the cooler (1.5 kW) and an electricity unit price of 0.14 £/kWh (UK average electricity variable unit 'Direct Debit' and 'Prepayment' tariffs for 2017; BEIS, 2018) to provide an equivalent cooling value (£/hr). The comparison is made with the operational cost of A/C units and does not include purchasing or maintenance costs.

The potential energy impact of evapotranspiration on building cooling systems

The direct comparison method described above is limited conceptually as A/C units are not designed for outdoor use. However, the results provide useful comparison to previous work. A more realistic, though novel, approach is to recognise that trees are cooling the outdoor ambient air, which in turn impacts the cooling load placed on A/C systems. Through building energy modelling the energy dynamics and local spatial factors of different types of building structures found in UK cities were used to assess the impact of E_t cooling by urban trees on building energy consumption. This approach provided a practical scenario that is transferable to building energy cost savings.

Modelling energy impact on a single building and a street canyon

To evaluate how trees cooling the surrounding environment impacts on a building's cooling requirement a dynamic thermal energy model: TRaNsient SYstems Simulation package (TRNSYS) (TRNSYS, 2010) with airflow analysis by TRNFLOW (TRNFLOW, 2009), was employed to capture both the indoor and outdoor processes. TRNSYS is a reference software and one of the listed simulation programs in the European/British Standard on thermal solar systems and components: BS/EN12977 (2018). TRNSYS is a recognised simulation package within the 'Best Directory of Building Energy Software Tools' (formerly hosted by US Dept. of Energy) and has been tested and validated by International Energy Agency (IEA; under Task 34/43). The IEA comprehensive study demonstrated the robustness of the algorithms used in the TRNSYS (Loutzenhiser et al., 2007; Neymark et al., 2008). In addition, the software has been successfully used over multiple decades in a broad range of built environment research (Bradley and Utzinger, 2007; Shahrestani et al., 2013; Shahrestani et al., 2017; Antoniadis and Martinopoulos, 2018; Stritih et al., 2018).

While, ultimately, the cooling load of a building is determined by the many different physical attributes of the indoor and outdoor environment (i.e. solar gains, humidity, surface temperatures, air temperature, wind speed, heat capacity and orientation), the indoor air conditions control the level of cooling demand and the outdoor air temperature influences the energy requirement to meet that cooling demand. For this reason, the modelling was broken into two conceptual parts: (i) E_t influence on outdoor air temperature, and (ii) a simplified representation of a building to understand cooling demand at a given cooling set-point temperature, as the energy needs for cooling are also impacted by relative humidity (RH).

For this element of the research, Inner London was adopted as the case study area. Using the i-Tree Eco published leaf area density and the average E_tR for the urban forest composition of Inner London it was possible to determine the change in absolute humidity of the volume of air surrounding a building (or in a street canyon, see below) at a given moment in time. Modelling the E_t effect of trees as an evaporative cooling process with constant enthalpy, a psychrometric chart (Supplemental Figure 1) was used to determine a temperature drop in the air surrounding the trees, assuming that the entire E_t was used in cooling the air, and that effects remained local to the tree and buildings (i.e. no boundary layer mixing). The minimum, mean and maximum E_tR (Table 1) were applied to the leaf area density of Inner London (from Table 2) and scaled to a modelled building area (Figure 2). This scaled E_tR was used to calculate a temperature drop in a volume of air immediately surrounding the simplified representations of a building, and these representations were assumed to be homogenously representative of Inner London when scaling the energy efficiencies for valuation purposes.

Two zonal models were developed using TRNSYS: (i) a single zone building in isolation, and (ii) a street canyon consisting of two single zone building blocks in parallel (Figure 2). In each, shade-casting by trees onto the buildings is not considered by the model; in the latter case, mutual shading of buildings is modelled. Each considered the influence of regional weather conditions (larger scale weather systems) on cooling as well as capturing some of the mixing processes of buoyancy and forced flow direction of air. A weather file representative of conditions of London (after: Levermore and Parkinson, 2006), determined the boundary conditions of the model at each time step. The single zone isolated building was 10m x 10m x 20m (h;w;l) and situated centrally in a total volume of 20m x 30m x 20m (h;w;l). For the street canyon, each building block was 18m x 20m x 100m (h;w;l) in a total volume of 36m x 80m x 100m (h;w;l). Simulations ran at 1 hr time steps from January 1st to December 31st.

The cooling season was taken as June 1st to September 30th - the warmest of the British summer months. A constant E_t was applied for the single building case and for the street canyon a fixed daily profile of E_t was applied following a simple polynomial curve based on work by Gerosa *et al*. (2012) to account for hourly changes in canopy transpiration. A 4th order polynomial was applied (Equation 2). Building cooling was considered to be available 24 hr a day with the cooling limited to a temperature set-point of 23˚C and a RH set-point of 50%, or 60%. A constant system Coefficient of Performance (CoP) of 2.0 was applied, as was the electricity unit price (0.14 £/kWh; BEIS, 2018).

$$E_t = \begin{cases} (0.00022\,(t-13)^4 - 0.03\,(t-13)^2 + 1) \times E_{t\max} & 6 \le t < 21 \\ 0 & t < 6 \;\text{ or }\; t \ge 21 \end{cases} \qquad (2)$$

where $E_{t\max}$ is the maximum E_t for the day and t is time, in 24 hr clock system.

Each building block had the same schedule of operation, set point cooling temperature, occupant density and internal heat gains (see Supplemental Material: Table S1).

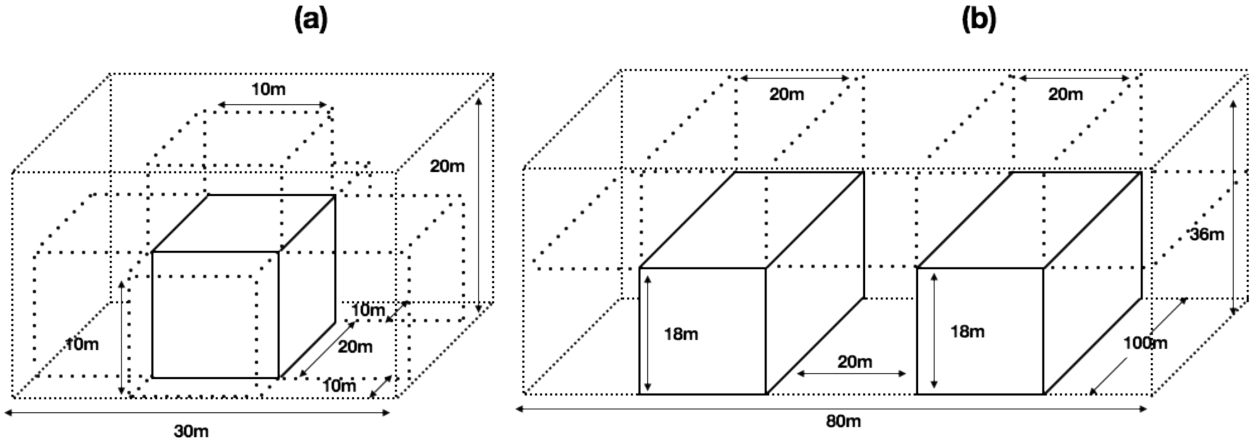

Figure 2. Model dimensions for representing (a) single, isolated building, and (b) a street canyon and row of buildings with each row considered as a single open plan zone. The surrounding volume (black dashed line) determined the area for calculating availability of E_t. Air flow from wind and buoyancy effects was considered by splitting the surrounding volume into equally sized sub-volumes, as depicted by the blacked dotted line. Each cuboid represents a different microclimate surrounding the building cuboid (solid black lines).

Ambient conditions are not only important to determining the loads under which a cooling system operates, but are also important for determining the influence of air infiltration and ventilation rates on cooling demands. For this study, the building ventilation was considered to be 100% mechanically driven in order to ascertain the level of cooling load offset provided by trees. Infiltration, however, is dependent on the pressure coefficients (C_p) on the surface of a building – important to airflow network programs (Cóstola *et al*., 2009). Whilst there is recognised uncertainty in use of standard C_p values, for a first approximation the values provided by (Grosso, 1992) using the CpCalc+ calculation program were applied to provide representative values of a building over 3 storeys in height. C_p values applied in the two models are shown as Supplemental Material (Table S2).

Results

Case study areas

Urban forest composition was similar across each case study area and for many of the genera E_tR values were available from the literature (Table 1). The most important species for providing E_t cooling were also similar across the case studies, with at least two of *Castanea sativa*, *Prunus avium* or *Platanus hybrida* featuring in the top three (Table 2). Edinburgh had the second highest number of trees per km^2, but the lowest normalised leaf area (Table 3). Outer London had fewer trees/km^2 but 27% more leaf area than Edinburgh, suggesting that Outer London's trees have larger canopies or species with larger leaves. Inner London's trees evapotranspired the most: on average 26.5 kg H_2O/tree/hr (Table 3). Total transpiration varied from 1,420 kg H_2O/s in Wrexham to 44,900 kg H_2O/s in Outer London (Table 3). When normalised by leaf area or case study area E_t ranged 47.4-54.1 kg H_2O/s/km^2 (by leaf area, Table 3) or 30.4-37.7 kg H_2O/s/km^2 (by land area, data not shown).

[insert Table 2. The three most common tree species and most important species for delivering E_t cooling in each of the case study urban forests]

[insert Table 3. Evapotranspiration across the case study urban forests]

Table 4 presents results for E_t cooling for each of the case study urban forests. Adjusted total E_t cooling energy (*q)* is presented along with the equivalent number of A/C units required to provide the same amount of cooling, value of cooling and the 95% confidence interval. Outer London with the largest urban forest and corresponding leaf-area (Table 3) produced the greatest total amount of cooling at 55,200 MW (Table 4) or £321 m/annum in A/C unit equivalents (assuming cooling 8 hr/day, June through Sept; £83.9 m/annum for Inner London). When normalised 'per tree' the range in the average values of cooling was 4.8 kW/tree (Wrexham) to 9.1 kW/tree (Inner London); equivalent to 0.03 to 0.05 (+/-0.01) £/hr/tree across the three urban forests (Table 4). The power ratings on a per tree basis are comparable to those reported by Rahman et al. (2011) who reported 1.4, 3 and 7 kW/tree for *Pyrus calleryana* in August growing in Amsterdam soil, grass verge or pavement, respectively.

[insert Table 4. Summary of the estimated value of the effective cooling from each urban forest case study]

Urban building energy savings - Single building model

On average, the level of reduction in cooling resulting from current levels of tree provision in Inner London ranged between 0.6 and 0.9% depending on indoor RH control levels (Table 5). Day *et al*. (2009) estimated that London accounted for 11% of Britain's total cooling load. Assuming that this almost exclusively applies to Inner London (i.e. 9 of the 11%), and taking the official government figures on total cooling load for the UK in 2016 to be 13,037 GWh (BEIS, 2017), then the trees in Inner London provide a cooling benefit of 7.0 – 10.6 GWh. Taking a midpoint of 8.8 GWh and a unit price of £0.14/kWh, the saving equates to £1.23 million per year under the current assumptions.

[inset Table 5: Total cooling supplied to single building with and without tree E_t cooling applied and for different RH control set points]

Urban building energy savings - Street canyon building model

The cooling energy provided by Inner London trees at the three rates of E_t (minimum, mean, maximum) are presented in Table 6. In the case of sensible cooling loads, trees in Inner London produced between 1.28% and 13.4% energy saving when RH of the building indoor environment was not controlled for. However, the latent cooling load increased in all instances as a result of the increased moisture from the E_t of trees. Accounting for both sensible and latent cooling loads, the presence of trees would cause an increase of between 0.09 - 1.15% when controlling indoor environments to 23°C at 50% RH, but would result in a decrease in cooling load of between 0.9% and 3.09% for an indoor RH of 60%. Cooling systems rarely (if at all) operate to tightly control indoor RH and as such the latent energy component of a building cooling system is likely to be much lower than shown here. Looking, therefore, at the effect on sensible cooling alone, a reduction of 1.28 - 13.4% in cooling demand for a typical summer could be associated with the presence of trees in Inner London when considering the full 95% confidence interval of species E_t rates. This equates to an annual cost saving of between £2.1 million to £22.0 million for a typical cooling season in Inner London (assuming that the savings in energy usage are applicable pan-Inner London and that 9% of the 13,037 GWh (BEIS, 2017) total cooling load for the UK applies to Inner London, as above).

[insert Table 6. Cooling energy demand and saving potential from trees for a range of E_t for the street canyon model scenario and with separation of sensible and latent cooling loads]

Discussion

Evapotranspiration Data

Review of the available literature revealed that E_tR is significantly influenced by the characteristics of plants and weather conditions (Heath, 1998; Atkinson *et al.*, 2004). In this study, therefore, E_t data were only used from studies in regions with similar climate to the UK. Of the 25 species for which E_t data were available, ten were not present in any of the case study's urban forests (Table 1); data for these subsequently featured in the genus average values. The influence of sunlight, temperature, humidity, water availability, and wind speed on E_t means that even within a single species, variation within a city due to microclimatic effects should be expected. Kruijt *et al. (*2008) and Bernacchi *et al. (*2011) have shown the impact of air quality (CO_2 and O_3 concentrations) on the rate of E_t; and Heath (1998) showed daily variation in g_s due to meteorological conditions. In this study, the variation of these influencing factors was accounted for through the use of minimum, mean and maximum E_t, only. One limitation of the study, therefore, is uncertainty due to changes in E_t under prolonged drought-stress conditions. Gill *et al*. (2013) note: increased length and frequency of summer droughts is likely to decrease the cooling potential of E_t, when it is most needed. Furthermore, E_tR values were not available at the species-level for ca. 90% of the three urban forests (data not shown). However, applying the range of E_tR values allowed estimation of a range of E_t cooling provided and further insight to the benefit of trees in urban settings that may otherwise go unrecognised yet is useful in urban planning and urban forestry management policy creation.

Evapotranspiration from an urban forest

The two defining parameters of E_t in this study are E_tR and leaf area. Species, genus and overall-average E_tR were assumed not to differ between the three case studies. The validity of this assumption should be tested further to check the applicability of the approach to cities across UK, Europe and areas of similar climate; however it was considered appropriate for this study due to the use of minimum, mean and maximum published values. Given this assumption, leaf area was the main parameter determining total E_t and hence cooling. An urban forest with more healthy mature and large stature trees will typically have a larger leaf area and, therefore, offer greater cooling potential. The case for more large stature trees in the urban environment is frequently made (e.g., UFWACN, 2015) on intuitive (a larger canopy *de* *facto* casts more shade) as well as scientific argument (Rahman, *et al*., 2018; Smithers, *et al*., 2018, for example). Our results support such claims: by virtue of their greater cumulative leaf areas larger canopied trees provided more of the climate regulation ES. Table 1 illustrates, however, that small stature trees including: *Crataegus laevigata*, *Prunus 'Umineko'*, *Pyrus calleryana* and *Sorbus arnoldiana* have average E_t rates that suggest they can be significant contributors to latent heat transfer (E_t >0.075 $g/m^2/s$). Their size means that these species can be suited to a range of planting locations, for example where there is insufficient room for a tree of large stature. Stratópoulos et al. (2018) showed that some small to medium stature trees, including *Acer campestre* and *Ostrya carpinifolia*, showed higher flexibility in response to changing weather with increased growth and transpiration under favourable conditions and more conservative water use when dry. Their inclusion in the urban forest may thus support efforts to build resilience to a changing climate through species diversification, however widespread use may reduce delivery of evapotranspirational cooling due to the regulated water use of these species.

Building energy efficiency

The results showed that E_t from the trees in Inner London is likely to provide significant energy savings due to the already high and increasing cooling energy demand. Even a reduction as small as 1% equated to a substantial financial benefit - £1.64 m - yet the study revealed that evaporative cooling may contribute a saving of up to a 13.4% reduction in energy consumption for sensible heat cooling. At the same time, moisture content in the microclimate is increased and this may increase the demand for latent cooling in buildings, which highly depends on the approach of humidity control in the indoor environment. For instance, under a very tight control of RH to 50%, E_t may lead to an increase to total cooling demand by up to 1.15%. But this is without consideration of other cooling mechanisms associated with trees (shading and short-wave energy reflection; Smithers et al., 2018). Furthermore, it is highly atypical for cooling systems to operate under tight humidity control, especially in the UK. Under the more realistic RH control mechanisms and set-point of 60%, the modelling showed that E_t from trees contributed an annual energy consumption saving across Inner London of up to 3.1% (when considering sensible and latent cooling together), equivalent to £5.09 m. If energy savings due to the shade-effect was also valued, the climate regulation ES valuation is likely to be even greater (Akbari et al., 2001; Akbari, 2002; Hsieh et al., 2018).

In using a combination of published E_t rates, tree population survey data and a first order modelling estimate of impact on cooling load, certain limitations in the estimates must be recognised. The results demonstrate value can be attributed to tree cooling, however the assumptions of homogeneity in both built form and urban forest canopy effects are limiting factors. The figures should be considered as estimates on order of magnitude. The mixing of air in the urban canopy layer and impact of building height on availability of tree cooling needs further consideration to demonstrate the impact of trees on cooling energy demand. Addressing some of the assumptions in this work could lead to a reduction in this estimated potential saving. Consideration of specific microclimatic effects – such as increased localised air temperatures leading to increased vapour pressure deficit and thus increased E_t (Peters et al., 2010) – could also, however, demonstrate increased cooling load offsets. Turbulence and mixing of air in the canopy layer immediately around a building have in part been accounted for by use of a zonal model that captured some of the mixing processes of buoyancy and forced flow direction of air. To represent the diffusion of cooling to the wider urban boundary layer and to take account of local (urban canyon) temperature variations (Grimmond, 2007) a more sophisticated modelling approach may be warranted. Furthermore, the study has not considered the influence that vegetative and built surface fractions can have on energy fluxes (Lorridon and Grimmond, 2012). Selection of different sites could lead to more representative values of overall city energy fluxes (Ward et. al., 2014).

Improving the valuation of urban tree ecosystem service provision

i-Tree Eco has been developed to help assess and manage urban tree populations for the benefits they can provide (i-Tree, 2017). To this end, a primary function of the tool is to quantify and monetarise environmental functions of the urban forest. The economic case for urban trees is stronger where a more comprehensive range of the benefits are valued. The current i-Tree Eco (version 6) provides *inter alia* an estimate of building energy use avoided based upon shade provision (summer time) and shelter provision (winter time) that result in decreases in electricity and gas consumption for cooling and heating, respectively. However the valuation is not fit-for-purpose internationally, where the model has not been parameterised for different construction materials. The first of our two modelling approaches is consistent with the i-Tree Eco approach with its calculation of leaf area according to urban forest (species) composition and deferring to genus data where species specific values are not available. However, as this approach is not a direct analogue of an anthropogenic service equivalent it’s suitability in natural capital accounting type situations should be further tested (Defra/ONS, 2017).

Comparisons to A/C units is limited since they are intended to cool air in enclosed buildings, not open air environments. However, they are useful conceptually to provide a comparative monetary value for the cooling service. The value produced here for the E_t cooling potential of Inner London was £84 m/annum. In comparison, the building energy modelling provided a cost saving, directly attributable to the trees, of between £2.1 m and £22.0 m annually (for Inner London) based upon the practical energy costs to cooling indoor environments in the same situations. As such, a way to value a particular outcome of E_t has been explored and shown to be significant. The sophistication of the evaluation is currently limited by its consideration of one hypothetical street scene, only. Modelling street canyons of varying size more representative of the heterogeneity of a large city such as London and comparison to other cityscapes needs to be tested prior to its application within or alongside a tool like i-Tree.

Conclusion

Evapotranspiration rate (E_tR) data proved to be limited. New data collection on g_s and E_tR of different tree species is required to improve understanding of the role of urban trees in cooling cities. Within these limitations, the study showed that the range of cooling potential provides energy saving associated with the sensible cooling load of buildings. The sensitivity to cooling regime (i.e. sensible versus latent), simplifications in the modelling approach, and focus on E_t effects demonstrate there is more to be done to understand the full impact of urban forest on building energy saving use. Such work must consider varying climatic conditions if the role of climate change and microclimatic effects are to be understood. Furthermore, transferability of E_t measures could be improved through the publication of standard metrics of tree height, trunk diameter and canopy sizes, which were often missing from the literature reviewed.

The case study results show that the amount of evapotranspirational cooling has substantial economic value – in the order of 10^6 £/annum when calculated through comparison with a replacement service or via direct impacting on building air-conditioning. Growing city populations, increased energy density and projected climate change (IPCC, 2014) are already causing city authorities to plan the mitigation of and adaptation to future heat stress. Including the assessment of E_t cooling energy into tools such as i-Tree Eco could improve the effectiveness of urban tree planning and management under a changing climate.

Acknowledgements

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Table 1 – Evapotranspiration rates for tree species taken from literature. "spp." used to indicate where species not specified. Underlined values calculated from the reported stomatal conductance values. (References are: [1]Heath, 1998; [2]Wullschleger et al., 1998; [3]Breuer et al., 2003; [4]Atkinson et al., 2004; [5]Betson and Scholefield, 2004; [6]Fini et al., 2009; [7]Leuzinger et al., 2010; [8]Hipps et al., 2014; [9]Rahman et al., 2015; [10]Gillner et al., 2015).

Common Name	**Scientific Name**	**Experiment Conditions**	**Age (years)**	**Height (m)**	**DBH* (cm)**	**E_t min ($g\ m^{-2}\ s^{-1}$)**	**E_t max ($g\ m^{-2}\ s^{-1}$)**	**Mean E_t ($g\ m^{-2}\ s^{-1}$)**	**Genus E_t (Mean) ($g\ m^{-2}\ s^{-1}$)**
Norway Maple[6,7]	*Acer platanoides*	Irrigated	n/a	n/a	3.5	0.034	0.075	**0.053**	**0.037**
Red Maple[2]	*Acer rubrum*	n/a	n/a	n/a	n/a	0.021	0.021	**0.021**	
Red Horse Chestnut[7,10]	*Aesculus × carnea Hayne*	n/a	15	9.2	20.75	0.009	0.009	**0.009**	**0.032**
Horse Chestnut[7]	*Aesculus hippocastanum*	n/a	n/a	n/a	n/a	0.053	0.053	**0.053**	
Chestnut spp.[1]	*Aesculus spp.*	In Ambient Air	2	n/a	n/a	0.029	0.041	**0.035**	
Turkish Hazel[10]	*Corylus corluna L.*	n/a	13	8.5	15.75	0.034	0.034	**0.034**	**0.034**
Midland Hawthorn[9]	*Crataegus laevigata*	n/a	n/a	6	1.37	0.074	0.089	**0.081**	**0.081**
Beech spp.[1]	*Fagus spp.*	In Ambient Air	2	n/a	n/a	0.035	0.045	**0.040**	**0.039**
Common Beech[2]	*Fagus sylvatica*	100-yr-old plantation	n/a	35	54	0.039	0.039	**0.039**	
Red Beech[2]	*Nothofagus fusca*	Pristine forest	n/a	34	60	0.077	0.077	**0.077**	**0.077**
Maidenhair Tree[10]	*Ginkgo biloba L.*	n/a	19	12.6	25.5	0.014	0.014	**0.014**	**0.014**
Tulip Tree[10]	*Liriodendron tulipifera L.*	n/a	14	10.65	19.75	0.004	0.004	**0.004**	**0.004**
Crabapple Tree[9]	*Malus 'Rudolph'*	n/a	n/a	6	1.37	0.046	0.077	**0.062**	**0.062**
Common Apple[3]	*Malus domestica*	n/a	9	n/a	n/a	0.063	0.063	**0.063**	
Sitka Spruce[3]	*Picea sitchensis*	n/a	n/a	11.5	n/a	0.044	0.044	**0.044**	**0.044**
Corsican Pine[5]	*Pinus nigra*	Forest	n/a	15	n/a	0.040	0.040	**0.040**	**0.030**
Cluster Pine[2]	*Pinus pinaster*	n/a	n/a	20	34	0.019	0.019	**0.019**	
London Plane[3,7]	*Platanus acerifolia*	fully expanded leaves	28	20	n/a	0.031	0.096	**0.063**	**0.063**

Common Name	**Scientific Name**	**Experiment Conditions**	**Age (years)**	**Height (m)**	**DBH* (cm)**	**E_t min ($g\ m^{-2}\ s^{-1}$)**	**E_t max ($g\ m^{-2}\ s^{-1}$)**	**Mean E_t ($g\ m^{-2}\ s^{-1}$)**	**Genus E_t (Mean) ($g\ m^{-2}\ s^{-1}$)**
Black Cottonwood[2]	*Populus trichocarpa*	n/a	n/a	15	15	0.120	0.120	**0.120**	**0.120**
Umineko Cherry Blossom[9]	*Prunus 'Umineko'*	n/a	n/a	6	1.37	0.070	0.085	**0.077**	**0.063**
Cherry spp.[4]	*Prunus spp.*	wild	n/a	n/a	n/a	0.048	0.048	**0.048**	
Callery pear[9]	*Pyrus calleryana*	n/a	n/a	6	1.37	0.097	0.155	**0.126**	**0.126**
Oak spp.[1]	*Quercus spp.*	In Ambient Air	2	n/a	n/a	0.041	0.058	**0.049**	**0.049**
Mountain Ash[9]	*Sorbus arnoldiana*	n/a	n/a	6	1.37	0.074	0.076	**0.075**	**0.075**
Small leaved lime[6,7,10]	*Tilia cordata*	Irrigated	n/a	n/a	3.5	0.031	0.075	**0.057**	**0.053**
Broad leaved lime[6,7]	*Tilia platyphyllos*	Irrigated	n/a	n/a	3.5	0.023	0.054	**0.041**	
Silver lime[6,7]	*Tilia tomentosa*	Irrigated	n/a	n/a	3.5	0.040	0.086	**0.061**	
Common lime[6]	*Tilia x europaea*	Irrigated	n/a	n/a	3.5	0.028	0.075	**0.052**	
Dutch Elm[10]	*Ulmus x hollandica Mill. 'Lobel'*	n/a	14	12.88	23.5	0.023	0.023	**0.023**	**0.023**
E_t average (all genera):									**0.054**

* DBH: diameter at breast height

Table 2. The three most common tree species and the three most important species for delivering E_t cooling in each of the urban forest case studies.

		Edinburgh	Inner London	Outer London	Wrexham
Most common species	1st	*Acer pseudoplatanus*	*Betula spp.*	*Acer pseudoplatanus*	*Acer pseudoplatanus*
	2nd	*Ilex aquifolium*	*Tilia x vulgaris*	*Quercus robur*	*Crataegus monogyna*
	3rd	*Betula pendula*	*Magnolia spp.*	*Crataegus pedicellata*	*Betula pendula*
Top E_t providers	1st	*Castanea sativa*	*Platanus hybrid*	*Castanea sativa*	*Platanus hybrida*
	2nd	*Acer platanoides*	*Quercus petraea*	*Crataegus monogyna*	*Fagus sylvatica*
	3rd	*Prunus avium*	*Prunus avium*	*Populus spp*	*Castanea sativa*

Table 3. Evapotranspiration across the three case study urban forests.

City	Area size (km^2)	Number of trees (000's)	Total leaf area (km^2) (000's)	Total E_t ($kg\ s^{-1}$)	Mean E_t per leaf area ($kg\ s^{-1}\ km^{-2}$)	Mean E_t per tree ($kg\ hr^{-1}\ tree^{-1}$)
Edinburgh	115	638	74	3,500	47.4	19.8
Inner London	310	1,587	217	11,700	53.9	26.5
Outer London	1,285	6,807	1,047	44,900	54.1	23.7
Wrexham	38	364	29	1,420	48.9	14.0

Table 4. Summary of the estimated value of the effective cooling from each urban forest case study.

City	Adjusted total q	A/C unit* equivalents	Cooling Value†	Average q	A/C unit* equivalents	Cooling value†
	(MW)	(000's)	(k £ hr^{-1})	(kW $tree^{-1}$)	($tree^{-1}$)	(£ hr^{-1} $tree^{-1}$)
Edinburgh	4,290 (±1,300)	123	26 (±8)	6.7 (±2.0)	0.2	£ 0.04 (±0.01)
Inner London	14,400 (±4,300)	411	86 (±25)	9.1 (±2.7)	0.3	£ 0.05 (±0.02)
Outer London	55,200 (±16,000)	1,580	329 (±97)	8.1 (±2.4)	0.2	£ 0.05 (±0.01)
Wrexham	1,740 (±510)	50	10 (±3)	4.8 (±1.4)	0.1	£ 0.03 (±0.01)

[*] based on 1.5 kW evaporative cooler (EcoCooling Ltd).

[†] at the 2017 UK Average rate of 0.14 £/kWh (BEIS, 2018)

Table 5: Total cooling (and energy demand for cooling) supplied to a single building with and without tree E_t cooling applied and for different relative humidity (RH) control set points.

Description	Cumulative cooling (and energy) demand MWh					
	Indoor RH=50%			Indoor RH=60%		
	E_t=0.015	E_t=0.055	E_t=0.165	E_t=0.015	E_t=0.055	E_t=0.165
With trees	6.68 (3.34)	6.65 (3.33)	6.57 (3.29)	5.51 (2.75)	5.47 (2.74)	5.37 (2.68)
Without trees	6.69 (3.35)	6.69 (3.35)	6.69 (3.35)	5.52 (2.76)	5.52 (2.76)	5.52 (2.76)
Cooling demand reduction (summer)	0.15%	0.60%	1.82%	0.24%	0.92%	2.73%

Table 6. Changes in cooling (and energy) demand with and without trees in the street canyon model scenario, over the one-year modelling period for a range of E_t values and relative humidity (RH) set-points of 50% and 60% (based upon a CoP=2).

Description	**Cumulative cooling (and energy) demand MWh** **Indoor RH=50%**											
	E_t=0.015				E_t=0.055				E_t=0.165			
	Eva Clg*	Sensible	Latent	Total	Eva Clg	Sensible	latent	Total	Eva Clg	Sensible	latent	Total
With trees	51.6 (25.8)	291.7 (145.9)	129.2 (64.6)	420.9 (210.5)	177.3 (88.7)	278.2 (139.1)	144.9 (72.5)	423.1 (211.6)	532.1 (266.0)	255.8 (127.9)	169.6 (84.8)	425.4 (212.7)
Without trees	0	295.5 (147.7)	125.1 (62.5)	420.6 (210.2)	0	295.5 (147.7)	125.1 (62.5)	420.6 (210.3)	0	295.5 (147.7)	125.1 (62.5)	420.6 (210.3)
% change in demand		-1.28%	3.30%	0.09%		-5.85%	15.9%	0.61%		-13.4%	35.6%	1.15%

Description	**Cumulative cooling (and energy) demand MWh** **Indoor RH=60%**											
	E_t=0.015				E_t=0.055				E_t=0.165			
	Eva Clg	Sensible	Latent	Total	Eva Clg	Sensible	latent	Total	Eva Clg	Sensible	latent	Total
With trees	51.6 (25.8)	291.7 (145.9)	58.3 (29.2)	350.0 (175.0)	177.3 (88.7)	278.2 (139.1)	68.0 (34.0)	346.1 (173.1)	532.1 (266.0)	255.8 (127.9)	84.4 (42.2)	340.2 (170.1)
Without trees	0	295.5 (147.7)	55.6 (27.8)	351.0 (175.6)	0	295.5 (147.7)	55.6 (27.8)	351.0 (175.5)	0	295.5 (147.7)	55.6 (27.8)	351.0 (175.5)
% change in demand		-1.28%	4.95%	-0.29%		-5.85%	22.4%	-1.39%		-13.4%	52.0%	-3.09%

* Eva Clg: evaporative cooling

Material to be supplied as Supplemental Information

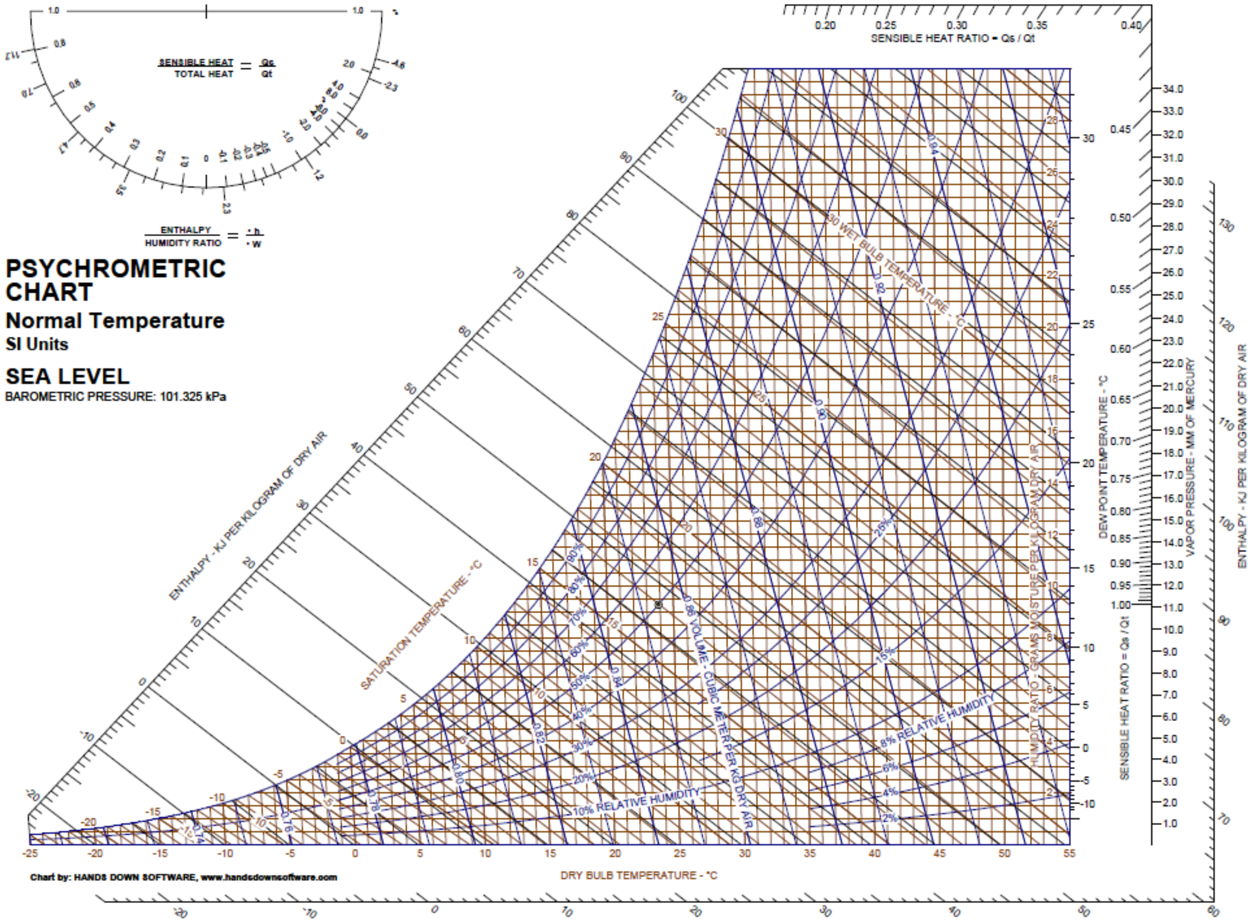

Figure S1. Psychrometric Chart for determining cooling from increased humidity (from: http://www.handsdownsoftware.com).

Table S1: Modelled internal gains, cooling system set points and daily period of operation used in the calculations.

Attribute	Value	Units
Indoor Setpoint Temperature	23	°C
Relative Humidity (RH) Set-point	50,60	%
Period Building Occupied	7am to 6pm	-
Occupant Density	12	m^2/person
Occupant Heat Gain (sensible)	60	W/person
Occupant Heat Gain (latent)	40	W/person
Equipment Heat Gain (sensible)	140	W/person
Lighting Heat Gain (sensible)	10	W/m^2

Table S2. Wind pressure coefficients of infiltration effects on building cooling requirements.

Façade Orientation (Height)*	Wind direction (Degree) **			
	0	90	180	270
South (9m)	-0.017	-0.039	0.02	-0.039
South (27m)	-0.022	-0.051	0.061	-0.051
East (9m)	-0.057	0.001	-0.057	-0.024
East (27m)	-0.028	-0.116	-0.028	-0.012
North (9m)	0.02	-0.039	-0.017	-0.039
North (27m)	0.061	-0.051	-0.022	-0.051
West (9m)	-0.057	-0.024	-0.057	0.001
West (27m)	-0.028	-0.012	-0.028	-0.166
Roof (36m)	0.008	0.008	0.008	0.008

* Height refers to the height of the location that the C_p value is calculated for.

** Direction of wind is determined from the North, e.g. 90 degrees represents Easterly winds.

Derived from: Cpcalc+ for buildings more than 3-storeys in height (Grosso, 1992)