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2.16 Tree shade for local heat reduction

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Tree shade for local heat reduction	**Climate Resilience**
Description and justification	Thermal comfort in cities has increased in importance due to impacts from global warming and high-density urbanisation. Metrics to measure the shading services provided by trees are largely based on quantifying differences in local air temperature from unshaded areas. The effect of tree shade on local temperature may be upscaled to a citywide impact if modelled and assessed cumulatively. This indicator principally concerns measuring how tree shade effects urban microclimates, in particular, by intercepting solar radiation preventing warming of the ground and thereby reducing surface temperature. Other basic measures of air temperature covered in Air temperature reduction indicator reviews, such as apparent temperature (the temperature equivalent perceived by humans – based on air temperature, relative humidity and wind speed), and Physiological Equivalent Temperature (thermal perception of an individual including thermal physiology), can also be used to evaluate the human thermal comfort conditions associated with tree shade (e.g., Kàntor et al., 2018). Various factors such as tree species (size, shape, leaf type, seasonality etc), tree age, distance between trees, type of surface beneath the tree, surrounding environment and climate will impact the degree of shade provided. Data on the reduction of air temperature by tree shade collected in these ways can be used to: • Quantify the benefits of trees as nature-based solutions in terms of cooling the local microclimate, reducing building energy use and providing thermal comfort zones for residents; • Target tree planting in areas prone to temperature extremes/UHI and/or to provide optimal shade

	benefit to commuting pedestrians (see also Langenheim et al., 2020); - Contribute towards other environmental and health and well-being indicators linked to temperature, air pollution, carbon storage, flooding and biodiversity.
Definition	Trees as nature-based solutions to create shade in neighbourhoods measured by °C or K per spatial unit (m^2)
Strengths and weaknesses	Robustness of evidence depends upon the level of precision of the equipment, the spatial design of the monitoring and the duration of temperature recording. Generally, direct measurement in the field can provide greater confidence than microclimate simulations, but it can be hard to accurately scale-up local measurements to the whole city. Photographic methods yield good results, but they typically require manual acquisition and processing of fisheye images, which is time consuming and not feasible at the neighborhood or city-scale (Middel et al., 2018). To accurately simulate the thermal performance benefits that trees provide, it is necessary to account for growth and phenological changes in tree shade amount and quality and the influence of street canyon geometry.
Measurement procedure and tool	The classical methodical approach for measuring tree shading was developed by Barlow and Harrison (1999) and considered different factors affecting shading, such as topography, time of day and year and geographical location. They provided mathematical descriptions and procedures used to calculate the length of the shadow and its duration (Barlow & Harrison, 1999). The shade from tree canopies can generate significant surface cooling in cities, particularly over impervious surfaces such as asphalt, where a temperature reduction of about 6°C has been recorded (Rahman et al., 2019). This study examined the vertical temperature gradient beneath two common urban street tree species *Tilia cordata* and *Robinia pseudoacacia*, recording a range of morphological measurements (e.g., diameter at breast height (DBH), tree height, crown projection area (CPA) and leaf area index (LAI) derived from hemispherical photographs), as well as air and surface temperature and various other meteorological data, collected using a combination of temperature loggers at 3 different heights and weather stations installed at the study sites (Rahman et al., 2019). Surface cooling was strongly correlated with LAI, and the relationship was found to be stronger over asphalt than grass, indicating therefore that tree species with higher canopy density might be preferential when planted over asphalt surfaces in cities, but low water using species with lower canopy density could be chosen over grass surfaces (Rahman et al., 2019).

In a meta-analysis of the characteristics of urban tree species that influence cooling potential, a total of 13 studies were analysed that reported on cooling by shading (as measured by surface temperature difference ΔST), and consensus from the review in terms of surface cooling was that the following parameters contributed to ΔST in order of relative importance: climate > below canopy surface > growing size > leaf thickness > LAI > crown shape > plant functional type > habitat > wood anatomy > leaf shape > leaf colour (Rahman et al., 2020). LAI was again reported as the most influential driver of cooling benefits in terms of human thermal comfort, although vertical leaf area densities can also be influential, and species with higher leaf density at the lower crown may ensure better cooling benefits (Rahman et al., 2020). Studies reviewed in the meta-analysis used various methods for gathering data on tree shade effects on surface temperature, for example:

- ***Field measurements***: empirical microclimate measures using for instance temperature sensors attached to dataloggers, infrared thermometers/thermal cameras, globe thermometers (to measure radiant temperature as a determinant of physiological equivalent temperature (PET) which is used to assess human thermal comfort), in combination with weather station data and tree species morphology (i.e., height, canopy spread and LAI (using a LAI analyser/ceptometer or hemispherical images) (Lin & Lin, 2010; Armson et al., 2012 & 2013; Devia & Torres, 2012; Berry et al., 2013 (building walls rather than ground level); Millward et al., 2014; Gillner et al., 2015; Napoli et al., 2016; Rahman et al., 2018; Stanley et al., 2019); also leaf colour (using colorimeter), leaf thickness (using thickness gauge) canopy coverage area (using handheld GPS and walking a transect round the tree canopy edge) and canopy thickness from photographs of individual trees (Lin & Lin, 2010); hemispherical photographs to measure tree shade cover on walls (Berry et al; 2013);
- ***statistical/modelling techniques***: linear mixed model and/or regression analyses of field data (Lin & Lin, 2010; Armson et al., 2012; Milward et al., 2014; Gillner et al., 2015; Rahman et al., 2018; Stanley et al., 2019), shade area analysis (Armson et al., 2013), vertical shading coefficient of walls (Berry et al., 2013); a heat transfer model, which was found to be effective at predicting surface temperatures of pavements and lawn under different trees (Napoli et al., 2016);

Rötzer (2019) presents different techniques for greening cities, particularly through planting trees in all climate zones, as effective tools to mitigate climate change and the Urban Heat Island (UHI), and provides empirical as well as modelling studies of urban tree growth and their services and disservices in cities worldwide, including the dynamics, structures, and functions of urban trees, as well as the influence of climate and climate change on urban tree growth, urban species composition, carbon storage, and biodiversity.

Stanley et al. (2019) analysed urban tree growth and regulating ecosystem services along an urban heat island (UHI) intensity gradient in Salzburg (Austria). For the phenological monitoring in spring March – May (and later verification in autumn), they used the well-established method presented by Wesolowski and Rowinski (2006). They developed a scale of point values from 0 to 2 for assessing the development status of a leaf bud. For each observation day, ten randomly selected apical buds in the upper, south-exposed part of the crown are evaluated and their sum is calculated. The monitoring starts when all buds are closed and thus evaluated as having zero points. As soon as all ten leaves are completely developed and each scores two points, the monitoring is finished. Moreover, for all observation trees, the height, trunk circumference at breast height, and leaf area index (LAI) were measured. Using these data, the tree age, crown area, and crown volume were further calculated. The tree height was measured using a Leica DISTOTM D810 Touch (Leica Geosystems); LAI was determined based on LAI-2200C Plant Canopy Analyzer from LI-COR (Lincoln, NE, USA). The measured values were then edited in the FV2200 software from LI-COR (2.1.1, Lincoln, NE, USA). The microclimate was measured using the difference of the surface temperatures between the crown-shaded area and the full sun-exposed area using an Infrared Radiometer, Model MI-220. Data were assessed using statistical analysis similar to those applied by Gillner et al. (2015). They found out, after leaves have developed, trees cool the surface throughout the whole growing season by casting shadows. On average, the surfaces in the crown shade were 12.2 ◦C cooler than those in the sun. Thus, the tree characteristics had different effects on the cooling performance. In addition to tree height and trunk circumference, age was especially closely related to surface cooling. They conclude, if a tree’s cooling capacity is to be estimated, tree age is the most suitable measure, also with respect to its assessment effort. Practitioners are advised to consider the different UHI intensities when maintaining or enhancing public greenery. The cooling capacity of tall, old trees is needed especially in areas with a high UHI intensity. Species differences should be examined to determine the best adapted species for the different UHI intensities. The results of such studies can be the basis for modelling future mutual influences of microclimate and urban trees.

An alternative methodology to those above used a high-resolution thermal imaging camera to record the crown temperature of trees from above (using a helicopter), and determined that urban tree temperatures are species-specific due to traits such as leaf size, stomatal conductance and canopy structure, and that foliage temperature was mostly influenced by the location of the tree (i.e., park or pavement) (Leuzinger et al., 2010). Generally small-leaved trees were cooler, but this trend did not always hold at temperature extremes (40°C), indicating that the cooling effect of urban trees could be species *and* context specific, which may be useful information for future urban tree planning projects (Leuzinger et al., 2010).

Thermal imaging (in combination with a range of other field measurements and photographic records) has also been used to record the surface temperatures of three common urban surfaces – asphalt, porphyry, and grass – in the shade of 332 single tree crowns, of 85 different species, during the peak temperature period of summer days, to evaluate which tree traits play an important role in cooling (Speak et al., 2020). Measurements at three locations within the shadow of individual trees revealed higher cooling in the centre and at the western edge and cooling was related to a multitude of tree traits, of which Leaf Area Index estimate (LAIcept) and crown width were the most important (Speak et al., 2020). Median average cooling of 16.4, 12.9 and 8.5 °C was seen in the western edge of the tree shade for asphalt, porphyry and grass, respectively (Speak et al., 2020). Tree traits recorded were modelled using descriptive and predictive multiple linear regression models and were able to predict cooling with some success from several of the predictor variables (LAIcept and gap fraction), which has implications for the selection of trees within urban design schemes by altering the weight given to certain tree traits if high shade provision is a desired outcome (Speak et al., 2020).

ENVI-met (a three dimensional microclimate simulation software) can be used to generate a microscale model simulating various tree canopy scenarios under various climate conditions and investigate the relationship between percentage tree canopy cover and temperature reduction at the neighborhood scale (Middel et al., 2015). The study findings suggested the relationship between percent canopy cover and air temperature reduction was linear, with 0.14 °C cooling per percent increase in tree cover for the neighborhood under investigation, although they highlight Envi-met has various shortcomings, for instance in terms of estimating nocturnal cooling under trees and accounting for anthropogenic heat (Middel et al., 2015). Beyond the local scale, the Weather Research and Forecasting (WRF) model has been coupled with urban land surface processes parameterized by urban canopy models (UCMs) to investigate the radiative shading effect of trees over the contiguous United States (Wang et al., 2018). This WRF-urban modelling framework can be informative to researchers and policy makers, but as it omits other biophysical functions of trees such as evapotranspiration, more work is needed to produce a more comprehensive and realistic representation of urban tree shade cooling effects (Wang et al., 2018).

Remotely sensed tree canopy cover has been widely used to estimate the amount of trees in an area. However, where this is limited to two-dimensional calculations, it may not fully evaluate the shading service of trees as the vertical structure and density of trees can also influence the solar radiation reaching ground level (Li et al., 2018). Google Street View (GSV) provides publicly available, high spatial resolution photographs of vegetation along streetscapes, which can be used to quantify the degree of shading under street trees (Richards & Edwards, 2017). The GSV panoramas can be transformed into hemispherical images and pixels classified into classes (i.e., sky, trees, buildings), and combined with remotely sensed data (i.e., LiDAR) to enable estimation of canopy cover provided by street trees (Li et al., 2018). A sky view factor (SVF) calculation - the ratio of sky hemisphere visible from the ground that is not obstructed by buildings, trees and terrain - can been applied to these images to quantify the shading effectiveness of street trees alone (SVF ranges from 0 to 1, indicating totally enclosed and totally open street canyons respectively) (Li et al., 2018). The quantitative information and spatial distribution of shade provision by street trees generated by this method can be used as a reference for urban planners and city officials for urban greening projects, for instance so they can target critical areas for urban heat island (UHI) mitigation (Li et al., 2018).

The influence of vertical and horizontal tree canopy structure on land surface temperature (LST) can also be measured using a combination of a high-resolution vegetation map, Light Detection and Ranging (LiDAR) data and various statistical analysis methods (Chen et al., 2020). Results from this method indicated that composition, configuration and vertical structure of tree canopy were all significantly related to both daytime LST and night-time LST, highlighting the important contribution measuring the vertical structure of tree canopies can have in determining LST in cities (Chen et al., 2020).

The influence of patch size of trees (from 500 m^2 – 80,000 m^2) on shading has been modelled, using a variety of field measurements (e.g., DBH, distance between trees, temperature, weather etc) and simulated using the solar radiation tool embedded in ArcGIS, and found that multiple small patches can provide more total area of shade than a single large one (Jiao et al., 2017). However, they also found a non-linear relationship between patch size and transpiration, both of which are key cooling services provided by trees, therefore there may be a trade-off between shading and transpiration at certain patch sizes, and with different tree species (Jiao et al., 2017).

A study of the effects of street trees in three contrasting street canyon environments found the cooling and human thermal comfort benefits of street trees were localised and highly variable both spatially and temporally, based on factors such as the amount of shading, street geometry, and the local meteorological conditions (Coutts et al., 2015). Thus, depending on their position in the street canyon, the prevailing conditions, and time of day, trees can have either a cooling or warming effect, highlighting the importance of strategic placement of trees to maximize their shade area whilst spacing them sufficiently to allow some nocturnal longwave cooling and ventilation, and reduce potentially detrimental impacts on urban cooling at night (Coutts et al., 2015).

i-Tree Canopy (https://canopy.itreetools.org/) is a web browser application that offers a quick and easy way to produce a statistically valid estimate of land tree canopy cover using aerial images available in Google Maps. This can be used as an easy to understand concept for communicating messages about tree cover to policy makers and the public, and can be linked to shading provision in terms of percentage cover/m^2 gained/lost in an area being an index of potential shading benefits gained/lost. i-Tree Canopy could also be used to map existing canopy cover in order to determine tree-less areas that may benefit from shade. The package i-Tree Design (https://design.itreetools.org/) can be used to evaluate the cooling benefits of shade from individual trees on building energy demand.

Mobile sensors (a fast-response, high-accuracy temperature probe, GPS device and data logger) mounted to bicycles have been used to measure temperature variability along urban transects in relation to tree canopy and impervious cover, both of which can interact to influence both daytime and nighttime summer air temperature (Ziter et al., 2019). In this study, generalised additive models were used to test the effect of percentage canopy and impervious cover and distance to nearest lake at 4 scales (10-90 metre radius) surrounding each temperature measurement (Ziter et al., 2019). This fine-scale method detected that canopy cover >40% can counter the warming effect of impervious surfaces during the daytime within a radius of 60-90 m (the scale of a city block). However, the impact at night-time was much less pronounced, indicating that reducing impervious cover as well as tree planting could be key to reducing UHI (Ziter et al., 2019). This method may also be suitable for citizen science projects (Ziter et al., 2019). Citizen science has also been successfully used to collect temperature data in cities using vehicle-mounted temperature sensors and global positioning system devices (GPS), with volunteers undertaking one-hour 'traverses' through study areas in a city to provide a snap-shot of temperatures, which can then be modelled against land use and land cover data to evaluate the role of trees in reducing/amplifying local temperatures and create a heat map for city planners (Shandas et al., 2019). Other participatory methods include the use of wearable sensors to detect human thermal stress (Sim et al. 2018), which could potentially be used to deliver a citizen science project on the effects of urban tree shade.

Berland et al. (2019) also confirmed that inventories relying on citizen scientists or virtual surveys conducted remotely using street-level photographs may greatly reduce the costs of street tree inventories since those ones conducted in the field by trained professionals are expensive and time-consuming. However, they pointed here several fundamental uncertainties regarding the level of data quality that can be expected from these emerging approaches to data collection. In particular, 16 volunteers were asked to inventory street trees in suburban Chicago using Google Street ViewTM imagery, and later this was assessed by comparing their virtual survey data to field data from the same locations conducted by experts. The findings suggest that virtual surveys may be useful for documenting the locations of street trees within a city more efficiently than field crews and with a high level of accuracy. However, tree diameter and species identification data were less reliable across all expertise groups, and especially analysts. Based on this analysis, virtual street tree inventories are best suited to collecting very basic information such as tree

	locations, or updating existing inventories to determine where trees have been planted or removed. It should be noted that measuring shade alone will not fully capture cooling services provided by trees, since evapotranspiration also plays a role in regulating temperatures. Also, if tree planting is poorly designed, it can lead to disruption of airflows, causing trade-offs such as localised increases in air pollution concentrations (e.g., Vos et al., 2013) and night-time temperatures (Bowler et al., 2010; Coutts et al., 2015).
Scale of measurement	Typically, tree shade effects on temperature are measured in terms of the local microclimate impact. Wang et al. (2018) propose a modelling framework for the shading effect of trees that can be used at the city and regional scale with moderate accuracy.
Data source	
Required data	Required data will depend on selected methods, for further details see applied and earth observation/remote sensing metrics reviews in: Connecting Nature Environmental Indicator Metrics Review Report
Data input type	Data input types will depend on selected methods, for further details see applied or earth observation/remote sensing metrics reviews in: Connecting Nature Environmental Indicator Metrics Review Report
Data collection frequency	Monitoring methods tend to be adopted for short-term snapshots, for instance to show benefits on days of extreme heat. Monitoring should be undertaken at repeated intervals to capture a more comprehensive overview of the performance of trees and account for change over time and under different climatic conditions. Establishing a network of sensors across the city could provide a useful baseline as tree-planting is upscaled across the city to a scale that impacted city-wide temperatures, if this was planned.
Level of expertise required	Some expertise may be required in relation to appropriately designing studies and with respect to the selection/use of specialist instrumentation and software such as ENVI-met. Expertise in relation to mapping (especially those based on remote sensing and GIS techniques) and modelling will be necessary.
Synergies with other indicators	Strong synergies with Air temperature reduction and with health and wellbeing indicators in relation to heat stress. Reducing temperatures in a specific location could also have links to social cohesion and accessibility as people may be more likely to use a space. Where weather stations are utilised, there are synergies in relation to capturing additional environmental parameters of relevance for other indicators (e.g., total rain fall for stormwater management indicators).
Connection with SDGs	Reduced impact of thermal stress on poorest communities; Reduced thermal stress impact of population health; Links

	to environmental education; Clean water and sanitation co-benefit; Job creation; Green infrastructure development; Social equality in relation to thermal stress; Sustainable urban development; Climate change adaptation; Habitat enhancement/creation, reduced thermal stress for locally adapted wildlife; Environmental Justice; Opportunities for collaborative working: SDG1, SDG3, SDG4, SDG6, SDG8, SDG9, SDG10, SDG11, SDG13, SDG15, SDG16, SDG17
Opportunities for participatory data collection	Opportunities are available for participatory processes in relation to collecting temperature measurements using mobile dataloggers or wearable sensors (Shandas et al., 2019), as well as collecting very basic information such as tree locations, or updating existing inventories to determine where trees have been planted or removed (as based on the findings of Berland et al. (2019).
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