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2.15.2 Air temperature reduction

Project Name: CONNECTING Nature (Grant Agreement no. 730222)

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Air temperature reduction (Applied and EO/RS combined)	**Climate Resilience**
Description and justification	NBS can contribute to reducing air temperature, thus reducing energy demand for cooling and reducing associated carbon emissions. Increasing NBS can reduce local temperatures through evapotranspiration and shading, ameliorating urban heat

	islands and heat stress. Metrics are based on changes in air temperature and can be employed on a range of scales. Local scale monitoring metrics would be more appropriate for small-scale projects; large-scale NBS projects, or city-wide replication of small-scale projects, might have a detectable impact at a city-wide scale (urban boundary layer). Basic measurements are typically: air temperature (Ta), apparent temperature, land surface temperature (LST), mean radiant temperature (Tmrt), Physiological Equivalent Temperature (PET) and are usually quantified in relation to specific thresholds e.g., decrease in mean/peak daytime local temperatures, % change in annual/monthly temperatures (citywide); heat stress, heatwave risk and urban heat island. Data on the reduction of air temperature by nature-based solutions collected in these ways can be used to: • Quantify the benefits of NBS in terms of providing thermal comfort zones for residents; • Quantify reduction in temperature extremes/heatwaves on a city-wide scale; • Contribute towards health and well-being evaluation linked to temperature extremes.
Definition	Measurement of the cooling effect of NBS by evapotranspiration and/or shading using applied methods or using high-resolution satellite images and thermal infrared (TIR) data to understand the thermal effect of urban fabric properties and the mechanism of urban heat island (UHI) formation.
Strengths and weaknesses	**Applied methods:** 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 can provide greater confidence than microclimate simulations, particularly for small-scale interventions. **EO/RS methods:** A great number of research projects confirm the usefulness of deriving air temperature from satellites, but the number of weather stations that regularly detect and collect air temperature records is limited and their distribution scattered, with a stronger concentration in developed countries, mainly USA and EU. The resulting records are often patchy in both space and time. An innovative method to enhance the quality of global air temperature information by analysing the land surface temperature records collected by weather stations and detected by satellites was recently developed. Based on this, a statistical model was developed that can improve monthly predictions of global air temperature. Satellites can access remote areas of the planet with few weather stations or poor-quality information.

Measurement procedure and tool	A variety of methods exist from applied/public participation techniques through to earth observation/remote sensing approaches. ***Applied/participatory methods*:** Temperature parameters are usually quantified in relation to specific thresholds: • Decrease in mean/peak daytime local temperatures (in relation to mean radiant temperatures); • Percentage change in annual/monthly temperatures (citywide); • Heat stress (in Europe - exposure of people to temperatures >30°C); • Heatwave risk (number of combined tropical nights (>20°C) and hot days (>35°C)); • Urban heat island (temperature difference between urban areas and surrounding rural landscapes). For local measurements of air temperature, a variety of thermometers/thermocouples can be used, usually in combination with dataloggers. When using the most basic types of thermometers and thermocouples, it is important that they are kept shaded. If the equipment is exposed to direct solar radiation, it can heat them and the reading thus measures heating due to solar radiation rather than the true air temperature. To avoid this, thermometers/thermocouples need to be combined with some kind of insulation from solar radiation to ensure they are measuring air temperature (Yu and Hien 2006). An example of a very basic solution to this is the combination of datalogging thermocouples with polystyrene insulation to measure the air temperature above green roofs (Connop et al. 2013). By using networks of such insulated thermocouples, it is possible to measure temperature at increasing distances away from an NbS such as a living wall or park (Doick et al. 2014; Eisenberg et al 2015; Ottelé et al. 2017; Morakinyo et al. 2019). For broader area measurements, standard practice for local temperature measurement involves the use of weather stations to monitor climatic parameters such as air temperature, windspeed, humidity. Such an approach is useful as it provides data on a wider range of temperature parameters in addition to air temperature, it also provides other climate parameters that can have synergies with other NbS indicators. Weather stations can range in size from off-the-shelf systems that have versatility in terms of installation location, to more accurate location-based monitoring, typically using a platinum resistance thermometer (*PRT*) inside a station fixed to the ground. The thermometer is exposed to air flow by natural ventilation through side louvers. This equipment includes a datalogger that takes readings at pre-programmed intervals to capture temperature changes for

calculation of daily, monthly or annual temperature fluctuations (MET Office 2019).

Ambient air temperature quantification is commonly calculated using combined ventilated temperature and relative humidity sensors (Jänicke et al. 2014). Apparent air temperature, or the temperature equivalent perceived by people, is measured by Dry- and Wet-bulb temperatures. These are common parameters measured to assess the apparent temperature regulation associated with NbS implementation (Shashua-Bar et al. 2009; Fung and Jim 2017). Typically, values recorded are referenced to climatic data from a nearby meteorological station (Shashua-Bar et al. 2009).

Frequency or duration of exposure to heat stress is typically measured using Wet Bulb Globe Temperature (WBGT) heat stress meters. It is a measure of the heat stress in direct sunlight, combining temperature, humidity, wind speed, sun angle and cloud cover (solar radiation). These meters can be used to measure the effects of NbS on evapotranspiration/cooling in relation to how somebody would feel at different distances from an NbS.

Emerging approaches to thermal temperature analysis also include the use of thermal imaging cameras to measure air temperatures. Thermal cameras have previously been used to capture the impact of NbS interventions (Connop and Clough 2016; Ottelé et al. 2017), however this method generally captures a measure of surface temperature rather than air temperature. Surface temperature is assumed to correlate with air temperature as it is strongly affected by the mean radiant temperature (Matzarakis et al. 1999*), as such it should give a good indication of local human comfort. However, the magnitude of any cooling effect in relation to distance from the NbS will be correlated with the scale of the NbS in comparison to surrounding hard surfaces. This correlation makes assumptions on the impact of small-scale NbS on air temperatures unreliable for distances greater than a few centimetres from the NbS. However, methods for capturing air temperatures using thermal cameras are now being developed using white test sheets and foil (to estimate background radiation), and might have potential as a small-scale rapid method to measure local air temperatures (Chui et al. 2018).

Many studies investigating the performance of NbS combine the use of dataloggers with dynamic simulation tools for microclimate analysis (Toparlar et al. 2017). Such simulation enables potential cooling benefits of NbS interventions to be calculated at a planning stage (Zölch et al. 2019), and for NbS to be appraised compared to predicted values following installation (Chow et al. 2011). The software ENVI-met (Bruse and Fleer 1998) has emerged as the industry standard simulation technique with good results when compared to physical monitoring (Tsoka et al. 2018). However, there are limitations to the ENVI-met simulation results (Tsoka et al. 2018), with some evidence to suggest that its reliability decreases with decreasing NbS scale of NbS intervention (López-Cabeza et al. 2018).

For evaluation of larger-scale NbS interventions or city-wide impacts, surface temperature modelling approaches have generally been adopted (Rizwan et al. 2008; Hall et al. 2012; Li et al. 2018). Drones are also increasingly used to measure surface temperatures over large scales (Honjo et al 2017). Networks of automatic weather stations have also been utilised to quantify urban heat islands over entire city scales (Yang et al. 2013).

***Remote sensing/Earth Observation methods*:**
In order to assess exposure to heat stress, different methodological approaches can be applied. Along with the analysis of a single parameter, such as air temperature (Ta), surface temperature, or mean radiant temperature (Tmrt), either by taking regular measurements, the use of **remote-sensing or modelling-based approaches**, which are spatially explicit, are recognised in several research papers (e.g., Alavipanah et al., 2015; Chen et al., 2014; Lindberg & Grimmond, 2011).

The combined usage of high-resolution satellite images and thermal infrared (TIR) data helps understanding the thermal effect of urban fabric properties and the mechanism of urban heat island (UHI) formation. In particular, it is suggested to undertake typical urban functional zoning, e.g., of downtown, for quantifying the relationship between fine-scale urban fabric properties and their thermal effect. As a result, a particular number of land surfaces and a number of aggregated land parcels extracted from, for instance, a QuickBird image can be used to characterize urban fabric properties. The thermal effect can be deduced from land surface temperature (LST), intra-UHI intensity, blackbody flux density (BBFD) and blackbody flux (BBF). The net BBF can be retrieved from the Landsat 8. The products should be resampled to fine resolution using a geospatial sharpening approach and further validated. The final results can show for instance that:

(i) On the level of urban functional zones, there is a significant thermal differential among land surfaces. Water, well-vegetated land, high-rises with light color and high-rises with glass curtain walls exhibited relatively low LST, UHI intensity and BBFD. In contrast, mobile homes with light steel roofs, low buildings with bituminous roofs, asphalt roads and composite material pavements showed inverse trends for LST, UHI intensity, and BBFD;

(ii) It can be found that parcel-based per ha net BBF, which offsets the "size-effect" among parcels, is more reasonable and comparable when quantifying excess surface flux emitted by the parcels;

(iii) When examining the relationship between parcel-level land surfaces and per ha BBF, a partial least squares (PLS) regression model can show that buildings and asphalt roads are major contributors to parcel-based per ha BBF, followed by other impervious surfaces. In contrast, vegetated land and water contribute with a much lower per ha net BBF to parcel warming.

Remote-sensing based indices used for this purpose:

- Temperature condition index (TCI) – Singh et al. 2003
- Satellite remote sensing with on-the-ground observations (combination of methods) - Lotze-Campen and Lucht, 2001

Methods for acquiring the surface air temperature include:

- temperature-vegetation index approaches (TVX)
- statistical approaches
- neural network approaches
- and energy balance approaches.

As underlined by a number of studies, remote sensing is one of the most used techniques to investigate the cooling effects of green infrastructures because large areas can be monitored and analysed simultaneously and continuously (Liwen et al., 2015). However, remote sensing does not allow for the prediction of the effects of possible NBS, or the prediction of how the NBS will develop in the future. For this purpose, modelling approaches are useful tools, that allow simulation of non-existing/future scenarios. The literature review has revealed that there are several studies which followed this methodology. Table 1 summarizes the reviewed studies that analysed NBS and urban temperature. However, in reality, heat stress is determined by multiple parameters, the most important being Ta, Tmrt, wind patterns and humidity (from the meteorological perspective), and metabolic rate, activity, age and clothing (from the physiological perspective) (Höppe, 1999). In this regard, use of ecosystem-based approaches can also have positive effects on a larger scale – for example a district of a city, or the whole city. Studies using remote sensing approaches (e.g., Alavipanah et al., 2015) or meso-scale climate modelling (e.g., Fallmann et al., 2014) show that the urban heat island effect can be significantly reduced by increasing the vegetative cover within a city, e.g., through green roofs or parks. Changes in albedo change the radiation balance of the urban environment, and lower surface temperatures (Zölch et al. 2016, 2017, 2018).

Table 1 Summary of the reviewed studies that analysed NBS and Urban temperature

Studies	Objective	Model
Boukhabla and Alkama, 2012	Study the impact of vegetation on air temperature	ENVI-MET
Feyisa et al., 2014	Examine the relationship between characteristics of the vegetation and observed temperature	LINEAR MIXED-EFFECT MODEL
Hu, et al., 2016	Quantify land surface temperature	MODIS LST
Kim et al. , 2016	Understand the cooling effect of changes in land cover on surface and air temperatures in urban micro-scale environments	ENVI-MET
Kong et al., 2014	Explore and quantify the combined effects of factors related to the urban cooling islands intensity	LINEAR REGRESSION MODELS
Kong et al., 2016	Examine the outdoor 3D thermal environmental patterns with and without green spaces	ENVI-Met
Koc et al., 2017	Methodological framework for a more accurate assessment of the thermal performance of green infrastructure	Remote Sensing
Mackey et al., 2012	Attempt to analyse a real large-scale application by observing recent vegetated	LANDSAT

	and reflective surfaces in LANDSAT images	
Lin & Lin, 2016	Characterize the influence of the spatial arrangement of urban parks on local temperature reduction	ENVI-MET
Sun et al., 2017	Assess the impacts of modifications in a park on the thermal comfort improving-effect of urban green spaces	ENVI-Met
Takebayashi, 2017	Examine air temperature rise in urban areas that are on the leeward side of green areas	Numerical Model
Wai et al., 2017	Determine the change in evapotranspiration from the new ecosystems	Variable infiltration capacity
Zölch, et al., 2016	Quantify the effectiveness of three types of UGI in increasing outdoor thermal comfort in a comparative analysis	ENVI-MET
Wu & Chen, 2017	Investigate how different spatial arrangements of trees in residential neighbourhoods affect the cooling effects of vegetation	ENVI-Met
Žuvela-Aloise, 2017	Evaluate the cooling potential of the blue and green infrastructure to reduce the UHI effect when applied to large areas of the city	MUKLIMO_3

As evidenced by the studies in Table 1, there is a plethora of models for studying the effects of NBS on urban air temperature. However, not all models are adequate for all objectives, and given a specific purpose, the models should be chosen accordingly.

In order to properly assess the urban heat component of a site, there is a need to analyse the heat fluxes (EEA, 2017a, 2017b). According to Rafael et al., (2016) the study of energy fluxes can be conducted in three main approaches:

i. studies that only consider the measurements of energy fluxes through the eddy covariance method, and usually compare different types of land;
ii. studies that combine flux measurements with model simulations;
iii. Studies that use models designed to simulate the key processes governing heat, moisture and momentum exchanges of the urban canopy for different applications.

All these approaches offer different benefits and present different challenges, and the chosen method should be dependent on the case study.

For further details on measurement tools and metrics, including those adopted by past and current EU research and innovation

	projects, refer to: [Connecting Nature Environmental Indicator Metric Reviews]
Scale of measurement	**Applied methods:** Typically, the type of metrics selected are based on the scale of the NBS being implemented. For example, small-scale interventions would not have a quantifiable impact on city-wide temperatures, thus city-wide networks of thermal sensors or remote sensing methods would not be appropriate. Small-scale NBS might, however, provide quantifiable local benefits in terms of creating an oasis from thermal stress for residents. **EO/RS methods:** Remotely sensed data are inherently suited to provide information on urban land cover characteristics, and their change over time, at various spatial and temporal scales. In most cases, however, methods of EO and RS have been used at meso-scales using satellite imagery to map and quantify the cooling effects of green infrastructures (Koc et al., 2017**).**
Data source	
Required data	Required data will depend on selected methods, for further details on applied and earth observation/remote sensing metrics refer to: [Connecting Nature Environmental Indicator Metric Reviews].
Data input type	Data input types will be depend on selected methods, for further details on applied or earth observation/remote sensing metrics refer to: [Connecting Nature Environmental Indicator Metric Reviews]
Data collection frequency	Data collection frequency will be depend on selected methods, for further details on applied or earth observation/remote sensing metrics refer to: [Connecting Nature Environmental Indicator Metric Reviews]
Level of expertise required	**Applied methods:** Some expertise is required for the spatial design of the sampling and choice of instrumentation. Once installed though, basic measurements of air temperature associated data processing require little expertise. For more complex thermal parameters, analysis requires a greater level of expertise if equipment used does not process such data automatically. The ENVI-met microclimate analysis software requires some expertise to operate and collect the environmental data necessary. Once trained, however, data processing is relatively straightforward. **EO/RS methods:** Expertise in mapping and interrogation of data using GIS software is typically required. Level of expertise required is greater with increasing complexity of software processing.
Synergies with other indicators	**Applied methods:** If weather stations are utilised, there are synergies in relation to capturing additional environmental parameters of relevance for other indicators (e.g., total rainfall

	for stormwater management indicators). Measurement of heat stress is also of relevance to health & well-being indicators associated with exposure to heat. Reducing temperatures in a specific location could also have links to social cohesion and accessibility in relation to people being more likely to use a space. **EO/RS methods:** Once purchased, spatial data can be used for many of the mapping indicators, including those for social and economic 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	**Applied methods:** Opportunities in relation to carrying out measurements, and downloading and processing data - weather stations located at local schools can be an effective method for engaging local communities in urban heat island education (Clough and Newport 2017); also include use of thermal comfort perception surveys (Canan et al. 2019), wearable sensors to detect thermal stress (Sim et al. 2018) and mobile dataloggers (e.g., attached to bicycles) (Yokoyama et al. 2018).
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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