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Climate Regulation Provided by Urban Greening

Examples from a High Latitude City

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Ph.D. thesis
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Front page photograph: A hemispherical photograph taken under an urban tree in Gothenburg, Sweden.

ABSTRACT

Cities exert a strong influence on urban climate, and consequently on human health and wellbeing. This increases the importance of considering climate issues in urban planning, particularly in the context of global climate change. One of the key adaptation strategies in climate-sensitive planning is urban greenery. The purpose of this thesis is to increase understanding of how urban greenery influences the air temperature and outdoor thermal comfort in a high latitude city. The thesis consists of three main parts. In the first part the aim is to describe the urban greenery at various scales in terms of the amount of foliage. In the second part different aspects of the cooling effect of urban vegetation and the resulting intra-urban thermal variations are discussed. Finally, the last part deals with the modelling of mean radiant temperature (T_{mrt}), an important parameter governing human thermal comfort, in vegetated urban areas.

The thesis is based on extensive meteorological and plant physiological measurements conducted in Gothenburg, Sweden. Study sites ranged from single street trees to parks and woodlands. Moreover, a LiDAR dataset and high resolution digital surface models (DSMs) of ground, buildings and vegetation were used to analyse spatial characteristics of the study sites, including effective leaf area index (L_e) describing tree foliage, and sky view factor (SVF), a measure of obstruction of sky commonly used in urban climate studies.

The results show substantial variations in L_e between different types of urban greenery, with the highest L_e observed in an urban woodland and the lowest in residential green yards. These variations were accurately modelled using LiDAR data. However, when averaged over large areas only partly covered by trees, variations in L_e were found to result mostly from tree fraction rather than structural characteristics of tree canopies.

Single urban trees of five common species were shown to provide a strong shading effect throughout the year, with a potentially positive effect on thermal comfort in summer and negative in winter in high latitude cities. Parameterisation of transmissivity of solar radiation through tree crowns significantly improved the modelling of T_{mrt} in SOLWEIG, a model simulating radiation fluxes in complex urban environments.

While tree transpiration in temperate climates is often assumed negligible in darkness, night-time transpiration was observed in all of seven common tree species, and data analyses indicated its contribution to the evening cooling on clear, calm nights of the warm season.

The cooling effect of trees due to both shading and transpiration was found to be influenced by tree growing conditions and access to sunlight. Trees growing on wide grass lawns had denser crowns and higher stomatal conductance than those surrounded by impervious surfaces. When provided with good growing conditions, sun-exposed trees can strongly influence microclimate by providing additional shade and by intensive transpiration.

Parks exhibited a cooler microclimate than built-up sites throughout the day and year, and in different weather conditions, with the strongest cooling effect on clear, calm days of the warm season. While the evening cooling in a high latitude city is best correlated with SVF, spatial characteristics describing buildings and vegetation proved useful in the analysis of intra-urban thermal variations. When high resolution DSMs are not available, near-infrared hemispherical photography can be used to calculate SVFs accounting for the obstruction of sky by buildings and trees separately.

The findings presented in this thesis can be used in climate-sensitive planning, in urban climate modelling as well as in valuation of ecosystem services provided by urban greenery.

Keywords: Gothenburg, Sweden, high latitude city, urban greenery, urban trees, leaf area index, tree transpiration, sky view factor, mean radiant temperature, hemispherical photography, climate-sensitive planning.

PREFACE

The following Papers are included in this thesis:

I. Klingberg J, **Konarska J**, Lindberg F, Johansson E, Thorsson S (2015) Mapping leaf area of urban greenery in a high latitude city using aerial LiDAR and ground-based measurements. *Submitted to Urban Forestry and Urban Greening*

II. **Konarska J**, Lindberg F, Larsson A, Thorsson S, Holmer B (2014) Transmissivity of solar radiation through crowns of single urban trees—application for outdoor thermal comfort modelling. *Theoretical and Applied Climatology* 117:363-376. DOI: 10.1007/s00704-013-1000-3

III. **Konarska J**, Uddling J, Holmer B, Lutz M, Lindberg F, Pleijel H, Thorsson S (2015) Transpiration of urban trees and its cooling effect in a high latitude city. *International Journal of Biometeorology*. In press. DOI: 10.1007/s00484-015-1014-x

IV. **Konarska J**, Holmer B, Lindberg F, Thorsson S (2015) Influence of vegetation and building geometry on the spatial variations of air temperature and cooling rates in a high latitude city. *International Journal of Climatology*. In press. DOI: 10.1002/joc.4502

V. **Konarska J**, Klingberg J, Lindberg F (2015) Identifying vegetation in near-infrared hemispherical photographs – potential applications in urban climatology and urban forestry. *Manuscript*

The studies were conducted in collaboration with colleagues from: Department of Earth Sciences, University of Gothenburg; Department of Biological and Environmental Sciences, University of Gothenburg; and Faculty of Landscape Planning, Horticulture and Agricultural Science, Swedish University of Agricultural Science.

In **Paper I**, the order of the authors is based on their contribution to data analysis and writing. All field measurements were carried out jointly by Dr Jenny Klingberg and me.

In **Paper II**, the field work was conducted by me and co-authors Annika Larsson and Dr Fredrik Lindberg. I had the main responsibility for data analysis and writing.

In **Paper III**, I carried out all field measurements together with co-author Martina Lutz or with field assistants, Thomas Berg Hasper and Ignacio Ruíz Guzmán. Dr Johan Uddling and Prof. Håkan Pleijel provided help with study design and expertise in plant physiology. I had the main responsibility for data analysis and writing.

In **Paper IV**, I was responsible for the study design and data collection. A field assistant Sandra Cimerman provided help with instrument setup. I did the data analysis, and the writing was performed in the order of the authors' appearance.

In **Paper V**, I had the main responsibility from the study design to image processing, data analysis and writing. Photographs were collected by me together with Dr Jenny Klingberg. Dr Fredrik

Lindberg provided help with the modelling of mean radiant temperature in the SOLWEIG model and Dr Jenny Klingberg performed the calculation of leaf area index in Hemisfer software.

The Papers are reprinted with permission from the respective journals.

Papers not included in the thesis:

Thorsson S, Rocklöv J, **Konarska J**, Lindberg F, Holmer B, Dousset B, Rayner D (2014) Mean radiant temperature – A predictor of heat related mortality. *Urban Climate* 10, Part 2:332-345.

Thorsson S, Rayner D, Lindberg F, Monteiro A, Katzschner L, Lau K, Campe S, Katzschner A, **Konarska J**, Onomura S, Velho S, Holmer B (2015) Outdoor heat stress across European cities – in a climate change perspective. *Submitted to International Journal of Biometeorology*

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ABBREVIATIONS

CR – cooling rate of the air (°C h^{-1})

D – diffuse solar radiation (W m^{-2})

DSM – digital surface model

E_L – leaf transpiration rate (mmol H_2O m^{-2} s^{-1})

G – total solar radiation (W m^{-2})

g_s – stomatal conductance (mmol H_2O m^{-2} s^{-1})

I_h – direct solar radiation (W m^{-2})

LAD – leaf area density (m^2 m^{-3})

LAI – leaf area index (m^2 m^{-2})

L_e – effective leaf area index (m^2 m^{-2})

NIR – near-infrared

PAI – plant area index (m^2 m^{-2})

PCI – park cool island (°C)

SVF – sky view factor, with subscripts indicating the obstruction of sky by buildings (subscript b), vegetation (v), buildings and vegetation (bv), or vegetation in front of buildings (av)

T_a – air temperature (°C)

T_{mrt} – mean radiant temperature (°C)

UHI – urban heat island

WAI – woody area index (m^2 m^{-2})

τ – transmissivity of solar radiation through tree crowns

INTRODUCTION

Urban areas are inhabited by more than half of the world human population, including 86% of the population of Sweden, and the process of urbanisation is expected to continue (UN DESA 2015). Cities exert a strong influence on urban climate, and consequently on human health and wellbeing (Revi et al. 2014). This increases the importance of considering climate issues in urban planning, particularly in the context of the global climate change (Brown et al. 2015). In the Nordic countries the observed and projected rates of warming are among the highest in Europe, with a projected mean air temperature rise in Sweden of 2-5°C by 2100 (Kovats et al. 2014). While in high latitude cities the problem of heat stress is less severe than at mid- or low latitudes, it poses health-related risks due to poor adaptation of northern populations to heat (Rocklöv and Forsberg 2008). Climate-sensitive urban planning in high latitude cities is also challenging due to large seasonal variations in meteorological parameters, mainly solar radiation and air temperature, influencing human thermal comfort.

One of the key adaptation strategies allowing a reduction of climate-related risks in cities, e.g. heat waves, flooding and air pollution, is urban greenery (Bowler et al. 2010; Roy et al. 2012; Andersson-Sköld et al. 2015; Salmond et al. 2015, Thorsson et al. 2015). Urban vegetation can improve various aspects of urban climate (Roy et al. 2012; Demuzere et al. 2014b) at different scales, from a microscale (10 cm – 1 km) to a local scale (100 m – 50 km)(Oke 1987). However, as noted by Nowak and Dwyer (2007), inappropriate planning and maintenance of urban vegetation may lead to a considerable reduction of its services, as well as to some disservices to society. Knowledge about different aspects of the climate regulation provided by urban greenery is thus essential for climate-sensitive planning and management.

The aim of this thesis is to increase understanding of how urban vegetation, from single trees of various common species to parks and woodlands, influences the air temperature and outdoor thermal comfort in a high latitude city, focusing foremost on the microscale effects. The thesis consists of three main parts. In the first part the aim was to describe the urban greenery at various scales in terms of the amount of foliage. In the second part different aspects of the cooling effect of urban vegetation and the resulting intra-urban thermal variations are discussed. The third part deals with the modelling of mean radiant temperature, an important parameter governing human thermal comfort, in vegetated urban areas. The results are also discussed in terms of their application in climate-sensitive urban planning.

BACKGROUND

Urban climate in high latitude cities

Urban areas differ substantially from their surroundings in terms of land use and surface cover, building geometry, the amount of vegetation, as well as human activities. Such radical alteration in the local environment over relatively small urban areas results in the development of an urban climate, a phenomenon studied since 19th century (Howard 1818). The most studied feature of the urban climate is the urban heat island (UHI), i.e. an elevated urban temperature compared to the rural surroundings. However, intra-urban differences of similar or even higher magnitude than UHI are also reported in literature (Oke 1989; Upmanis et al. 1998; Unger 2004; Lindén 2011). Both urban-rural and intra-urban thermal patterns result from spatial variations in how much heat is received and stored during the day, and how quickly it can be released during the night. According to Oke (1987) and Arnfield (2003), in cities of temperate climates these spatial variations are mostly governed by urban geometry, thermal properties of urban materials and, particularly in winter, anthropogenic heat flux. The importance of urban geometry on spatial thermal variations in a high latitude city was also reported by Holmer et al. (2007), who described a two-phase development of nocturnal cooling. Around sunset, in Phase 1, the cooling is controlled by radiative divergence and sensible heat flux, and thus depends on site characteristics, mostly urban geometry. In Phase 2, starting around 3 h after sunset, the turbulent heat transfer diminishes due to decreased wind speed and development of a capping inversion, leading to a slow and spatially homogeneous cooling independent of site characteristics. This two-phase cooling is a common pattern observed in various climate zones, from low to high latitudes (Oke and Maxwell 1975; Chow and Roth 2006; Erell and Williamson 2007).

Urban geometry is often described by sky view factor (SVF), a dimensionless measure of sky obstruction defined as the ratio of radiation received by a planar surface to that received from the entire hemispheric radiating environment (Watson and Johnson 1987). In urban climate studies, SVF has been commonly calculated based on hemispherical photographs. More recently, high resolution digital surface models (DSMs) were used to derive spatial variations in SVF in urban environments (Ratti and Richens 1999; Lindberg 2007; Lindberg and Grimmond 2011). As argued by Unger (2004), the spatial approach allows a consideration of the influence of a wider area and thus is more suitable in the analysis of the intra-urban patterns in air temperature (T_a). High resolution DSMs including ground, buildings and vegetation can be derived from LiDAR data (Lindberg et al. 2013). Aerial LiDAR utilizes a scanning laser mounted on an airplane with an integrated GPS unit to collect 3-dimensional data points and thus provide detailed information about surface geometry, including tree canopies.

While SVF is undoubtedly a major determinant of the micro- and local climate in high latitude cities, several authors, e.g. Eliasson (1996), Upmanis et al. (1998) and Jansson et al. (2007), reported intra-urban thermal variations at high latitudes related to urban greenery.

Urban greenery and its leaf area

Urban greenery has been recognized to provide a number of ecosystem services, with environmental, social, economic, psychological, medical and aesthetic benefits to human population (Roy et al. 2012; Gómez-Baggethun and Barton 2013; Salmond et al. 2015). One of these services is the improvement of urban climate, e.g. by moderating the air and surface temperature (Bowler et al. 2010; Shashua-Bar et al. 2011), storm-water runoff attenuation through rainwater interception and soil infiltration (Roy et al. 2012), carbon storage, as well as noise reduction and improvement of air quality through absorption of gaseous pollutants and interception of particles (Nowak et al. 2006, Demuzere et al. 2014b). Most of these ecosystem services, including urban temperature regulation (Hardin and Jensen 2007; Lin and Lin 2010; Gillner et al. 2015), depend on the amount of foliage, often described as leaf area index (LAI). LAI is defined as one-sided leaf area in a canopy per unit ground area (Asner et al. 2003). Since the direct measurements of LAI are labour-intensive and often destructive in nature (i.e. trees are cut down for sampling), indirect methods based on light attenuation by vegetation canopies are widely used. However, unless corrections are made, these optical methods cannot distinguish leaves from stems and branches. LAI estimated optically is commonly referred to as effective leaf area index, L_e or – when corrected for the non-random distribution of canopy elements (clumping) – plant area index, PAI (Jonckheere et al. 2004).

The indirect methods were mostly developed for forest studies and are often difficult to apply in urban areas due to the presence of buildings and the lack of a continuous tree cover. In cities, trees are exposed to different stress factors than in forests, e.g. high evaporative demand and poor infiltration of rainwater into the soil due to surrounding impermeable surfaces (Roberts 1977; Sieghardt et al. 2005), thus L_e estimates of forest canopies may not accurately describe urban trees. However, despite the importance of accurate estimates of leaf area of urban greenery for the valuation of ecosystem services or for micro- and local climate modelling, such estimates are scarce. Recent studies indicated a potential of using LiDAR data to model L_e over larger areas, including urban environments (Richardson et al. 2009; Alonzo et al. 2015).

Thermal effect of urban greenery

Urban vegetation provides a cooling effect at street level due to shading and evapotranspiration. By providing a shadow, trees and bushes limit solar radiation reaching the ground and buildings, while also decreasing long-wave radiation fluxes emitted by the shaded and thus cooler surfaces. In the process of evapotranspiration – a combination of evaporation of water from wet surfaces and transpiration of water from plants to air through leaf stomata – the daytime air temperature is reduced by converting solar energy into the latent rather than sensible heat flux (Shashua-Bar et al. 2011).

Since the shading effect is only provided during the day and evapotranspiration occurs mostly during daytime due to incoming photosynthetically active radiation and a higher evaporative demand of the air, a stronger cooling potential of trees and parks could be expected during daytime than night-time. However, as suggested by Spronken-Smith and Oke (1998), the timing of the maximum cooling effect of parks, often referred to as a park cool island (PCI), depends on park characteristics, mainly tree cover, with densely vegetated parks exhibiting the strongest cooling during the day, and open parks – during the night. This can be attributed to the fact that a dense tree cover, which favours the development of a strong daytime PCI, limits its intensity at night-time due to hindering long-wave radiation loss and turbulent heat exchange (Spronken-Smith and Oke 1999). An opposite diurnal pattern was observed in a hot, arid city of Ouagadougou, Burkina Faso (Lindén 2011), where the intensive nocturnal cooling effect of highly vegetated areas was attributed to so-called midday depression of the leaf stomata – a water conservation strategy of plants by limiting the transpiration during the hottest part of the day and opening the stomata in the evenings (Gao et al. 2002). However, night-time transpiration in cooler climates is often assumed to be negligible (Daley and Phillips 2006), with little research done particularly regarding urban trees. Despite the fact that human activities, including the use of urban green areas, are concentrated during daytime, nocturnal cooling effect of vegetation is of high importance, as it could potentially provide a relief from heat during hot summer nights and thus decrease the heat-related mortality (Rocklöv et al. 2010).

PCI intensity varies also throughout the year. While in most studies the focus is on summertime (Bowler et al. 2010), in those few conducted in different seasons, PCI was found to be more pronounced in summer than winter (Chang et al. 2007; Cohen et al. 2012).

Compared to urban parks, the cooling effect of which can extend into the surrounding areas (Upmanis et al. 1998; Hamada and Ohta 2010), single urban trees provide a limited reduction of T_a both in scale and intensity. However, in many studies a strong influence of single trees on short- and long-wave radiation in their shadow was reported (Oke 1989; Akbari et al. 2001; Streiling and Matzarakis 2003; Mayer et al. 2009; Shashua-Bar et al. 2011). While most studies focus on the shading effect of foliated trees and its positive influence on summertime outdoor thermal comfort, wintertime shading effect needs a careful consideration in high latitude cities due to the limited access to sunlight during the cold season. Knowledge about the inter-species differences in the cooling effect of urban trees is also necessary in climate-sensitive planning.

Modelling of mean radiant temperature

As mentioned above, even single urban trees can significantly affect the radiative environment by reducing both incoming short-wave and outgoing long-wave radiation fluxes in their shadow. As a result, the mean radiant temperature (T_{mrt}), which sums up radiation fluxes to which the human body is exposed, is significantly decreased. T_{mrt} is defined as "the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure" (ASHRAE 2001), and is an important parameter in human energy balance, particularly during clear, warm weather. The most accurate method of deriving T_{mrt} is based on measurements of 3-dimensional radiation fluxes (Thorsson et al. 2007). T_{mrt} can also be estimated in urban microclimate models, e.g. ENVI-met (Bruse and Fleer 1998), RayMan (Matzarakis et al. 2007) or SOLWEIG (Lindberg et al. 2008). In SOLWEIG, the calculations of radiation fluxes and thus T_{mrt} are based either on point input data in form of hemispherical images or high resolution DSMs including ground, buildings and, if available, trees. Including a vegetation scheme was found to greatly improve the performance of the SOLWEIG model (Lindberg and Grimmond 2011). Due to the difficulty in distinguishing trees from buildings in standard hemispherical images recording visible light, a vegetation scheme has not yet been developed for the 1-dimensional version of the model. However, substantial differences in the reflectivity of buildings and trees in the near-infrared (NIR) spectrum indicate a potential use of NIR photography in urban climate studies.

AIM OF THE THESIS

The overall aim of the thesis is to investigate climate regulation provided by urban greenery in a high latitude city, focusing on the thermal effect of single trees and parks. Specific objectives are to:

a. Describe urban greenery in terms of leaf area index using ground-based measurements and LiDAR estimates (**Papers I, V**);
b. Investigate the cooling effect of urban trees of different species due to shading and transpiration (**Papers II, III, IV**);
c. Analyse intra-urban variations in air temperature and cooling rates, with focus on the effect of urban vegetation and building density (**Paper IV**);
d. Improve the modelling of the mean radiant temperature in vegetated urban areas by parameterization of transmissivity of solar radiation through the tree crowns and the usage of near-infrared hemispherical photography (**Papers II, V**).

STUDY AREA

The field measurements presented in this thesis were conducted in the city of Gothenburg, Sweden (57°42’N, 11°58’E, Fig. 1). A considerable number of studies on urban climate have been done in Gothenburg, including several studies focusing on the influence of urban greenery on intra-urban thermal variations (Eliasson 1996; Upmanis et al. 1998; Upmanis and Chen 1999; Eliasson and Svensson 2003; Svensson et al. 2003) and outdoor thermal comfort (Thorsson et al. 2004; Eliasson et al. 2007; Knez and Thorsson 2008; Lindberg and Grimmond 2011; Lindberg et al. 2014).

Founded in 1621, Gothenburg is the second largest city in the country, with a population of 533 000 (SCB 2013). It is located on the west coast of Sweden, at the mouth of the Göta river. The joint aligned valley landscape of the area results in a varying topography in the city, with broad valleys and hills reaching 100 m above the sea level.

The oldest, central part of the city is characterized by a dense building structure with mostly low-rise (2-3 stories) and mid-rise (3-5 stories) buildings and narrow street canyons. While there are several parks and green areas near the city centre, street trees are relatively scarce. Farther away from the city centre, the building structure is less compact, with numerous single trees and green areas. In total, 30% of the city area is built-up (SCB 2010), while green areas with a size of ≥ 1 ha constitute 55% of the area. More than half of the city dwellers live within a 300 m distance from a green area of ≥ 10 ha.

Gothenburg has a maritime temperate climate (*Cfb* in the Köppen classification). Due to the coastal location, summers are relatively cold and winters relatively warm for this latitude, with an additional warming influence of the Gulf Stream in winter. The mean diurnal T_a ranges from -1.1°C in February to 17.0°C in July, and the mean annual precipitation is 758 mm (SMHI 2015, data from 1961-1990). Due to the high latitude, the length of daylight varies considerably throughout the year, from around 6 h in December to 18 h in June.

Gothenburg is located near the border of two vegetation zones – the hemi-boreal zone dominated by conifers, and the nemoral zone characterised by temperate, deciduous forests. In the urban woodlands in and around the city, the portion of conifers and deciduous trees is comparable (Gundersen et al. 2005). However, park and street trees are mostly deciduous, with *Tilia* (lime) being the dominant genus (Sjöman et al. 2012). Deciduous trees usually foliate in April-May and defoliate around October in this area.

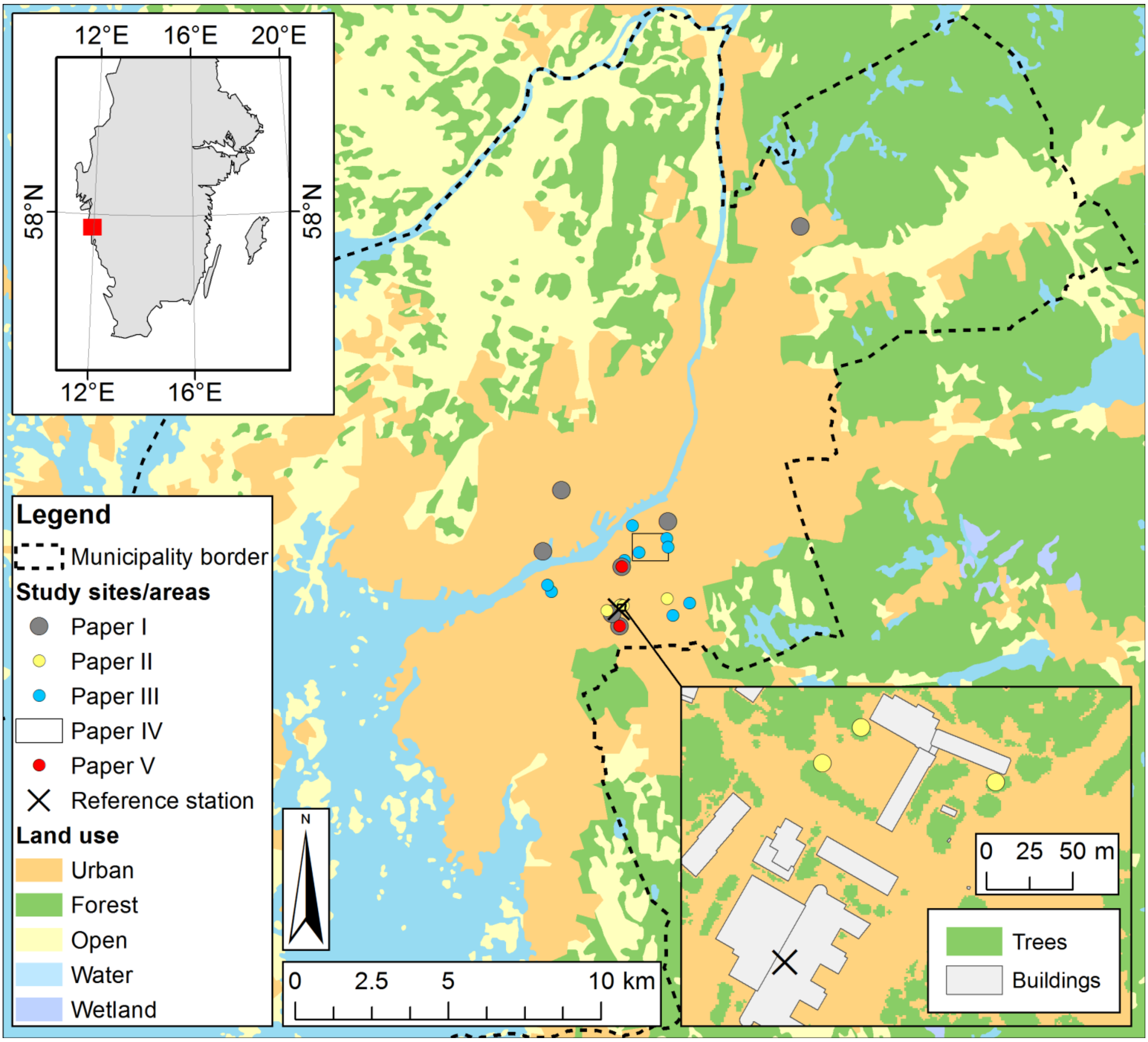

Figure 1. Map of the Gothenburg municipality covering the study sites from Papers I-V. For clarity, the area covering all measurement sites from Paper IV was shown instead of the ten sites. 'Urban' land use type includes built-up area as well as urban parks and forests.

DATA AND METHODS

Most of the data presented in this thesis were collected during extensive fieldwork conducted between May 2010 and September 2015. The measurement sites in **Papers I-V** represent different types and scales of urban greenery, from single trees (**Papers I-IV**), to parks (**Papers I, IV, V**) and woodlands (**Papers I, V**). An overview of the measurements is shown in Table 1, followed by a short summary of the data and methods. Detailed descriptions of the study sites, measurements and data analysis are presented in **Papers I-V**. Photographs of the instrument setup during various field measurements are shown in Figure 2.

FIELD MEASUREMENTS

Leaf area

In **Paper I**, focusing on the leaf area of urban vegetation, seven study areas were chosen to represent different types of urban greenery – a suburban forest, an urban woodland, urban parks, gardens as well as greenery within residential areas or between traffic infrastructure. In addition, single street trees of six species common in Gothenburg and other high latitude cities were measured: common lime (*Tilia europaea*), English oak (*Quercus robur*), silver birch (*Betula pendula*), Norway maple (*Acer platanoides*), horse chestnut (*Aesculus hippocastanum*) and Japanese cherry (*Prunus serrulata*). At each site, effective leaf area index (L_e) was measured using two indirect methods based on gap fraction analysis: a Li-Cor LAI-2200 Plant Canopy Analyzer and hemispherical photography. Since unlike in homogeneous forest canopies, L_e of single trees varies depending on the position within their canopy, in their case leaf area density (LAD, m^2 m^{-3}, one-sided leaf area per unit canopy volume) was calculated instead.

Shading effect of single trees

Tree shading effect was investigated during field measurements conducted on single street trees of five common species: small-leaved lime (*Tilia cordata*), horse chestnut (*Aesculus hippocastanum*), silver birch (*Betula pendula*), cherry (*Prunus* sp.) and European black pine (*Pinus nigra*). Five fully grown tree individuals located at relatively open sites were chosen for the study. The shading effect was estimated by simultaneous measurements of solar radiation under the studied tree and at an open reference site, from morning to evening hours. Based on the above and below canopy readings from the two sunshine pyranometers, transmissivity of solar radiation through the tree canopy (τ) was calculated. To analyse seasonal differences in the shading effect, measurements were conducted for both foliated and defoliated trees. In addition, 3-dimensional radiation fluxes were measured at three of the study sites to calculate T_{mrt} in the shadow of foliated and defoliated trees.

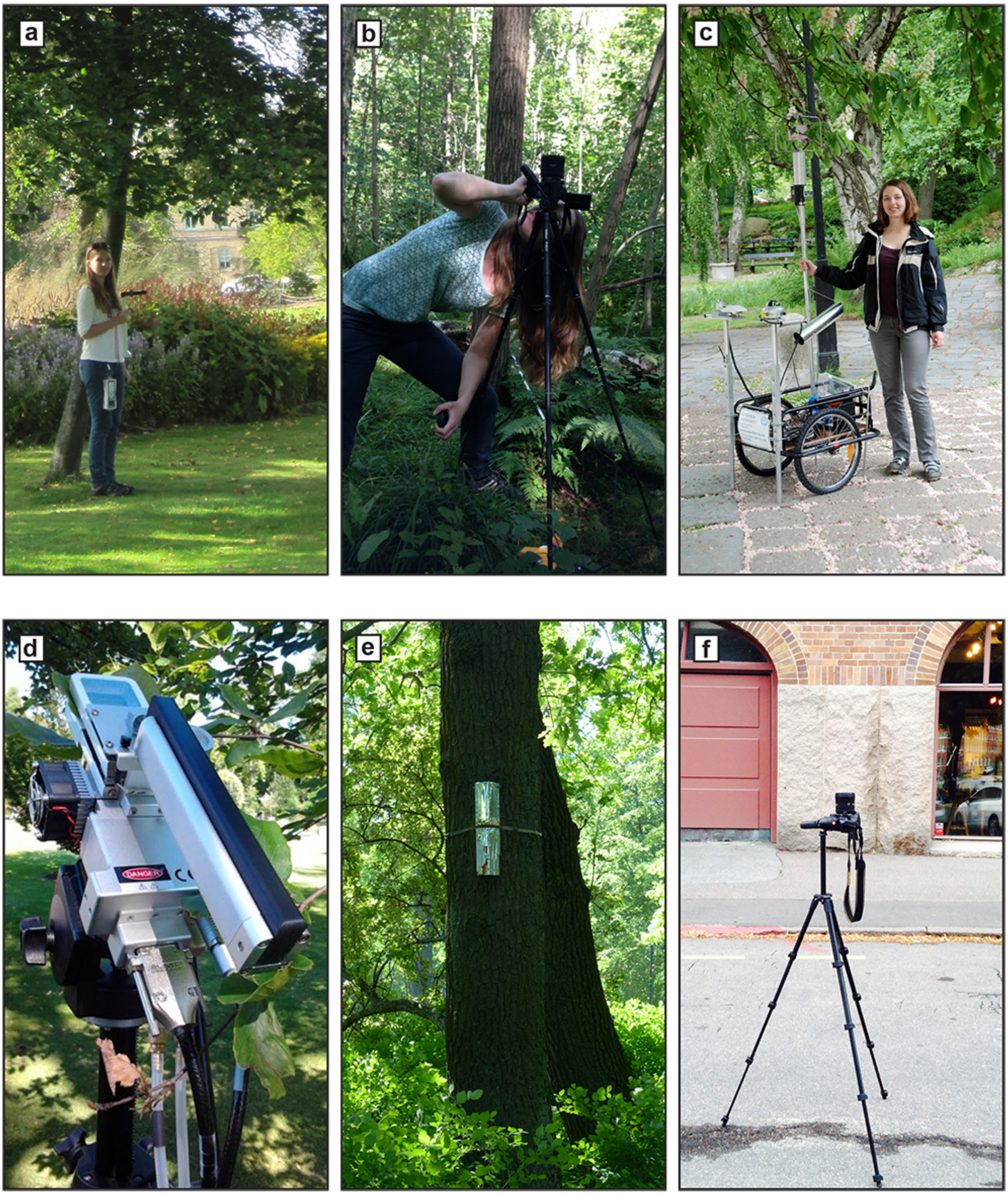

Figure 2. Instrument setup during fieldwork campaigns focusing on: a) effective leaf area index measured with a Li-COR LAI-2200 Plant Canopy Analyzer; b) effective leaf area index measured using hemispherical photography c) tree shading effect measured with SPN1 sunshine pyranometers; d) tree transpiration measured with a Li-COR 6400XT Portable Photosynthesis System; e) intra-urban thermal variations measured with TinyTag Plus 2 air temperature loggers; f) total and partial sky view factors calculated based on near-infrared hemispherical photographs.

Table 1. Overview of the field measurements used in Papers I-V. The parameters measured include: total (G) and diffuse (D) solar radiation; air temperature (T_a); mean radiant temperature (T_{mrt}); leaf transpiration rate (E_L); stomatal conductance (g_s); sky view factor (SVF); leaf, woody and plant area indexes (LAI, PAI, WAI, respectively), and effective leaf area index (L_e).

Paper	Focus of the study	Field measurements		
		Parameters measured	Sites	Period
I	Leaf area	L_e	Seven types of urban greenery	July-August 2014, March and June 2015
II	Shading effect of single trees	G, D T_{mrt}	Five single street trees of different species	Six winter and nine summer days in 2010-2012
III	Tree transpiration and its cooling effect	E_L, g_s T_a L_e	Nine sites with street and park trees of different species	July 2012, July-September 2013
IV	Intra-urban thermal variations	T_a SVF	Six park sites, three street sites and one open site	January 2012-December 2013
V	Applications of NIR hemispherical photography	SVF LAI, PAI, WAI	Urban woodland, urban old park	March, June and September 2015

Urban tree transpiration

In **Paper III**, transpiration of street and park trees of seven species common in Gothenburg and other high latitude cities was measured on warm summer days using a Li-Cor LI-6400XT Portable Photosynthesis System. Measurements were conducted on single street trees studied in **Paper I**, as well as European beech (*Fagus sylvatica*) and common lime (*Tilia europaea*) park trees. Since one of the aims was to analyse the influence of surrounding surfaces on tree transpiration, the studied trees were chosen to represent different types of tree growing conditions in urban areas – from small pits with soil surrounded by impervious surfaces, to grass lawns of different width, to park sites. Four to six individuals of each species were measured. To study the diurnal variation of tree transpiration, measurements at each site were conducted during daytime and night-time. On four occasions, continuous hourly measurements lasting from around noon until a few hours after sunset were conducted. In addition, T_a was measured at each site using a TinyTag Plus 2 logger.

Intra-urban thermal variations

In **Paper IV**, intra-urban thermal variations were studied based on T_a measurements conducted at ten sites located in two urban parks and at their surrounding built-up areas near the city centre. The measurements points were chosen to represent a varying type and amount of vegetation, building density as well as openness. T_a was simultaneously recorded by ten TinyTag Plus 2 loggers with accuracy of ±0.5°C (Gemini Data Loggers, Chichester, UK). An inter-comparison of all loggers in a climate chamber before and after the field measurements showed a narrow range of values (from 0.15-0.20°C in ambient T_a of 10-20°C, to less than 0.30°C in ambient T_a below -10°C), indicating accuracy higher than reported by the manufacturer. All loggers were calibrated to avoid systematic errors in the measurement data. During the field measurements, the loggers were located in naturally ventilated radiation shields, on the northern side of tree trunks or lamp poles, at heights of around 2.2

m above the ground. Measurements were conducted continuously for two years (2012-2013) with a temporal resolution of 5 minutes. Data from all loggers were collected every 10 days to reduce the risk of data loss in case of a malfunctioning or stolen instrument.

Based on the simultaneous T_a measurements, park cool island (PCI) was calculated as the difference in daytime maximum or night-time minimum T_a between street and park sites. Mean T_a among street sites and park sites were used in the analysis. While the term ‘park cool island’ may suggest negative values used to describe park being cooler than the surroundings, PCI is commonly calculated as $T_{a\ urban} - T_{a\ park}$ (Spronken-Smith and Oke 1999; Chow and Svoma 2011; Brown et al. 2015). For consistency, the same calculation method was used in this thesis, with positive values indicating the park being cooler than the surrounding built-up areas.

Near-infrared hemispherical photographs

The camera used to collect hemispherical photographs in **Paper I**, a Nikon D5100, was converted to obtain images in both visible and NIR bands of the electromagnetic spectrum, which allowed differentiation of green plant elements from tree stems, branches and other objects (e.g. buildings) in the photographs. Throughout the thesis, these dual-wavelength photographs are referred to as NIR photographs. Images collected at two sites studied in **Paper I** (the urban woodland and the urban old park) were reanalysed in **Paper V** using the NIR channel of the image to correct the leaf area estimates for the interception of light by woody plant elements and buildings. Based on photographs taken in foliated and defoliated conditions, plant (PAI), leaf (LAI) and woody (WAI) area indexes were estimated.

Additional photographs were also taken at various urban sites for the calculation of partial SVFs accounting for the obstruction of buildings and sky separately.

Reference weather station

In addition to data collected during field measurements, in **Papers II-IV**, meteorological data (air temperature and humidity, solar radiation, wind speed, precipitation and atmospheric pressure) with a temporal resolution of 10 minutes were collected from an automated weather station located around 2 km south from the city centre, on the roof of the Department of Earth Sciences.

DATA ANALYSIS

In **Papers I-IV** measurement data were used to analyse spatial and/or temporal variations of L_e or LAI (**Papers I and V**), solar radiation (**Paper II**), T_a (**Papers III, IV**) and T_{mrt} (**Paper II**). In **Papers III** and **IV**, T_a data were used to calculate cooling or warming rates, i.e. T_a change per hour. Cooling rates were analysed in two phases – Phase 1 of intensive, site-dependent cooling around sunset, and Phase 2 of weaker, spatially homogeneous cooling later at night. Both phases are described in more detail in **Papers III** and **IV**. In **Paper IV**, spatial variations in T_a and cooling rates were analysed in two types of weather conditions – clear, calm and cloudy, windy, divided based on meteorological data recorded at the reference weather station. Data were also divided into a warm (May-September) and cold (November-March) seasons, with October and April excluded from the analysis due to changes in tree foliation. Simple and stepwise multiple regressions were performed to analyse the relationship between spatial characteristics and intra-urban thermal variations in different seasons and weather groups.

Spatial analysis

In all papers except **Paper II**, LiDAR data obtained from Gothenburg Municipality were used to calculate various spatial characteristics describing buildings and vegetation. The data were sampled in October 2010 with a flight altitude of 550 m and the mean pulse density of 13.65 m^{-2}, with the purpose of creating a high resolution ground and building DSMs. The pulse returns were classified into ground, vegetation, buildings etc. by the data provider. In **Paper I**, these data were used to model leaf area at various scales and in several spatial resolutions.

A gridded digital elevation model as well as three surface models including building heights, canopy heights and trunk heights (the lower limit of the tree canopy) were derived from the classified LiDAR files. The process of the development of the surface models was described in Lindberg et al. (2013). These surface models were used in **Papers II, IV** and **V** to calculate SVFs and/or various spatial characteristics describing buildings and vegetation. For each pixel, SVFs accounting for the obstruction of sky by buildings (SVF_b), vegetation (SVF_v) or both (SVF_{bv}), as well as trees in front of buildings (SVF_{av}) were calculated.

Image processing

Hemispherical photographs were used to calculate total and partial SVFs in the SOLWEIG model (**Papers II-V**) and L_e in the software Hemisfer 2.11 (Schleppi, WSL) (**Papers I, V**). In **Paper V**, NIR hemispherical photographs were processed in MATLAB R2013a software to classify pixels into sky, green and woody plant elements, and other objects (e.g. buildings). An example of an input photograph and the classified image is shown in Figure 3. The classified images were further used in the SOLWEIG model to calculate total and partial SVFs described in the previous section, and in Hemisfer to calculate L_e unbiased by the interception of light by woody plant elements.

Modelling of mean radiant temperature

SOLWEIG (the SOlar and Longwave Environmental Irradiance Geometry) is a model simulating spatial variations of shadow patterns, radiation fluxes and T_{mrt} in complex urban settings (Lindberg et al. 2008). The model has two versions: 1-dimensional (SOLWEIG 1D), where SVF is calculated from hemispherical photographs or specified by the user, and 2.5-dimensional (SOLWEIG 2015a), with SVF calculations based on input DSMs. In the former version both input and output data are provided for a given point, while in the latter input data are in a form of a grid with height attributes (hence 2.5 dimensions), providing 2-dimensional output values.

In this thesis both versions of the model were used to simulate T_{mrt}. In **Paper II**, transmissivity of solar radiation through tree crowns was parameterized in the 2.5-dimensional model based on the observed values. In **Paper V**, radiation fluxes from buildings and trees were calculated based on partial SVFs, which can be derived from post-processed NIR hemispherical images.

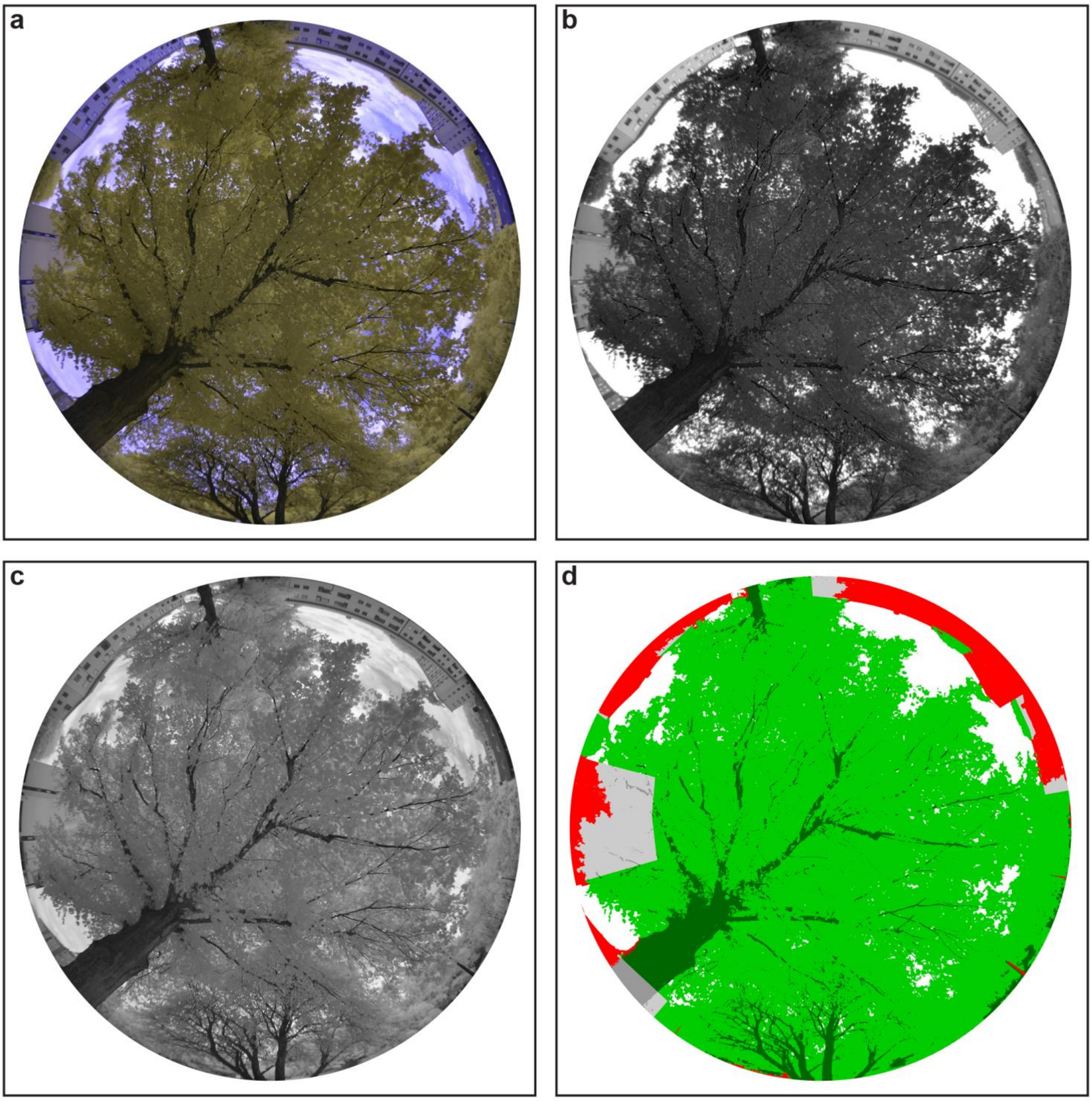

Figure 3. An example of a dual-wavelength hemispherical photograph taken under an urban tree (a), with visible blue light recorded in the blue channel (b) and near-infrared (NIR) in the green and red channels (c, data from the red channel showed). Subplot d shows a post-processed image with pixels classified as sky (white), buildings (red), and leaves and woody plant elements obstructing sky (light and dark green) or in front of buildings (light and dark grey). Figure source: Paper V (modified).

RESULTS

LEAF AREA OF URBAN GREENERY

The amount of foliage is an important control of the climate regulation provided by urban greenery. While **Papers II-IV** focused on the thermal effect of urban trees and parks, in **Paper I** the aim was to describe urban greenery itself in terms of its foliage area.

Mean L_e varied significantly between the seven types of urban greenery included in the study, from 2.6 in residential green yards to 4.5 in the urban woodland. Large variations in the amount of foliage were also observed in single trees, with mean LAD varying from 0.7 m^2 m^{-3} for common limes to 1.6 for English oaks. These variations emphasise the importance of detailed estimations of L_e for urban applications, e.g. microclimate modelling. Interestingly, in case of single trees, the crown density described by LAD showed a significant positive correlation ($R^2 = 0.61$, $p < 0.05$) with the fraction of permeable surfaces within their vertically projected crowns.

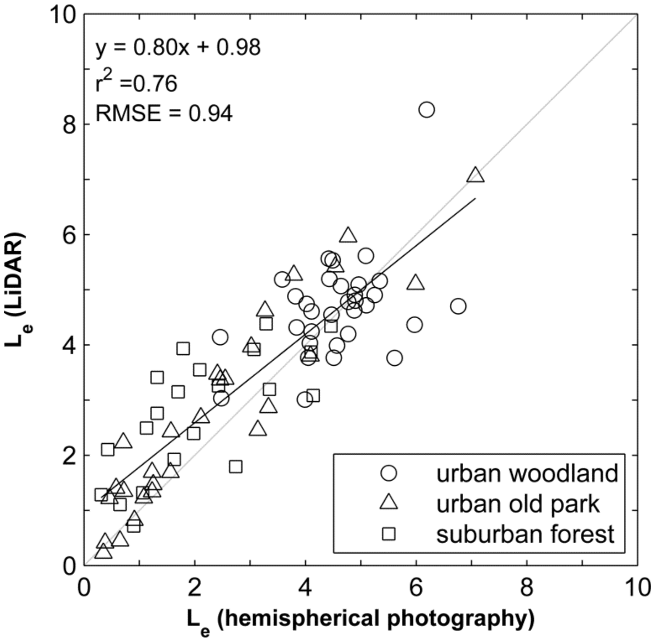

Figure 4. Effective leaf area index (L_e) in three green areas in Gothenburg, Sweden, measured using hemispherical photography versus modelled based on LiDAR data. Figure source: Paper I (modified).

In overcast conditions, both ground measurement methods – Li-Cor LAI 2200 Plant Canopy Analyzer and hemispherical photography – gave comparable estimates of L_e ($R^2 = 0.87$, $p < 0.001$). However, the results showed a sensitivity of both methods to light conditions, with erroneous estimates during clear or partly cloudy weather. These errors were caused by the reflection of light by sunlit leaves (leading to an underestimation of L_e by LAI-2200 by 13% in the urban woodland, **Paper II**) as well as difficulties in distinguishing sky and canopy pixels on hemispherical photographs (leading to an overestimation of L_e using hemispherical images by 10% in the urban woodland). Due to these difficulties, it was of interest to investigate if a LiDAR dataset could be used to map L_e at different scales in an urban environment, from single trees to the whole municipality. Despite the fact that the scanning angle and pulse density of the LiDAR data were not optimised for vegetation mapping, a comparison of ground-based measurements and LiDAR-based estimates showed that LiDAR data can produce reasonable L_e values at various scales and in different types of urban greenery (Fig. 4).

When aggregated over larger scales (from 250x250 m to 1x1 km) and averaged over both vegetated and non-vegetated areas, the spatial variations in L_e were found to be related to tree cover rather than differences in foliage density or canopy height (Fig. 5, filled dots). Tree fraction explained 97% of variance in L_e, indicating that at these scales it can be a good estimate of the mean L_e. However, for many applications mean L_e of trees, forest canopies or green areas rather than an average over an entire tile (e.g. 1x1 km) is needed. When averaged over only vegetated grids (Fig. 5, empty dots), spatial variations in L_e became evident and therefore structural parameters such as mean tree canopy height (Fig. 5a) and total tree volume (**Paper I**) explained more (73-74%) of variation in L_e than tree fraction (60%).

The results indicate that the use of LiDAR data can considerably increase the available information about the structure of urban greenery at various scales.

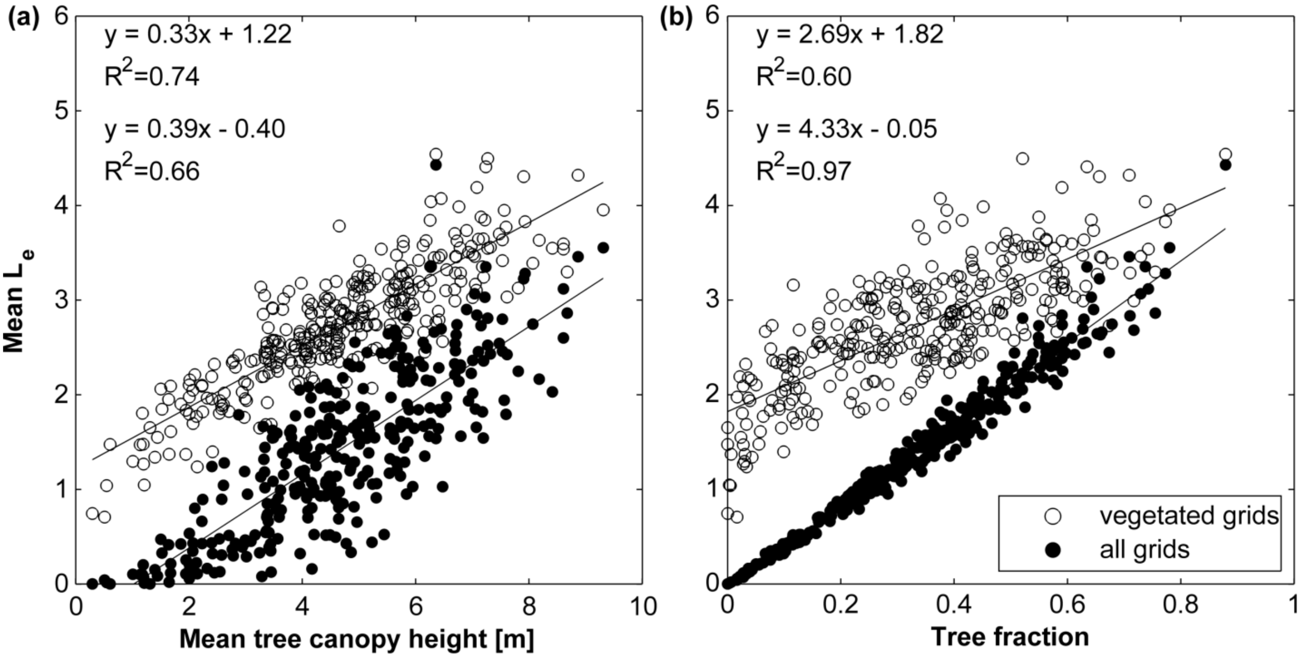

Figure 5. Mean effective leaf area index (L_e) based on LiDAR in 5 m resolution compared to average tree canopy height (a) and tree fraction (b) for 325 1x1 km^2 tiles covering the Gothenburg municipality. Empty dots represent L_e averaged over the vegetated grids within each tile, while filled dots represent L_e averaged over the entire tiles. All correlations are significant at 0.001 level. Figure source: Paper I (modified).

In **Paper V,** NIR hemispherical photographs taken in the urban woodland and the urban old park from **Paper I** were reanalysed to correct the obtained values for the light interception by stems, branches and buildings, allowing the calculation of PAI (i.e. L_e corrected for clumping of canopy elements), LAI and WAI. LAI was found to be only 3-4% lower than PAI. WAI estimated from NIR pictures taken in summertime amounted to only 21% of WAI calculated based on pictures taken in wintertime, suggesting that in fully leaved conditions most of the stems and branches were preferentially masked by leaves, and thus biased LAI estimates to a small extent. The influence of buildings on the estimated PAI was also small due to the fact that the buildings occupied only a small part of the images taken in the urban old park, with no buildings in the urban woodland. The possibility of excluding building pixels based on the NIR channel would, however, prove useful in the measurements of e.g. single trees in dense street canyons, where buildings occupy a large portion of the hemispherical images.

THERMAL EFFECT OF URBAN GREENERY

The cooling effect of single trees through shading and transpiration were studied in **Papers II** and **III**, respectively. Intra-urban thermal variations (**Paper IV**), partly resulting from the presence of vegetation, will be described in the subsequent section.

Shading effect – transmissivity of solar radiation

The measurements of transmissivity of solar radiation through crowns of single urban trees showed that the foliated trees were almost impermeable for solar radiation (**Paper II**). On average, only 8-15% of the total solar radiation and 1-5% of its direct component reached the ground in the tree shadow. The transmissivity values of foliated trees showed small diurnal variations (Fig. 6) and differences between species, indicating that a constant transmissivity parameter could be used in the modelling of solar radiation fluxes in vegetated urban areas.

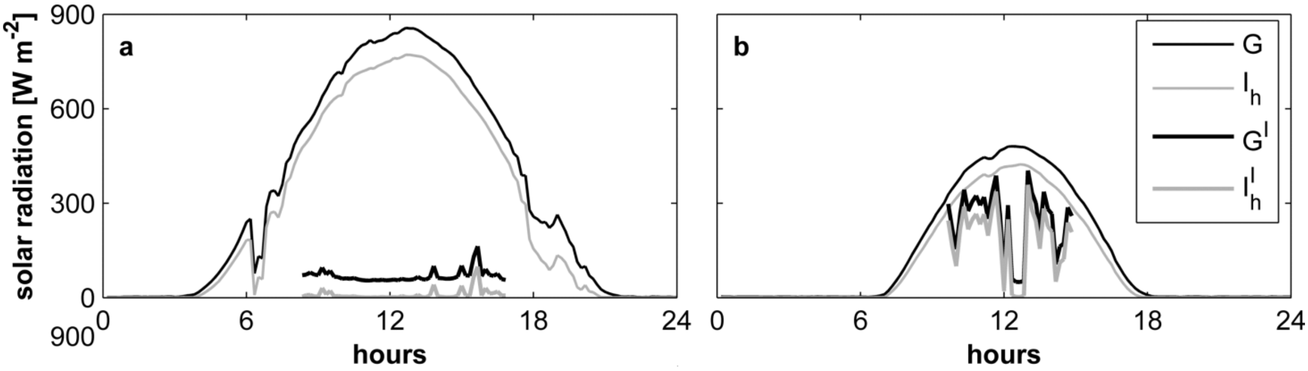

Figure 6. Diurnal course of total (G) and direct (I_h) solar radiation on clear a) summer and b) winter days of 2011 in Gothenburg, Sweden, measured below the canopy of the studied chestnut tree (G’, I_h’), and at a reference site. Figure source: Paper II (modified).

In wintertime, the shading effect of deciduous trees showed a considerable temporal variation, but the mean transmissivity was similar for all studied trees. Despite the crowns being defoliated, they blocked on average 48 to 60% of the direct solar radiation.

The studied cherry tree, which had the highest transmissivity among the studied trees in leaf, blocked the most solar radiation when defoliated. Lime and chestnut showed an opposite seasonal variation, with a strong summertime and a relatively weak wintertime shading effect compared to other studied trees. This suggests that transmissivity should be considered in tree species selection for urban areas, particularly in case of street trees and trees around buildings.

Tree transpiration

In **Paper II**, transpiration rate (E_L) and stomatal conductance (g_s) were measured for street and park trees of seven common tree species. Sunlit leaves transpired three times as intensively as the shaded leaves, indicating an influence of the tree’s access to sunlight on its transpirative cooling effect. Trees growing on wide grass lawns were found to transpire more than those surrounded by impervious surfaces. While the soil moisture was not measured, a strong positive correlation was found between

E_L and estimated available rainwater, calculated as a product of the accumulated rainfall in 20 days prior to measurements and the fraction of permeable surfaces within the vertically projected crown area (Fig. 7). Although this simple measure does not account for the extent of the root systems, soil compaction, soil evaporation and tree interception, it explained over two thirds of the variance in g_s, which controls transpiration and thus regulates the tree water use. The results indicate that trees growing over grass can both develop denser crowns (**Paper I**) and transpire more intensively (**Paper III**) than those surrounded by impervious surfaces.

Tree transpiration is often assumed to be negligible in darkness. However, the measurements of all seven common species studied showed an incomplete stomatal closure after sunset. While E_L became less intensive in the evening with decreasing solar radiation and vapour pressure deficit, night-time transpiration remained active and reached on average 7 and 20% of daytime transpiration rate of sunlit and shaded leaves, respectively, with the highest values observed for those trees which transpired most during daytime.

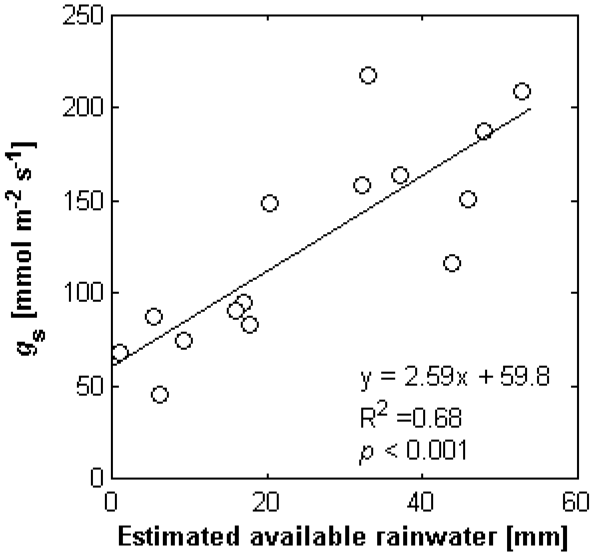

Figure 7. Response of daytime stomatal conductance (g_s) of sunlit leaves to estimated available rainwater, calculated as the product of precipitation sum in 20 days prior to measurements and the fraction of permeable surfaces within the vertically projected crown area. Data are based on measurements conducted on warm summer days of 2012 and 2013 in Gothenburg, Sweden, at urban trees of seven common species. Each point represents a different measurement day. Figure source: Paper III (modified).

Two-phase nocturnal cooling

Based on the leaf gas exchange and T_a data, a significant relationship between E_L and the cooling rate of the air was observed in Phase 1 of nocturnal cooling ($R^2 = 0.51$, $p = 0.03$). On average, with an increase of E_L by 0.1 mmol m^{-2} s^{-1}, cooling rate intensity in Phase 1 increased by 0.25 °C h^{-1}.The transpirative cooling effect in Phase 1 was also indicated by a more intensive cooling at the vegetated sites compared to a non-vegetated reference site with a similar SVF. Later at night (Phase 2), however, the cooling rates were low at both sites, and while the tree transpiration was still active, no correlation with the cooling rate was found.

This two-phase cooling was further studied in **Paper IV** based on simultaneous, two-year T_a measurements at ten urban sites with varying openness and amount of greenery. The temporal development of nocturnal cooling at these ten sites on clear, calm nights is shown in Figure 8.

Statistical analyses showed that the cooling rates in Phase 1 depended mostly on the total SVF (SVF_{bv}), with the open sites – both vegetated and non-vegetated – cooling most intensively (on average -2.0 to -2.4°C h^{-1} on clear, calm nights of the warm season). These relationships were strong (R^2 of 65-86%, $p < 0.01$) in both warm and cold seasons and in different weather conditions. With such a strong control of cooling by SVF, the influence of other factors was limited. However, on clear, calm nights of the warm season, the regression analysis indicated an enhancement of Phase 1 cooling due to the presence of vegetation. A similar effect was not observed on cloudy, windy nights of the warm season, when the trees transpire less intensively, or in the cold season, when they are defoliated. Therefore, the results of both **Paper III** and **Paper IV** indicate a contribution of tree transpiration to nocturnal cooling on warm summer nights.

In Phase 2, the cooling intensity and its spatial variations were low, thus the intra-urban thermal patterns developed in Phase 1 were preserved for the rest of the night. Data analysis in **Paper III** showed that despite active tree transpiration in Phase 2, it no longer contributed to nocturnal cooling. On the contrary, statistical analysis in **Paper IV** showed a weak, but significant negative influence of vegetation on the cooling intensity in Phase 2 in both seasons.

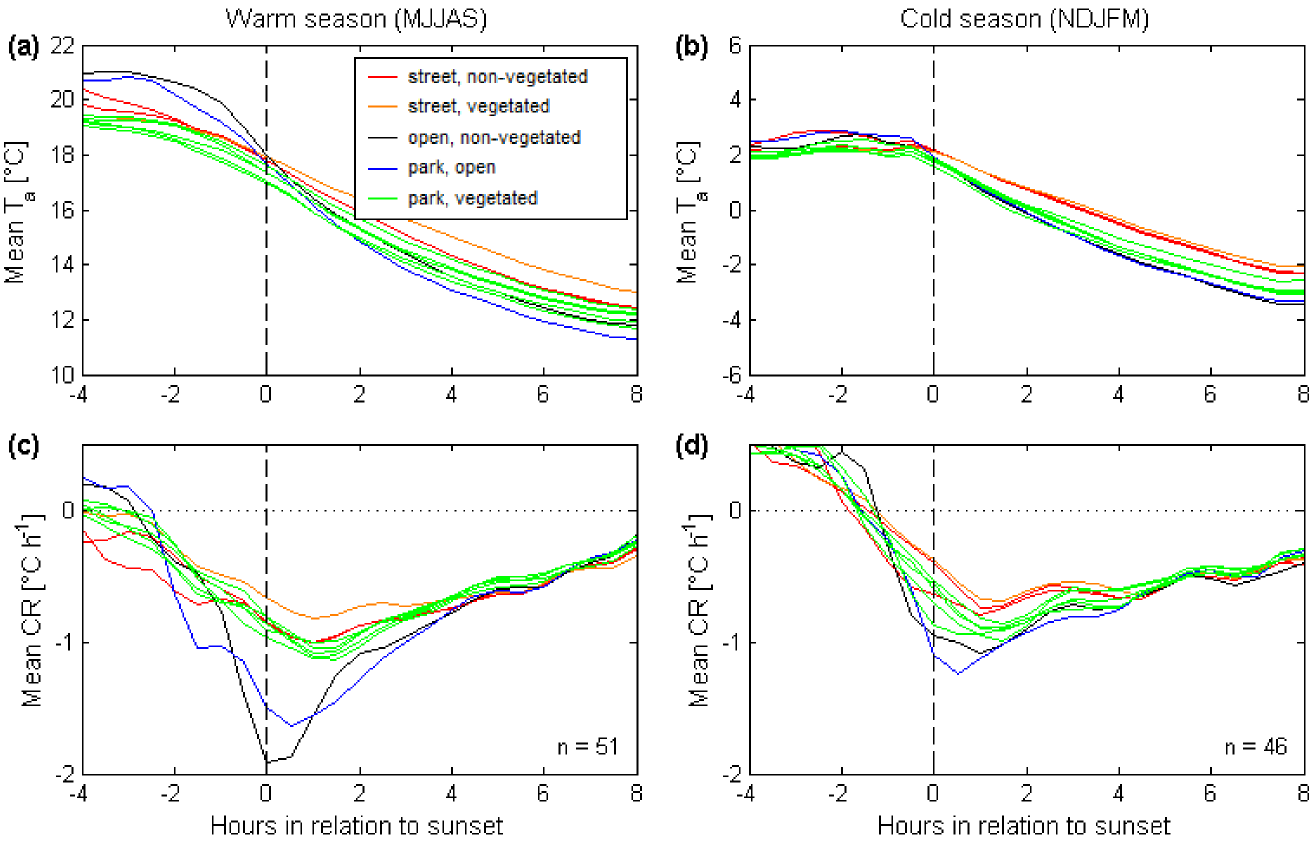

Figure 8. Mean air temperature (T_a, subplots a-b) and cooling rates (CR, subplots c-d) on clear, calm nights of the warm (May-September) and cold (November-March) seasons of 2012-2013 at ten measurement sites in Gothenburg, Sweden. Number of analysed nights in each season (n) is shown in subplots c and d. Figure source: Paper IV (modified).

INTRA-URBAN THERMAL VARIATIONS

In **Paper IV**, intra-urban variations in T_a in relation to vegetation and building geometry were analysed in more detail.

The parks exhibited a cooler microclimate than built-up sites throughout the day and year and in different weather conditions. The park cool island (PCI) was found to be most intensive (0.8°C on average) on clear, calm days of the warm season (Fig. 9). The lowest daytime maximum T_a was observed at densely vegetated sites, and the highest at the two open sites. However, while the open sites warmed up most during the day, they also cooled most intensively during the night due to their high SVF, resulting in a cool nocturnal microclimate.

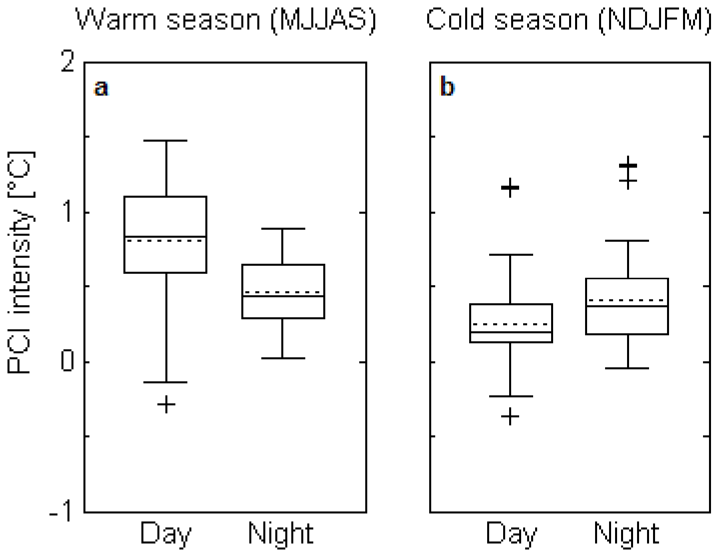

Figure 9. Park cool island (PCI) intensity observed in the warm (a) and cold (b) seasons of 2012-2013 in Gothenburg, Sweden, calculated as the difference in mean daytime maximum or night-time minimum air temperature between street and park sites. Positive values indicate a park cooler than built-up area. On each box, the central solid and dashed lines are the median and mean, respectively, the edges of the box are the 25th and 75th percentiles, and the whiskers show the extreme data points not considered outliers. Figure source: Paper IV.

Throughout the year, night-time minimum T_a was strongly affected by the building density expressed by SVF_b, suggesting the influence of increased heat storage and anthropogenic heat flux in street canyons. Among the street sites, the lowest daytime T_a in the warm season was observed under a street tree, probably mostly due to the strong shading effect (**Paper II**). However, the dense tree canopy limited night-time cooling, resulting in the highest night-time T_a among all sites. In wintertime, due to a leafless canopy, this thermal behaviour was less pronounced. These observations along with the results of multiple regression indicate that in a high latitude city the hindering effect of tree canopies on the evening cooling is stronger than its enhancement by tree transpiration. However, among the sites with similar SVF, the vegetated ones cooled more intensively than those with little vegetation (**Papers III, IV**).

Calculation of sky view factors in vegetated urban areas

The spatial characteristics described in **Paper IV**, used in the site description and regression analysis, were averaged over circular calculation areas. Circular areas of radii ranging from 10 to 150 m were tested. Most of the analyses were conducted based on weighted calculation areas accounting for the influence of the nearest (10 m) and wider (25 m) surroundings, which were found to explain the intra-urban thermal variations to the largest extent.

Total sky view factor (SVF$_{bv}$) was also calculated based on hemispherical photographs taken at the measurement points. It showed a significant relationship with the intra-urban thermal patterns, similar to, although weaker than the spatially averaged SVF.

While SVF$_{bv}$ is an important parameter governing intra-urban thermal variations, the analysis in **Paper IV** showed that the spatial patterns can be explained to a larger extent by considering additional characteristics describing buildings and vegetation, e.g. SVF$_{b}$ and SVF$_{v}$. These characteristics can be calculated based on DSMs describing ground, buildings and vegetation, which, however, are not always available. The differentiation of buildings and vegetation in complex urban environments based on hemispherical photographs recording only visible light is complicated and time consuming, and thus impractical. However, as shown in **Paper V**, NIR hemispherical photographs can be used to easily classify pixels into sky, buildings and vegetation, and thus calculate different SVFs (SVF$_{bv}$, SVF$_{b}$, SVF$_{v}$ and SVF$_{av}$). The method was tested by taking photographs at 16 urban sites with varying building and vegetation density. The obtained values showed a very good agreement with those calculated for the same points based on high resolution DSMs (R^2 of 0.85 to 0.96, Fig. 10). This demonstrates that NIR hemispherical photography can be a useful tool in urban climate studies, e.g. in microclimate modelling (**Paper V**) and in the analysis of intra-urban thermal variations which SVF$_{bv}$ alone cannot explain (**Paper IV**). This good agreement also shows that partial SVFs calculated based on LiDAR-derived vegetation DSMs are modelled accurately, which was earlier difficult to evaluate due to the lack of other calculation methods.

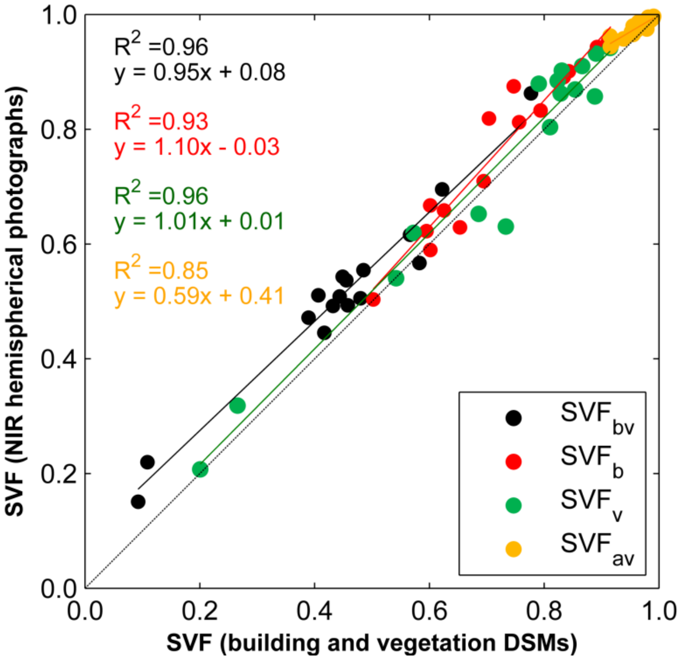

Figure 10. Sky view factors (SVFs) at various points in Gothenburg, Sweden, calculated based on high resolution digital surface models (DSMs) versus SVFs based on near-infrared (NIR) photographs. SVF$_{bv}$ – total sky view factor; SVF$_{b}$ and SVF$_{v}$ – sky view factors accounting for the obstruction of sky by buildings and vegetation, respectively; SVF$_{av}$ – sky view factor accounting for the obstruction of sky by buildings with trees in front of them. Figure source: Paper V (modified).

MODELLING OF MEAN RADIANT TEMPERATURE

Results from **Papers II** and **V** were used to improve the modelling of T$_{mrt}$ in vegetated urban areas in 2.5- and 1-dimensional versions of the SOLWEIG model, respectively.

In **Paper II**, the observed mean transmissivity values were used for parameterisation of the vegetation scheme in 2.5-dimensional version of the SOLWEIG model (Fig. 11). The model was validated against data observed under three of the studied trees; foliated small-leaved lime and horse chestnut, and a defoliated cherry.

Both observations and model results showed that in the shade of a foliated and defoliated tree, respectively, the T_{mrt} was as much as 30°C and 20°C lower than at an exposed site (**Paper II**). While in the summer the decreased T_{mrt} can improve the thermal comfort and reduce the risk of heat stress, in winter even a defoliated deciduous tree can reduce already limited access to sunlight and increase cold stress.

By setting the transmissivity according to the mean values measured in summer and winter, respectively, the model performance was improved, with RMSE of 2.9°C and 5.9°C compared to 7.6°C and 14.0°C with preceding transmissivity settings used in the model (transmissivity of direct radiation of 20% in the summer and 100% in winter). These results emphasise the importance of accounting for the shading effect of trees in microclimate modelling in both seasons.

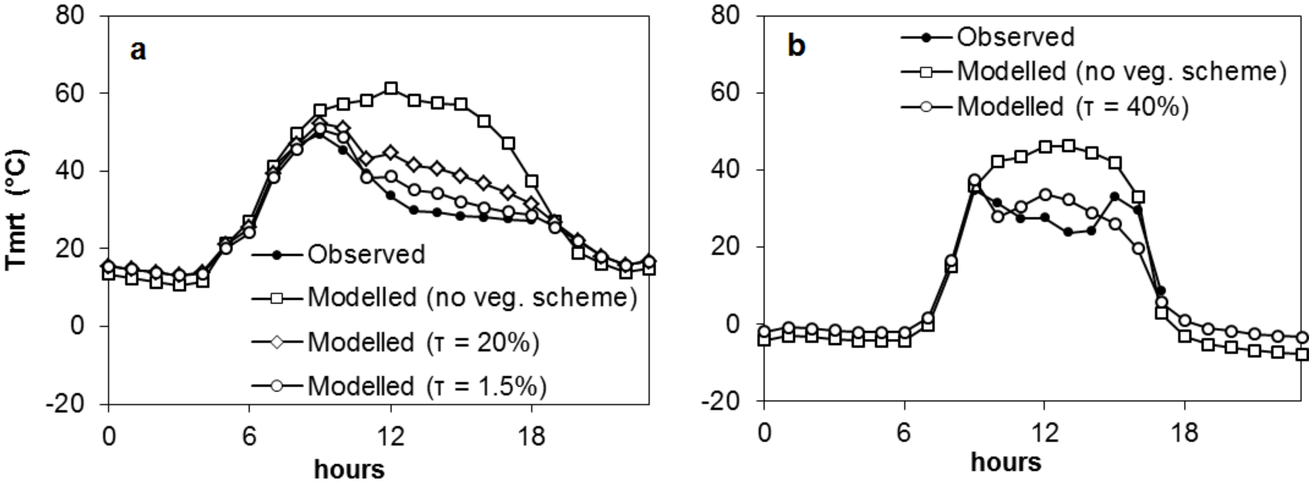

Figure 11. Observed versus modelled values of mean radiant temperature (T_{mrt}) in Gothenburg, Sweden, in the shadow of a) a foliated small-leaved lime on a clear summer day, b) a defoliated cherry on a clear winter day, with different settings of transmissivity of direct solar radiation through the tree crowns (τ). Figure source: Paper II (modified).

In **Paper V**, the 1-dimensional version of SOLWEIG model was used to model point values of T_{mrt}, with partial SVFs, obtainable from NIR hemispherical photographs, as an input. Since hitherto the model did not differentiate between buildings or trees, it was modified to account for the weaker longwave radiation fluxes from trees than sunlit building walls resulting from their lower surface temperature. It should be noted that in the current version of the model, albedo and emissivity of both buildings and trees were set as equal (0.15 and 0.90, respectively) based on the mean values for urban areas (Oke 1987).

A sensitivity test was performed to analyse how modelled T_{mrt} varied with amount of vegetation at sites of different SVF_{bv} (Fig. 12). For each SVF_{bv}, five scenarios with different amount of vegetation placed in front of buildings (covering 0, 25, 50, 75 or 100% of the building wall) were analysed. T_{mrt} was modelled for a point located in Gothenburg, Sweden, using default meteorological settings described in Figure 12 caption.

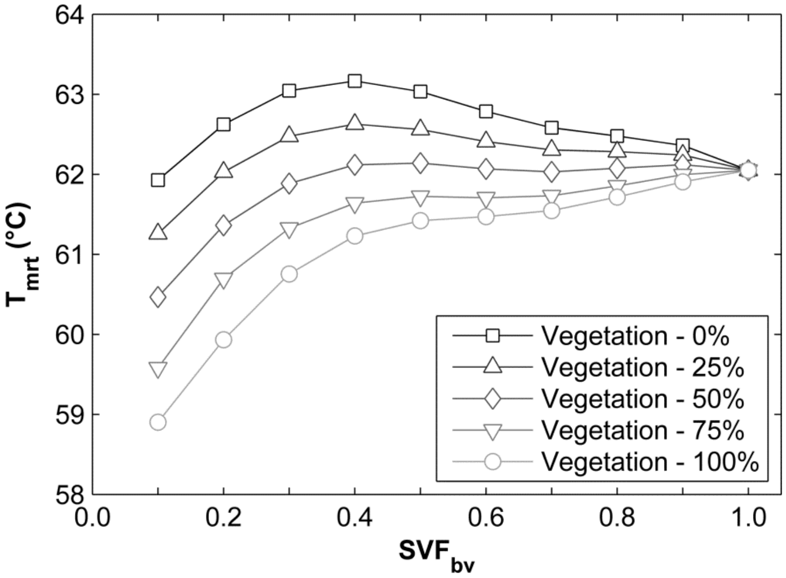

Figure 12. Modelled mean radiant temperature (T_{mrt}) versus total sky view factor (SVF_{bv}), with changes due to added vegetation. T_{mrt} was calculated for Gothenburg, Sweden on the 21^{st} of June 2012 at 12:00 local time, with air temperature of 25°C, relative humidity of 50%, and global, diffuse and direct (perpendicular to the solar beam) radiation of 880, 150 and 950 W m^{-2}, respectively. Figure source: Paper V.

Compared to the reduction of T_{mrt} by the tree shading effect (**Paper II**), the reduction caused by lower long-wave radiation from trees than buildings was relatively small, up to 3°C. Regardless of SVF_{bv}, the highest T_{mrt} was modelled for the case with no vegetation, and with values gradually decreasing with increasing the amount of vegetation (Fig. 12). The largest reduction due to the presence of vegetation was modelled at low SVF_{bv} due to the trees blocking strong long-wave radiation fluxes emitted by the tall building walls.

In the "100% vegetation" scenario, T_{mrt} increased with increasing SVF_{bv} due to strong short-wave radiation fluxes at open sites. On the contrary, in the case with no vegetation, the highest T_{mrt} was modelled at SVF of 0.4. This is caused by the fact that at very low SVF most of the building walls are in shade, and thus the modelled long-wave radiation fluxes are lower than at more open areas where a higher SVF allows a higher fraction of building walls to be sunlit.

DISCUSSION

LEAF AREA OF URBAN GREENERY

The mean L_e of the green areas studied in **Paper I** ranged from 2.6 in residential green yards to 4.5 in the urban woodland. Mean LAI of deciduous and coniferous forest in temperate climates were estimated by Breuer et al. (2003) to 5.4 and 6.3, respectively. The relatively low values obtained in **Paper I** could be caused by the methodology applied, the sampling of LiDAR data in October, when the trees start to defoliate, as well by physiological characteristics of urban trees caused by their exposure to stress factors absent or less severe than in a natural environment (Roberts 1977; Sieghardt et al. 2005). On the other hand, single urban trees can be assumed to have higher LAI than forest trees due to a lower competition for light, unless they are shaded by buildings or subjected to other stress factors, e.g. air pollution or insufficient access to water. In urban areas, access of trees to water is often limited by compacted soils as well as the surrounding impervious surfaces. The results showed that the crown density of single urban trees, described by LAD, was positively correlated with the fraction of permeable surfaces surrounding them.

As discussed in **Paper I**, field measurements of L_e are time consuming and prone to weather-related errors, and thus difficult to conduct over large areas. Moreover, additional difficulties arise in cities because of the presence of buildings and a limited access due to infrastructure or private property. At the same time, information on leaf area of urban greenery is needed as an input parameter in surface energy balance or microclimate models (Bruse and Fleer 1998; Chen et al. 2011) as well as for the valuation of ecosystem services. However, as shown in **Paper I**, LiDAR data can be used to produce accurate estimates of L_e at different scales, from single trees to municipality. Good agreement between ground measurements and LiDAR estimates was also reported by other authors for an urban park (Richardson et al. 2009) or downtown areas (Alonzo et al. 2015). However, while substantial variations in L_e can be observed between different types of urban greenery, when aggregated over larger areas only partly covered by trees, mean L_e was found to depend mainly on tree fraction rather than structural characteristics of the tree canopy. This suggests that while spatial variations of foliage area in different types of urban greenery can be accurately assessed by L_e mapping, simple and more widely available information on tree fraction can be used as a good indicator of mean L_e over larger areas.

A source of bias in indirect measurement of L_e, both using optical sensors (LAI-2200 and hemispherical photography) and laser pulses (LiDAR), is the light interception by woody plant elements. There has been a debate in literature on whether the woody area values should be subtracted from the L_e or PAI estimates (Kucharik et al. 1998; Gower et al. 1999). As shown in **Paper V**, LAI calculated by excluding the woody elements from the analysis based on NIR hemispherical photographs taken in fully foliated park and woodland was lower than PAI by only 0.1, i.e. 3-4%. A reduction of 0.1 was also reported for forest sites in Switzerland by Schleppi et al. (2011). The limited contribution of stems and branches to PAI calculated in **Paper V** indicates that in case of fully foliated canopies, most woody elements are preferentially masked by leaves and thus standard optical methods can be used to obtain reasonable LAI estimates without correcting for the light interception by woody elements. NIR hemispherical photographs can, however, prove useful in the calculation of LAI or LAD of isolated urban trees surrounded by buildings. Measurements on single trees were not included in this study, as the calculation of leaf area of isolated trees is not yet included in the Hemisfer software.

THERMAL EFFECT OF URBAN GREENERY

The results from **Papers II-IV** demonstrated various aspects of the thermal effect of urban greenery. In the warm season, single trees were found to significantly influence daytime thermal comfort by reducing T_{mrt} up to 30°C in their shadow (**Paper II**), yet in terms of T_a the cooling effect of a street tree observed in **Paper IV** reached barely 1°C on clear, calm days of the warm season. A comparable daytime cooling effect of single trees, ranging from 0.5 to 2.2°C, was observed in cities of various climate zones, e.g. in Freiburg, Germany (Streiling and Matzarakis 2003; Mayer et al. 2009), Athens, Greece (Tsiros 2010), Bloomington, Indiana (Souch and Souch 1993) and Campinas, Brazil (de Abreu-Harbich et al. 2015). The reasons behind this limited local reduction of T_a despite shading and transpiration are the strong mixing of the air within the urban boundary layer and its vertical extent up to 1 km or more (Oke 1987), which lead to a rapid dispersion of cooled air (Nowak and Dwyer 2007). At night-time, however, the air is more stable and the nocturnal urban boundary layer can be limited to less than 100 m (Eliasson and Holmer 1990), thus even a weak latent heat flux due to tree transpiration can contribute to nocturnal cooling. Night-time transpiration was observed in trees of all seven common species studied, and results of **Papers III** and **IV** indicated its contribution to nocturnal cooling in Phase 1 on clear, calm nights of the warm season. Evening evapotranspirative cooling was also suggested as a reason behind intensive cooling at vegetated sites in a tropical city of Ouagadougou, Burkina Faso (Lindén 2011; Holmer et al. 2013). In those studies the intensive cooling at vegetated sites was accompanied by an increase in specific humidity. Although air humidity was also measured in our study, due to the high sensitivity of the humidity sensor to outdoor conditions combined with a long exposure, data quality was not sufficient for an accurate analysis of intra-urban humidity variations.

While in hot, dry climates vegetation was found to be the most important parameter governing cooling in Phase 1 (Jonsson et al. 2004; Lindén 2011; Holmer et al. 2013), in the high latitude city of Gothenburg the enhancement of cooling by tree transpiration at vegetated sites did not compensate for the reduced long-wave radiation loss and turbulence due to low SVF. Therefore, despite active nocturnal transpiration, the street tree site was the warmest at night-time due to large heat storage combined with a limited cooling in the street canyon. Night-time warming effect of street trees was also reported by e.g. Taha et al. (1991); Souch and Souch (1993), Spronken-Smith and Oke (1998), Emmanuel et al. (2007), Huang et al. (2008) and Coutts et al. (2015). However, as noted by Coutts et al. (2015), the improvement of daytime thermal comfort by street trees strongly outweighs their potentially negative influence during night-time.

Cooling rates in Phase 2 are commonly regarded as independent on surface characteristics and governed by the radiative balance between urban canopy layer and the capping inversion (Holmer et al. 2007; Holmer et al. 2013). However, the results of **Paper IV** showed that while the cooling intensity was indeed similar at all sites, a significant influence of tree cover was observed in both seasons, with densely vegetated sites cooling less intensively than those with few trees. This can be attributed to an even weaker turbulence than in Phase 1 due to a decreasing wind speed. While non-vegetated street canyons also have a low SVF, there is no canopy hindering the outgoing long-wave radiation and turbulent heat fluxes. Although tree transpiration was observed in Phase 2, it was not significantly correlated with cooling rates.

INTRA-URBAN THERMAL VARIATIONS

In **Paper IV**, parks were found to be cooler than their surroundings throughout the day and year, with the most intensive PCI (0.8°C) observed on clear, calm days of the warm season. This is less than a typical park cooling effect reported in literature, e.g. 0.94°C (Bowler et al. 2010) or 1-2°C (Oke 1989). Even weaker PCI (0.5°C) was observed at night-time, although the nocturnal T_a reduction in urban parks is often more pronounced than during daytime (Bowler et al. 2010). The possible reasons behind this relatively weak PCI and the stronger daytime than night-time cooling effect are related to the both study area characteristics at various scales as well as to the applied methodology. Firstly, the daytime cooling of urban parks is enhanced by irrigation and usually observed at high ambient temperature (Spronken-Smith and Oke 1998; Shashua-Bar and Hoffman 2000; Pearlmutter et al. 2007; Oliveira et al. 2011). In high latitude cities parks are usually unirrigated and the summers are relatively cool. However, in **Paper IV** the highest PCI intensity was observed on the hottest days of the warm season, which suggests that parks provide the strongest cooling effect when it is most needed, and that it may increase in the future in the warming climate.

At night-time, the highest cooling is usually observed in open parks with few trees and low soil moisture (Taha et al. 1991; Spronken-Smith and Oke 1999). In Gothenburg most parks have a high tree fraction, which promotes daytime cooling due to shading and evapotranspiration (although relatively weak compared to irrigated parks in warmer climates), while at night-time it prevents intensive cooling due to the trapping of long-wave radiation and limiting below-canopy turbulence. Moreover, the street sites in **Paper IV** were located in a close proximity to the parks and could thus be influenced by a park breeze, i.e. an advection of cool air from the park into the built-up area (Upmanis et al. 1998), limiting the observed PCI intensity.

Secondly, differences in reported T_a reductions by urban parks can result from different calculation of PCI and/or the analysed seasons. While in some studies (e.g. Oliveira et al. 2011) the calculation of PCI is based on two sites with extreme air temperature values (the warmest street site and the coolest park site), in this thesis differences between mean values among street sites and park sites were used. It is also common to analyse only summertime (or dry season) data, when the PCI is usually most pronounced, while here data from May-October and November-March were analysed to obtain a large number of days in different seasons and weather groups.

According to Oke (1987) and Arnfield (2003), the climate of cities in temperate climate zones is governed mostly by urban geometry and thermal properties of urban materials. Indeed, SVF and building density were found to be the most important parameters influencing intra-urban variations in daytime maximum T_a, cooling rates in Phase 1 as well as night-time minimum T_a. However, as discussed in the previous section, the presence of vegetation was also an important factor, with parks being cooler than their surroundings throughout the day and year. In general, significant relationships between spatial characteristics describing openness, vegetation and buildings, and T_a or cooling rates were found in both seasons, at daytime and night-time, as well as in different weather conditions. As noted by Upmanis and Chen (1999) and Unger (2004), while SVF strongly influences surface temperature, relationships between SVF and T_a are often weak and insignificant. Three plausible reasons behind strong correlations found in this study are: i) the calculation of SVF based on spatial information rather than point values, ii) using various spatial characteristics (e.g. partial SVFs or tree volume) instead of SVF_{bv} only, as well as iii) the proximity of studied sites. Spatially averaged SVF allows the consideration of the influence of both nearest and wider surroundings on T_a. Partial SVFs

(SVF_v, SVF_b) as well as other spatial characteristics (e.g. tree volume and fraction of permeable surfaces) can explain intra-urban thermal patterns depending not only on openness, but also on the presence or absence of buildings and vegetation. Finally, all measurement sites in **Paper IV** were located within the radius of 500 m, in a similar distance from the city centre, and at the same height above sea level. As a result, advection of air within the city affected the thermal variations between the sites to a smaller extent compared to studies analysing T_a data from stations covering a larger area, e.g. Eliasson (1996). The importance of the nearest surroundings on T_a variations between closely located sites was also indicated by the small radius of calculation areas for which the strongest correlations were found, i.e. 10 and 25 m compared to e.g. 100 m (Eliasson and Svensson 2003; Lindberg 2007), 200 m (Hamada and Ohta 2010) and 400 m (Lindén 2011) commonly used in other studies. Therefore it should be noted that while the results from this thesis can be useful for modelling intra-urban thermal patterns at a local scale, several additional parameters – e.g. topography and the distance from city centre, water bodies or parks should be considered.

Intra-urban thermal variations are also strongly dependant on meteorological conditions. In **Paper IV** these were classified into two groups (clear, calm and cloudy, windy) by using thresholds of sky clearness and wind speed, a common approach in urban climate studies (Oke 1987; Eliasson and Svensson 2003; Holmer et al. 2007). In clear, calm conditions the mixing of the air is limited and the radiative cooling is not hindered by cloud cover, thus allowing the development of large intra-urban and urban-rural thermal variations due to differences in surface geometry, thermal properties or the amount of vegetation (Park 1986; Oke 1987; Unger 1996; Upmanis and Chen 1999). Since local meteorological conditions are strongly controlled by synoptic scale atmospheric circulation, another approach is a weather classification based on spatial variations in synoptic scale sea level pressure, e.g. Lamb Weather Types (Lamb 1950). Such classification proved useful e.g. in the analysis of mean regional T_a in January (Chen 2000) or wintertime urban air quality (Grundström et al. 2015), but is less suitable for the analysis of summertime data due to the weak pressure gradient and localised processes such as convection. Therefore, in this thesis local meteorological data on wind speed and sky clearness from a nearby station were used in the analysis of intra-urban thermal variations.

As shown in **Papers I, II** and **IV**, high resolution DSMs including ground, buildings and vegetation can be used to calculate various spatial characteristics, SVFs, shadow patterns and radiation fluxes. While spatially averaged SVF can explain intra-urban variations of T_a and cooling rates to a larger extent than SVF calculated from hemispherical photography, high resolution surface models are not always available. For this reason hemispherical photography is still commonly used to calculate SVF in urban climate studies. Results from **Paper V** demonstrated the potential of NIR hemispherical photography to calculate partial SVFs, which in **Paper IV** proved useful in explaining intra-urban thermal variations. Moreover, the post-processed NIR photographs enabled the evaluation of partial SVFs derived from high resolution DSMs, which is not possible using standard hemispherical photographs recording only visible light.

IMPLICATIONS FOR CLIMATE-SENSITIVE URBAN PLANNING

The results show that trees growing in sun-exposed locations can provide a strong cooling effect due to their shadow (**Paper II**) as well as enhanced transpiration (**Paper III**) compared to shaded trees. However, while the sun-exposed locations are the ones where the cooling effect is most needed on hot summer days (Lindberg et al. 2014, Thorsson et al. 2015), they are also the ones where the street trees are exposed to most severe stress factors. One of the main reasons behind the short lifespan and limited cooling capacity of urban trees is the water stress caused by strong evaporative demand combined with insufficient access to water (Clark and Kjelgren 1990; Ferrini et al. 2014). As mentioned by Whitlow and Bassuk (1988), tree species differ in their sensitivity to drought, with some being drought-tolerant (i.e. maintaining high transpiration in periods of low water availability) and others – drought-avoiding (i.e. limiting transpiration to avoid water stress). Results of **Paper III** showed that English oaks, described by Aasamaa et al. (2002) as a drought-tolerant species, had a relatively intensive transpiration compared to other species, while drought-avoiding limes (Whitlow and Bassuk 1988), which are the dominant genus in Gothenburg, transpired relatively little. High transpiration of English oak saplings was also reported by other authors (Aasamaa and Sõber 2001; Aasamaa et al. 2002). These results suggest that a proper species selection, e.g. planting drought-tolerant instead of drought-avoiding species, should be considered in climate-sensitive urban planning.

In urban areas, water stress experienced by trees is often worsened by the strong compaction of soils and impervious surfaces surrounding the trees (Cregg 1995; Ferrini and Baietto 2007; Rahman et al. 2011). Impermeable surfaces not only limit rainwater infiltration into the soil, but also alter the radiative environment, increasing the stress factors the urban trees are exposed to (Kjelgren and Clark 1992; Kjelgren and Montague 1998). In **Papers I** and **III**, the fraction of permeable surfaces within the vertically projected crown area, used as a simple indicator of the growing conditions of trees, was found to be positively correlated with their foliage density and transpiration. Combined with accumulated rainfall, it was used as a crude estimate of the available rainwater (Fig. 7). Such estimate could serve as a proxy for not widely available information on soil moisture and thus provide a useful tool for urban tree maintenance. The results indicate that the cooling effect of trees due to both shading and transpiration can be enhanced by improving tree growing conditions and access to water. However, it should be noted that the observed differences in canopy density and transpiration rates between trees surrounded by grass and impermeable surfaces could partly result from differences in soil characteristics, mainly its compaction. Street trees are often planted in compacted soils which can bear the weight of pavement and vehicles, but limit root growth (Grabosky et al. 2002). However, Grabosky et al. (2002), Smiley et al. (2006) and Rahman et al. (2011) reported an enhanced growth or water use of urban trees planted in so called structural soils, characterised by a low compaction and allowing root penetration, while at the same time meeting engineers' specifications for load bearing. Nevertheless, Nielsen et al. (2007) suggested increasing the surface of the unpaved planting pit as the most obvious solution to improve trees' access to water. Higher transpiration, cooling effect or biomass production of trees growing over grass compared to those surrounded by impervious surfaces was reported in studies conducted in various climate zones (Souch and Souch 1993; Close et al. 1996; Celestian and Martin 2005; Mueller and Day 2005; Ferrini and Baietto 2007).

In the future the heat waves are expected to be more frequent and more severe (IPCC 2012), thus providing trees with good growing conditions, both in terms of soil characteristics and surface cover, can support their health and cooling capacity in the warming climate. However, in densely built-up areas increasing the fraction of permeable surfaces is not always possible. Apart from planting trees in the abovementioned structural soils and expanding planting pits vertically (Nielsen et al. 2007), other strategies supporting the health and access to water of street trees include storm-water harvesting and reuse (Coutts et al. 2012; Demuzere et al. 2014a), which was also found to enhance tree transpiration. Not implementing any strategies may lead to a shortened lifespan of trees as well as choosing drought-avoiding species or tree pruning (Chen et al. 2011), which result in a limited climate regulation provided by trees.

The results also show that while the effect of single urban trees on T_a is rather small, they can reduce T_{mrt} by up to 30°C on warm summer days by providing shadow (**Papers II, IV**). Since T_{mrt} is a better predictor of heat-related mortality than T_a (Thorsson et al. 2014), the reduction of heat stress by urban trees has important implications for human health and well-being. However, while the shading effect is positive for the thermal comfort on hot summer days, tree canopies can hinder night-time cooling as well as access to sunlight in winter, when it is already limited in high latitude cities (**Papers II, IV**). As noted by Coutts et al. (2015), street trees should thus be planted with sufficient spacing allowing long-wave radiation loss and ventilation. Moreover, trees with a low transmissivity of solar radiation in leaf and high transmissivity when defoliated are preferable in high latitude cities in terms of the cooling effect due to shading (Gardner and Sydnor 1984; Cantón et al. 1994). However, tree species with sparse branches are not likely to develop dense foliage (Heisler 1986), thus not only species selection, but also a proper location, size and maintenance need to be considered. For example, trees planted in east-west directed street canyons with a high height to width ratio may provide a shading effect in warm months, while in wintertime they would remain shaded by buildings due to low sun altitude, thus not creating an additional shade. Moreover, while trees with dense branches limit the penetration of sunlight, they can provide shelter from strong winds (Sjöman et al. 2015), which in the cold season can improve outdoor thermal comfort at exposed urban sites.

This raises the issue of the complex function of trees in the urban environment. As noted by Salmond et al. (2015), climate-sensitive urban planning should not be based on a single parameter, e.g. the cooling effect due to shading and transpiration, but should rather take a holistic approach considering various ecosystem services and disservices provided by urban trees. A holistic assessment of the climatic and health-related impacts of urban trees can increase our understanding of the potential co-benefits and trade-offs in different contexts and scales. For example, while the wintertime cooling effect of parks, observed in **Paper IV**, may be considered negative, it may also lead to the development of a park breeze improving urban ventilation (Eliasson and Upmanis 2000). Another example is the improvement of thermal environment by trees, which can lead to an increased usage of urban outdoor spaces, with co-benefits for social, psychological and health-related ecosystem services (Demuzere et al. 2014b). Moreover, while at microscale trees can directly affect the thermal comfort (Ali-Toudert and Mayer 2005; Shashua-Bar et al. 2011) as well as building energy consumption for heating and cooling (Thayer and Maeda 1985; Simpson and McPherson 1996), vegetation cover can also influence the urban climate and thus building energy demands and greenhouse gas emissions at larger scales (McPherson 1994; Akbari et al. 2001). Therefore urban greenery enables not only adaptation to, but also mitigation against the changing climate (Demuzere et al. 2014b; Salmond et al. 2015).

CONCLUSIONS

The following main conclusions can be drawn from this thesis:

- The amount of foliage of urban greenery can be accurately mapped at various scales (from a single tree to municipality) using a LiDAR dataset. Substantial variations in leaf area index were observed between different types of urban greenery. However, when averaged over larger areas only partly covered by trees, variations in modelled leaf area resulted mostly from tree fraction rather than height or density of tree canopies;

- Single urban trees can provide a strong shading effect throughout the year, with a potential positive effect on outdoor thermal comfort in summer, but negative in winter in a high latitude city. The shading effect of both foliated and defoliated trees should thus be considered in climate-sensitive planning or when modelling radiation fluxes in the urban environment;

- Night-time tree transpiration was observed in trees of all seven common species studied. While the evening cooling in a high latitude city is mostly governed by SVF, data analysis indicated that on clear, calm days of the warm season it is also enhanced by night-time tree transpiration;

- The cooling effect of trees due to both shading and transpiration is influenced by tree growing conditions and access to sunlight. Trees growing on wide grass lawns were found to have denser crowns and higher stomatal conductance than those surrounded by impervious surfaces. Sun-exposed trees can influence the microclimate to a higher extent than those planted at locations with low access to sunlight not only by providing additional shade, but also by a stronger transpiration;

- Parks exhibited a cooler microclimate than built-up sites throughout the day and year and in different weather conditions, with the strongest cooling effect on clear, calm days of the warm season;

- Spatial characteristics describing vegetation and buildings proved useful in the analysis of intra-urban thermal variations which the total SVF alone could not explain. The influence of both the nearest and wider surroundings should be accounted for in such analysis. However, when high resolution spatial data are not available, NIR hemispherical photographs can be used to calculate SVFs accounting for the obstruction of sky by buildings and trees separately.

FUTURE OUTLOOK

The results of this thesis demonstrated that in a high latitude city SVF is the most important parameter governing the evening cooling, although on warm summer nights it is also enhanced by evapotranspirative cooling. An opposite pattern was earlier observed in tropical cities of Gaborone, Botswana (Jonsson 2004) and Ouagadougou, Burkina Faso (Lindén 2011; Holmer et al. 2013), with vegetation suggested as the dominant factor. Future measurements in cities of different climates would increase our understanding of the relative importance of SVF and vegetation on intra-urban thermal variations and its dependence on regional climate.

The measurement sites in the field study on urban tree transpiration were characterised by a variety of growing conditions of trees, typical in an urban environment. This allowed investigating the effect of water availability on the cooling efficiency of urban trees, but it constrained the analysis of intra-species differences in water use or stress tolerance. Moreover, the growing conditions were compared based on the surface cover, not soil characteristics. Further studies focusing on the inter- and intra-species variations in the water use of urban trees planted in soils of different compaction in combination with different surface covers would be valuable from the point of view of climate-sensitive urban planning and tree maintenance.

The results showed that trees and parks influence the local climate throughout the day and year, with implications for human health and thermal comfort. It would be of interest to compare these findings with people's perception of the effect of urban greenery on urban climate as well as human thermal comfort and well-being.

In SOLWEIG 1D model, the simple vegetation scheme using partial SVFs needs to be improved to account for differences in albedo and emissivity of trees and urban materials, which could increase the potential of NIR photographs to improve the modelling of radiation fluxes and T_{mrt} in urban areas. Model performance with the vegetation scheme will be evaluated against measurement data. NIR hemispherical photographs can also prove useful in the indirect measurements of leaf area of single street trees surrounded by buildings.

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