The effect of urban green infrastructure on local microclimate and human thermal comfort

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on

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Thesis

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谨以此书献给我的父母和亲友们

To my dearest family and friends

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CHAPTER 1

General introduction

1.1 Background

Although urban areas currently cover less than 5% of the world's land surface (Seto and Reenberg 2014), more than half of the world's population lives in cities and this will likely increase to 70% in 2025 (WHO 2013). With this rapid growth of cities, urban ecosystems are becoming one of the most important habitats for human beings.

The term 'urban ecosystem' was used by many scientific studies since the 1970s, whereas people generally referred to a city as a centre of commerce or as a transportation and communication hub, but rarely as an 'ecosystem' (Rees 1997). During the last two decades, various ecosystem studies were carried out on both 'ecosystems within cities' and 'ecosystems of cities' (Rees 1997, Bolund and Hunhammar 1999, Grimm et al. 2000, Alberti and Marzluff 2004, Wolch et al. 2014, Wang et al. 2014).

Urban ecosystems usually contain remnants of natural ecosystems, such as forests, lakes and rivers (Bolund and Hunhammar 1999, Guidotti 2010). Hence, urban ecosystems are composed of a mix of natural biological elements (e.g. plants and animals), physical elements (e.g. water, climate and topography) and built infrastructures. Urban ecosystems thus combine natural and anthropogenic components that interact with one another, that provide both natural and artificial benefits (Guidotti 2010) and that influence the quality of urban life.

In this thesis, the semi-natural elements in cities are jointly referred to as Urban Green Infrastructure (UGI) or 'urban green space', such as green lawns and parks, green walls and green roofs. This concept originated in the United States in the 1990s to merge an ecosystem-based approach with the more technical solutions in urban planning (Sandström 2002).

The natural processes and components of UGIs underpin their functions (Garnier et al. 2004), which in turn provide so-called Ecosystem Services (ESs) (Bolund and Hunhammar 1999, Nowak et al. 2001). The concept of ESs dates back to the 1980's but was only firmly mainstreamed by the Millennium Ecosystem Assessment (2005) and the study on The Economics of Ecosystems and Biodiversity (TEEB 2010). Depending on the characteristics and types (e.g. forest, lawn and lake), UGIs provide many different ESs. The TEEB report (2010) proposed 22 ESs from four main categories (provisioning, regulating, habitat and cultural services). However, not all ESs play a role in the urban ecosystem.

Gómez-Baggethun et al. (2013), for example, listed fifteen ESs in the urban context from the four main categories: food supply, water supply, urban temperature regulation, noise reduction, air purification, moderation of climate extremes, runoff mitigation, waste treatment, pollination, pest regulation and seed dispersal, global climate regulation, recreation, aesthetic benefits, cognitive development, place values and social cohesion, and habitat for biodiversity. After analysing these services in more detail, I selected four ESs that are most relevant for human urban habitats in the context of my PhD study (Wang et al. 2014). These services are microclimate regulation, air quality regulation, sonic environment regulation (i.e. noise abatement) and aesthetic information (see Figure 1.1). Better information on how these ESs contribute to human comfort, is important for decision making and urban planning and likely will improve sustainable management of urban ecosystems.

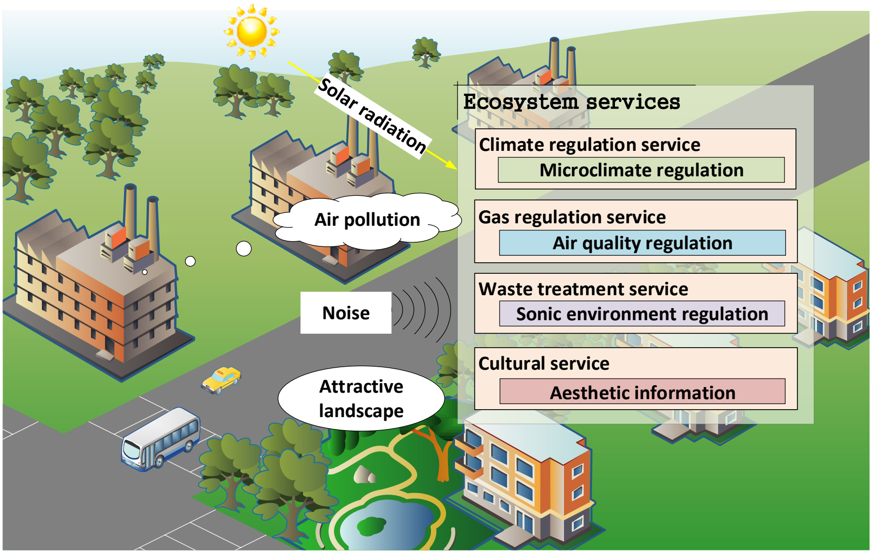


Figure 1.1 The main ESs provided by Urban Green Infrastructure (UGI) in human urban habitats.

After a detailed literature review (see Chapter 2), I decided to focus the quantitative analysis of my PhD study on UGI's microclimate regulation service and its effects on human thermal comfort. The research objective and methods are defined and explained in more detail in Sections 1.3 and 1.4 respectively.

Figure 1.2 shows the ecosystem functions of UGI involved in the provision of these ESs (ecosystem function is defined as the capacity to provide an ES (De Groot 1992)). Microclimate regulation is provided through shading, evapotranspiration and wind shielding (e.g. Simpson and Mcpherson 1997, Akbari 2002, Chen and Jim 2008, Wang et al. 2014). Air quality is regulated through dry deposition, carbon storage and sequestration, releasing pollen and spores of fungi, and emitting biogenic volatile organic compounds (Bolund and Hunhammar 1999, Konopacki and Akbari 2000, Thornes et al. 2010, Wang et al. 2014). Regarding the sonic environment regulation, green spaces act as acoustic screen and both attenuate noise and generate pleasant sounds (from birds and rustling leaves) to mask noise (Nijland et al. 2003, Irvine et al. 2009, Wang et al. 2014). Last but not least, natural scenery provides aesthetic amenities to many people (Taylor et al. 2002, Van den Berg et al. 2010, Wang et al. 2014).

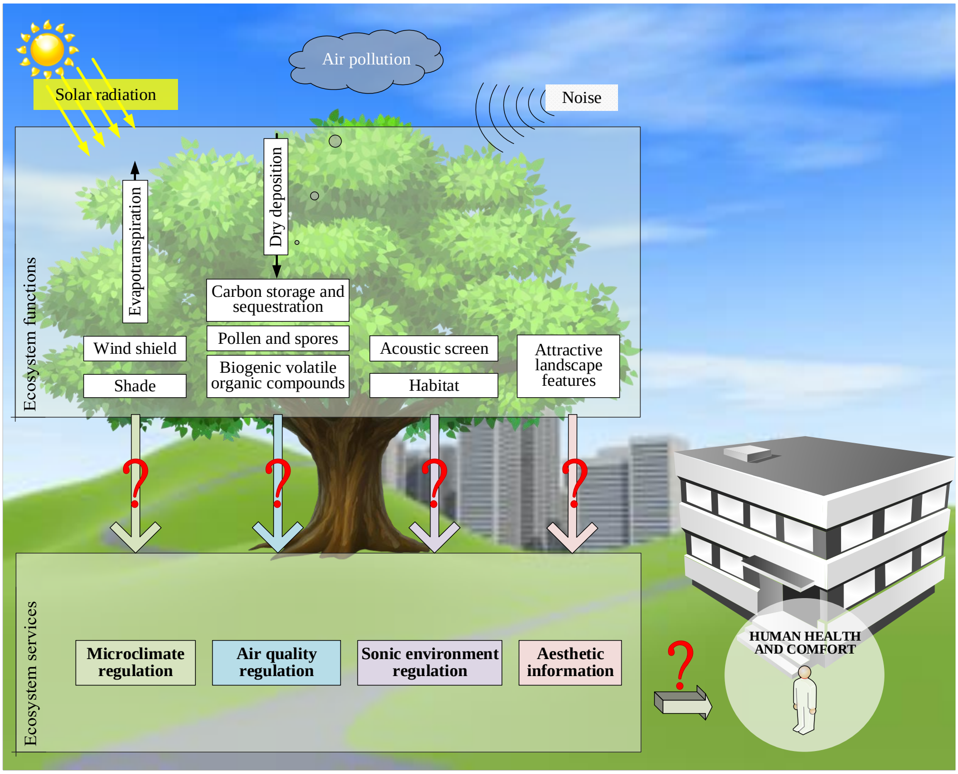


Figure 1.2 The main ecosystem functions linking ESs of Urban Green Infrastructure (UGI) to human health and comfort.

Since social and ecological systems are intricately linked in urban ecosystems, cities can be at the forefront of integrating social and ecological sciences (Elmqvist et al. 2013). Through proactive planning of associations between UGI, ecosystems and human health, urban development is potentially able to find a balance between economic growth and nature conservation (Walmsley 2006, Tzoulas et al. 2007). UGI, therefore, should have the same importance as the built infrastructure in efforts to achieve sustainable urban development (Tzoulas et al. 2007).

1.2 Problem statement

Urbanization on the one hand creates social and economic opportunities, and provides a chance to create more sustainable land use, thereby protecting natural ecosystems, but on the other hand, it destroys and fragments natural ecosystems, and implies high pressure on natural resources and the environment (Elmqvist et al. 2013).

The acceleration of urban construction and population growth changes the urban environment. Air quality can, for example, deteriorate and urban areas can warm faster. In what way and how strongly those changes affect human thermal comfort (and ultimately their health status and general wellbeing), has received increasing attention in the past decade (Millennium Ecosystem Assessment 2005, Campbell-Lendrum and Corvalán 2007, Matzarakis and Amelung 2008, Franck et al. 2013). However, the links between urbanization and human comfort are complex (Grimmond 2007). First, the changes of surface geometry associated with the construction of buildings alter the vertical surface area and the sky view factor, which is the ratio of radiation received by a planar surface from the sky to that received from the entire hemispheric radiating environment (Watson and Johnson 1987). This leads to changes in energy, water exchange (Susca et al. 2011) and airflow (Yang et al. 2010). Second, low-albedo surface materials of buildings, roads, and other infrastructures increase the thermal admittance, enhancing urban warming (Akbari et al. 2001). In addition, anthropogenic heat emissions (including human metabolic heat and fuel combustion heat release) affect surface and air temperature (Yang et al. 2011). Finally, the lack of natural elements in urban areas aggravates the negative impacts on inhabitants' thermal comfort in many ways (see Box 1).

Box 1 Human thermal comfort

Thermal comfort was defined by British Standard BS EN ISO 7730 (1994) as being "that condition of mind which expresses satisfaction with the thermal environment." It is related to both subjective sensation and objective interaction with the environment. The factors influencing thermal comfort can be classified into environmental and personal aspects. The environmental factors include air temperature, radiant temperature, air relative humidity and wind velocity. Moreover, some non-thermal environmental factors, such as ambient light and noise, may also affect people's thermal sensation. In terms of the personal factors, metabolic dissipation rate (depending on activities) and clothing insulation influence the heat and mass transfer rates between human body and ambient environment (ASHRAE 1992). Additionally, demographic characteristics (including gender, age and nationality), previous accommodation, personal preferences and mood may also have influence (ISO 7730 1994). UGI affects human thermal comfort in a variety of domains (physical, physiological, behavioural and psychological) (Chen and Ng 2012). In general, UGI regulates the microclimate and positively influences human thermal comfort. Further, most people display a preference for nature, resulting in a positive effect on thermal comfort sensation in psychological terms within green spaces.
To assess human thermal conditions, many human thermal assessment indices have been developed, for example, predicted mean vote (PMV) (Fanger 1972), physiologically equivalent temperature (PhET) (Mayer and Höppe 1987), and standard effective temperature (SET) (Gagge et al. 1986). These indices combine the environmental and personal factors and are able to provide information about the corresponding comfort/discomfort level (see Chapter 5 for details).

A wide range of strategies were proposed to mitigate urban warming and improve thermal comfort by for example, using high-albedo materials for building and pavement construction (Akbari and Taha 1992, Susca et al. 2011), insulating roofs and walls (Carver et al. 2004) and increasing UGI (Shahidan et al. 2012). Using UGI to mitigate microclimatic 'heat island' effects and enhance human comfort has been proposed by various studies in the recent past (e.g. Yang et al. 2011, Park et al. 2012, Blanusa et al. 2013, Skoulika et al. 2014) because UGI not only contributes to microclimate regulation but also improves air quality and the sonic environment, and has many other benefits. Finding feasible urban designs to take full advantage of UGI and achieve the best possible thermal comfort is a big challenge for researchers and urban designers in times of both rapid population growth and climate change.

1.3 Objective and research questions

Most previous studies on urban comfort were modelling studies (e.g. Huang et al. 2008, Shahidan et al. 2012, Sawka et al. 2013, Ouldboukhitine et al. 2014, Middel et al. 2014), while only few focused on local microclimate regulation via experiments and measurements (e.g. Akbari et al. 1997, Laband and Sophocleus 2009, Morakinyo et al. 2013). These empirical studies were also typically carried out in unconnected urban green spaces (e.g. urban forests, urban parks and green façades). However, UGI is very heterogeneous and the benefits derived vary by location and probably differ over larger areas. To better manage green spaces and account for the apparent heterogeneity, the effects of UGI on microclimate should therefore be investigated locally. In addition, UGI has many and complex interlinkages with local microclimate and human thermal comfort. This should be investigated through combining different research approaches.

This study aims to determine the effects of UGI on local microclimate and human thermal comfort as part of the broader human urban habitat. This objective is achieved by addressing the following research questions (RQs):

RQ1. What are the ESs of UGI that influence human urban habitats?

RQ2. What factors influence the capacity of UGI to regulate microclimate?

RQ3. How can the effect of UGI on local microclimate and human thermal comfort be measured?

RQ4. How do people perceive thermal comfort in small urban green areas locally and how is this related to UGI planning and management?

1.4 Research methodology

This PhD study investigated the effects of UGI on local microclimate regulation and human comfort through an integrative approach that combines literature review, field measurements, modelling and social surveys.

To investigate the relationship between UGI and human urban habitat (RQ1), the initial step of my study was to identify the ESs involved and to analyse existing relevant methods, techniques and models (Figure 1.3). The state-of-the-art in the field of urban ESs and habitats was based on a thorough literature review (see Chapter 2). The results revealed the strengths and weaknesses of the existing studies and the main factors influencing the UGI effects. In order to examine the impacts of the main controlling factors and quantify UGI's effects on the local urban microclimate (RQs 2 and 3), I combined field measurements with modelling and surveys. In Chapter 3, field measurements were synthesized through numerical modelling to investigate the spatial and temporal microclimate differences under different local morphology and weather conditions in the summer of 2013 and winter of 2014. The follow-up study in Chapter 4 examined the impact of vegetation characteristics on the microclimate in terms of vegetation density and plant area index (PAI). The field measurements were conducted during the growing season in 2014, and gap fraction analysis was used to quantify PAI. In the last phase of my PhD-research (Chapter 5) I performed field surveys on a university campus to explore the human thermal perception and preference in small urban green areas (RQ4). Furthermore, other environmental and personal variables that may influence human thermal perception and preference, such as their behaviour adjustment and thermal history, were also examined. These surveys helped to better evaluate the influence of different UGIs on microclimate conditions and link this to the preferred thermal comfort.

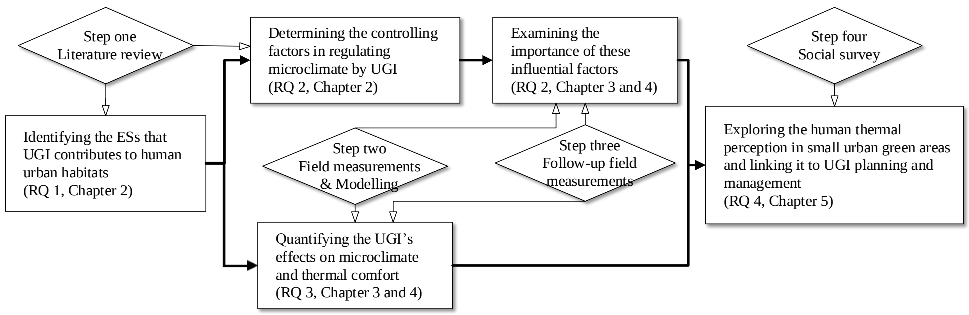


Figure 1.3 Flowchart of main research questions and steps in this PhD study. Rectangular boxes contain the main challenges and corresponding chapters; diamond boxes contain the research steps and the major methods used.

1.4.1 Literature review (RQ1)

In order to obtain a systematic overview of the UGI's effects on human urban habitats, I undertook a critical review of the literature on the quantification and valuation of four important ESs in the urban context (i.e. microclimate regulation, air quality regulation, sonic environment regulation and aesthetic information services). By analysing the design of the reviewed studies and their interpretations and findings, the relations between the ESs provided by UGI and the outdoor and indoor environment (including direct and indirect effects) were established. Subsequently, the main ecosystem functions associated with each service provided by UGI were used to classify the selected papers and to structure the chapter

(Chapter 2). The UGIs discussed in the reviewed literature were categorized into two main groups, i.e. vegetation adjacent to buildings (e.g. urban street trees, urban forest, etc.) and vegetation cover on buildings (i.e. green roofs and walls). Finally, the economic importance of the ESs provided by UGI was studied by utilizing different valuation methods.

1.4.2 Field measurement of the microclimate (RQs 2 and 3)

Field measurements were carried out in the vicinity of INCAS[3], located in Assen (see Figure 1.4). INCAS[3] was the collaborating institute that funded my research, and where I was located most of the time during my PhD study. This part of The Netherlands mainly enjoys a typical oceanic climate with mild winters and cool summers, and precipitation is evenly spread over the year. On average, the warmest months are July and August (average maximum temperature is approximately 22 ℃), and the coolest month is January (average minimum temperature is approximately -1 ℃).

Local measurements on the major microclimatic parameters, consisting of air temperature, relative humidity and wind velocity, were conducted at the sites with different environmental characteristics using Davis wireless weather stations. These stations were placed at a height of 1.5m above the ground. To minimize the solar interference, temperature and humidity sensors were housed in radiation shields. All the measurements were taken at ten second intervals and averaged when logged at ten minute intervals by a Davis data logger during the observation period.

We first tested the wireless weather stations and network in a rural area, i.e. a small village, Ruinen (Figure 1.4). The data obtained from this test were also used to validate the microclimate model. After testing, the weather stations were transported and installed in a small urban area in Assen (Figure 1.4).

1.4.3 Modelling (RQs 2 and 3)

Besides field measurements, this study also used the ENVI-met and RayMan models to simulate the urban microclimate and calculate thermal comfort values.

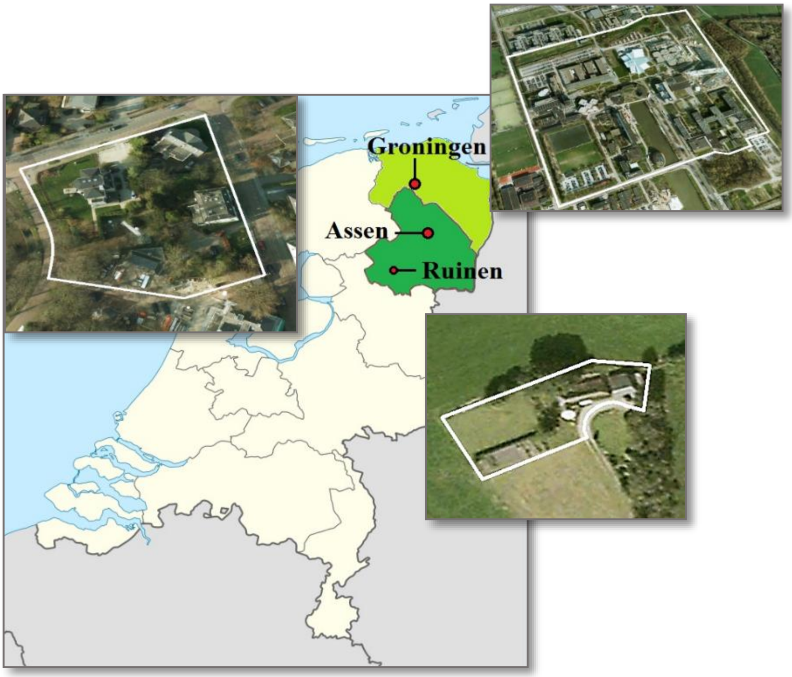


Figure 1.4 Location of Assen, Ruinen and Groningen in The Netherlands.
(Source: Google Earth and German Kartenwerkstatt).

ENVI-met was designed in 1994 and was first introduced by Bruse and Fleer (1998). It is a three-dimensional numerical model simulating local microclimatic conditions by using computational fluid dynamics and an energy balance model. Based on the fundamental laws of fluid dynamics and thermodynamics, ENVI-met contains the simulation of flow around and between buildings, exchange processes at ground surface and at building walls, building physics, impact of vegetation of local microclimate, bioclimatology, and pollutant dispersion. This model, with a high spatial and temporal resolution (a minimum of 0.5m in space and 1–5 sec in time with a maximum of 250 × 250 × 30 3D grids), is able to display how local microclimate varies in the research area over time. In its input and database files, the geometry (e.g. position and height of buildings and plants, distribution of surface materials and soil types), plant database (e.g. type, height, leaf density), soil database (e.g. type, volumetric water content) and building properties (e.g. heat transmission, albedo) were specified. In addition, meteorological factors and data are needed for the model initialization. After running the simulation, the model provides large amounts of output data containing the air temperature, relative humidity, wind velocity, etc. at each grid and time step. Currently, a new public preview of ENVI-met V4 is available. However, errors and changes are still anticipated. Hence for my study I utilized the previous and stable version, ENVI-met V3.

In order to calculate the thermal comfort value, the free model, RayMan was used (RayMan stands for "radiation on the human body") (Matzarakis et al. 2007). Basic meteorological data (air temperature, relative humidity and wind speed, mean radiate temperature and cloud cover) and personal data (height, weight, age, gender, clothing and activity) are required respectively to calculate radiation fluxes and to assess thermal human bioclimate. The output of the model describes the thermos-physiological acquisition of thermal conditions using thermal indices, i.e. predicted mean vote (PMV) (Fanger 1970), physiologically equivalent temperature (PhET) (Höppe 1984) and standard effective temperature (SET*) (Gagge et al. 1986).

1.4.4 Social survey (RQ4)

To elucidate and analyse the association between the outdoor thermal environment and thermal adaptation, physical measurements and an onsite questionnaire survey have been performed to investigate thermal comfort perception and preference in small urban green areas. In order to include the variables corresponding to the thermal history, my questionnaires have been distributed to Dutch and international students at a Dutch university campus, Zernike Campus of University of Groningen.

Groningen, the capital city of the Groningen province in the north of The Netherlands, is about 25 km north from Assen. It is a university city and houses one of the oldest and largest university in The Netherlands (University of Groningen). It has most students percentagewise in The Netherlands, as students occupy almost one third of the whole city population. The weather in Groningen is influenced by the North Sea all year round. The Zernike Campus is situated in the north western side of the city. Figure 1.5 shows the aerial view of Zernike Campus.

Based on ASHRAE Standard 55 (ASHRAE 1992), the questionnaire with two sides of a single page consisted of three sections: **1)** demographical information, activity level and clothing worn; **2)** thermal response votes (thermal, humidity, wind speed and comfort sensation votes) and behavioural adjustment; **3)** reason of coming, frequency of visiting, time of staying, previous place of stay and activities. On five warm and cloudless days, the questionnaires have been distributed in five green spaces of Zernike Campus. Simultaneously, mobile measurements of air temperature, globe temperature, relative humidity and wind velocity were conducted to obtain the microclimatic information at the time of the survey.

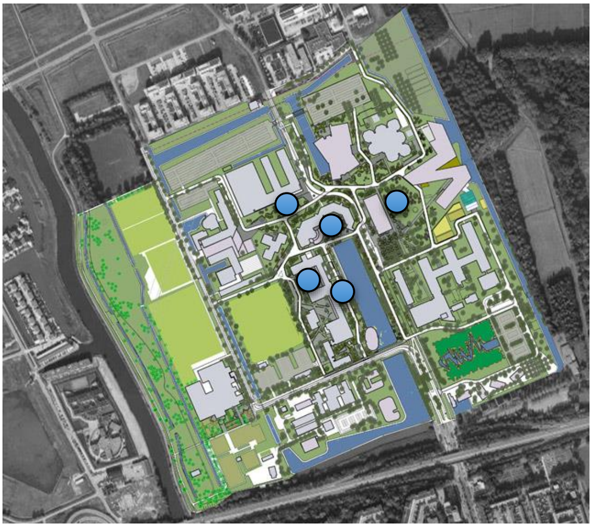


Figure 1.5 Map of the study area, Zernike Campus, University of Groningen, The Netherlands. The blue circles represent the survey locations. (Source: http://www.west8.nl/projects/zernike_campus/).

1.5 Outline of the thesis

In order to address the research objective and questions, this research is implemented in several sequential steps (see Figure 1.3). These steps thus form the basis for the structure of this thesis and each chapter addresses one of the research questions.

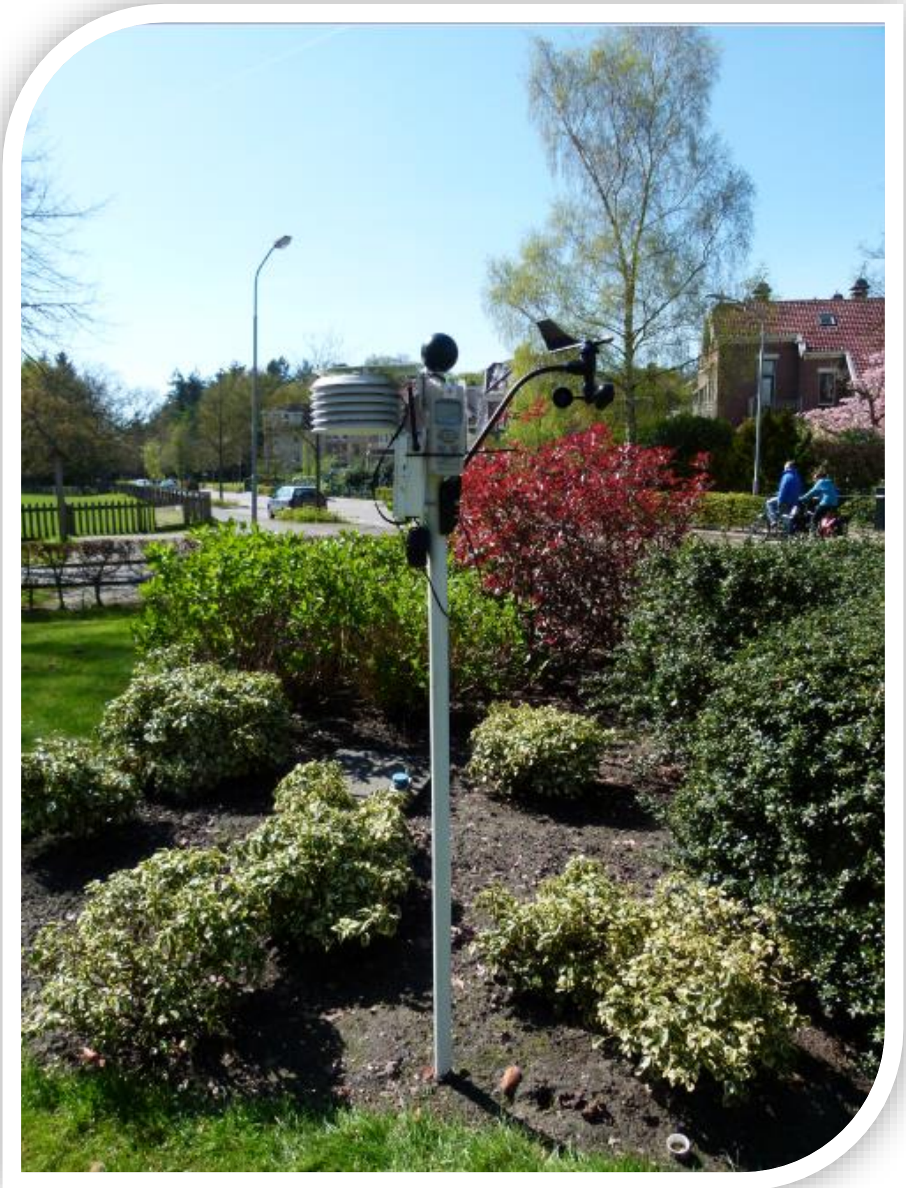
The first step to better understand the effects of UGI on human urban habitats is to identify the ESs involved and to study the existing methods, techniques and models in this field. In Chapter 2, I therefore presented the results of my literature review including different disciplines to summarize the urban ESs and their effects on human health and comfort. The main factors and sub-factors influencing the four main ESs by UGI have been well studied and described in literature. After identifying the strengths and weaknesses of the methods used in the reviewed publications over multi-spatial and temporal scales, I decided to focus my research on microclimate regulation and its links with human thermal comfort at a local scale. Based on my research I provided suggestions for future research to improve the knowledge base in this important research area.

In Chapter 3, I applied the microclimatic data obtained from the field measurements at the sites with different environmental characteristics to investigate the UGI's (targeting at trees) effects on microclimate and human thermal comfort during summer and winter. In addition, I used a microclimate model, ENVI-met, to examine the spatial differences of UGI's performance on the microclimate. The effect of weather conditions on UGI's thermal performance was also analysed.

In Chapter 4, follow-up field measurements paid attention to the impact of vegetation density and PAI on regulating microclimate by different UGIs. In order to better quantify the effects of changes in vegetation density and PAI, I carried out field measurements at the study site locations covered by different types and configurations of UGI during the growing season. I used the hemispherical photography method (a technique to characterize plant canopy geometry using photographs taken looking upward through an extreme wide-angle lens) (Rich 1988) and globe-thermometer methods (a method calculates radiant temperature from globe temperature, air temperature and air velocity) (ISO 7726 1998) to quantify PAI and thermal comfort, respectively.

Chapter 5 presents the results of a thermal comfort survey at a Dutch university campus in Groningen. This study aimed to explore people's perception of and preference for microclimatic conditions in small urban green areas, on warm and cloudless days. By applying statistical analysis, the neutral operative temperature (comfort temperature) and preferred temperature (the temperature people stated they would prefer) were obtained. Additionally, the impacts of thermal adaptation (behaviour adjustment, purpose of coming, visiting frequency and exposure time, previous thermal environment and activity, and thermal history) on human thermal sensation were also discussed.

Chapter 6 provides a general synthesis and discussion of the main findings and key conclusions. By integrating the findings from previous chapters, answers to the research questions are provided and placed in context. The importance of the combined methodologies, including field measurements, modelling and social survey, adopted in this thesis is emphasized to improve our understanding of the role of UGI on thermal environmental condition. Several essential factors (e.g. local morphology, geographical conditions and vegetation characteristics), which were found to influence the role of UGI in human urban habitats from previous chapters, are discussed from a wider and more comprehensive perspective. After combining and interpreting the results of each chapter, Chapter 6 highlights the major contributions, strengths and limitations of this thesis and provides specific recommendations for future research on UGI's thermal effects in human urban habitats.



Weather station equipped with temperature and humidity sensors, anemometer and globe thermometer at INCAS[3], Assen (latitude: 53º 0’ 0’’ N, longitude of 6º 55’ 00’’ E).

CHAPTER 2

Effects of ecosystem services provided by urban green infrastructure (UGI) on human urban habitats: A literature review

Based on:

Wang, Y., Bakker, F., de Groot, R., & Wörtche, H. (2014). Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Building and Environment*, *77*, 88–100.

Abstract

The influence of urban green infrastructure (UGI) on habitats in outdoor and indoor spaces and the effects on human comfort and economic consequences are still unclear. This chapter gives a systematic overview of the relationship, in terms of so-called ‘ecosystem services (ESs)’, between UGI and human urban habitats through a literature review in different disciplines. UGI was found to contribute both positively and negatively to urban environmental quality by influencing the microclimate, air quality, sonic environment and aesthetic quality. Four main factors that influence these effects were identified, being local morphology, geographical conditions, vegetation characteristics, and building characteristics. Although the reviewed papers have investigated the different ESs on a wide range of spatial and temporal scales, the performance of UGI on microclimate regulation at national and regional/local level has received less attention. Another finding is that, whereas the modelling approach on microclimate regulation has been widely adopted by researchers throughout the world, empirical studies are much fewer and have mainly been performed in the USA. We also analysed the data found on economic implications. The economic effects of adjoining vegetation and green roofs on microclimate regulation provided energy savings of up to almost US$250 per tree per year, while the air quality regulation was valued between US$0.12 and US$0.6 per m^2 tree cover per year. Maximum monetary values attributed to noise regulation and aesthetic appreciation of urban green (e.g. parks and forests) were US$20 and US$25 per person per year, respectively. Of course these values are extremely time- and context-dependent but do give an indication of the potential economic effects of investing in UGI. Based on this review, we conclude that new methods, measurement instruments and field experiments are needed to improve empirically supported correlations and develop concrete recommendations for urban planning and design.

Key words: Urban ecosystem services, Green infrastructure, Vegetation, Urban habitats, Human comfort, Literature review

2.1 Introduction

People living in urban areas depend on natural ecosystems not only beyond the city limits, but also within the urban area (Bolund and Hunhammar 1999). Natural elements in urban areas have many proven benefits to human society, including material and spiritual aspects (Folke et al. 1997, Gómez-Baggethun and Barton 2013, Watson 2005) which are positively related to human health and comfort, as demonstrated by numerous epidemiological studies (Akbari 2002, Takano et al. 2002, Tzoulas et al. 2007). The influence of ecosystems on human health and comfort can be described in terms of Ecosystem Services (ESs) (Millennium Ecosystem Assessment 2005). Due to the different types of ecosystems (e.g. grasslands, forests, wetlands), the types of ESs are different as well. A recent study by Gómez-Baggethun and Barton (2013) identified fifteen important ESs in urban areas (e.g. urban temperature regulation, air purification, waste treatment). Within the urban system, indoor areas take up a large amount of space and people spend most of their time indoors. Low quality indoor environments can therefore pose serious risks to human health (WHO 2009).

This chapter focuses on the urban ESs and disservices relevant for human habitats in both outdoor and indoor spaces. Many studies have discussed the contribution and effects of urban green infrastructure (UGI), especially urban forests, to the outdoor and indoor environments through both direct and indirect processes. Human urban habitats are generally affected by UGI (e.g. urban trees, green walls and roofs) via four main ESs. First of all, the microclimate is regulated through buffering solar radiation, lowering wind speeds, and evapotranspiration (Akbari 2002, Chen and Jim 2008, Heisler 1986, Huang et al. 1987, Simpson and Mcpherson 1997). Secondly, UGI affects the air quality through removing air pollutants by dry deposition and by influencing the smog (O_3) formation process (Bolund and Hunhammar 1999, Akbari 2002, Konopacki and Akbari 2000, Nowak 1994, Taha et al. 1997, Thornes et al. 2010). The third ES relates the UGI to noise abatement (González-Oreja et al. 2010, Kommunförbundet 1998, Nijland et al. 2003), and noise masking by generating pleasant sounds in the canopy (Irvine et al. 2009, Matsui et al. 2009, Miller 1997). Finally, natural views provide aesthetic information to citizens and visitors (Driver et al. 1978, Kaplan 1983, Kong et al. 2007).

In this chapter, we reviewed literature from different disciplines to synthesize the current knowledge on the effects (both positive and negative) of UGI on human urban habitats and human comfort. The aim of this study was to (1) provide a systematic overview of state-of-the-art in the field of urban ESs and human comfort in human urban habitats; (2) logically classify the reviewed studies and information into four main categories of urban ESs; (3) identify the strengths and weaknesses in the existing literature; and (4) provide suggestions for future studies to improve the knowledge base in this important research area.

2.2 Methods

The methods used for this review are described in three sub sections: 1) search strategy; 2) establishing the relation between UGI and human urban habitats; and 3) typology of the benefits and economic analysis.

2.2.1 Search strategy

In the first selection stage, the keywords “urban ecosystem services”, “urban green infrastructure”, “indoor environment”, “outdoor environment” and “human comfort” were used and peer reviewed scientific papers were selected. Since the comprehensive relationship between UGI and human urban habitats (especially indoor environment) is difficult to establish, this study reviewed literatures that focused on the quantification of four major urban ESs (i.e. microclimate regulation, air quality regulation, sonic environment regulation and aesthetic information services). For the air quality regulation service, direct effects of the UGI on the indoor air quality were rarely studied. To gain more insight into these effects, specific literatures on indoor pollutants from outdoor sources and the impact of UGI on these pollutants were reviewed. In addition, articles studying the relationship between UGI and indoor sonic environment have not be found, so that only the studies exploring the effect of UGI on the outdoor sonic environment were reviewed. In the second selection stage, socio-economic aspects were obtained by adding additional keywords: “socio economic valuation” and “costs and benefits”. After screening, in total 148 papers were selected, of which, 86 investigated the quantification of UGI’s effects, and 24 explored the costs and benefits of UGI. The remaining papers were analysed for gaining general knowledge on urban ESs.

2.2.2 Establishing the relation between UGI and human urban habitats

The 86 articles focused on the quantification of UGI's effects (see Section 2.1) were reviewed by analysing the study design and their interpretations and findings. Figure 2.1 shows the established relations between UGI's ESs and human urban habitats. The main ecosystem functions associated with each service provided by UGI were used to classify the selected papers.

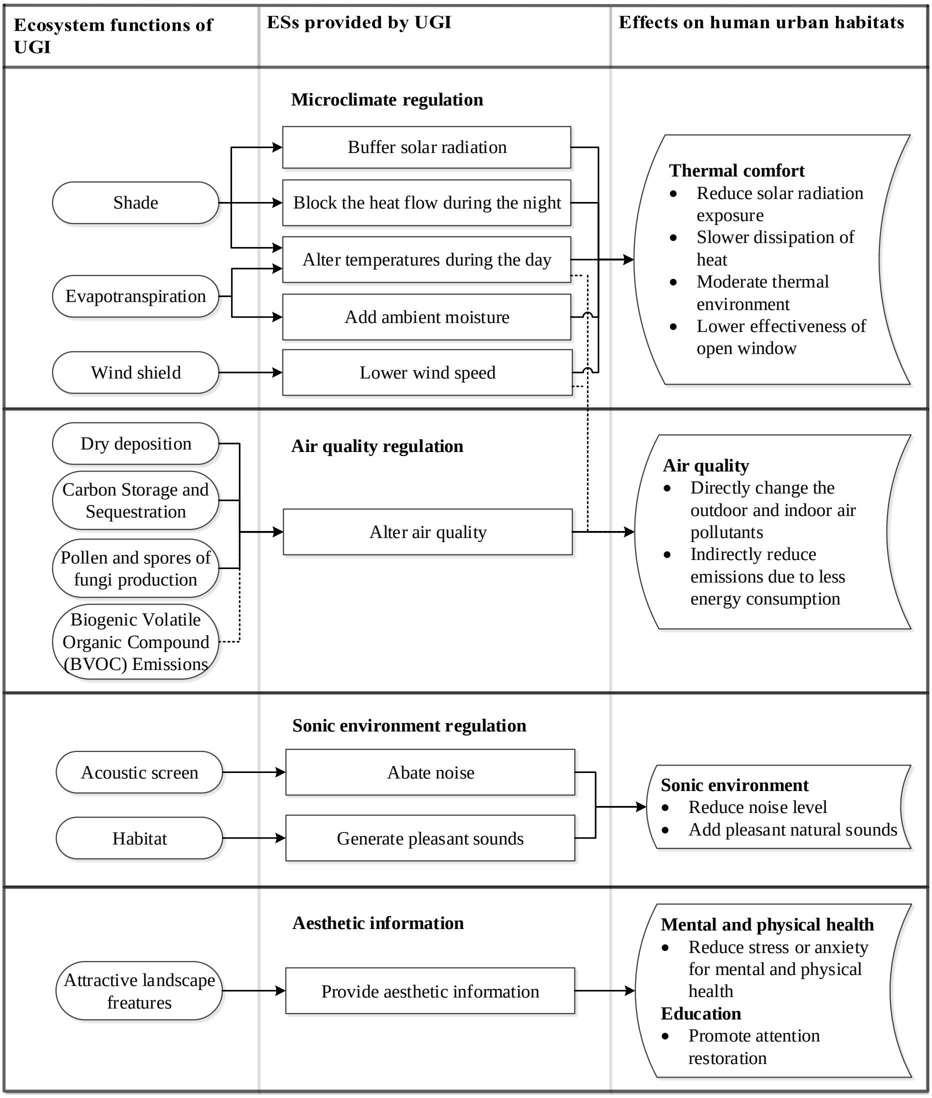


Figure 2.1 The ESs provided by Urban Green Infrastructure (UGI) to human urban habitats. Solid line and dash lines correspond to direct and indirect effects, respectively.

The literatures that described the effects of UGI on the outdoor and indoor microclimate and energy use mainly focused on two major categories, i.e. adjoining vegetation (e.g. Heisler 1986, Akbari et al. 1997, Berry et al. 2013), and roof and wall greenery (e.g. Hien et al. 2007, Parizotto and Lamberts 2011, Ouldboukhitine et al. 2014). For both categories we analysed three main ecosystem functions, being shading, evapotranspiration and wind shield (Appendix 2.1).

Due to the complex biophysical processes involved in the air quality regulation service, the UGI's effects were grouped into direct and indirect effects. Direct effects are comprised of removing air pollution via dry deposition processes (e.g. Escobedo et al. 2008, Tallis et al. 2011, Martin et al. 2012), storing and sequestering carbon (e.g. Redondo-Brenes 2007, Martin et al. 2012, Wang and Lin 2012), and releasing pollen and spores of fungi (e.g. Liao et al. 2004, Nayar and Jothish 2012, Yli-Panula 2012). In addition, vegetation indirectly affects the air quality through biogenic volatile organic compound (BVOC) emissions and by regulating the microclimate, thereby reducing the potential air pollution as a result of energy saving (e.g. Owen et al. 2003, Geron et al. 2006, Fu and Liao 2012). A potential indirect effects of vegetation on air pollution concentration through regulating temperature and air flow have been investigated recently (Baik et al. 2012, Vos et al. 2013). Finally, reduced energy consumption due to the contribution of UGI can also reduce the carbon dioxide (CO_2) emission (Akbari 2002, Fahmy and Sharples 2011, Lin et al. 2011) (Appendix 2.2).

UGI not only acts as an acoustic screen between noise sources and receivers (e.g. González-Oreja et al. 2010, Van Renterghem and Botteldooren 2011, Van Renterghem et al. 2013), but also masks noise by generating pleasant sounds from rustling leaves and through providing a wide variety of habitats (Irvine et al. 2009). This literature study reviewed both perspectives.

Finally, we summarized and integrated the results of studies that investigated the aesthetic information service of UGI seen from the point of people's mental and physical health (Ulrich 1984, Ulrich 1986, Ulrich et al. 1991, Van den Berg et al. 2010), and based on the effect of views on outdoor green and effect of green spaces on children's educational results (Kaplan 2001, Taylor et al. 2002).

2.2.3 Typology of benefits and economic analysis

UGI directly affects the human urban habitats in microclimate, air quality, sonic and aesthetic aspects. Further, UGI also has many secondary effects on human health and comfort and the economy.

Reduced energy costs resulting from the outdoor and indoor temperature modification provided by UGI is often used to value the benefits of the microclimate regulation service. The reviewed articles focused on the UGI's direct contribution on the energy saving (for cooling and heating) via altering the thermal environment (e.g. Konopacki and Akbari 2000, Konopacki and Akbari 2002, Claus and Rousseau 2012), and the indirect contribution through changing the wind speed (Mcpherson et al. 1988).

The potential value of the air quality regulation service, associated with both air pollutant removal (e.g. Jim and Chen 2008, Martin et al. 2012, Claus and Rousseau 2012) and carbon storage and sequestration (Nowak and Crane 2002), was calculated by measuring the effects on health care and replacement costs of artificial treatment systems.

The benefits of sonic environment regulation (noise abatement) were derived from the survey based valuation studies, such as assessing the citizens' willingness to pay (WTP) for quiet acoustic environments and small group discussions and consensus building (Kommunförbundet 1998, Nijland et al. 2003, Bjørner 2004, Howarth et al. 2001).

In terms of aesthetics information services, the difference in price of building units in relation to the surrounding vegetation situation and density (so called "hedonic pricing") was often used to calculate its monetary value (e.g. Tratsaert 1998, Kong et al. 2007, Sander and Haight 2012). In addition, people's WTP was another method to estimate the value of this service (Tyrväinen and Väänänen 1998, Jim and Chen 2006).

2.3 Effects of UGI on microclimate and energy use

During the summertime, trees or tall bushes provide shade from solar radiation to human beings and buildings, and reduce the ambient temperature during the day. At night, they prevent heat flow by altering the heat exchange between the vegetation and atmosphere (Akbari 2002, Huang et al. 1987, Akbari et al. 2001, Heisler and Grant 2000). The ambient temperature can be also lowered through evaporation and transpiration from vegetation and surrounding soil (Akbari 2002, Huang et al. 1987). In addition, trees as shield could lower the wind speed, and consequently reduce the air ventilation and infiltration (Akbari 2002, Huang et al. 1987, Heisler 1990). At the same time, wind shield from trees also contribute to maintain a comfortable air temperature by reducing hot wind blowing in the summer; as evergreen trees reduce the cold wind blowing in the winter. Moreover, the evapotranspiration of vegetation adds the ambient moisture, which could also raises the outdoor and indoor humidity (Akbari 2002, Huang et al. 1987).

On the other hand, evergreen vegetation may reduce the air temperature in the winter, which could increase the energy consumption for heating (Akbari 2002, Mcpherson et al. 1988). Furthermore, lowered wind speeds possibly impede heat dissipation from sunlit surfaces, and reduce the effectiveness of open windows in the summer by lowering the air infiltration rate (Akbari 2002). In addition, the effects of the increased moisture on human comfort could be positive or negative, which are various in dry and humid areas. The most important types of UGI were classified as adjoining vegetation, and roof and wall greens. The research methods were grouped into field measurements and experiments, and modelling studies.

2.3.1 Influence of adjoining vegetation on the microclimate & energy use

In order to gather reliable data, field measurements and experiments dedicated to vegetation effects on microclimate and energy use have been conducted in scientific research. To fill in the inevitable data gaps that still exist, a number of models were designed. These models are considered very helpful to understand the processes in detail and to conduct predictive and retrospective analyses.

Field measurements/experiments

Adjoining UGIs ranging from single tree to large green area have been investigated via field measurements in various settings. The contribution of individual tree on the solar control and evaporative cooling has been well studied over the past decades. The radiative and thermal loads, wall and roof temperature, and air temperature were confirmed to be significantly lower in the shade of the trees compared to unshaded areas. It has been found that insulation in the walls and roof can be reduced by approximately 80% when trees are in leaf (Heisler 1986). Due to the shading of trees on wall and roof, the surface temperature was reported to be reduced by 11.0–25.0 ℃ in Sacramento, California, USA (Akbari et al. 1997), 9.0 ℃ in Melbourne, Australia (Berry et al. 2013), and 5.0–7.0 ℃ in Akure, Nigeria (Morakinyo et al. 2013). Moreover, the indoor air temperature was reported to be lowered by up to 3.0 ℃ (Morakinyo et al. 2013). Akbari et al. (1997) measured both indoor and outdoor thermal parameters at two houses by placing 16 mobile trees during summertime. The measurements included indoor and outdoor temperature and humidity, wind speed and direction, roof and ceiling temperature, interior and exterior wall temperature, horizontal insolation, and air conditioning energy use. It was concluded that over 30% of annual cooling energy was saved in the hot period. Another experimental study on the cooling impact of shade trees compared the electricity consumption in two identical buildings under different shade conditions (Laband and Sophocleus 2009). The study revealed that the cooling energy required for maintaining a constant indoor temperature was approximately 13% less in the shaded building compared to the unshaded building.

Besides investigating the effects of (groups of) individual tree on the single building, the regional effects of trees on the microclimate have also been studied. With the vegetative canopy, an average ambient air temperature reduction of 0.9–2.0 ℃ was established (Heisler 1986, McPherson et al. 1989, Taha et al. 1991), while the energy use for air conditioning was lowered by 20–30% (McPherson et al. 1989).

Plants can act as wind shield, thereby reducing or blocking outdoor air movement, which has been confirmed by many experimental studies. Wind speed reduction differs with the structure, size and orientation of the UGI (Akbari et al. 1997, Papadakis et al. 2001, Taha et al. 1991, Heisler 1990). In 2012, Park et al. carried out a study in an urban street canyon. As many as 512 concrete cubes with 8 different vegetation conditions were formed to simulate the urban outdoor thermal environment. The results indicated that the sidewalk trees reduced wind speed in the canopy by 51%. However, a vegetated median strip does not significantly mitigate wind speed or temperature.

Modelling studies

Both the positive and negative effects of microclimate regulation by vegetation have been investigated by a number of modelling studies. A few studies quantified the impacts of vegetation on energy consumption regionally. Mcpherson et al. (1988) explored the effects of irradiance reductions on the energy consumption in 4 US cities (Madison, Salt Lake City, Tucson and Miami). The simulation results indicated that, in the warm period, shade provided by vegetation saved cooling costs by 53%–61%, but lowered wind speeds by 50%, which reduced the need for heating but increased the need for cooling. Another study investigated the individual and combined impacts of shading, wind shield, and evapotranspiration in 4 cities in Canada (Toronto, Edmonton, Montreal and Vancouver) by increasing 30% of the vegetation cover in the neighbourhood (Akbari and Taha 1992). By utilizing a building energy simulation program, the energy savings for heating and cooling were estimated at 10% and 40% in urban houses, and at 20% and 30% in rural houses. Shashua-Bar and Hoffman studied the cooling effects of green areas in the urban cluster/canyon in 2000, 2002 and 2004 (Shashua-bar and Hoffman 2000, Shashua-bar and Hoffman 2002, Shashua-bar and Hoffman 2004). The average cooling effects of urban trees ranged from 2.8–4.5 ℃, and approximately 80% of the effects was attributed to shading.

Modelling studies on urban outdoor and indoor thermal comfort were performed at a broad range of the spatial scales. The effects of tree species, leaf area index (LAI), distance and orientation of vegetation on the microclimate mitigation were all addressed. In the northern hemisphere, energy saving for cooling can be maximized when trees were positioned on the south and west sides of buildings (Akbari and Taha 1992, Mcpherson et al. 1988, Sawka et al. 2013), whereas the heating costs/loads were found most sensitive to south and east wall shading (Mcpherson et al. 1988). Fahmy et al. (2009) investigated the microclimate effects of two types of trees on the thermal comfort in residential buildings in Cairo, Egypt. It was found that tree type, LAI and evapotranspiration rate have their specific impacts on the urban microclimate. A study by Shahidan et al. (2012) laid emphasis on the optimum cooling effects of trees on mitigating the urban heat island (UHI) effect and building energy performance in Putrajaya, Malaysia through modifying the tree canopy density and quantity. The results revealed that trees with a high LAI can lead to a reduction in building cooling load, while the average outdoor air temperature was reduced via doubling the amount of trees with low LAI (0.9) and high LAI (9.7) by 0.9 ℃ and 1.2 ℃, respectively. Furthermore, 20% of the tree coverage in Toronto was estimated to contribute to 77,140 kWh (167 kWh per tree) of cooling energy savings in 2009 (Sawka et al. 2013). However, these benefits highly dependent on tree species, canopy, and the tree distance and orientation from buildings.

2.3.2 Influence of roof and wall greens on the microclimate and energy use

Vegetation is often planted on roofs or walls of buildings complementary to adjoining vegetation, and can regulate both indoor and outdoor microclimate. Green roofs and walls primarily reduce the heat flux through the roof, shield the roof slab from direct sunlight and provide evaporative cooling.

Field measurements/experiments

Roof and wall plants affect the thermal environment via solar control and evaporation, which has been clarified by a number of empirical studies. First of all, green roofs and walls were reported to lower the ambient air temperature by 1.0–4.3 ℃ among different countries (Susca et al. 2011, Wong et al. 2003, Niachou et al. 2001), whereas the surface temperature reduction varied by 1.9–60.0 ℃ (Eumorfopoulou and Kontoleon 2009, Onmura et al. 2001, Parizotto and Lamberts 2011, Wong et al. 2003, Blanusa et al. 2013, Lin et al. 2013). Furthermore, the heat flux through roof and wall, which is responsible for heat gain in the summer and heat loss in the winter, was observed to decrease due to the presence of vegetation in several case studies (Eumorfopoulou and Kontoleon 2009, Onmura et al. 2001, Parizotto and Lamberts 2011). Due to these effects, the indoor air temperature was found to be lowered by 0.5–5.0 ℃ (Eumorfopoulou and Kontoleon 2009, Rashid and Ahmed 2009, Niachou et al. 2001). The energy savings that can be achieved by green roofs and walls is also significant. The installation of a green roof and wall resulted in an energy reduction of approximately 2–48%, as demonstrated by Niachou et al. (2001). The performance of urban green walls and roofs on energy saving depends on the properties of façades and substrate, location, local climate, species and amount of plants (Wong et al. 2003, Niachou et al. 2001, Blanusa et al. 2013). Plants contribute to energy reduction (associated with temperature reduction) in particular for the buildings without insulation (Niachou et al. 2001).

Although the positive effects of green roofs and walls have been confirmed by many studies, an experiment, carried out before and after establishing an extensive rooftop garden above a multi-storied car park, put forward that a green roof with sparsely covered vegetation may increase the substrate and ambient temperatures when the substrate is dry and wind speed is low (Hien et al. 2007). Nevertheless, a well-covered green roof can stop over 60% of the heat gain of a building and reduces the risk of glare for surrounding buildings (Hien et al. 2007).

Modelling studies

In the past decades, many models based on biophysical processes have been created for evaluating the dynamic thermal behaviour of green roofs. The convective, conductive, evaporative and radiative heat fluxes on the green roof and wall have been thoroughly investigated. The presence of green roofs and walls in the summer time were estimated to lower the ambient air temperatures by 0.4–1.7 ℃ (Ouldboukhitine et al. 2014, Peng and Jim 2013, Wong et al. 2009) and the surface temperature by 0.7–30.0 ℃ (Alexandri and Jones 2008, Kontoleon and Eumorfopoulou 2010, Ouldboukhitine et al. 2011, Ouldboukhitine et al. 2014, Susorova et al. 2013, Takakura et al. 2000). Moreover, the average indoor air temperature of the buildings with green roofs and walls was reduced by approximately 2.0 ℃ in the summer, which lead to a reduction of the cooling load by 5%–90% (Alexandri and Jones 2008, Jaffal et al. 2012, Kontoleon and Eumorfopoulou 2010, Kumar and Kaushik 2005, Zinzi and Agnoli 2012). A decrease of energy use for heating due to the reduced heat losses was also reported (Castleton et al. 2010, Ouldboukhitine et al. 2014). However, green roofs may also increase energy consumption in the wintertime. Jaffal et al. (2012) compared the surface temperature of conventional and green roofs on a single-family house in the wintertime. It was reported that the green roof lowered heat losses by 5.5 kWh per day on a cold day, but increased that value by 4.0 kWh per day on a sunny day.

Weather and climate condition, properties of façades and substrate, façade orientation, and properties of plants were often used as the key parameters to estimate the effects of green roof and wall on the thermal performance of buildings (He and Jim 2010, Kumar and Kaushik 2005). Alexandri and Jones (2008) examined the effects of green roof and wall on microclimate in the built environment with different urban geometries and weathers. The results showed that orientation plays a measureable role when there is a significant change of solar insolation on the façade. Kumar and Kaushik (2005) simulated the thermal performance of a green roof-top garden. The results revealed that a larger LAI (i.e. 3.5 compared with 0.5) stabilized the fluctuation of the canopy air temperature and reduced the penetrating flux to nearly 4 $W \cdot m^{-2}$. Moreover, it was estimated that the mean indoor air temperature was reduced by 0.3 ℃ when changing the LAI of the green roof from

0.5 to 2.0 (Jaffal et al. 2012). Furthermore, the thicker soil substrate on the roof, the greater the reduction of heat flux into the building was (Castleton et al. 2010).

The main findings from the field measurements and modelling studies are systematically presented in Appendix 2.3. Appendix 2.4 lists the models used in the reviewed modelling studies.

2.4 Effects of UGI on air quality

Vegetation positively affects urban air quality through three ecosystem functions: removing air pollutants through dry deposition processes (Bolund and Hunhammar 1999, Nowak 1994, Thornes et al. 2010), storing and sequestrating carbon through photosynthesis (McPherson and Simpson 1999), and slowing down smog (O_3) formation process by cooling the ambient temperature (Konopacki and Akbari 2000, Taha et al. 1997). On the other hand, UGI also has negative effects on the air quality. For example, BVOC emissions from vegetation can contribute to the formation of O_3 through a photochemical reaction with NO_x (Akbari 2002), the formation of secondary organic aerosols (SOA) through photo oxidation process (Fu and Liao 2012) and the formation of carbon through oxidation or reduction processes (Bouvier-Brown et al. 2012). Also, human allergic response to pollen and fungi spores is an environmental health issue (Townsend et al. 2003). In addition, UGI may also increase air pollution inside buildings by reducing the air ventilation. Inadequate air ventilation due to the shield of trees reduced the dilution effects of outdoor air on emissions of indoor sources, and lowered the transfer rate of indoor air pollutants when the inside pollution concentration is higher than outside (Barro et al. 2009).

The building envelope demarcates indoor and outdoor air by restricting the movement of airborne contaminants (Hayward 1986). Nevertheless, the concentration of outdoor pollutants still affects the quality of indoor air, since many indoor particles are of outdoor origin (Dockery and Spengler 1981, Koponen et al. 2001, Long and Sarnat 2004, Meng et al. 2005). Particulate matter (PM), as one of the most important air pollutants, poses a potential health hazard to humans (Colbeck et al. 2010, Riley et al. 2002). According to the particle size categorizations (referred to as fractions), PM_1, $PM_{2.5}$ and PM_{10} are the most common particulate matter pollutants. Nitrogen dioxide (NO_2) and nitric oxide (NO), originating from outdoor sources, can also cause adverse health effects (Baxter et al. 2007, Zipprich et al. 2002). Moreover, elemental carbon (EC) pollutants with more spatial heterogeneity were confirmed (Baxter et al. 2007, Kinney et al. 2000). As early as 1972, Benson et al. indicated that indoor pollution levels including sulphur dioxide (SO_2), carbon monoxide (CO), and CO_2 appeared to be primarily controlled by outdoor concentrations. The BVOC emissions, especially biogenic non-methane volatile organic compound (BNMVOC), are mainly emitted by vegetation to act against various stresses in the environment (Owen et al. 2003, Guenther et al. 2000). Moreover, vegetation is the main source of indoor pollen and spores of fungi (Hugg and Rantio-Lehtimäki 2007, Sterling and Lewis 1998, Lee et al. 2006). The main indoor pollutants from outdoor sources are summarized in Appendix 2.5.

2.4.1 Direct effects of urban green on air quality

Dry deposition

The trunks, branches and leaves of trees and vegetation remove gaseous pollutants and particulate matter by dry deposition. This process was mainly investigated via modelling studies. To help the managers and researchers valuate the urban vegetation, the Urban Forest Effects (UFORE) model was developed by Nowak and Crane (2000) to quantify the structure of the urban forest and its contribution to air pollution removal. The capability of atmospheric cleansing by trees in congested cities in all over the world was assessed via the UFORE model (Escobedo et al. 2008, Jim and Chen 2008, Nowak et al. 2006, Nowak 2006, Tallis et al. 2011, Yang et al. 2005). The removal rates for NO_2, O_3, SO_2, PM_{10} and CO were estimated to be 0.4–2.88 $g \cdot m^{-2} \cdot yr^{-1}$, 1.1–7.6 $g \cdot m^{-2} \cdot yr^{-1}$, 0.2–2.73 $g \cdot m^{-2} \cdot yr^{-1}$, 1.1–17.3 $g \cdot m^{-2} \cdot yr^{-1}$ and 0.1–0.57 $g \cdot m^{-2} \cdot yr^{-1}$, respectively (see Appendix 2.6). These values differed mainly because of the vegetation coverage and pollutant concentration. Based on these values, the total air pollutants could be removed by 0.1–0.5%, 0.1–0.8%, 0.1–0.7%, 0.2–1.4% and 0.001–0.003% for NO_2, O_3, SO_2, PM_{10} and CO, respectively.

Besides the vegetation coverage and pollutant concentration, plant species, health, structure and size determine the efficiency of air pollutant uptake by vegetation as well. In 2011, Yin et al. conducted an experiment to estimate the attenuation effects of urban vegetation on levels of air pollution at six parks in Shanghai, China. LAI was proven to be key predictor influencing pollutants removal rate. Tallis et al. (2011) pointed out that the coniferous trees offer a greater PM_{10} mitigation potential compared to broadleaved trees. Furthermore, street trees were proven to have the greatest exposure to PM_{10}, thereby generating the greatest benefits. Another study by Martin et al. (2012) estimated the air pollution removal between protected and maintained urban forests in Auburn, Alabama, USA. The results indicated that the differences in pollutant removal rate provided by the protected and maintained urban forests are caused by variations in the forest structure, tree condition and size. Generally, trees in the protected areas are larger and healthier than in the maintained area.

Carbon Storage and Sequestration

During photosynthesis, carbon is captured and stored in the plants as biomass. Carbon storage and sequestration by trees has been explored as a strategy to alleviate global warming (Leung et al. 2011). The capability of carbon storage and sequestration of vegetation does not only determine the outdoor carbon emissions, but also affects the indoor pollution concentration (Benson et al. 1972). Total carbon storage and gross sequestration by trees have been studied in different cities in the world (Yang et al. 2005, Cox 2012, Nowak and Crane 2002, Ren et al. 2011, Wang and Lin 2012). The amount of carbon stored by the UGI ranges from 321 g $C \cdot m^{-2}$ in Xiamen, China to 36,100 g $C \cdot m^{-2}$ in Sacramento, California, USA. The gross carbon sequestration rates were lowest in New Jersey, USA (21 g $C \cdot m^{-2} \cdot yr^{-1}$) and highest in Beijing, China (202 g $C \cdot m^{-2} \cdot yr^{-1}$). Appendix 2.7 summarizes the total amount carbon storage and annual gross carbon sequestration from the reviewed literatures.

In principle, the trees with the higher LAI and higher photosynthetic rates have more carbon sequestration capability. Location and structure of the trees were considered as the two main factors influencing the amount of carbon accumulation (Elias and Potvin 2003). The other factors, arranged in order of importance, are the following: density, slope, canopy and humidity (Gratani and Varone 2006, Nowak and Crane 2002). Redondo-Brenes (2007) also reported that the wood specific gravity of plants, which varies within species, locations, and specific growth conditions, determines the amount of carbon sequesters. In the short term, fast growing species accumulate more carbon than slower growing species. However, in the long term, slower growing species accumulate more (Cox 2012, Redondo-Brenes 2007). The study by Martin et al. concluded that the trees in protected areas are larger and healthier than in maintained area, which lead to higher carbon storage and sequestration rate

(Martin et al. 2012). Moreover, evergreen species can perform photosynthesis continuously throughout the year, which enables the uptake of more carbon than the deciduous species (Gratani and Varone 2006).

Pollen and fungi spores

Indoor airborne pollen and fungi mainly come from outdoor sources. They enter a home by infiltration through open areas (i.e. windows and doors) (Hugg and Rantio-Lehtimäki 2007). Their indoor concentrations are dependent on a combination of factors that comprise the geographic location and local climate, season, and characteristics of the buildings and occupants (Sterling and Lewis 1998). Yli-Panula (2012) measured concentrations of pollen inside and outside a block of flats, a detached house, and a regional central hospital in Turku, Finland. The highest indoor concentrations were observed in the central hospital, which had the highest frequency of door openings and a large door. A study carried out in Kerala, India, indicated that peak spore and pollen incidence were recorded during the late rainy and dry seasons (October to February) in both indoor and outdoor environments (Nayar and Jothish 2012). A modelling study in Taiwan demonstrated the indoor and outdoor airborne fungi concentration (Liao et al. 2004). Air relative humidity (RH) was found to be significantly correlated with the concentration of indoor/outdoor ratios of airborne fungi. This can be explained by the fact that the increase of particle diameter by condensation or water absorption can influence the kinetics of aerosols.

2.4.2 Indirect effects on air quality

Biogenic Volatile Organic Compound (BVOC) Emissions

In urban areas, the materials used for road, building, etc. have higher reflectivity; solar radiation and UV exposure occurs routinely compared to the natural area. The higher radiation exposure for most of the plants' foliage and the higher temperature lead to the increase of BVOC emissions. These emissions may offset, or even overwhelm the benefits of vegetation. During 2001–2006, the inter annual variations in BVOC lead to 2–5% differences in simulated O_3 and SOA concentrations in the summer in entire China (Fu and Liao 2012). The BVOC emissions also contribute to the net ecosystem carbon flux. During 1999–2000, BVOC emissions caused loss of carbon by 9.4 g $C{\cdot}m^{-2}$ at Blodgett Forest, California, USA (Bouvier-Brown et al. 2012). These adverse effects can be reduced by carefully controlling the factors that can lower BVOC emission potential of the plants. The biophysical environment and vegetation characteristics were identified as the main factors which determine the emission of BVOC for a specific region (Chang et al. 2012).

A BVOC emission model, developed by Guenther et al. (1993) has been widely used to estimate the BVOC emission potential by many researchers. Isoprene (a common organic compound) and monoterpenes (a class of terpenes), which constitute a major fraction of BVOC, were mainly investigated among these studies. The annual BVOC emission from the UGI ranged from 0.1 to 8 g $C \cdot m^{-2} \cdot yr^{-1}$ (Chang et al. 2012, Geron et al. 2006, Geron et al. 2002, Owen et al. 2003). To a large extent, the plant species selection for an urban environment determines the amount and type of BVOC emissions (Chang et al. 2012, Fu and Liao 2012, Geron et al. 2006, Geron et al. 2002, Owen et al. 2003, Parra et al. 2004, Poupkou et al. 2010). Urban forests were considered the most important sources of BVOC emission (Geron et al. 2002, Poupkou et al. 2010), whereas desert vegetation was a relatively small source (Geron et al. 2006).

Temperature, concentrations of air pollutants, soil moisture and plant species were proved to affect the BVOC emission in the long term (Owen et al. 2003). Parra et al. (2004) showed that approximately 50% of the annual BVOC were emitted during June, July and August in Catalonia, Spain. In the Mojave and Sonoran Desert regions of the USA, at least a threefold difference in the total annual BVOC emissions between dry and wet years was observed (Geron et al. 2006). Fu and Liao (2012) pointed out that isoprene emissions were more dependent on meteorological parameters, whereas monoterpene emissions were more sensitive to changes in the plant functional types and the LAI.

Effects on air quality by microclimate regulation

A potential indirect effect of vegetation on air quality through microclimate regulation has been investigated recently. Baik et al. (2012) examined the effects of green roofs on air quality in street canyons in Seoul, South Korea, with a computational fluid dynamics (CFD) model (Baik et al. 2003). It was shown that cool air produced by green roofs flowed into the street canyon resulting in a strengthened street canyon flow. Therefore, pollutant dispersion was enhanced and the pollution concentration was decreased near the road. However, another study by Vos et al. stated that dense vegetation in street canyons should be avoided, especially in busy street canyons with much traffic (Vos et al. 2013). Roadside urban vegetation leads to increased pollutant concentrations, because the vegetation reduces the air ventilation that is responsible for diluting the pollutants from traffic. Only high impermeable green barriers led to a significant improvement in air quality (Vos et al. 2013).

Potential energy saving

The savings in energy consumption due to the vegetation have been translated into reduced CO_2 emissions. In two papers in 2000 and 2002, Konopacki and Akbari estimated an annual reduction in carbon emissions from power plants of 1.9×10^{10} g C, 6×10^{10} g C, and 1.3×10^{10} g C in Baton Rouge, Sacramento, and Salt Lake City, respectively, using the North American average emission of 200 g $C\cdot kWh^{-1}$ for generated electricity (Konopacki and Akbari 2000, Konopacki and Akbari 2002). A modelling study estimated that the CO_2 emissions were reduced by between 1.7% and 2.8% through adding 8 cm high grass and 15 m high trees (Fahmy and Sharples 2011). In 2011, Lin et al. computed a total amount of 1.3×10^{10} g C savings as a result of the green areas' cooling effect. A strong correlation between biomass, size and shape of green areas and carbon savings was confirmed in this study.

2.5 Effects of UGI on the sonic environment

Noise is defined as an unwanted sound that disturbs people or prevents people from hearing preferred sounds (Stansfeld and Matheson 2003). Unwanted sound affects various ecosystem components (e.g. animal habitat) (Brown and Raghu 1998, Warren et al. 2006), human health (Stansfeld and Matheson 2003, Babisch 2005, Sobotova et al. 2010) and human behaviour (Garza 2004). Growing amounts of traffic and other noise-sources have increased people's exposure to noise, leading to many health problems, especially in urban areas. There is much scientific evidence demonstrating that noise exposure can induce hearing impairment, hypertension, ischemic heart disease, annoyance, sleep disturbance, and decreased school performance (Bolund and Hunhammar 1999, Stansfeld and Matheson 2003, Babisch 2005, Sobotova et al. 2010). Evans et al. (1995) have demonstrated that chronic noise exposure was associated with elevated neuroendocrine and cardiovascular measures among elementary school aged children, resulting in deficits in long term memory, speech perception and standardized reading test scores. In addition, children living in the proximity of a major airport showed increased annoyance and lower quality of life according to the assessments of noise impact on their physical, psychological, social, functional daily life domains (Passchier-Vermeer and Passchier 2000).

The foliage of trees or shrubs is similar to a sound absorbing wall. When the sound waves pass through, the flexible leaves of trees or shrubs absorb part of the energy, thereby contributing to noise reduction (Magrab and Jackson 1973). In addition, UGI also generates pleasant sounds in the canopy through rustling leaves and providing habitats to support a range of species (e.g. birds) (Irvine et al. 2009, Miller 1997).

2.5.1 Noise abatement

Noise abatement is considered as an important service generated by UGI. Yet, the environmental effects of noise and the health risk that arise from it are typically neglected in economic analysis of investments in UGI (Nijland et al. 2003). A recent experimental study by Van Renterghem and Botteldooren (2011) discussed the effects of green roofs on sound propagation. Extensive green roofs were found to lead to consistent and significant sound reduction by up to 10 dB(A) for both single and double diffraction cases. This reduction was highly dependent on sound frequency. Another study by Van Renterghem et al. (2013) demonstrated that a green roof and wall have the highest potential to reduce noise and enhance quietness in courtyards with maximum reductions up to 7.5 dB(A) in confined courtyards.

Some scientists pointed out that the sonic environment had often been evaluated by measuring sound levels without considering the diversity of sound sources, whereas this could significantly influence people's impression on a sonic environment in the real world (Matsui et al. 2009, Hiramatsu et al. 2008). A two dimensional graphic chart, called a time component matrix chart (TM Chart), is used to present the sonic environment. The TM Chart, based on the sound source and sound level, aims to predict the changes of a sonic environment when a new sound is added or an existing sound is removed. The relationship between UGI and sound attenuation was elaborated to a certain extent, yet the effects of UGI on indoor sound attenuation or quality has not been studied in detail. A study, carried out in 21 urban green spaces in the city of Puebla, Mexico proved that both park size and total tree canopy cover could significantly influence noise levels, irrespective of park location and composition of tree species (González-Oreja et al. 2010).

2.5.2 Generation of pleasant sounds

In 2009, Irvine et al. studied the soundscapes of three green spaces in Sheffield, UK with psychological, ecological and acoustical approaches. They interviewed seventy park users, measured habitats and recorded sound levels. Species rich bird communities were demonstrated to directly impact the quality of the soundscape in urban parks. In addition, the sound of rustling leaves was also considered as being pleasant (Matsui et al. 2009). Research in this particular field has thus far not received much scientific attention.

2.6 Effects of UGI on health and education associated to aesthetic information

In general, there is a positive correlation between exposure to nature and human health (Ulrich et al. 1991, Van den Berg et al. 2010). Natural landscapes provide important environmental amenities to citizens and visitors (Driver et al. 1978, Kaplan 1983, Kong et al. 2007). Attractive scenery helps people to cope with stress or anxiety by providing pleasant visual quality. An investigation at a hospital revealed that green views influence patient recovery. After an operation, patients who had access to green views through the bedroom windows required less medication and nursing attention, and recovered faster (Ulrich 1984, Ulrich 1986, Ulrich et al. 1991, Van den Berg et al. 2010).

Buildings surrounded with visible natural elements or scenes through windows stimulate peoples' ability to concentrate (Kaplan 2001). Taylor et al. (2002) examined the relationship between near-home nature and self-discipline in Chicago, USA. The results showed that green views and green spaces close by homes had a positive effect on children's performance on concentration, impulse inhibition, and had ability to delay gratification.

2.7 Economic effects of ESs provided by UGI

The ESs of UGI do not only have important benefits for human urban habitats, but also provide considerable economic benefits in terms of reducing energy and health care costs. The monetary value of these ESs has been studied by utilizing different valuation methods, which are briefly explained below.

The avoided cost method is often used to calculate cost-savings due to the presence of an ES. For example, the avoided cost of energy consumption and carbon storage and sequestration have been calculated in order to value the microclimate and air quality regulation service. The value of air pollutant removal by UGI can be estimated by determining the cost of replacing this service with human-made infrastructure. This valuation method is called the replacement cost method. Survey-based valuation (i.e. contingent valuation method) can be used to determine the value people place on sonic environment regulation and the aesthetic information service. For example, a questionnaire could be designed to assess the respondents' willingness to pay (WTP) for quiet and attractive environments, or the willingness to accept (WTA) compensation for exposure to higher noise levels. Finally, hedonic pricing can be used to analyse the added value of building units due to favourable surrounding vegetation or other landscape features (De Groot et al. 2002).

All the values found in this review have been converted to US dollars, according to the exchange rate in that specific year. However, it was not possible to express all monetary values in the same unit (e.g. per tree, surface area or number of people) due to the wide variety of valuation methods and purposes of each service. The direct and indirect cost savings from microclimate regulation by adjoining vegetation were calculated as US$ per tree whereas the costs and benefits of urban green roofs on microclimate regulation were calculated as US$ per m^2 roof area. The avoided costs of air pollutant removal and carbon storage and sequestration was calculated as US$ per m^2 tree cover area. Finally, the costs and benefits of sonic environment and aesthetic information services were calculated as US$ per person.

2.7.1 Monetary valuation of microclimate regulation

Avoided cost by direct energy saving

Based on computer simulations by Mcpherson et al. (1988) in four US cities (Madison, Salt Lake City, Tucson and Miami), the reduction of solar irradiance by dense shading was calculated to reduce cooling costs with 53%–61%, being US$155–249 $tree^{-1}\cdot yr^{-1}$; and heating costs by 24%, saving on average US$115 $tree^{-1}\cdot yr^{-1}$. Experiments were conducted within turf and shrub landscapes in Tucson, Arizona, USA, reported that vegetation can offset cooling energy up to US$33 $tree^{-1}\cdot yr^{-1}$ in the summer time (McPherson et al. 1989). In four cities in Canada (Toronto, Edmonton, Montreal and Vancouver), the annual costs saved for heating and cooling by an individual tree ranged from US$10 to US$60 $tree^{-1}\cdot yr^{-1}$ in urban areas (Akbari and Taha 1992).

The costs and benefits of urban green roofs have been studied in 10 US metropolitan areas (Taha et al. 1996). The results showed that approximately US$0.1–0.35 per m^2 roof area could be saved on the annual energy consumption for both residential and commercial buildings. In two studies in 2000 and 2002, Konopacki and Akbari estimated the net annual dollar savings in energy expenditure by shading of trees on the roof area as US$0.1–0.23 per m^2 in Baton Rouge, Sacramento and Salt Lake City (all in the USA) (Konopacki and Akbari 2000, Konopacki and Akbari 2002). Another study investigated the impacts of green roofs in the federal state of Belgium over the past two decades (Claus and Rousseau 2012). The annual energy saving for both cooling and heating consumption was estimated by US$0.2 per m^2 green roof surface in 2008 (US$1.00 = €0.7 in 2008).

Avoided cost by indirect energy saving

Mcpherson et al. (1988) also discussed the effects of wind on energy saving in the USA, through altering the air infiltration rate and convective heat transfer. If wind speed was reduced by 50% due to trees, the annual heating costs could be reduced by US$63 $tree^{-1}\cdot yr^{-1}$. However, this wind reduction also caused the increase of annual cooling costs by US$68 $tree^{-1}\cdot yr^{-1}$. Hence, the net annual energy savings caused by wind reduction were not significant (and in fact slightly negative). To maximize the benefits of UGI, the vegetation should be orientated in such a way that it reduces wind in the winter, but avoids wind obstruction in the summer.

2.7.2 Monetary valuation of air quality regulation

Avoided/replacement cost by air pollutants removal

The marginal/additional costs of producing one unit of air pollutant have often been used to estimate the value of the air quality regulation service. A study in Guangzhou, China, stated that on average 3.12×10^8 g of air pollutants (i.e. SO_2, NO_2 and PM) were removed by urban trees in 2000. By determining the marginal costs for removing each pollutant with a human-made service, the removed pollution was valued at US$$6.67\times10^{-4}$ m^{-2} of tree cover per year (US$1.00 = RMB8.26 in 2000) (Jim and Chen 2008). Nowak et al. (2006) concluded that the total monetary value of air pollutants removal, including O_3, PM_{10}, NO_2, SO_2 and CO, was on average US$$6\times10^{-2}$ per m^2 of tree cover per year in 55 US cities. The value of pollution removal ranged from US$$4\times10^{-2}$ to 12×10^{-2} per m^2 of tree cover per year dependent on the tree cover area and pollution concentrations (Nowak 2006).

The value of air pollutants removal by green roofs has been studied by Claus and Rousseau (2012). In 2004, the value of NO_x absorption by green roofs was estimated at US$$1.5\times10^{-2}$ per m^2 per year in Detroit and Chicago (both in the USA); and US$$3\times10^{-1}$–$6\times10^{-1}$ per m^2 per year in Sint-Agatha-Berchem, Belgium (US$1.00 = €0.8 in 2004).

Martin et al. (2012) pointed out that, besides the amount of green area, the structure of green area, the tree condition and the size determine the extent of air pollutants removal. Protected forest areas could provide more ESs at a lower maintenance cost by allowing trees to grow more naturally (i.e. without management). The capacity of air pollutant removal by protected forests with minimal tree management was estimated at 1.25 $g\cdot m^{-2}\cdot yr^{-1}$ (equal to US$$6.7\times10^{-3}$ $m^{-2}\cdot yr^{-1}$) and by managed forests was estimated at 1.02 $g\cdot m^{-2}\cdot yr^{-1}$ (US$$5.5\times10^{-2}$ $m^{-2}\cdot yr^{-1}$).

Avoided cost by carbon storage and sequestration

From 1996 to 1999, 700 million tonnes carbon was stored by the 27% tree cover in the USA (Nowak and Crane 2002). Based on the estimated marginal social costs of CO_2 emissions in 1994 (US$$2.03\times10^{-5}$ per g C), the monetary value associated with carbon storage and sequestration can be calculated. It was reported that, by 1999, 7×10^{14} g C of carbon were stored by urban trees in the USA which were valued at US$$5\times10^{-2}$ m^{-2}. The gross carbon sequestration rate was estimated at 2.28×10^{13} g C per year (equal to US$$1.6\times10^{-3}$ $m^{-2}\cdot yr^{-1}$).

2.7.3 Monetary valuation of sonic environment regulation

The overall health costs attributed to noise from traffic and other sources were estimated to be in the range of 0.2–2% of the GDP in the EU in 1998 (Kommunförbundet 1998). A study in The Netherlands suggested that the WTP per avoided extra decibel of unwanted noise was around US$14–19 per person per year in 2000 (Howarth et al. 2001). Based on this study, the total WTP in The Netherlands was calculated to be US$5.3 billion (Nijland et al. 2003).

Bjørner (2004) pointed out that WTP significantly depended on the initial noise level. The expected WTP for one dB(A) noise reduction increased with the noise level, such as from US$1.87 per person per year at 55 dB(A) to US$9.35 per person per year at 75 dB(A) in Copenhagen, Denmark (US$1.00 = €1.07 in 2002).

2.7.4 Monetary valuation of aesthetic information

A study by Tratsaert (1998) stated that the main reason of population loss in the city was the lack of public green spaces and children's playgrounds. To value attractive landscapes, the Hedonic Pricing (HP) method and the Contingent Valuation (CV) method are the two most popular valuation approaches. They reflect people's WTP for attractive landscapes by measuring the variation in housing prices due to the differences in environmental amenities.

Hedonic Pricing (HP)

In Bellingham, Washington (USA), the market price of houses with full ocean view was 60% higher than those without, whereby the value of a view varies substantially depending on type and quality (Benson et al. 1998). A study on nearly 3000 house transactions in The Netherlands showed a considerable increase in price by 8–10% for houses overlooking water, and by 6–12% for houses surrounded by open space (Luttik 2000). In Helsinki, Finland, house prices were found to drop by 5.9% with increasing distance (up to 1 km) from natural landscapes. Moreover, residents paid, on average, 4.9% more for dwellings with a forest view (Tyrvainen and Miettinen 2000). A study conducted in Jinan, China, valued the amenities of urban green space (Kong et al. 2007), and revealed that 1% improvement in accessibility to parks increased housing prices by 1.6% per m^2. Each extra percentage point of green space within a 300 m radius increased the price by about 2.1% per m^2. Sander and Haight (2012) stated that in Dakota County, Minnesota, USA, road distance to parks greater than 1 ha had a significantly negative relationship to the housing price.

Despite the positive effects, Kong et al. (2007) highlighted that the recreation in green spaces can cause negative effects within a 500 m radius around a property through the impact of noise and neon lights at night, so that housing prices declined in these areas.

Contingent valuation (CV)

The CV method has often been used to estimate the WTP for changes in the quantity and/or quality of an environmental commodity by using survey techniques. An empirical study in Joensuu, Finland, indicated that approximately half of the respondents were willing to pay for the preservation of forested parks (Tyrväinen and Väänänen 1998). The total annual WTP of the households in favour of preventing the reduction of forested parks and construction was US$0.73 million in the whole town area, which was US$2–10 per person per year (US$1.00 = FIM5.19 in 1997). Another study conducted in Guangzhou City, China, explored the recreational opportunities and amenities provided by green spaces (Jim and Chen 2006). Most respondents were willing to pay to use urban green spaces, stressing the importance of outdoor recreation as a leisure pursuit. Conservative estimates of the average WTP was US$25 per person per year (US$1.00 = RMB8.26 from 2004 to early 2005). Table 2.1 shows a summary of the monetary value for each ES. Although the UGI can cause slightly higher energy costs, the overall benefits are much larger.

2.8 Major findings

2.8.1 Main factors influencing the service performance of UGI

In the previous sections, the effects of UGI on human urban habitats in outdoor and indoor environment were reviewed. Table 2.2 summarizes the main factors, and sub-factors that are important in the relationship between UGI and human urban habitats.

The effects of local morphology and geographical conditions were often discussed in literature on microclimate and air quality studies. Higher air temperatures could enhance both the BVOC emissions and pollutant deposition rate. Vegetation quality and quantity, which determine the total ESs capacity, strongly influences all aspects of human habitats. In addition, the variation of the vegetation's PAI or LAI and structure were proven to highly affect the urban microclimate, air quality and sound environment. Species composition has a strong relation with the air quality regulation of UGI, since the species determines the amount and types of pollutant removal. Furthermore, building characteristics, including façade property and air ventilation & infiltration rate, vary the heat transfer coefficient, indoor and outdoor air exchange, and reflection and absorption of solar radiation. Consequently, indoor ESs provision can be either directly or indirectly influenced by building characteristics.

Table 2.1 Overview of monetary values for each ES

ESs	Valuation methods	Monetary value (approx.)		References
Microclimate regulation	Avoided Cost	Direct energy saving:	US$10–249 $tree^{-1}\cdot yr^{-1}$ (Adjoining vegetation)	McPherson et al. 1989, Akbari and Taha 1992, Mcpherson et al. 1988
			US$0.1–0.35 $m^{-2}\cdot yr^{-1}$ (Green roofs and walls)	Konopacki and Akbari 2000, Claus and Rousseau 2012, Konopacki and Akbari 2002, Taha et al. 1996
		Indirect energy saving:	- US$5–63 $tree^{-1}\cdot yr^{-1}$ (Adjoining vegetation)	Mcpherson et al. 1988
Air quality regulation	Replacement Cost	Pollutants removal:	US$$7\times10^{-4}$–$12\times10^{-2}$ $m^{-2}\cdot yr^{-1}$ (Adjoining vegetation)	Jim and Chen 2008, Martin et al. 2012, Nowak et al. 2006, Nowak 2006
			US$$1.5\times10^{-2}$–$6\times10^{-1}$ $m^{-2}\cdot yr^{-1}$ (Green roofs and walls)	Claus and Rousseau 2012
	Avoided Cost	Carbon storage	US$$5\times10^{-2}$ m^{-2} (Adjoining vegetation)	Nowak and Crane 2002
		Carbon sequestration	US$$1.6\times10^{-3}$ $m^{-2}\cdot yr^{-1}$ (Adjoining vegetation)	Nowak and Crane 2002
Sonic environment regulation	Contingent Valuation (WTP)		US$2–20 $person^{-1}\cdot yr^{-1}$ (Adjoining vegetation)	Kommunförbundet 1998, Nijland et al. 2003, Bjørner 2004, Howarth et al. 2001
Aesthetic information	Hedonic Pricing; Contingent Valuation (WTP)		US$2–25 $person^{-1}\cdot yr^{-1}$ (Adjoining vegetation)	Kong et al. 2007, Benson et al. 1998, Luttik 2000, Sander and Haight 2012, Tyrvainen and Miettinen 2000, Tyrväinen and Väänänen 1998, Jim and Chen 2006

Table 2.2 Main factors influencing ESs generation by UGI on human urban habitats. + have influence; /? may have influence with unknown extent; and 0 no information from the reviewed papers.

Main factors	Microclimate regulation	Air quality regulation	Sonic environment	Aesthetic information
Local morphology				
Configuration of building and vegetation	+	+	+	+
Orientation of building and vegetation	+	0	0/?	0
Geographical conditions				
Ground property (e.g. soil types, surface mulching)	+	+	0/?	0
Local climate and weather condition	+	+	0	0/?
Vegetation characteristics				
Vegetation quality and quantity	+	+	+	+
PAI or LAI & Structure (height, width and crown property)	+	+	+	0/?
Vegetation species (especially for deciduous or evergreen plants)	+	+	+	0/?
Building characteristics				
Façade property (e.g. material, isolation, construction)	+	0	0/?	0/?
Air ventilation and infiltration rate	+	+	0	0

2.8.2 Distribution of spatial and time scales covered by the reviewed studies

The studies reviewed in this chapter covered a broad range of spatial and time scales (Table 2.3). The spatial area covered by the studies ranged from single tree and house to multiple cities in different countries, while the time scale for the four major services ranged from hours to years. Ideally, the reviewed studies would have been presented in sufficient number at multi-spatial and temporal scales. However, in practice, the majority of the field measurement and experimental studies only focused on some specific ESs in the relatively short period. To identify those data gaps for each service, the reviewed articles were categorized into a temporal scale (day(s), month(s)/season(s) and year(s)) and a spatial scale (specified as: single/several tree(s) or building(s); street canyon/block/site etc.; village/town/city; and countries) (Table 2.3).

Microclimate regulation by the UGI was mainly investigated at the single and several trees or buildings level on a daily basis. The information at the national (country), regional (village/town/city) and local levels (street canyon/block/site etc.) was fragmented and mainly

(80%) derived from modelling. On the other hand, studies on the effects of vegetation on the air quality were conducted nationally, regionally and locally, but mainly on an annual basis. The review also showed that direct effects of the UGI on indoor air quality have rarely been studied. The quality of the sonic environment and aesthetic information were often only measured or evaluated in short time periods to obtain instant information. The effects of UGI on aesthetic information were studied for the single and several trees or buildings; whereas the sonic environment was studied at a broad range of scale, but only outdoors (no articles were found on the relationship between the UGI and the indoor sonic environment).

Table 2.3 Comparison between the spatial and time scales of the reviewed studies for the four main ESs.
MC – microclimate regulation, AQ – air quality regulation, SE – sonic environment, AI – aesthetic information. The bar represents the number of publications.

TIME / SPATIAL	Day(s)				Month(s)/season(s)				Year(s)				No. publications
	MC	*AQ*	*SE*	*AI*	*MC*	*AQ*	*SE*	*AI*	*MC*	*AQ*	*SE*	*AI*	
Country	0	0	1	1	0	0	0	0	4	9	0	1	16
Village/town/city	0	0	2	0	1	1	0	0	2	13	0	0	19
Street canyon/block/site etc.	4	3	2	0	3	3	0	0	0	3	0	0	18
Single/several tree(s) or building(s)	20	0	2	4	6	1	0	0	1	0	0	0	34
No. publications	39				15				33				**87**

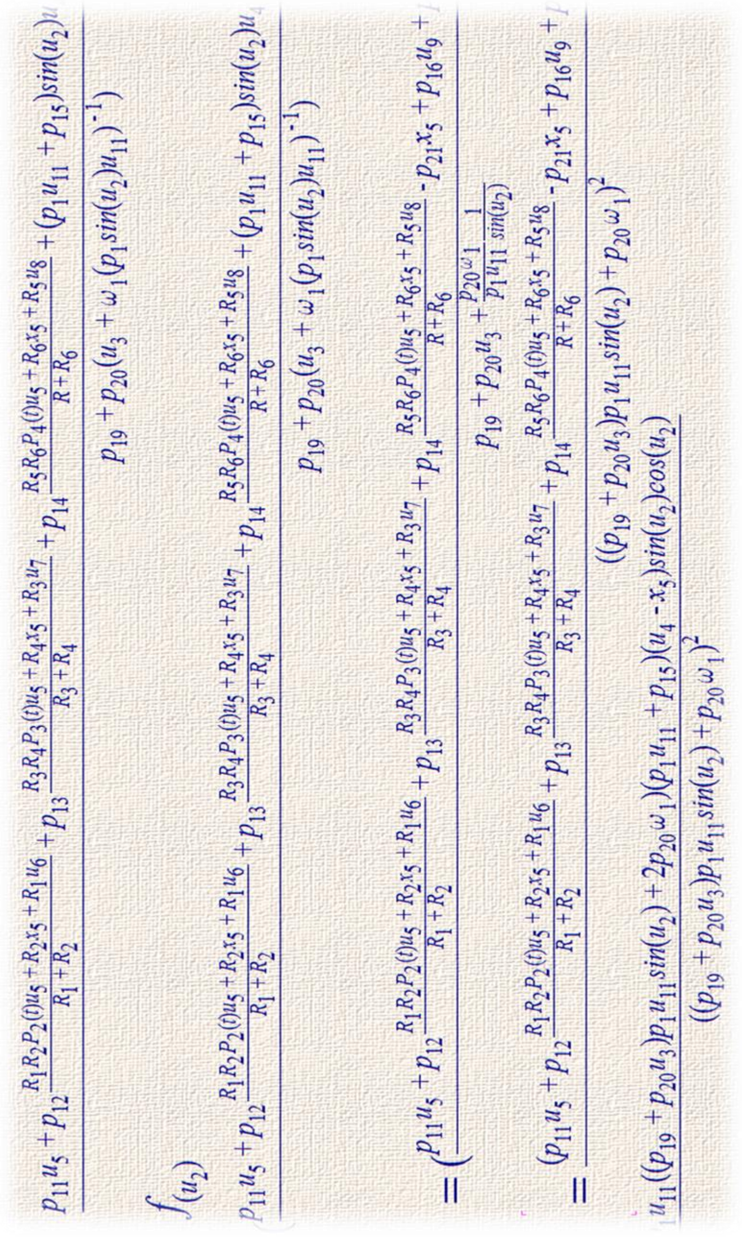
2.9 Discussion and conclusions

This study has reviewed 148 publications discussing the role of UGI in human urban habitats and human comfort. The main ESs were identified as: microclimate regulation, air quality regulation, sonic environment regulation and aesthetic information. Also, the economic effects were included in the analysis.

The review found that, in general, the influence of the main ESs on microclimate regulation by UGI has been well studied. However, most of these ESs were investigated via simulation or modelling. Experiment and field measurement studies on the involved ESs were few. About 80% of the information on microclimate regulation service at national, regional and street levels was derived from modelling, and empirical studies were mainly performed in the USA. Moreover, the relationship between UGI and the indoor air and sonic environment was rarely studied locally. Future studies will require better integration of modelling with experimental research and field measurements.

The review also revealed that economic information on the effect of UGI on urban environmental quality is fragmented and incomplete, and that more and better empirical studies are needed. The economic effects of adjoining vegetation and green roofs on microclimate regulation provided energy savings of up to almost US$250 $tree^{-1}\cdot yr^{-1}$, while air quality regulation was valued between US$0.12 $m^{-2}\cdot yr^{-1}$ and US$0.6 $m^{-2}\cdot yr^{-1}$. Maximum monetary values attributed to noise regulation and aesthetic appreciation of urban green (e.g. parks and forests) were US$20 $person^{-1}\cdot yr^{-1}$ and US$25 $person^{-1}\cdot yr^{-1}$, respectively. Of course these values are extremely time- and context-dependent, but they do give an indication of the potential economic effects of investing in UGI. Valuation of the urban ESs can provide important information to develop effective and cost-efficient urban planning to optimize management of UGI.

From this review, we conclude that new methods, measurement instruments and field experiments are needed to improve empirically supported correlations (both biophysically and economic). This review can help to identify the main research gaps and support better integration of field measurements and modelling studies to determine the relations between UGI and human urban habitats, and the consequences for human comfort and socio-economic effects.



Relevant equations of heat transport (incl. radiation, convection and conduction) between tree canopy and surrounding environment.

CHAPTER 3

Effects of urban trees on local outdoor microclimate: Synthesizing field measurements by numerical modelling

Based on:

Wang, Y., Bakker, F., de Groot, R., Wörtche, H. & Leemans, R. (2015). Effects of urban trees on local outdoor microclimate: Synthesizing field measurements by numerical modelling. *Urban Ecosystems*, 1-27. doi: 10.1007/s11252-015-0447-7.

Abstract

This study investigated the effects of trees, as the main element of urban green infrastructure (UGI), on urban local microclimate and human thermal comfort under different local weather conditions in a small Dutch urban area in Assen. In both summer and winter, continuous air temperature and relative humidity measurements were conducted at five selected sites having different environmental characteristics in tree cover. Measurements demonstrated that the microclimatic conditions at each observation site showed significant differences in the summer. The cooling effects of trees on clear and hot days were two times higher than on cloudy and cold days. In the winter, air temperature was only slightly reduced by the evergreen trees, and weather conditions did not cause a notable change on performance of trees on the microclimate. ENVI-met, a three-dimensional microclimate model was used to simulate the spatial distribution of temperature and humidity. After selecting representative days, we simulated the study site as it currently is and for a situation without trees. Spatial differences of trees' effects were found to vary strongly with weather conditions. Furthermore, human thermal comfort is indicated by the Predicted Mean Vote (PMV) model. During the hottest hours, trees improved the thermal comfort level by reducing 'very hot' (PMV > 5.5 ℃) and 'hot' (PMV range of 2.5–3.5 ℃) thermal conditions by about 16% on clear days and 11% on cloudy days. Generally, our findings demonstrate that urban microclimate and human thermal comfort varies significantly in close geographical proximity. Both are strongly affected by the presence of trees. Weather conditions play an important role on the trees' performance, especially in the summer.

Key words: Trees, Outdoor thermal comfort, Urban microclimate, Numerical simulation, Field Measurements

3.1 Introduction

Urban sprawl accompanied with the decline of natural landscapes, is a major driver of changes in urban microclimate (Millennium Ecosystem Assessment 2005). In the past decades, several studies proved that urban green infrastructure (UGI), especially its main elements – trees, can positively affect outdoor microclimate and moderate the urban heat island effect in the summer (Frelich 1992, Akbari et al. 2001, Bonan 2002, Berry et al. 2013, Skoulika et al. 2014). The shade of trees or taller shrubs attenuate solar radiation and prevent the night's heat flow from the surface to the sky, thereby altering local climates and comfort levels (Akbari 2002, Heisler and Grant 2000, Mcpherson 1988). In addition, evaporation and transpiration from vegetation could lower air temperature and increase moisture content (Taha et al. 1991, Chen and Jim 2008, Huang et al. 2008, Park et al. 2012, Shahidan et al. 2012, Hedquist and Brazel 2014, Middel et al. 2014). Trees reduce wind velocities and consequently reduce heat convection (Shahidan et al. 2012, Hedquist and Brazel 2014). Previous studies typically measured or modelled several representative but unconnected landscapes (e.g. Huang et al. 2008, Shahidan et al. 2012, Middel et al. 2014). Additionally, the influence of weather conditions, which affect the mediating effects of trees (Morakinyo et al. 2013, c.f. Wang et al. 2014), are poorly understood.

This study aims to enhance the understanding of the role of UGI on local microclimate by targeting at trees. We continuously measured temperature and humidity and combined them with numerical modelling in a small urban area during summer and winter. We determined the spatial variations in temperature and humidity due to the distribution of trees in a local area. Additionally, by classifying the actual weather conditions during the observation period, the cooling effects of trees under different weather conditions can be established.

3.2 Materials and Methods

Two approaches, field measurements and numerical modelling, were used in this study. We empirically analysed continuous summer and winter field measurements (temperature and humidity) at five sites in the Dutch city of Assen, that together characterize the heterogeneity of the small urban area (e.g. no tree cover, high tree cover and shading from buildings). The effects of trees on the microclimate at these sites were analysed under varies synoptic weather conditions. We clustered weather conditions of monitoring days. The days representing the weather conditions of 'clear and hot' and 'cloudy and cool' in the summer and 'clear and mild' and 'cloudy and cold' in the winter were used for the analysis. Since the effects of geometric factors (e.g. orientation and location of buildings and trees) on temperature and humidity distributions are complex and cannot completely be determined from our spot measurements, we combined the empirical data with comprehensive computer simulations using the ENVI-met model. The simulated days were selected at random from 'clear and hot' and 'cloudy and cool' days in the summer and 'clear and mild' and 'cloudy and cold' days in the winter days. Using the simulation model, the relationship between tree location, size and shape, and the temperature and humidity distribution are explored. Further, the simulations allowed us to relate variations in microclimate due to trees and buildings with human comfort.

3.2.1 Sites and observation period

Assen, the capital of the province of Drenthe, generally has a moderate maritime climate. July and August are the warmest months and January and February are the coldest months of the year. The leaf-off period is normally from November to March (http://www.klimaatinfo.nl). Our study was conducted in a 3,600 m^2 area (latitude: 53 º0' 0'' N, longitude of 6º 55' 00'' E) in the built-up area of Assen (Figure 3.1). The total surface cover fractions for trees, buildings, shrub, grass, hedge and pavement are 5%, 14%, 2%, 41%, 1%, and 37%, respectively. Two thirds of the trees are conifer evergreen trees. The field measurements were conducted in one summer (from 20th July–31st August, 2013) and one winter (from 1st January–28th February, 2014).

(a) **(b)**

Figure 3.1 The City of Assen, The Netherlands (a); the study area is located in an urban area close to the city centre (b).
(Source: screenshot of OpenStreetMap and Google Earth).

3.2.2 Field measurements

Field measurements were conducted to investigate the (spatial and temporal) temperature and humidity differences among sites with different environmental characteristics under different weather conditions.

Measurement items

Five air temperature (Ta) and relative humidity (RH) stations (6382OV Davis Temp/Hum Station, accuracy: ±0.5 ℃ and ±3%) were mounted in locations with different environmental characteristics, at the same height of 1.5 meters above ground. The location of these stations are illustrated in Figure 3.2. In addition, one weather station (6162 Davis Wireless Vantage Pro2 Plus) was placed above the best exposed part of the tallest building (approximately 10 meters above the ground) within study area. All the temperature and humidity sensors were placed in radiation shields to minimize the effects of radiation. Data from all stations is simultaneously acquired every ten minutes and stored in a database through a data receiver (6318 EU Davis Weather Envoy 8X) and data logger (6510 USB Davis USB Datalogger).

Data from the weather station (including Ta, RH, solar radiation, rainfall and wind velocity and direction) was recorded every minute.

Figure 3.2 The location of the observation sites in the study area.
The bottom-right image shows an example of a temperature/humidity station, combined with an anemometer.

Data analysis methods

Each observation day was divided into daytime and night time to explore the different trees' effects (e.g. providing shade during daytime, blocking heat flow at night). In the summer, daytime was defined from 06:00 to 21:00, while in the winter, daytime ran from 8:30 am to 17:30 pm.

For each observation period (summer and winter), we tested whether specific parameters of the microclimate differed and varied and ranged differently among the five observation sites. Hence, a one-way Multivariate Analysis of Variance (MANOVA) test was performed on the temperature and humidity data. The diurnal values (i.e. maximum, minimum and average value, change rate (CR) and the range) for Ta/RH were modelled as dependent variables, while the observation sites were the independent, fixed variables. Maximum, minimum and average Ta/RH strongly related to outdoor comfort and were therefore also included in the analysis. However, the microclimate in Assen varied greatly in both summer and winter, and the variance of Ta/RH during the observation periods at the specific sites was large. Hence, the MANOVA test on the maximum, minimum and average Ta/RH among the observation sites might be obscured. We therefore calculated the differences between these factors and their mean values for all Sites $D(t)$. A one-way MANOVA was then performed for these differences.

$$D(t)_{dj} = max/min\,/average_i(x_{dji}) - \frac{1}{M}\sum_{j=1}^{M} max/min\,/average_i(x_{dji}) \qquad \text{(Equation 3.1)}$$

Where t stands for maximum, minimum and average Ta/RH, and x stands for Ta and RH.

In addition, CR and the range are also important because they implies the level and amount of Ta/RH change along a day regardless of average temperature or seasons. The one-way MANOVA, Tukey post-hoc tests helped to compare the different observation sites. For all our statistical analysis, significance was defined as a P value less than 0.05. CR and the range are expressed as:

$$CR_{dj} = \frac{\sum_{i=1}^{N}[max_i(x_{dji}) - x_{dji}]}{N[max_i(x_{dji}) - min_i(x_{dji})]} \qquad \text{(Equation 3.2)}$$

$$Range_{dj} = max_i(x_{dji}) - min_i(x_{dji}) \qquad \text{(Equation 3.3)}$$

Where x stands for Ta and RH, with the different parameters defined below:

j: index of observation site (j=1,…, M), M=5
M: total number of observation sites
d: index of observation day (d=1,…, K), K= 43 in the summer and 58 in the winter
K: total number of observation days in the summer and winter
i: index of data point in one day (i=1,…, N), N=144
N: total number of data points in one day

First, the differences of these factors were tested among all the five observation sites to prove the spatial variation in the study area. Second, we compared these microclimatic factors between shaded and unshaded sites (i.e. Site one and four) by subtracting the values from the shaded site from the unshaded site. This comparison indicates the level of microclimate regulation by the trees. Additionally, as the biological and physical processes involved in microclimate regulation by trees are affected by the weather conditions (c.f. Wang et al. 2014), the trees' effect on microclimate should be evaluated under similar weather conditions. The influence of weather conditions on the trees' cooling effects was determined afterwards. All of these effects should be bigger than the range of measurement accuracy (i.e. ≥ 0.5°C and 3%).

3.2.3 Clustering weather conditions

In order to classify the weather conditions of the observation days, we utilized a clustering method, which included three features: clearness index (Kt), fluctuation of solar radiation (FR), and maximum Ta (MaxTa). After defining the cluster boundaries, t both summer and winter observation days were clustered separately.

Clearness index (Kt)

Kuye and Jagtap (1992) proposed a clearness index (ranging from 0 to 1) to characterize the sky conditions. Larger values represent clear weather, while low values represent cloudy weather. The index is calculated as the ratio of the global solar radiation measured at the surface and the clear sky solar radiation:

$$Kt_d = R_d / R0_d \qquad \text{(Equation 3.4)}$$

With the global solar radiation R based on the hourly average solar insolation (measured at weather station with 1 minute sample interval). The clear sky solar radiation, $R0$ is given by:

$$R0 = (0.75 + 2 \times 10^{-5} z) Ra \qquad \text{(Equation 3.5)}$$

The elevation z of the weather station was 15 m above sea level (elevation of the study height plus height of the weather station). The extraterrestrial radiation Ra for each day was determined by the geographical position and the time of the year, according to:

$$Ra = \frac{T*G*dr}{\pi} [\omega \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega] \qquad \text{(Equation 3.6)}$$

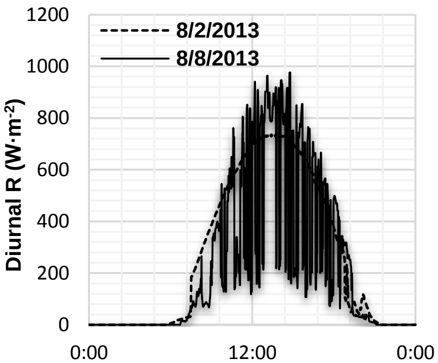
Where T is the length of day (24 h), G is the solar constant (1353 $W \cdot m^{-2}$), dr is the inverse relative distance Earth-Sun, ω is the sunset hour angle, φ is the latitude and δ is the solar declination.

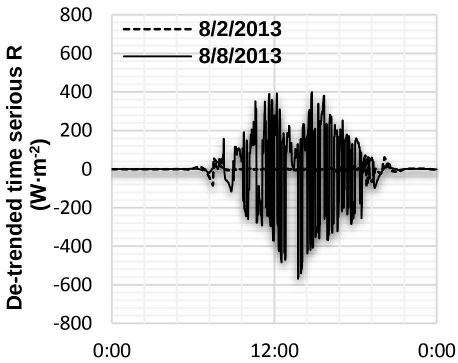
Fluctuation of solar radiation (FR)

Since the clearness index Kt only represents the daily value based on the hourly average solar insolation, it fails to capture the variation of solar intensity in the daily pattern. Therefore, we included the fluctuation rate (FR) of solar radiation to compute the variation of sunlight intensity for a given period. To determine the fluctuation rate of diurnal solar radiation (FR), we first de-trended the solar radiation time series (R_{di}) by subtracting the local trend value (R_{di}^{fit}), and then calculated the root-mean-square of the cumulative difference between measurements and the local trend as:

$$FR_d = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(R_{di} - R_{di}^{fit}\right)^2} \quad \text{(Equation 3.7)}$$

To acquire the local trend value, a local regression using weighted linear least squares and a 2nd degree polynomial model was applied to fit smooth curves with a four hours window span on a daily basis. Compared with the traditional moving average, this smoothing captures the major trends in the data but is less severely affected by the short-term fluctuation. FR is high when large changes in weather conditions occur, or when the weather varies during the day, and vice versa. As an example of a similar Kt but a very different FR, the diurnal R and de-trended time series ($R_{di} - R_{di}^{fit}$) on 2nd and 8th August 2013 are presented in Figure 3.3. Although the Kt's of these two days were nearly equal (≈ 0.7), the FR's were very different. On 8th August, the weather conditions varied strongly leading to a higher FR (FR=152 W·m^{-2}) compared to the 2nd August that was a clear day (FR=16 W·m^{-2}).





(a) **(b)**

Figure 3.3 Diurnal solar radiation time series R (a) and the de-trended time series R (b) on 2nd and 8th August, 2013.

Maximum Ta (MaxTa)

To investigate the effects of trees on extremely uncomfortable days, the maximum air temperature during the day (MaxTa) is also included as a feature for the clustering of the weather conditions. It highlights the hot days and relates to outdoor comfort level.

Definition of clusters

To define the clusters, FR and MaxTa were normalized to switch to the same scale as Kt, using:

$$F(f)_d = \frac{f_d - min_d(f_d)}{max_d(f_d) - min_d(f_d)} \quad \text{(Equation 3.8)}$$

In this formula f stands for FR and MaxTa. The terms max(f) and min(f) are the maximum and minimum values among the observation days in the summer and winter respectively. We adopted a fast clustering method to classify the synoptic weather conditions using fixed cluster boundaries for all features. A value of 0.5 was set as cluster boundary for all the tree features included in this analysis. After the permutation and combination of the Kt, F(FR) and F(MaxTa), the observation days were classified into eight clusters. Note that the normalization process leads to cluster boundaries that depend on the dataset itself. Hence, if the changes of the weather conditions were negligibly small during the observation days, this clustering method may fail. Since the observation days should cover a variety of different weather conditions, a long-term observation period is essential for this method.

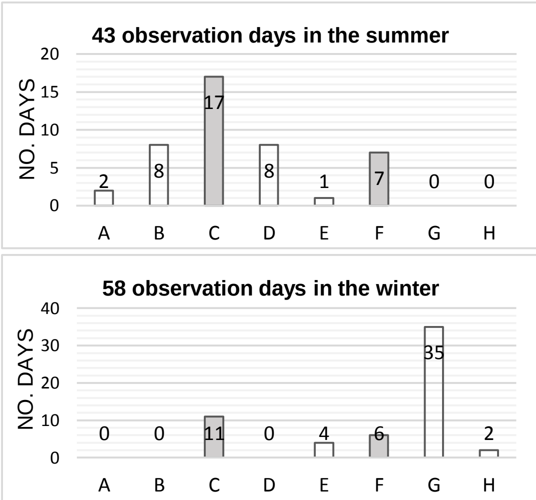
The definitions of each cluster were detailed below in Figure 3.4 (a). Although all of the eight clusters characterize the different weathers, the analysis of this study focuses on cluster C and F since they stand for obvious different weather conditions. Cluster F, having Kt ≥ 0.5, F(FR) < 0.5, F(MaxTa) ≥ 0.5, stands for the days having steady and strong solar radiation and a high maximum air temperature. Those days are relative clear and hot in the summer and clear and mild in the winter. In contrast, days with low fluctuations and intensity of solar radiation and a lower maximum air temperature (i.e. 'cloudy and cool' and 'cloudy and cold' weather condition) were classified as cluster C (Kt < 0.5, F(FR) < 0.5, F(MaxTa) < 0.5).

Clustering results

Figure 3.4 (b) represents the clustering results for both summer and winter observation days. In the summer, 43 observation days fell under six clusters (A–F). Most of these days (40%)

were relatively cloudy and cool (cluster C), whereas only seven days (16%) were relatively clear and hot (cluster F). Among the 58 observation days in the winter, most days (80%) were cloudy (cluster C and G), indicated by a low Kt (< 0.5) and F(FR) (< 0.5). However, only eleven days (19%) had a low F(MaxTa) (< 0.5) and fell under cluster C. Additionally, clear and mild weather conditions (cluster F) were found in six days (10%).

Clusters	Kt	F(FR)	F(MaxTa)
A	≥ 0.5	≥ 0.5	< 0.5;
B	≥ 0.5	< 0.5	< 0.5;
C	**< 0.5**	**< 0.5**	**< 0.5;**
D	< 0.5	≥ 0.5	< 0.5;
E	≥ 0.5	≥ 0.5	≥ 0.5;
F	**≥ 0.5**	**< 0.5**	**≥ 0.5;**
G	< 0.5	< 0.5	≥ 0.5;
H	< 0.5	≥ 0.5	≥ 0.5;



(a) **(b)**

Figure 3.4 The definitions of clusters of the synoptic weather conditions (a) and clustering results for the summer and winter observation days (b).

The features mentioned in Section 2.2.2 were computed and compared among different clusters. Furthermore, representative days were selected from the 'cloudy and cool' and 'cloudy and cold' clusters C and 'clear and hot' and 'clear and mild' clusters F for the model simulation.

3.2.4 Numerical modelling

Three-dimensional numerical microclimate simulations using ENVI-met were conducted to explore the relation between tree characteristics and temperature and humidity distribution in the study area. Based on the fundamental laws of fluid dynamics and thermodynamics, ENVI-met (http://www.envi-met.com) is designed to simulate surface-plant-air interactions in an urban environment and has been used in different studies (Emmanuel et al. 2007, Fahmy et al. 2009, Hedquist and Brazel 2014, Middel et al. 2014). ENVI-met allows to simulate the urban environment from a microclimate scale to the local climate scale with a resolution of 0.5m to 10m in space and 10 sec in time with 250 grids at maximum. In this study, the geometry, buildings, vegetation, and surface materials of the study area are defined on a 3D grid of 120 × 120 × 30 cells, with a 0.5m grid cell size. This resolution allows to investigate local microclimate variations. The geometry, plant and soil database, and building properties specified for this study were based on data from the Top10NL map (https://www.kadaster.nl) and measurements. For the plant database, ENVI-met requires the vertical distribution of leaf area density in ten different heights. We first determined the vegetation leaf index (LAI) of the trees within model area with a LAI-2000 Plant Canopy Analyser under cloudy weather condition. Subsequently, leaf area density values in ten different heights were calculated using the method by Lalic and Mihailovic (2004). In addition, the field measurements were used as the input data for model initialization. These include wind velocity, wind direction, initial air temperature, relative and specific humidity, and indoor temperature.

In addition, ENVI-met allows to select the points inside the model area where the processes in the atmosphere and the soil are calculated in more detail. These selected points are named ‘receptors’. In order to capture this detailed information within the study area, 81 equidistant receptors were added in the area input file (labelled AA–II in Figure 3.5). However, the 13 receptors that were located on the façade of buildings, did not monitor the outdoor processes and were eliminated from the statistical analysis. After running a 24 hours simulation with a half hour interval the following features were extracted from the receptors at 1.5 meters height: Ta and RH, wind velocity (Va), longwave and shortwave radiation, and the Predicted Mean Vote (PMV). PMV determines thermal comfort (ISO 7726 1998), ranging from -3 = ‘very cold’ to +3 = ‘very hot’) (Matzarakis and Mayer 1998); and is calculated by combining Ta, RH and Va with parameters that describe the heat exchange processes of the human body. To calculate PMV in ENVI-met, we set biometeorological values for people’s slow walk to 1.4 $m \cdot s^{-1}$ and a 150 $W \cdot m^{-2}$ energy exchange. Thermal resistance of clothing was adjusted depending on summer and winter clothing.

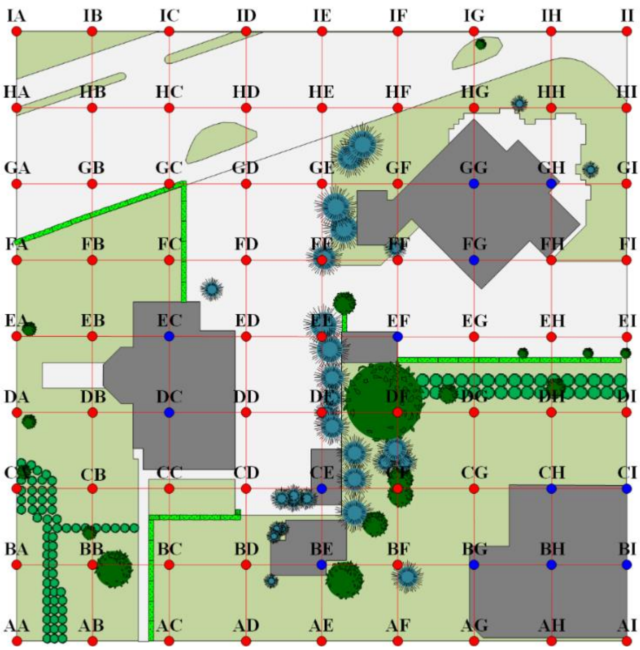


Figure 3.5 ENVI-met map of the study area where 81 equidistant receptors are indicated with a grid identifier ranging from AA to II.
The blue circles represent 13 receptors located on the façade of buildings; while the red circles indicate the rest receptors.

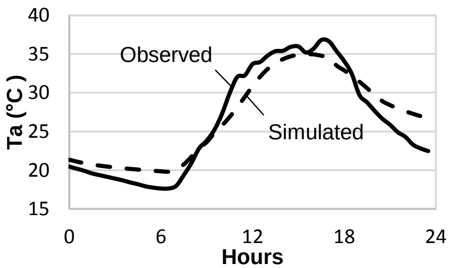
<u>Selection of comparable days and model validation</u>

Using the clustering results, four days in the summer and winter were selected at random from cluster C and F (i.e. 2nd, 3rd August, 2013 and 18th, 21st January, 2014). The weather conditions of these selected days are shown in Table 3.1. On the clear days (e.g. 2nd August and 18th January), the daily total solar radiation was much higher than on cloudy days. The wind velocity was less than 3 Beaufort (< 11 km·h^{-1}) during these four days. The dominant wind direction was SE on both 'clear and hot' summer day and 'clear and mild' winter day, but SW on the 'cloudy and cool' summer day and 'cloudy and cold' winter day.

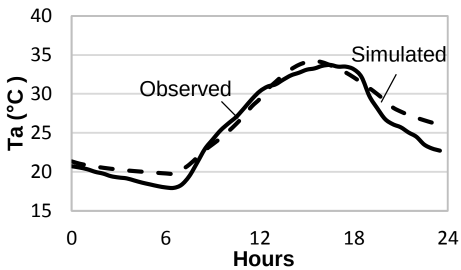
An evaluation of the accuracy of predicted ENVI-met (P) values with observed temperature at five sites was performed among these four selected days. Figure 3.6 shows the results from Sites one and four on August 2nd as an example. A notable contrast between the observed and simulated Ta can be observed. As expected, the maximum Ta within the tree canopy (Site four) was approximately 1.0 ℃ lower than that of the area without trees. However, the simulation and measurement results show two discrepancies. First, the simulation results tend to underestimate daytime temperatures and overestimate night-time temperatures. Second, the poorer model performance appeared in the afternoon when temperature and humidity strongly swung. ENVI-met failed to simulate these rapid microclimatic changes. One of ENVI-met's limitations is that its simulation output is time and space (within one grid) averaged (Emmanuel et al. 2007, Peng and Jim 2013). Therefore, the diurnal temperature variations are contracted. Furthermore, the simulated data cannot represent instant temperature conditions because such models always keep a constant tendency (Peng and Jim 2013). The possible immediate disturbances, which are observed from measurements, cannot be realistically reflected in the model outputs. This leads to the underestimation of the reduction of the temperature and its fluctuations caused by trees.

Table 3.1 Weather conditions of selected days

Days	Cluster	Weather Condition	Daily Total Solar Radiation ($W \cdot m^{-2}$)	Relative Humidity (%)	Wind Velocity ($km \cdot h^{-1}$)	Dominant Wind Direction
Summer						
2nd, Aug, 2013	F	Clear	6378.82	69%	6.8	SSE
3rd, Aug, 2013	C	Cloudy	4906.10	71%	10.7	WSW
Winter						
18th, Jan, 2014	F	Clear	614.03	92%	5.1	ESE
21st, Jan, 2014	C	Cloudy	101.73	96%	3.2	WSW



(a)



(b)

Figure 3.6 Measured and simulated temperature values at an unshaded site – Site ONE (a) and shaded site – Site FOUR (b) on the 2nd August, 2013.

Despite this deficiency, the simulated Ta showed good qualitative agreement with the measurements based on both correlation coefficient (R^2) and error indices (root mean square error – RMSE and mean absolute error – MAE). Lower RMSE and MAE values indicate a better model performance. The index of agreement (d), which was developed by Willmott (1981), measures the degree of model prediction error and ranges from 0 to 1. A higher value indicates a better agreement between simulation and measurement. R^2 among the five sites ranged between 0.73 and 0.97 on the selected two summer days, and between 0.79 and 0.95 on the selected two winter days. RMSE and MAE were low throughout all sites and d was generally > 0.60. Table 3.2 shows the evaluation results for each site in detail on the four selected days.

Table 3.2 R^2, RMSE, RSR, MAE and d between the measured and the computed air temperatures in 24 hour period.

Days	**Correlation coefficient**	**Root mean square error**	**Mean absolute error**	**Index of agreement**
	R^2	*RMSE (℃)*	*MAE (℃)*	*d*
Summer				
2nd, Aug, 2013				
Site one	*0.97*	*1.66*	*1.41*	*0.97*
Site two	*0.96*	*1.14*	*0.89*	*0.99*
Site three	*0.95*	*1.65*	*1.35*	*0.98*
Site four	*0.98*	*1.90*	*1.76*	*0.96*
Site five	*0.95*	*1.76*	*1.56*	*0.97*
3rd, Aug, 2013				
Site one	*0.92*	*1.47*	*1.13*	*0.73*
Site two	*0.81*	*1.66*	*1.18*	*0.70*
Site three	*0.82*	*2.13*	*1.71*	*0.73*
Site four	*0.81*	*1.65*	*1.41*	*0.68*
Site five	*0.73*	*1.97*	*1.62*	*0.63*
Winter				
18th, Jan, 2014				
Site one	*0.89*	*0.70*	*0.60*	*0.87*
Site two	*0.91*	*0.86*	*0.79*	*0.80*
Site three	*0.91*	*0.63*	*0.45*	*0.89*
Site four	*0.91*	*0.61*	*0.42*	*0.88*
Site five	*0.95*	*0.64*	*0.43*	*0.87*
21st, Jan, 2014				
Site one	*0.81*	*0.28*	*0.25*	*0.85*
Site two	*0.79*	*0.28*	*0.24*	*0.85*
Site three	*0.87*	*0.64*	*0.63*	*0.64*
Site four	*0.86*	*0.54*	*0.51*	*0.70*
Site five	*0.85*	*0.31*	*0.27*	*0.81*

Simulation design and data analysis

In order to examine the effects of the trees at the study site on microclimate and thermal comfort, we compared the simulations of the current situation (CU) (i.e. with 5% total tree cover and 3% evergreen tree cover in the summer and winter, respectively) and no tree (NT) conditions on selected days. In the NT simulation, we removed all the trees, including both deciduous and evergreen trees, from the model area.

First, we investigated how trees affect the microclimate over the entire area. Based on the 24 hour simulations for all 68 receptors, the maximum, minimum and average CR and the range for air temperature were calculated. The mean of these features for all the receptors was derived separately on the four selected days as expressed in Equation 3.9.

$$Mean\ of\ receptors = \frac{1}{M}\sum_{j=1}^{M}\left(DFcu_j - DFnt_j\right) \qquad \text{(Equation 3.9)}$$

In this formula, M is the number of the receptors and j is the index of receptors. DFcu and DFnt are the daily values of different features in the CU and NT simulations, respectively. We calculated the difference between DFcu and DFnt, and then derived the average value for all the receptors.

Second, we investigated if the spatial temperature distribution changes over time. The Ta differences (ΔTa_{ji}) between CU and NT simulations were calculated at each receptor j and each time step i. To quantify the spatial differences of the effects of the trees, the time-series range of ΔTa among the receptors is defined in Equation 3.10.

$$(Range\ of\ \Delta Ta)_i = max_j\left(\Delta Ta_{ji}\right) - min_j\left(\Delta Ta_{ji}\right) \qquad \text{(Equation 3.10)}$$

Where the terms of $max_j\left(\Delta Ta_{ji}\right)$ and $min_j\left(\Delta Ta_{ji}\right)$ are the maximum and minimum Ta of 68 receptors at time i. Time and place in which the temperature was greatly influenced by the trees is determined in this way.

Due to the effects on the microclimate, trees altered the outdoor human comfort level as well, especially during the hottest hours of the day (from 12:00 to 18:00). After extracting the PMV value during the hottest hours from ENVI-met, we calculated the occurrence frequency of the PMV value at different scales under CU and NT conditions. The comparison between CU and NT conditions helped us to analyse how the trees determine the outdoor human comfort.

3.3 Results

3.3.1 Measurement results

Effect of trees on microclimate in the summer

a) Microclimatic differences among the observation sites

During daytime in the summer period, a significant difference in CR and the range of Ta/RH among the observations sites was revealed by one-way MANOVA ($p < .0005$). In terms of the air temperature, the observation location has a statistically significant effect on both CR ($p = .033$) and the range ($p < .0005$). The results from the multiple comparisons showed that CR and the range of Site one were significantly different from that of the other sites ($p < .05$ for both CR and the range). Similar results were also found for RH. Generally speaking, the variation rates and ranges of air temperature and humidity varied significantly among the observation sites. Although the maximum, minimum and average Ta/RH did not show significant differences for the observation sites, the differences between these features and their mean values of all sites, i.e. D(t), were significant ($p < .0005$ for all). Hence, we conclude that, during the daytime of the summer period, the microclimatic conditions at the observation sites had significant differences. In terms of the microclimate at night, the spatial differences of temperature and humidity were significant among the sites, with D(t) of Ta/RH varied significantly among the different sites ($p < .0005$ for all).

b) Microclimatic differences between shaded and unshaded areas

According to the statistical tests, tree canopy significantly reduced CR by approximately 0.04 (standard deviation (SD) = 0.03) and the range of Ta by 2.4 ℃ (SD = 0.9 ℃) in the daytime. This means that trees efficiently reduce the daily temperature difference and variation during the hot months. Moreover, the shade of trees reduced the air temperature significantly during daytime with D(t) ($p < .05$ for all). Figure 3.7 illustrates the differences in average and maximum Ta between the shaded and unshaded area during this period. This difference was computed by subtracting Ta measured in shaded areas from that of unshaded areas. The average Ta and RH in tree covered areas was 1.0 ℃ (SD = 0.4 ℃) lower and 3% (SD=1.2%) higher than those of unshaded areas. However, the differences of maximum Ta and minimum RH were enlarged to 2.5 ℃ (SD=0.9 ℃) and 5% (SD=2.3%), while they could reach a maximum of 4.1 ℃ and 10% at noon. At night, the tree covered area has a slightly lower range of Ta (approximately 0.1 ℃). This difference was also observed on the calm or light air days with relatively little heat convection.

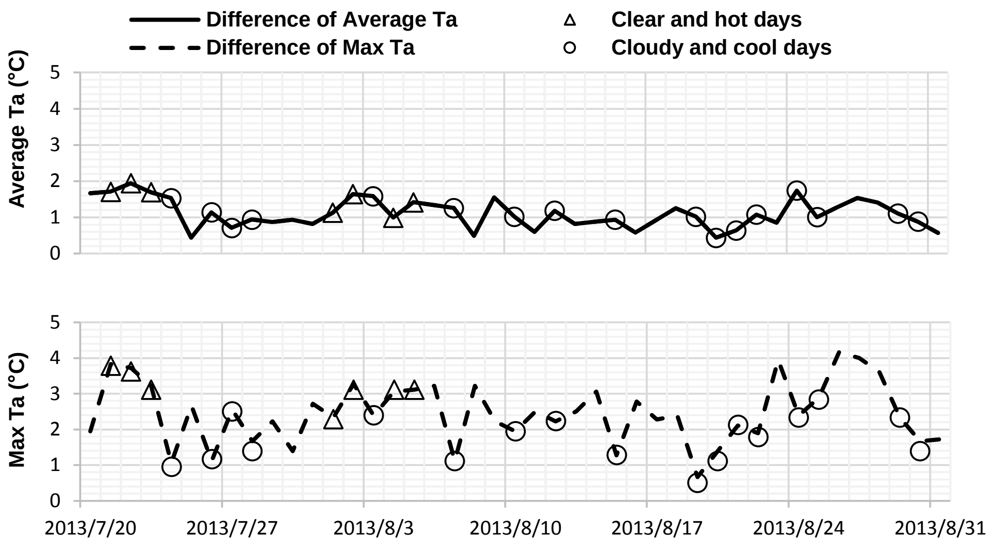
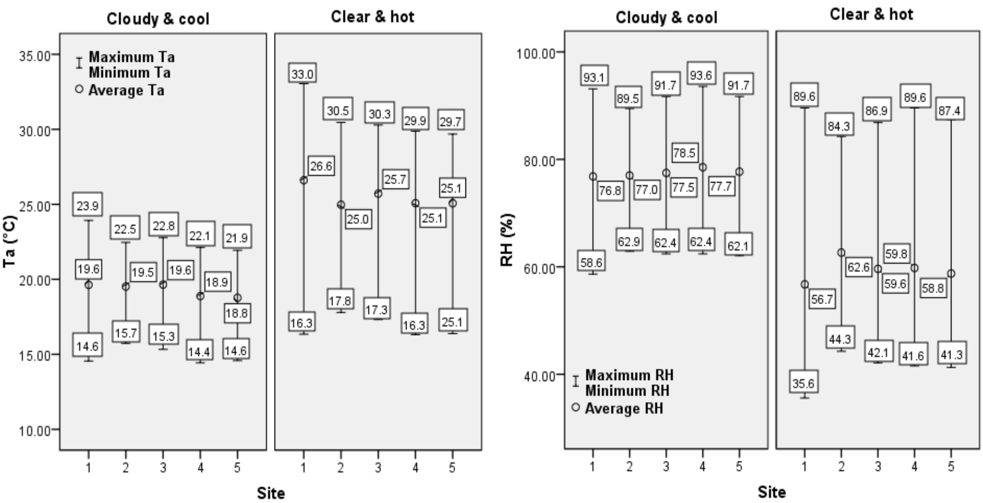


Figure 3.7 Difference in average Ta (up) and maximum Ta (bottom) between the shaded and unshaded site of the trees ($Ta_{unshaded}$ minus Ta_{shaded}) in the summer daytime (from 06:00 to 21:00).

c) Weather's effects in the daytime

To investigate the weather's effects on the microclimatic condition, the comparison of Ta and RH between relatively cloudy and cool days (cluster C) and clear and hot days (cluster F) during the daytime was made, highlighted by respectively circles and triangles in Figure 3.7. The results revealed that on the cloudy and cool days, both CR and the range of Ta/RH was not significantly different among the sites ($p > .05$ for all). However, these features differ significantly for the different sites on the clear and hot days ($p < .0005$ for all). In addition, the differences of D(t) for Ta/RH among the different sites were significant on both cloudy and cool days and clear and hot days, with $p < .0005$ for all the features. Figure 3.8 shows the maximum, minimum and average Ta and RH for each observation site, on average during both cloudy and cool and clear and hot days.

We compared the maximum, minimum and average Ta and RH in the shaded area with those ones in the unshaded area. On relatively cloudy and cool days, the maximum and average Ta within the tree canopy were approximately 1.8 ℃ (SD=0.7 ℃) and 0.8 ℃ (SD=0.2 ℃) lower than those of the unshaded area. These temperature differences were enlarged to 3.2 ℃ (SD=0.5 ℃) and 1.5 ℃ (SD=0.2 ℃) on relatively clear days. The average RH of shaded areas exceeds that of unshaded areas by 3% (SD=0.8%) on cluster C days, and 3% (SD=1.4%) on cluster F days. In general, on relatively clear and hot days, the Ta reduction by the trees was about two times higher than that on the cloudy and cold days. A table summarizing daytime Ta and RH between cloudy and cool and clear and hot days is shown in Appendix 3.1.



(a) **(b)**

Figure 3.8 Comparison of maximum, minimum and average Ta (a) and RH (b) at five sites between cloudy and cool and clear and hot days.

<u>*Effect of trees on microclimate in the winter*</u>

a) Microclimatic differences among the observation sites

Although the effects of trees did not lead to significant differences in CR and the range for Ta/RH ($p > .05$ for all) during both daytime and night time, the distribution of air temperature and humidity was significantly different ($p < .0005$ for all the D(t) of Ta/RH in both daytime and night time) among the observation sites.

b) Microclimatic differences between shaded and unshaded area

The positive cooling effect of 3% by evergreen trees in the study area in the summer may lead to disservices in the winter. In the daytime there was no significant difference in CR and the range of Ta/RH between shaded and unshaded area but we found that the trees significantly lowered the average Ta and raised the average RH by respectively 0.5 ℃ (SD=0.2 ℃) and 3% (SD=0.6%). The maximum differences of maximum Ta and minimum RH were up to 1.0 ℃ and 5% at noon (Figure 3.9). The decreased air temperature may lead to an increase of heating energy consumption and a decline of outdoor thermal comfort.

Theoretically, at night, tree canopy prevents the heat flow from the surface to the surroundings and slows down heat losses, thus increasing the Ta and lowering CR and the range of Ta. However, the measured effect of the evergreen trees on the microclimate at night was not significant, with $p > .05$ for both the trends and values of Ta. Wind velocity was a significant factor in explaining the Ta range differences between the shaded and unshaded area, with $p = 0.042$. On calm or light air days, the Ta range was slightly lowered by the trees.

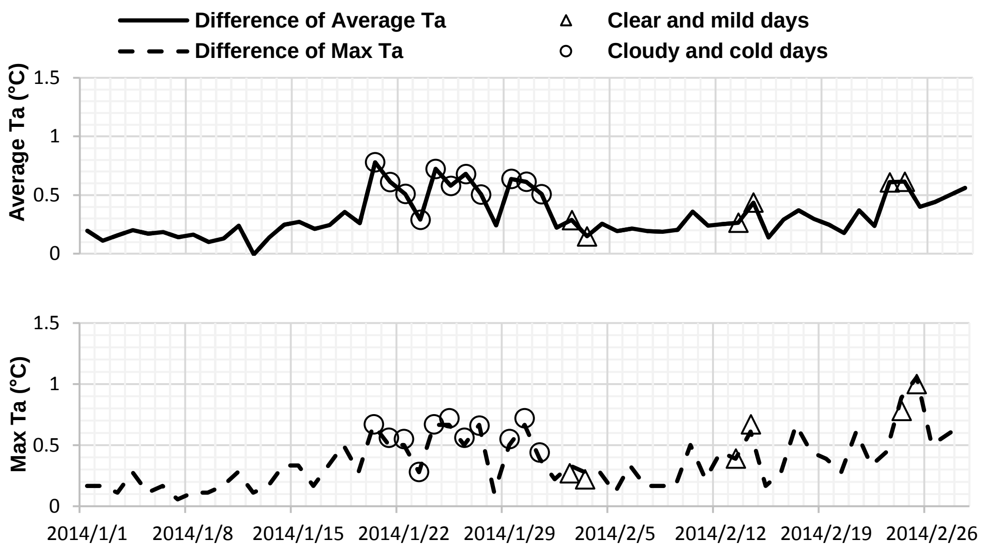


Figure 3.9 Difference in average Ta (up) and maximum Ta (bottom) between the shaded and unshaded sites (Ta $_{unshaded}$ minus Ta $_{shaded}$) in the winter daytime (from 06:00 to 21:00).

c) Weather's effects in the daytime

In terms of the weather's effects during the daytime in the winter, the statistical tests indicated that no significant differences on either measured value or trend for both Ta and RH between cloudy and cold and clear and mild days ($p > .05$ for all) were found (see also the marked days by the circles and triangles in Figure 3.9). Accordingly, we concluded that the weather conditions in the winter did not cause a notable change on performance of trees on the microclimate. Appendix 3.2 summarizes the daytime maximum, minimum and average Ta and RH under the cloudy and cold and clear and mild weather conditions.

3.3.2 Modelling results

<u>*Effect of trees on outdoor microclimate*</u>

Appendix 3.3 shows the maximum, minimum and average air temperature for both current (CU) and no-tree (NT) conditions on selected days in detail. To better understand the impact of the trees on the microclimatic condition, we calculated the Ta difference (ΔTa) caused by the absence of trees (i.e. Ta in CU condition was subtracted from Ta in NT condition at each receptor and each time step for four selected days). Figure 3.10 represents the ΔTa between CU and NT for all the receptors in 24 hours.

a) Spatial variation on the summer days

On a selected clear and hot day (2^{nd} August 2013), 5% tree cover reduced maximum Ta with 1.1 ℃ (SD=0.23 ℃). At Site four with trees, the maximum Ta differed by as much as 1.4 ℃ for simulated situations with and without trees. In addition, trees reduced the daily range of Ta by approximately 1.0 ℃ (SD=0.24 ℃). Unlike the remarkable differences in the range, the differences of CR between CU and NT conditions were small. Appendix 3.4 shows the daily average value, CR and the range for Ta in both CU and NT conditions on a clear and hot day. On the selected cloudy and cool day (3rd August 2013), the influence of trees on Ta was much smaller, with only 0.3 ℃ (SD=0.05 ℃) maximum Ta reduction at Site four. The reduction of CR and the range was small.

Although the simulated results cannot reflect the large fluctuation in air temperature and humidity at a specific location (see 3.2.1), the differences in the effect of trees among the receptors were notable. On the clear and hot day, the range of ΔTa between the area with the strongest effect and the area with the weakest effect was about 0.6 ℃ (SD=0.41 ℃) on average. This range went up to 1.5 ℃ at the time of the peak reduction at 18:00 (Figure 3.10). The spatial variation on the cloudy and cool day was much smaller than that on the clear and hot day. The daily average range of ΔTa was about 0.2 ℃ (SD=0.03 ℃), and went up to 0.3 ℃ at 13:30.

b) Spatial variation on the winter days

According to the simulation results, the reductions of maximum Ta were estimated to be 0.2 ℃ (SD=0.05 ℃) and less than 0.1 ℃ (SD=0.02 ℃), on the clear and mild day and the cloudy and cold day (i.e. 18^{th} and 21^{st} January 2014), respectively. During the afternoon of these two winter days, the temperature in areas with trees was slightly higher than in area without trees. This was reflected by the negative values of ΔTa in Figure 3.10, which could increase human thermal comfort. The effect of these trees on CR and the range of Ta was negligibly small.

Among the receptors from the locations far from to close to the trees, the daily average range of ΔTa was about 0.2°C (SD=0.14°C) on clear and mild days. The variation of ΔTa among the receptors reached a peak at 15:30, with 0.5 ℃ difference between the areas with the strongest and weakest effect (Figure 3.10). On the cloudy and cold winter day, the effect of trees on the temperature distribution was small. Hence, the spatial differences of ΔTa tended to be small as well (i.e. less than 0.1 ℃ on average).

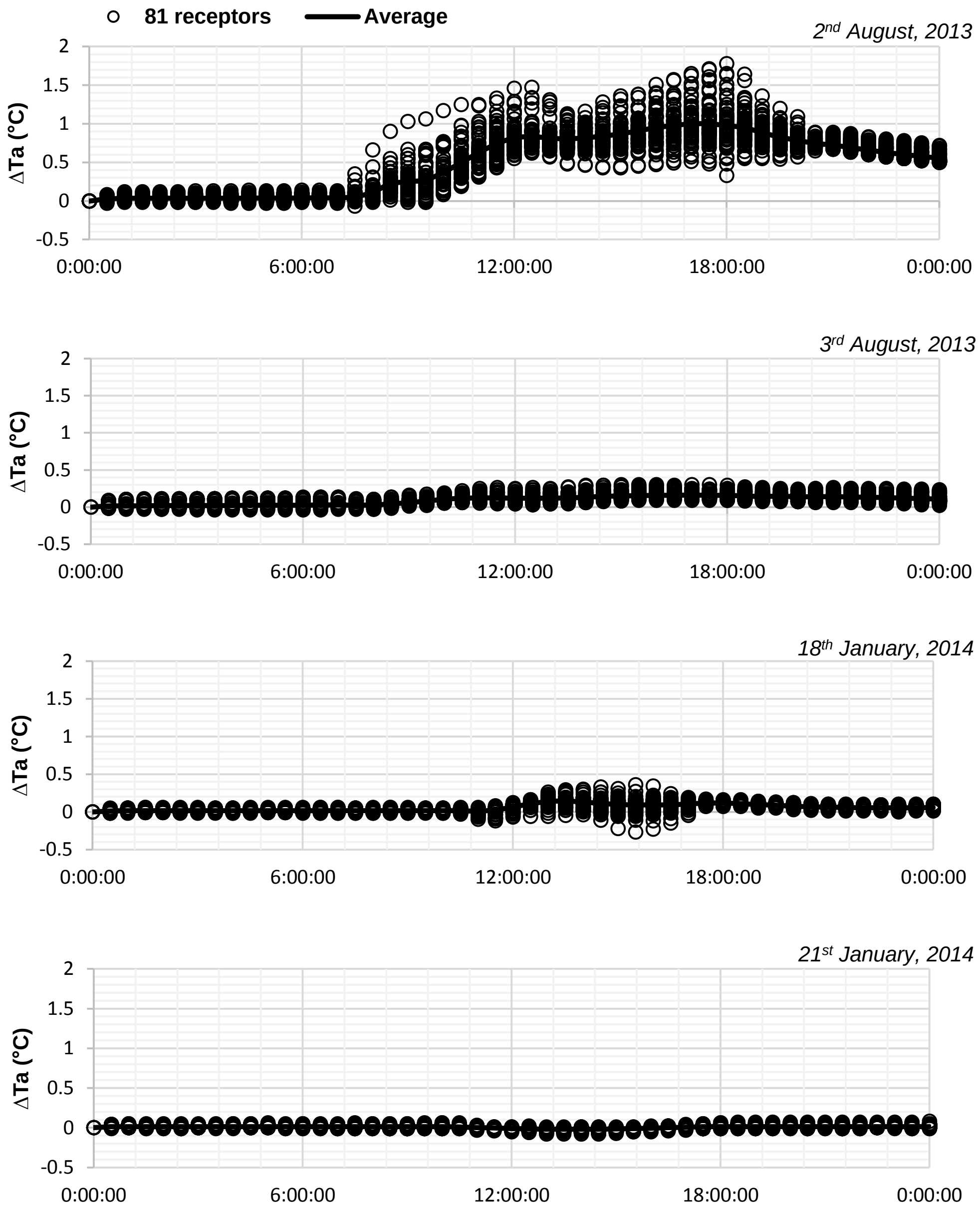
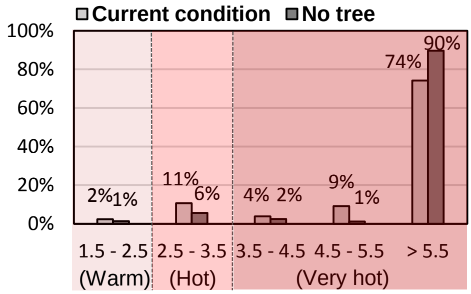


Figure 3.10 The differences of ΔTa under CU and NT conditions (Ta $_{NT}$ minus Ta $_{CU}$) among 68 receptors on selected days.

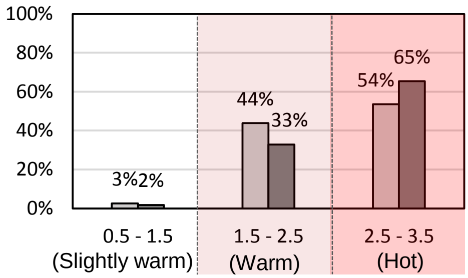
Effect of trees on outdoor thermal comfort

a) Predicted Mean Vote on the summer days

To better understand how trees affect outdoor thermal comfort during the hottest hours in the summer, the PMV value during 12:00–18:00 at each receptor was derived from the model results under CU and NT conditions respectively. Figure 3.11 shows the occurrence frequency of the PMV value at different scales from 12:00 to 18:00 on both clear and hot days and cloudy and cool days.



(a)



(b)

Figure 3.11 Frequency of PMV value at different scales from 12:00 to 18:00 on clear and hot day (a) and cl oudy and cool day (b).

On the clear and hot day, tree shading during the hottest hours significantly influenced human comfort simulation results. Comparison of the average PMV indicates that in this period trees could reduce the high PMV of > 5.5 ℃ by 16% while increasing the low PMV of 1.5–2.5 ℃ by 1% and 2.5–3.5 ℃ by 5%. Although the comfort level in most areas was still uncomfortable it is better than the 'very hot' thermal condition experienced for the same time period at all other places within model area. Under the tree canopy, the PMV value was decreased by 2.7°C. During the hottest hours of the cloudy and cool day, the 'hot' thermal condition (2.5–3.5 ℃) was reduced by 11%. The moderation of temperature at night by trees led to different effects on human comfort depending on the weather conditions. However, these impacts were small with thermal conditions ranging from 'comfortable' to 'warm'. Appendix 3.5 and Appendix 3.6 display the comfort level under CU and NT condition at 14:00 and 22:00 of the selected days.

b) PMV value on the winter days

During the two selected days in the winter, the comfort was highest in the afternoon hours. On the clear and mild day, PMV values, though slightly lower in the shade, were estimated to be at ‘comfort’ and ‘slightly warm’ levels over the entire area (Appendix 3.5). In theory, evergreen trees could improve human comfort at night by retarding heat losses and reducing cold wind blowing and block heat loss. However, the changes on the comfort level were negligible small on both selected days (Appendix 3.6).

3.4 Discussion

3.4.1 Measurement results

Microclimatic differences

The measurement results confirmed that tree covered areas show lower average air temperature during the daytime in the summer than the unshaded area by approximately 1.0 ℃. This agrees with previous studies that reported a 0.9–2.0 ℃ reduction of average ambient air temperature in areas with vegetative canopy (McPherson et al. 1989, Taha et al. 1991, Park et al. 2012). Additionally, previous studies proved that evergreen trees also reduce the temperature in the winter (Akbari 2002, Mcpherson 1988). This was also observed in our measurements.

Theoretically, evergreen trees can prevent the vertical heat transfer and reduce the heat exchange between areas below and above the canopy at night in the winter (Akbari 2002, Heisler and Grant 2000, Mcpherson 1988), thereby increasing Ta and lowering CR and the range of Ta. However, this has not been observed from our measurements. A plausible explanation is that the heat convection in the winter was strong. This affected the temperature spatial distribution, since the wind velocity was a significant factor in explaining the differences of the range of Ta between the shaded and unshaded area.

Weather’s effects

In our study we used a cluster methodology to characterise the sky conditions, integrating the clearness index, the variation of solar intensity and the maximum air temperature. Cooling effects of trees on relatively clear and hot days were about two times higher than on the cloudy and cold days. Similar results were also reported by another study that investigated the thermal conditions of the typical shaded and unshaded buildings in the summer and dry season (December–February) in Nigeria (Morakinyo et al. 2013). This study in Nigeria analysed the variation of outdoor air temperature in relation to different weather conditions. A clearness index was used to characterize weather conditions and their results confirmed that the influence of trees on the outdoor air temperature became less with increasing cloudiness.

Our findings also indicate that, during the daytime in the winter, different weather conditions did not cause a notable change in tree effects on microclimate. That is most likely due to the fact that the variation of incoming solar radiation under the different weather conditions was rather small because of the low solar intensity.

3.4.2 Modelling results

Numerical models such as ENVI-met probably introduce a bias in the simulations. The model results poorly represent instant temperatures and fail to capture the real instantaneous changes of air temperature and humidity. This inability of ENVI-met has been reported by several studies (e.g. Emmanuel et al. 2007, Peng and Jim 2013). The good simulations' agreement with our measurements, however, indicated that our input parameters were adequate for the local simulations.

Spatial variation

In the summer, the spatial differences of ΔTa among the receptors in the model were found to vary strongly, being 1.5 ℃ and 0.2 ℃ at maximum values on clear and cloudy days respectively. In the winter, the maximum spatial differences were smaller but still apparent with 0.5 ℃ and 0.1 ℃ on clear and cloudy days, respectively. This demonstrates that, when the weather is clear and hot, trees efficiently alter local microclimate and cause large variations in temperature in close geographical proximity. To better understand the effects of trees on the local urban microclimate and to identify and quantify the effect of urban trees on local outdoor microclimate and human thermal comfort, empirical information on the microclimate must be collected in close geographical proximity.

Thermal comfort

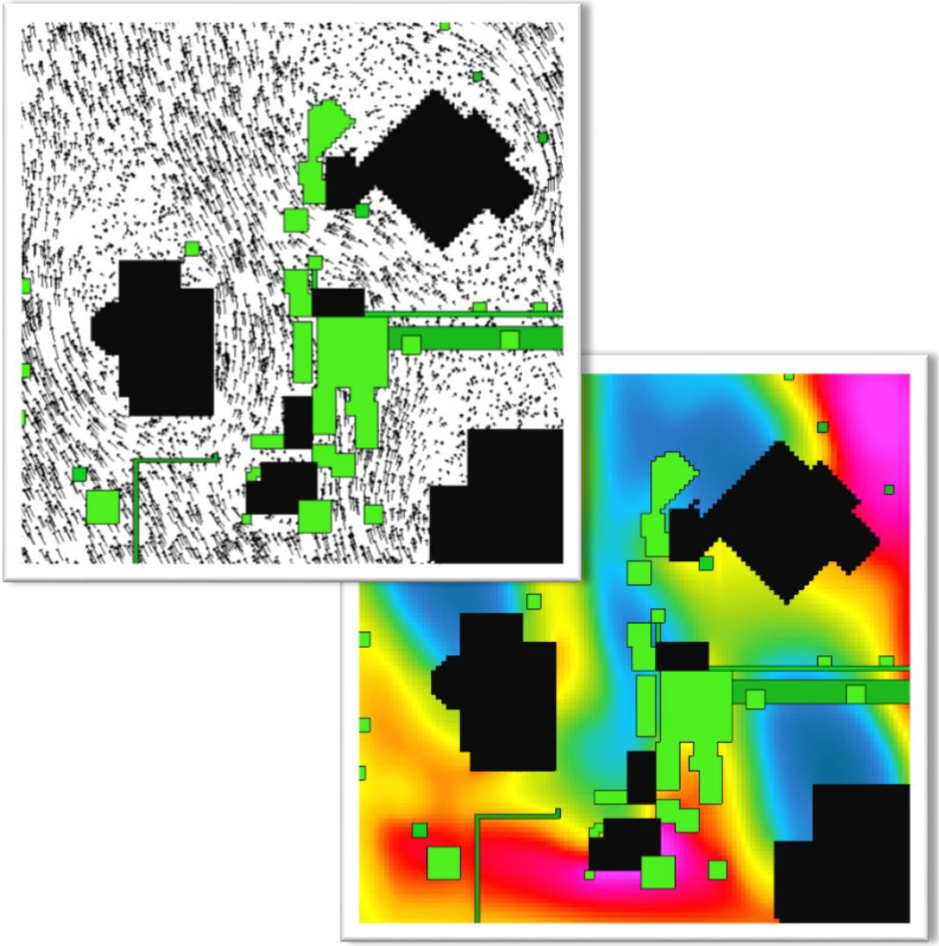
We extracted the simulated PMV value from ENVI-met to illustrate the thermal condition in the study area. The maximum PMV (i.e. extra uncomfortable thermal condition) was notably reduced during the hottest hours on both clear and cloudy days. Fahmy et al. (2009) stated that PMV differs depending on the density of the trees. Further study is necessary to compare the cooling effects among trees with different density and height. Although PMV was developed based on a large database, human comfort levels highly depend on human thermal perception, expectation and preference in the particular study context (area and time). Hence, field surveys are necessary to investigate the subjective responses for people's thermal sensations in a local area.

3.5 Conclusion

This study provides new insights into the influence of trees on microclimate and human thermal comfort in a local urban area through field measurements and modelling. The effect of weather conditions on the cooling performance of trees was analysed. Observed weather conditions were clustered to investigate the differences in cooling effect of trees and to select the appropriate days for the model simulations.

The results from both the measurements and the simulations showed that trees significantly altered the surrounding microclimate in the summer. Comparison of the measurements between the shaded and unshaded area showed that the daily maximum air temperature differed by 2.5 ℃. Significant spatial variations in temperature were caused by the trees. Trees considerably improved the thermal comfort level through reducing the 'very hot' (PMV > 5.5°C) and 'hot' (PMV range of 2.5–3.5 ℃) thermal conditions by about 16% on clear days and 11% on cloudy days. Additionally, we found that the evergreen trees also lowered the average winter air temperature by 0.5 ℃. This effect can potentially offset the benefit of the evergreen trees by increasing energy costs in the winter.

The biological and physical processes involved in microclimate regulation by trees are affected by, among others, the surrounding temperature, humidity and solar radiation, whereby the cooling effect of trees was greatly influenced by prevailing weather conditions. The measurements in the shaded and unshaded areas revealed that, on relatively clear and hot days, the Ta reduction by the trees was about two times higher than that on cloudy and cold days. Also the simulations with the ENVI-met model showed strong spatial variation in temperature conditions. Hence, when studying the influence of trees on the microclimate, weather conditions must be considered, especially in the summer. We conclude that trees, as an important element in UGI, are very effective in regulating the microclimate and enhancing thermal comfort locally. Weather conditions, however, strongly influence the trees' performance of microclimate regulation, especially in the summer.



The spatial pattern of wind flow and air temperature at INCAS[3], Assen (latitude: 53º 0’ 0’’ N, longitude of 6º 55’ 00’’ E) on 2nd August 2013 (12:30) by ENVI-met.

CHAPTER 4

Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season

Based on:

Wang, Y., Bakker, F., De Groot, R., Wörtche, H., & Leemans, R. (2015). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. *Environmental Monitoring and Assessment*, *187*, 732–745.

Abstract

This study analysed how the variations of plant area index (PAI) and weather conditions alter the influence of urban green infrastructure (UGI) on microclimate. To observe how diverse UGIs affect the ambient microclimate through the seasons, microclimatic data were measured during the growing season at five sites in a local urban area in The Netherlands. Site A was located in an open space, Sites B, C and D were covered by different types and configurations of green infrastructure (a multiple tree grove, a single deciduous tree and a group of street trees respectively), and Site E was adjacent to buildings to study the effects of their façades on microclimate. Hemispherical photography and globe-thermometers were used to quantify PAI and thermal comfort at both shaded and unshaded locations. The results showed that groves with high tree density (Site B) have the strongest effect on microclimatic conditions. Monthly variations in the differences of mean radiant temperature (ΔT_{mrt}) between shaded and unshaded areas followed the same pattern as the PAI. Linear regression showed a significant positive correlation between PAI and ΔT_{mrt}. The difference of daily average air temperature (ΔT_a) between shaded and unshaded areas was also positively correlated to PAI, but with a slope coefficient below the measurement accuracy (± 0.5 ℃). This study showed that weather conditions can significantly impact the effectiveness of UGI in regulating microclimate. The results of this study can support the development of appropriate UGI-measures to enhance thermal comfort in urban areas.

Key words: Green infrastructure, Urban microclimate, Outdoor thermal comfort, Plant area index, Field measurements

4.1 Introduction

The global urbanization process accelerates population growth in cities, causing changes in the urban microclimate and ultimately affects people's health. Although the mitigation of urban warming and amelioration of thermal comfort by urban green infrastructure (UGI) have been well established (Taha et al. 1991, Akbari et al. 2001, Yang et al. 2011, Ng et al. 2012, Berry et al. 2013, Skoulika et al. 2014), the underlying mechanisms and quantitative effects on the microclimate and human thermal comfort are still poorly understood. In an earlier study (Wang et al. 2014), we summarized the factors that possibly influence the performance of microclimate regulation by UGI, which are vegetation characteristics (quality and quantity, plant area index (PAI) (PAI = leaf area index (LAI) + wood area index (WAI)), vertical structure, species composition), local morphology (distribution of buildings and vegetation), ground properties and weather conditions. However, it is less clear how strongly these factors affect the performance of UGI especially trees on microclimate regulation in different times of the year.

In our previous field study (Wang et al. 2015a), temperature and humidity were continuously measured in a small local urban area during summer and winter, and combined with numerical modelling. A significant effect of the local morphology and weather conditions on microclimate regulation by trees was found, and vegetation density and PAI of trees seemed to strongly affect the microclimate regulation capacity (Wang et al. 2014). However, the relation between the trees' PAI and the surrounding thermal environment was mainly analysed by applying models (Shashua-bar and Hoffman 2000, Ng et al. 2012, Shahidan et al. 2012). To examine the impact of vegetation characteristics in terms of vegetation density and PAI on the capacity of UGI to regulate microclimate, field measurements were conducted at different locations covered by various types and configurations of green infrastructure during the growing season (from April to August 2014) to quantify the effects of changes in PAI and to provide empirical evidence. In addition, the effect of weather conditions on the microclimate regulation performance of UGI during the growing season were measured and are presented and discussed in this chapter.

4.2 Materials and Methods

4.2.1 Site description and field measurements

Site description

Assen, the capital of the Drenthe Province, is located in the north-western part of The Netherlands. It mainly enjoys a typical oceanic climate with mild winters and cool summers. May and June (spring) are the sunniest months of the year, and July and August (summer) are the warmest months. In the autumn, the weather becomes cooler, cloudy and rainy, with frequent winds, while the sunshine time is only around two hours each day. During this period, microclimate regulation by UGI is less important with less shade and evapotranspiration, and does not play an essential role in human thermal comfort. Therefore, our study was targeting on spring and summer, and the measurements were carried out during the growing seasons, which were from leafless season (April and May) to full leaf season (June to August). We have conducted field measurements at five sites in a small urban area (approximately 3,600 m^2, latitude: 53º 0’ 0’’ N, longitude of 6º 55’ 00’’ E) in Assen (Figure 4.1). The microclimatic data obtained from study site’s open space (Site A) supplied the reference data to compare with the other observation sites. This particular site was selected because of its best sunlight exposure, which minimized the influence from the surroundings. Different types of UGI were included in the study area: Site B was surrounded by a group of trees (situated in a grove); Site C was beneath a single deciduous tree; Site D was located at the street side to observe the impact of street trees; and Site E was placed adjacent to the building to determine the effect of the building’s façade on ambient microclimate.

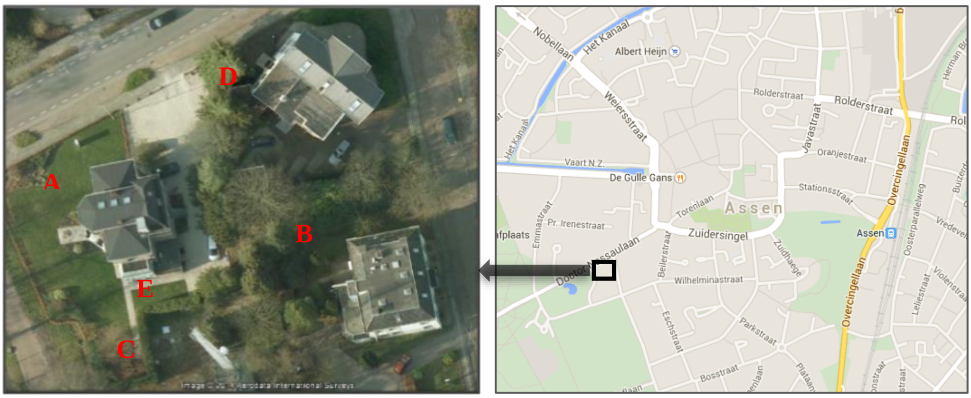


Figure 4.1 The location of the observation sites in the city of Assen, The Netherlands. (Source: Google Earth and screenshot of OpenStreetMap).

Field measurements

Temperature and humidity stations were mounted at a height of 1.5m. To observe variations in the effects of trees on the microclimate in the growing season, air temperature (Ta) and relative humidity (RH) were consistently measured at all five sites from April to August 2014 (a 134 day period). Besides, globe temperature (Tg) and wind velocity (Va) were also measured in Sites A and B to examine outdoor thermal comfort (predicted mean vote (PMV) or Physiological equivalent temperature (PhET) value) with and without surrounding vegetation respectively. In this study, Va was continuously measured by a Davis Anemometer. However, technical limitations of the globe thermometer (globe diameter: 75 mm) allowed us to measure Tg only on 23 clear, sunny days throughout the observation period. All data were acquired with a ten minutes interval and stored in a dedicated database.

To observe the variations in tree canopy, hemispherical images were taken during the growing seasons at all observation sites using a Panasonic Lumix DMC-FZ100 digital camera equipped with a Panasonic super fisheye wide-angle lens. Because Sites A and E were located outside vegetative canopies, and Site D was only shaded by evergreen trees where the changes of a canopy are negligible, the images were most frequently taken at the Sites B and C. At each of these two sites, eight images surrounding the station were taken toward the sky at 1.5m high. The top of the photographs faced north. To avoid the interference due to variation in sunlight, the images were generally taken twice a week on overcast days. In total 576 images were taken during 36 days throughout the observation period. Table 4.1 lists the measured items and instruments at five observation sites.

Table 4.1 Measured items and instruments at each observation site

Measured items	Instruments	Features	Observation sites
Ta	6382OV Davis Temp Station	• Range: -25 ℃ to 50 ℃ • Resolution: 0.1 ℃ • Accuracy: ±0.5°C	A & B & C & D & E
RH	6382OV Davis Hum Station	• Range: 0-100% • Resolution: 1% • Accuracy: ± 3%	A & B & C & D & E
Va	7911 Davis Anemometer	• Range: 0 to 56 $m{\cdot}s^{-1}$ • Resolution: > 0.05 $m{\cdot}s^{-1}$ • Accuracy: ± 0.5 $m{\cdot}s^{-1}$	A & B
Tg	Heat Index WBGT Meter (2010SD)	• Range: 0°C to 80°C • Resolution: 0.1°C • Accuracy: ±0.6°C	A & B
PAI	Panasonic Lumix DMC-FZ100 digital camera with a fisheye wide angle lens (VLB1658B)	-	B & C

4.2.2 Statistical tests

We first investigated whether the microclimatic data differed among the five observation sites. Since the daily maximum, minimum and average Ta, RH and Va were not normally distributed, the statistical significance for differences in these values among the observations sites were analysed by a non-parametric Kruskal-Wallis H test. However, this test might be obscured by the daily fluctuations of temperature and humidity that were higher than the differences among the sites (especially during spring and summer). To circumvent this problem, we calculated the mean value of all observation sites, and used this to determine the relative microclimatic data at each station. The difference between the mean value and the data x at each station was given as D(x). This resulting relative value for the daily maximum, minimum and average is calculated for Ta, RH and Va as:

$$D(x)_{dj} = max_i/min_i\,/average_i\left(x_{dji}\right) - \frac{1}{M}\sum_{j=1}^{M} max_i/min_i\,/average_i\left(x_{dji}\right) \qquad \text{(Equation 4.1)}$$

Where D(x) denotes the relative daily maximum, minimum or average value for Ta , RH or Va, and x_{dji} stands for Ta, RH or Va data, with the different indices and parameters defined below:

j: index of observation site (j = 1,…, M), M = 5
M: total number of observation sites
d: index of observation day (d = 1,…, K), K = 134 days
K: total number of observation days
i: index of data point in one day (i = 1,…, N), N = 144
N: total number of data points in one day

Subsequently, a Kruskal-Wallis H test was performed on D(x) where x represents either Ta, RH or Va and with the observation sites as the independent variable. A P-value of < 0.05 indicates that the differences of the dependent variables among the observation sites are significant.

4.3 Thermal comfort level

4.3.1 Mean radiant temperature (Tmrt)

Apart from understanding the effects of the vegetation on the microclimate, this study also investigates the influence of vegetation on thermal comfort. The mean radiant temperature (Tmrt) as the most influential factor that determines outdoor thermal comfort, was derived for the open space (Site A) and the grove (Site B). There exist two common methods to calculate Tmrt. The first method is the six direction radiation method, in which Tmrt is calculated according to the short wave and long wave radiation in six directions (VDI 1998). The second method, which is the called the globe-thermometer method, calculates Tmrt from Tg, Ta and Va using the standardized Tmrt equation from Equation 4.2 (ISO 7726 1998). In this study, we used the second method.

$$Tmrt = \left[\left(T_g + 273.15\right)^4 + \frac{3.42\times10^9 Va^{0.119}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right)\right]^{0.25} - 273.15 \quad \text{(Equation 4.2)}$$

T_g: Globe temperature (℃)
V_a: Air velocity ($m \cdot s^{-1}$)
T_a: Air temperature (℃)
D: Globe diameter (m)
ε: Globe emissivity

Where the globe diameter of the heat index WBGT Meter (D) is 75 mm and globe emissivity (ε) is normally assumed as 0.95 (Taleghani et al. 2013). Ta, Tg and Va were based on the measurements at Sites A and B with a ten minutes sample interval.

4.3.2 Thermal comfort indices

In order to assess outdoor comfort, various indices combining microclimatic data and biometeorological factors have been developed. A predicted mean vote (PMV) approach is often used to quantify thermal comfort. PMV ranges from -3.5 ‘very cold’ to 3.5 ‘very hot’ (Fanger 1970). Physiological equivalent temperature (PhET) was regularly used in recent studies (Peng and Jim 2013, Abdel-Ghany et al. 2013, Klemm et al. 2014). PhET is equivalent to the Ta, with a widely known unit (℃). Hence, PhET is more intuitive and comprehensive compared to PMV. Both indices can be simply calculated by the RayMan model (RayMan stands for "radiation on the human body") (Matzarakis et al. 2007). It requires the following inputs: Ta, RH, Va, Tmrt and the parameters that describe the heat exchange processes of the human body (personal data, clothing and activity).

4.4 Estimation of plant area index (PAI)

4.4.1 Gap fraction analysis

LAI is the ratio of single-sided leaf area (m^2) to ground surface area (m^2) (Watson 1947). This is a key parameter to estimate the canopy architecture and ecosystem processes. In the past decades, numerous methods have been developed to quantify LAI directly and indirectly. The direct measurement consists of harvesting the vegetation, applying the allometric equations and collecting leaf litter fall (Wilson 1963, Nizinski and Saugier 1988, Mäkelä et al. 1995, Maguire and Bennett 1996, Thomas and Winner 2000). Although these methods are accurate, they are both destructive and time- and labour consuming (Gower et al. 1999). Therefore, many new studies have estimated LAI indirectly. One of these methods is gap fraction analysis that infers the LAI by measuring the light transmittance of the canopy (Smith et al. 1991, Welles and Cohen 1996, Cutini et al. 1998, Stadt and Lieffers 2000, Finzel et al. 2012). This method is based on the Beer-Lambert law for light attenuation through a canopy and requires measurements of above and below canopy radiation. Ideally, the foliage is randomly distribute in the canopy. However, this is generally not the case in reality (Bréda 2003). Hence, the gap fraction depends on both LAI and leaf inclination distribution (Bréda 2003). In this study, we applied the hemispherical photography method to estimate the canopy structure and light transmittance. Firstly, upward-oriented fisheye photographs were taken at eight locations surrounding each observation station. CAN-EYE V6.3 image analysis software (used to extract the canopy structure characteristics from true colour images) was used to analyse the resulting images. We then generated several canopy structure characteristics including LAI, average leaf inclination angle, fraction of absorbed photosynthetically active radiation, vegetation cover fraction and bidirectional gap fraction. The resulting LAI could be overestimated in our study, because stem and branch areas (i.e. WAI) are included in this method. CAN-EYE V6.3 supports the masking of parts of the image, but neglects the leaf areas behind these elements and likely underestimates LAI. For this reason, CAN-EYE V6.3 outputs correspond to the PAI that include the ratio of the sum of stems, branches or trunk and leaf area (m^2) to ground surface area (m^2) (Weiss and Baret 2010, Zhao et al. 2012).

4.4.2 Regression model

PAI values on each day during the observation period were estimated from the measured PAI at Sites B and C using a regression model. We found that quadratic equations provided the best fit to the collected data, as theoretically expected for the variation of PAI in this period.

Site B: $PAI = -0.0004x^2 + 0.154x - 8.596\ (r = 0.840)$ (Equation 4.3)

Site C: $PAI = -0.0001x^2 + 0.055x - 2.592\ (r = 0.801)$ (Equation 4.4)

Where x stands for Julian day numbers. Figure 4.2 and Figure 4.3 show the regression curves derived from the measured PAI, and two examples of sky-view images in leafless and full leaf seasons for Sites B and C respectively. The R-square for the two relationships were 0.706 and 0.642, respectively; while the adjusted R-square were 0.685 and 0.617. This indicates that the two linear models fit the sets of observations. Using the predicted PAI from Equations 4.3 and 4.4, we calculated the monthly average PAI. Subsequently, variation of monthly average PAI was compared with the changes of differences in Ta (ΔTa) and Tmrt (ΔTmrt) between shaded areas and unshaded area. Afterwards, we examined how the time-varying PAI affected the differences of Ta (ΔTa) between shaded and unshaded area. The relationship between predicted PAI and the differences of Tmrt (ΔTmrt) between Sites A and B was also estimated.

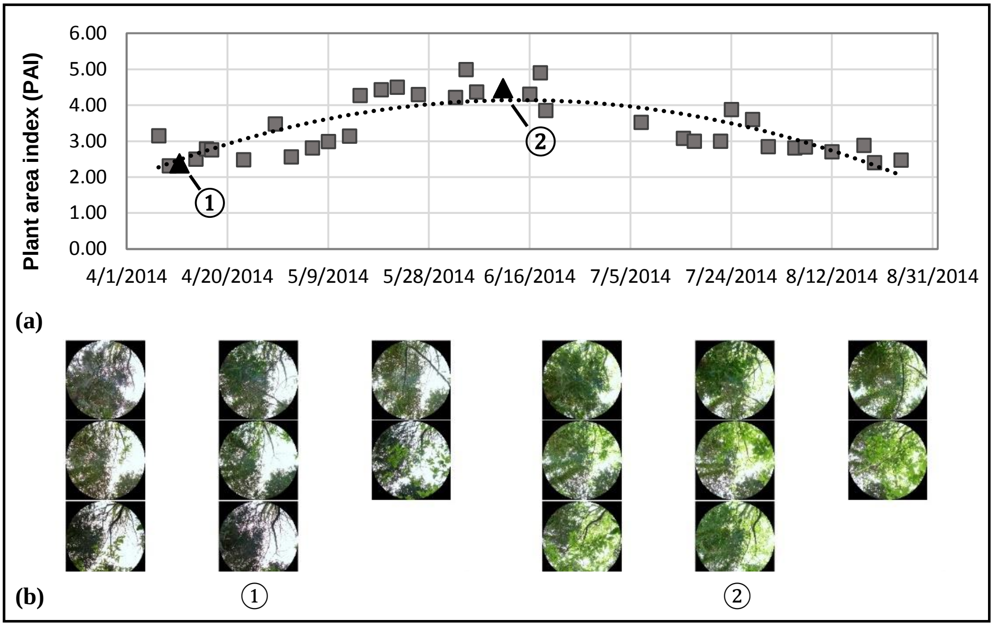


Figure 4.2 (a) The regression curves derived from the observed PAI in the grove (Site B). (b) The examples of sky-view images in leafless season (on 4/11/2014) ① and in full leaf season (on 6/11/2014) ②.

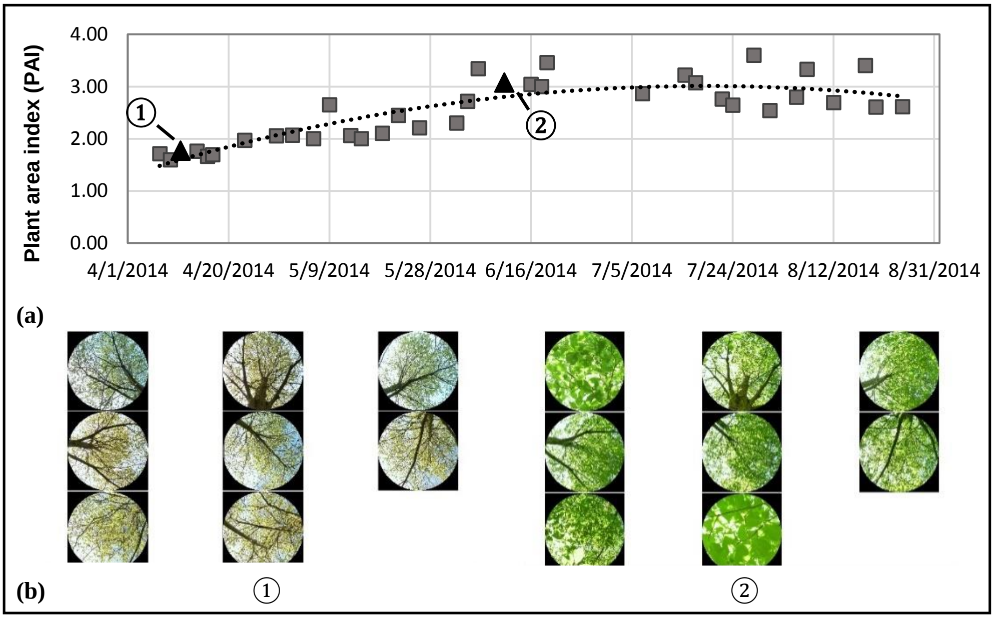


Figure 4.3 (a) The regression curves derived from the observed PAI beneath a single deciduous tree (Site C). (b) The examples of sky view images in leafless season (on 4/11/2014) ① and in full leaf season (on 6/11/2014) ②.

4.5 Clustering weather conditions

4.5.1 Definition of clusters

Our previous study employed a cluster method which integrates the clearness index (Kt), the fluctuation of solar radiation (FR) and the maximum air temperature (MaxTa). This method characterized the weather conditions during the summer and winter observation periods individually (Wang et al. 2015a). Kt and FR helped to classify the weather conditions during the observation period via calculating the average solar insolation and determining the fluctuation rate of diurnal solar radiation. Meanwhile, MaxTa highlighted the most uncomfortable days in the summer and winter (hottest and coldest days). The current study aims to quantify the changes in the different green infrastructures' effect on the local urban microclimate from April to August. As using MaxTa for clustering would only highlight the uncomfortable days in the hottest months (July and August), it was not required in this study. Hence, only Kt and FR were used to characterize the weather conditions. Kt is the ratio of the global solar radiation measured at the surface and the clear sky solar radiation, which was proposed by Kuye and Jagtap (1992). Kt, calculated according to the hourly average solar insolation, does not reflect the variation of solar intensity. To capture this, we calculated the fluctuation rate of diurnal solar radiation (FR) to compute the variation of sunlight intensity for a given period (for a one minute time interval). Since Kt ranges from 0 to 1, FR was transformed to the same scale by applying unity-based normalization. According to the classification of Kt by Liu and Jordan (1960) and our earlier study (Wang et al. 2015a), we defined the days having $Kt \geq 0.65$ and $FR \leq 0.5$ as clear days; the days with $Kt < 0.35$ and $FR \leq 0.5$ as cloudy days; and the remaining days were the near-cloudy or near-clear days.

4.5.2 Cluster results

The cluster results for the weather conditions from April to August 2014 over 134 sampling days are illustrated in Figure 4.4. Notably, the days with incomplete data were eliminated from the total sampling days. In total there were 23 cloudy days and 35 clear days in the observation period. The rest 76 days were near-cloudy or near-clear days. The clustering approach classified the microclimatic effects of green infrastructure under different weather conditions. Additionally, Kruskal-Wallis significance test the differences of microclimatic data for different weather conditions was performed for each month.

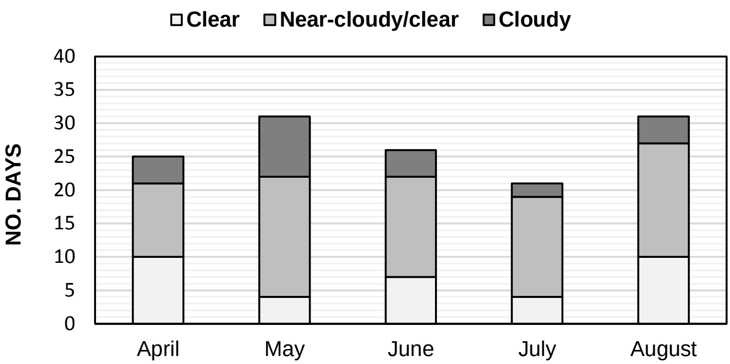


Figure 4.4 Clustering results for the weather conditions during the observation days from April to August 2014.

4.6 Results

4.6.1 Microclimatic differences

As far as (x) (differences in Ta, RH and Va between each observation site and the mean value) were concerned, the Kruskal-Wallis H test revealed significant differences with $p < .0005$ during the daytime. Comparisons among multiple observation sites showed that D (daily maximum, average, minimum Ta) of Site A differed significantly from the other Sites ($p < .0005$ for all). However, the differences of D(maximum, average, minimum RH) between Sites A and D were not significant with $p > .05$ for all. Similar results were also found during the nights.

Figure 4.5 depicts the differences of daily average Ta between unshaded area (Site A) and the four shaded areas by trees (Sites B, C and D) or buildings (Site E). As expected, Site A always had higher daily average Ta compared to Sites B, C and D. During the whole observation period, daily average Ta in the three shaded areas were respectively 0.9 ℃ (standard deviation (SD) = 0.2 ℃), 0.8 ℃ (SD = 0.2 ℃) and 0.6 ℃ (SD = 0.1 ℃) lower, compared to unshaded area. These difference in daily maximum Ta between shaded and unshaded area increased to 1.9 ℃ (SD = 0.5 ℃), 1.6 ℃ (SD = 0.4 ℃) and 1.4 ℃ (SD = 0.4 ℃). All these differences were larger than the accuracy of the instruments (> 0.5 ℃). On hot dry days, the maximum temperature differences could reach 3.3 ℃, 2.7 ℃ and 2.3 ℃ for the tree-shaded sites respectively. These results showed that the grove site had best cooling capability compared to the other sites, although the difference was rather small. Appendix 4.1 gives the observed range of Ta differences and the average difference over a single day during the observation period. Moreover, we found that, compared to the unshaded area, the building façade remarkably increased the daily maximum Ta by 1.6 ℃ (SD = 1.0 ℃). This difference peaked (3.5 ℃) on 19th May. However, the shade of the building could also decrease the daily average Ta by as much as 0.5 ℃.

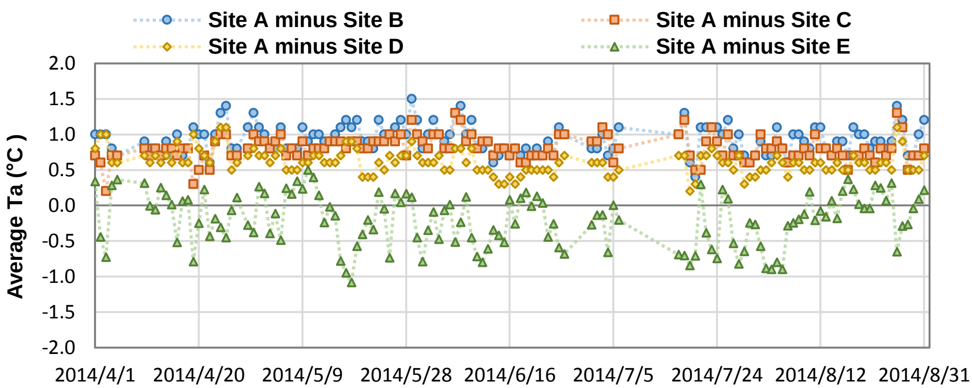


Figure 4.5 Differences of daily average Ta during the daytime.
Site A – open space; Site B – a multiple tree grove; Site C – a single deciduous tree; Site D – a group of street trees; Site E – building façade.

In terms of RH, the grove (Site B) had the highest daily average RH (76%); Site E, which was adjacent to the building façade, presented the lowest daily average RH (72%). However, the SDs of average RH of all five sites (9%–10%) were much bigger than the differences among them. This indicates that RH was not varying much in the research area and that trees have a rather limited effect on the RH distributions. As described in the above paragraph, no statistically significant difference in RH between Sites A and D was found (average RH = 75% for both sites). Tables that summarize the differences of daytime Ta and RH between unshaded and the shaded areas, are shown in Appendix 4.2 to Appendix 4.5.

Theoretically, Ta in open spaces decreases more markedly and quickly than in tree shade areas after sunset (Akbari 2002). Hence, this effect enlarges the Ta range and its rate of change. Although the differences of Ta and RH were significant, the expected higher Ta range and its rate of change in the open space were not observed. In addition, we found that the Va significantly influenced the nightly Ta trends among the observation sites ($p < .0005$).

The wind measurements were taken simultaneously in the open space and in the grove. Figure 4.6 shows that the average Va in the open space significantly differed from that in the grove ($p < .0005$). The daily maximum and average Va in the grove were 0.8 $m{\cdot}s^{-1}$ (SD = 0.4 $m{\cdot}s^{-1}$) and 0.1 $m{\cdot}s^{-1}$; whereas these values in the open space were approximately 2.8 $m{\cdot}s^{-1}$ (SD = 1.1 $m{\cdot}s^{-1}$) and 0.6 $m{\cdot}s^{-1}$ (SD = 0.3 $m{\cdot}s^{-1}$). That is to say, trees as shelter lowered the wind speed dramatically.

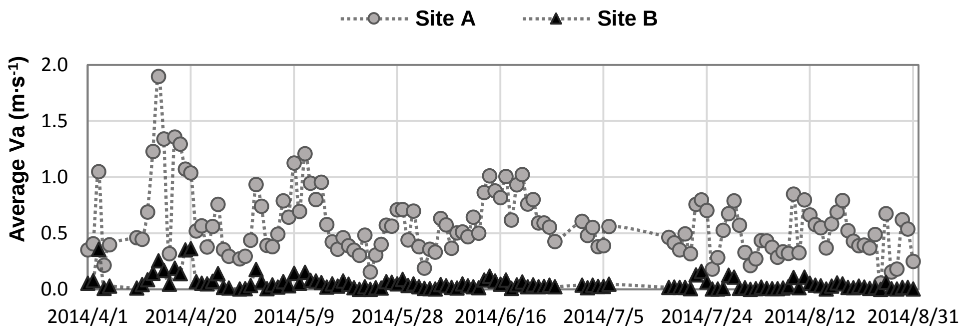


Figure 4.6 The average wind velocity at Sites A and B.

4.6.2 Thermal comfort level in daytime

The values of mean radiative temperature (Tmrt; Equation 4.2) at Sites A and B were calculated. The result showed that the measurements in the open space exhibited higher Tmrt values when compared with the measurements in the grove, being 7.4 ℃ (SD = 2.0 ℃) and 11.5 ℃ (SD = 2.5 ℃) higher for the average and maximum Tmrt, respectively.

After analysing the Tmrt differences between Sites A and B, we analysed the diurnal ranges in these two areas through calculating the thermal comfort indices (predicted mean vote (PMV) and physiological equivalent temperature (PhET)). Both PMV and PhET values are expressed as a percentage of thermal condition (Figure 4.7). The results showed that trees drastically improve comfort, resulting in higher percentage of ‘comfortable’ condition and lower percentage of ‘hot’ and ‘cool’ conditions. Taking, for example, one of the hottest days (18^{th} July), during the hottest afternoon hours, open space experienced around four hours of ‘hot’ period. In the grove, however, ‘slightly warm’ and ‘warm’ thermal condition sustained during the same time period, whilst ‘hot’ sensation were absent. Appendix 4.6 lists these diurnal PhET and PMV values from 10:00 to 18:00 on 18th July.

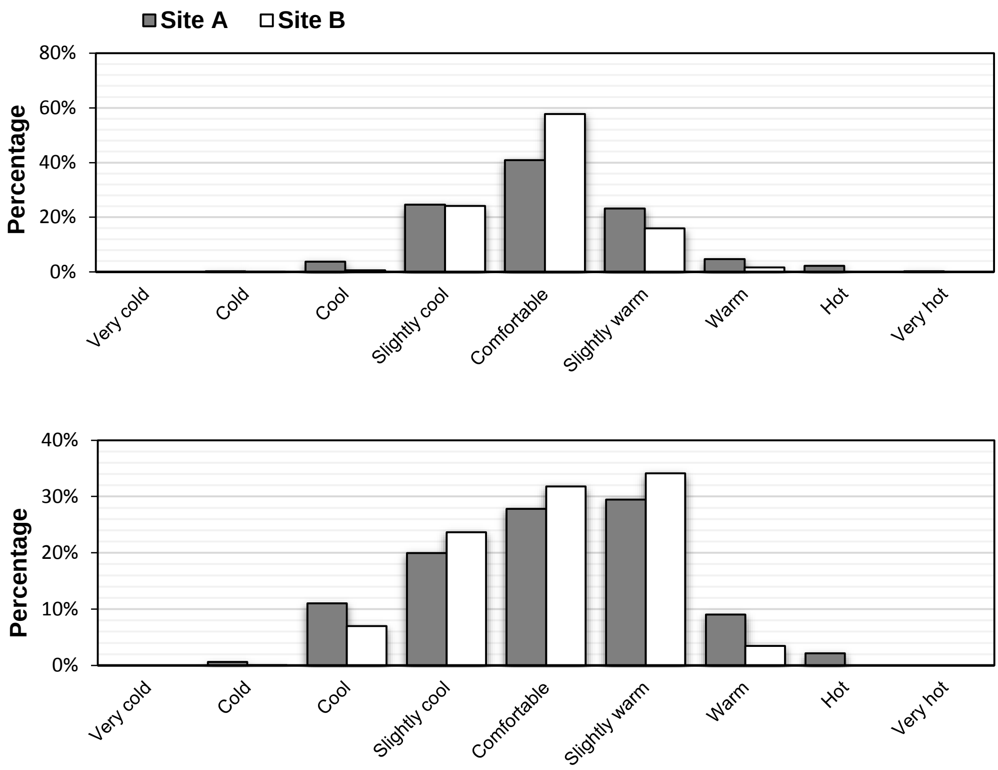


Figure 4.7 Percentage of diurnal PMV (top) and PhET (bottom) value for the different thermal condition in the open space (Site A) and in the grove (Site B).

4.6.3 Effects of Plant area index (PAI)

The average values of PAI, ΔTa and ΔTmrt (between shaded areas and unshaded area), were calculated for each month. Figure 4.8 depicts the variation of monthly average PAI, ΔTa and ΔTmrt. It can be observed that monthly average ΔTa has not undergone much variation during the growing season. In contrast, ΔTmrt shows a sensitivity to the changes of PAI. Starting from April, the monthly average ΔTmrt gradually increased and ended up at 8.9°C in June, when the average PAI reached a peak level of 4.2. Subsequently, both values declined simultaneously. This behaviour revealed that most probably, the changes in monthly average ΔTmrt follow the same pattern of the variations in average PAI.

To better understand the relationship between PAI and temperature reduction by green infrastructure, a linear regression analysis was applied between the predicted PAI towards the differences in daily average Ta and Tmrt. The simple correlation equations with 95% confidence limits are as follows:

$$\Delta Ta = 0.696 + 0.059PAI \ (r = 0.237)$$ (Equation 4.5)

$$\Delta Tmrt = 0.097 + 2.054PAI \ (r = 0.655)$$ (Equation 4.6)

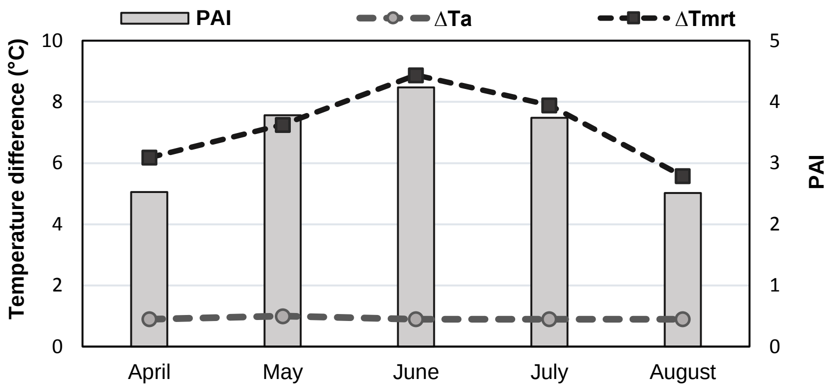
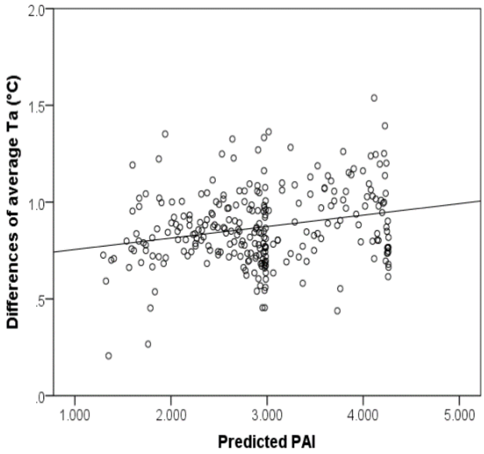
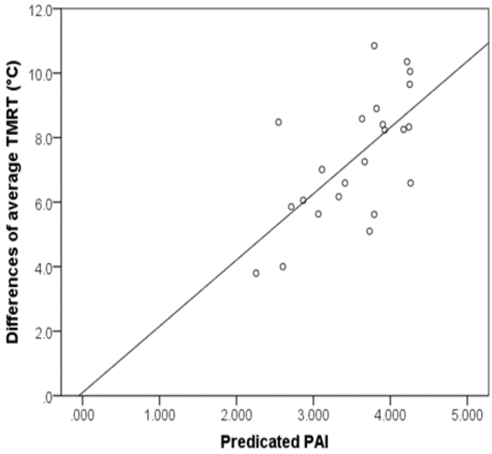


Figure 4.8 The variation of monthly average PAI, ΔTa and ΔTmrt.

The scatter plots in Figure 4.9 shows the linear-fit estimation of ΔTa and ΔTmrt with the PAI. The values of the t-statistic on the coefficients of these two linear regressions were 3.980 and 3.975 respectively; while both P-values were less than 0.05. These results indicate that the resulting coefficients are significant and the variations explain by the models are robust. However, the gradient coefficient of PAI for the temperature regression equation was only 0.059. In other words, a gain in the PAI value by one unit would result in a ΔTa increase of 0.059 ℃, which is smaller than the measurement accuracy (±0.5 ℃). Therefore, this linear relationship seems unreliable. The variation in PAI was found to have a stronger correlation with the ΔTmrt changes (c.f. the gradient coefficient of 2.1). This is likely due to the fact that, compared to Ta, Tmrt is more strongly affected by trees (Matzarakis et al. 1999). Regarding the thermal comfort level, the monthly average PAI of trees in the grove reached their highest value in June and this led to more 'comfortable' thermal condition by 14% compared to open space.





(a) **(b)**

Figure 4.9 Scatter plots and linear-fit estimation of ∆Ta versus PAI (a), and ∆Tmrt versus PAI (b).

4.6.4 Effects of weather

Figure 4.10 compares ∆Ta (for Site A minus Site B, Site A minus Site C, Site A minus Site D, and Site A minus Site E) between daytime cloudy days and clear days. The weather condition was a significant factor explaining the differences in daily average Ta between tree shaded areas (Sites B, C and D) and the unshaded area (Site A) ($p < .05$ for all). It also explained the difference of daily average Ta between the open Site A and Site E (adjacent to the building façade) ($p < .0005$). When performing an Kruskal-Wallis H test for each month, as expected, the weather conditions had a significant impact on the differences of daily average Ta between tree shaded and unshaded area, but only during the period that trees had a high PAI (summer months). In contrast, weather conditions always played a crucial role in defining the difference of daily average Ta between Sites A and E during the entire observation period ($p < .05$ for every month). Notably, on the cloudy days, the daily average Ta adjacent to the building (Site E) was lower than the open space (Site A); whereas, on clear days, the values were opposite. Most likely, the building façade absorbs incident solar radiation and releases heat to the ambient environment.

To account for the weather's effects during full leaf season, we compared the difference of Ta between the open space and the grove for different weather types from June to August.

On cloudy days, the trees in the grove reduced daily maximum and average Ta by about 1.6 ℃ (SD = 0.3 ℃) and 0.8 ℃ (SD = 0.1 ℃), while on clear days, the temperatures reduction were 2.2 ℃ (SD = 0.4 ℃) and 1.1 ℃ (SD = 0.2 ℃). For the cooling effects of the single tree at Site C, the daily maximum and average Ta were 1.2 ℃ (SD = 0.2 ℃) and 0.6 ℃ (SD = 0.1 ℃) lower than those in the open space under cloudy weather conditions. However, on clear days, the differences increased to 2.2 ℃ (SD = 0.3 ℃) and 1.0 ℃ (SD = 0.2 ℃) for daily maximum and average Ta, respectively.

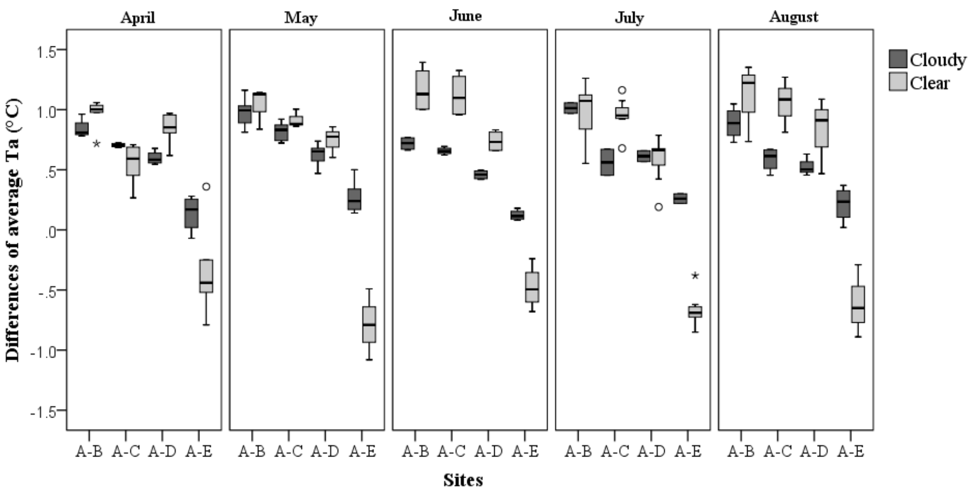


Figure 4.10 Box plot of ∆Ta for Site A minus Site B, Site A minus Site C, Site A minus Site D, and Site A minus Site E on cloudy and clear days from April to August 2014.

4.7 Discussion

4.7.1 Microclimatic differences

Based on our measurements, we determined the ranking for the cooling capability of different types of UGI: a multiple tree grove (Site B) > a single deciduous tree (Site C) > a group of street trees (Site D). Our results confirmed a model-based study by Shahidan et al. (2012) who showed that a large number of trees reduced temperature more than single trees, although we found that the ground surface also contributes to a Ta reduction. The grove with the most trees in our study yielded the best cooling capability but a single tree had a larger cooling effect than a group of street trees, probably due to the paved surface that offsets (some of) the temperature reduction. Furthermore, we also found that the difference in RH between open space and street trees was not significant. A plausible explanation is that both locations were adjacent to the street. RH’s value and trend were therefore significantly influenced by the paved surfaces. In addition, the expected higher Ta range and rate of change at night in the open space were not observed. Va was found a significant factor in explaining the Ta trend. Hence, heat convection likely plays the most important role at night in small urban areas.

4.7.2 Thermal comfort indices

Both estimated PMV and PhET values based on the Raymen model confirmed that trees in the grove improved human comfort levels. However, the results of PMV and PhET showed a slightly different frequency pattern (c.f. Figure 4.7) because these two indices are derived from different models and approaches. PMV is based on Fanger's model (Fanger 1970) and calculates the energy loss from the body by determining the skin temperature and evaporative sweat rate. The heat transfer through and from a body is assumed to be at steady-state with the environment. PhET estimates the thermal sensation and the corresponding heat stress based on the Munich Energy Balance Model for Individuals (MEMI) (Höppe 1993), which calculates the thermal conditions of the body by integrating surrounding meteorological parameters and the physical activity and clothing of the individual. PhET is not constrained by a steady state heat balance approach.

4.7.3 Plant area index (PAI)

To exclude the radiation that is reflected or transmitted by leaves from the observed radiation, upward-oriented fisheye photographs must be taken under diffuse light conditions, i.e. cloudy days or twilight periods on sunny days (Zhao et al. 2012). Although we selected the cloudy days to obtain these images, Dutch daily weather changes quickly, leading to abrupt changes in solar intensity and this probably causes the deviation between the true value and the measured value. Shahidan et al. (2012) compared the cooling performance of trees with high (LAI = 9.7) and low (LAI = 0.9) canopy densities in an ENVI-met model. Their result showed that air temperature increased by 0.034 ℃ when LAI decrease 1 integer unit. This is slightly less than our finding (0.059 ℃ increase in ΔTa). However, as described in Section 4.4, the slope coefficient of the regression line was smaller than the accuracy of measurements. This linear regression relationship is, therefore, probably unreliable. To study the effects of changes in PAI (or LAI) on air temperature, future studies will require a temperature sensor with better resolution and accuracy. Additionally, in this linear model, PAI was the only independent variable. There might be other factors that could mimic or perhaps obscure the effects of PAI on ΔTa. A comprehensive relationship between ΔTa and possible factors should be explored in future studies.

4.8 Conclusion

This empirical study reports on the effect of different types of urban green infrastructure (UGI) on the microclimate and thermal conditions during the growing season in a local urban area based on actual weather measurements and estimated human thermal condition. From April to August, microclimatic data were acquired at five different locations: an open space, a multiple tree grove, a single deciduous tree, a group of street trees and a building façade.

The results showed that the grove (with most trees) had the best cooling capability among the studied types of UGI although the difference in the daily average air temperature (Ta) reduction was small (max. 0.3 ℃). In addition, lower wind velocity (Va) values were also found in the grove. The effects of these meteorological changes on human thermal comfort were confirmed through demonstrating the condition of thermal comfort, which made it possible to establish a quantitative relationship between different types of UGI, their microclimate effects and influence on human thermal condition. Another finding was that street trees performed worse in terms of microclimate regulation than a single tree, probably due to the presence of paved surfaces which offset temperature reductions. Furthermore, the Ta differences between the open space and the area adjacent to the building façade fluctuated (the Ta differences could be both positive and negative) due to the weather conditions and the direction of the sun. The weather conditions were also a significant factor in explaining the Ta differences between open space and the other tree-shaded areas. In general, the cooling effect of the trees on clear days was shown to be almost two times higher than on cloudy days. Changes of monthly average ΔTmrt followed the same pattern of the variations in monthly average PAI, with a peak level of 8.9 ℃ when PAI reached a maximum of 4.2 in June. Through linear regression analysis, the relationship between ΔTa and PAI was determined. The slope coefficient of PAI for the regression equation was too small to explain the changes in ΔTa, but the differences in ΔTmrt between the open space and the grove were significantly related to PAI (gradient coefficient = 2.054).

Increasing the PAI through appropriate UGI-measures may thus considerably reduce Tmrt and enhance thermal comfort locally during spring and summer. In order to verify and further quantify this finding, the effects of changes in PAI need to be explored further in a more comprehensive regression model supported by empirical data on climate and human thermal perception. It should thereby be realized that weather conditions have a notable effect on the climate regulation performance of green infrastructure.

A hemispheric photo of the sky view taken with Panasonic Lumix DMC-FZ100 digital camera with a fisheye wide angle lens and a normal angle of view for an oak tree on 15th May 2014.

CHAPTER 5

Thermal comfort in urban green spaces: A survey on a Dutch university campus

Based on:

Wang, Y., Bakker, F., de Groot, R., Wörtche, H. & Leemans, R. Thermal comfort in urban green spaces: A survey on a Dutch university campus. *International Journal of Biometeorology*, submitted.

Abstract

To better understand the influence of urban green infrastructure (UGI) on outdoor human thermal comfort, physical measurements and a survey were performed at the campus of the University of Groningen, The Netherlands, in spring and summer 2015. 389 respondents (77% Dutch and 23% from other countries) were interviewed in five different locations. The survey's purpose was to analyse people's local thermal comfort perception and preference, to specify the combined effects between the thermal environmental and personal factors on their thermal perception, and to combine the use of a social survey and field measurements to quantify the role of UGI in microclimate regulation. The results imply that non-physical environmental and subjective factors were more important in perceiving comfort than the actual thermal conditions, at least in the context of this study. By applying a linear regression and probit analysis, the actual comfort temperature was found to be 22.2 ℃ and the calculated preferred temperature was found at a surprisingly high 35.7 ℃. This can be explained by the observation that most respondents, who live in temperate regions with relatively cool climates, disliked to describe their preferred state as 'cooler'. Using the Kruskal-Wallis H test, the four significant factors influencing thermal comfort were people's exposure time in green spaces, previous thermal environment and activity, and their thermal history. The results suggest that people's preferences and adaptation factors should be included when interpreting human thermal comfort measurements in green spaces. By providing evidence for the role of all objective and subjective factors on human thermal comfort, the relationship between UGI, microclimate and thermal comfort that was specified in this study can assist urban planning to make better use of green spaces for microclimate regulation.

Key words: Outdoor thermal comfort, Urban green infrastructure, Thermal adaptation, Temperate regions, Correlation analysis

5.1 Introduction

The accelerated population growth in urban areas, associated with the increase of impermeable concrete surfaces, industrial pollution and destruction of natural habitats negatively changes the urban microclimate (Watson and Johnson 1987, Akbari et al. 2001, Grimmond 2007). The impacts of these changes in microclimate and thus human thermal comfort, has a negative effect on human health and this is received increasing attention (Campbell-Lendrum and Corvalán 2007, Zhao et al. 2011, Franck et al. 2013). In addition, interest in the effects of urban green infrastructure (UGI) on thermal perception and microclimate is growing (Hwang et al. 2010, Krüger et al. 2011, Lin et al. 2013, Yang et al. 2013). Besides physical factors (e.g. actual weather conditions), behavioural factors (e.g. adaptive behaviour to restore the heat balance and previous activities) and psychological factors (e.g. thermal history and expectations) also play important roles in assessing the influence of thermal environments on human comfort (De Dear and Brager 1998b, Nikolopoulou et al. 2001, Lin 2009, Yang et al. 2013). Previous studies typically focused on citizens who share the same thermal history (Feriadi and Wong 2004, Hwang et al. 2010, Klemm et al. 2014). Knez et al. (2009) proposed a conceptual model to reveal direct and indirect effects of a given place on human thermal responses. They found that long-term memory significantly influenced people's experience of, and expectations towards the weather and the appreciation of outdoor urban places. People's long-term memory on thermal comfort differs with their thermal history due to the different originated regions. Therefore, a survey study across different nationalities is required to include the variability in thermal history. Furthermore, Wang et al. (2015a and 2015b) found that small green infrastructure (e.g. a tree grove or a single tree) in a local urban area significantly affected the microclimate and human thermal comfort. This indicates that such survey should be carried out locally.

To this end, we combined a survey on human subjective responses with simultaneous field measurements of the local microclimatic parameters in a small urban area in The Netherlands. The purpose of this study was to analyses people's thermal comfort perception and preferences in this local area and to specify the combined effects between thermal environmental and personal factors on their thermal perception. Through further statistical analyses we aimed to quantitatively relate the social survey, the field measurement data and the role of UGI in microclimate regulation.

5.2 Methods and materials

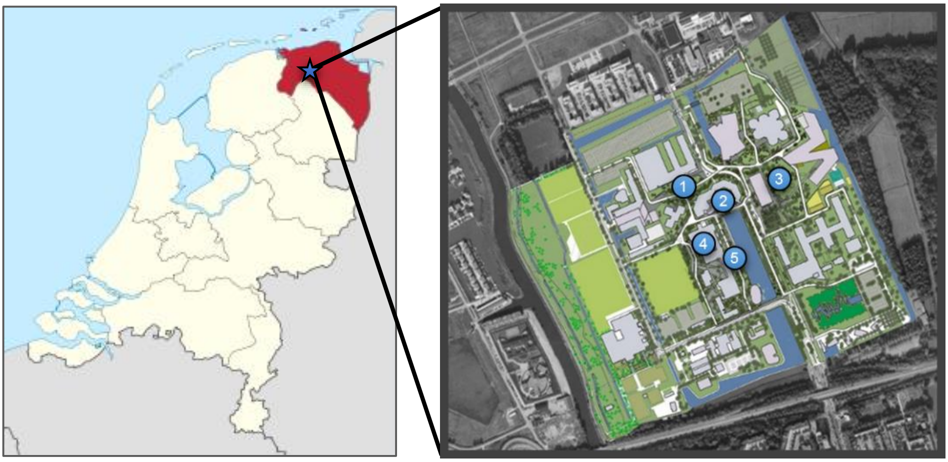
In this study, physical measurements of microclimatic data and a survey on people's subjective thermal perceptions were carried out at the Zernike Campus of the University of Groningen in the Northern part of The Netherlands (see Figure 5.1). The information on people's thermal perception, sensation and preference was obtained by conducting a questionnaire-based survey among students, employees and other people in five green urban spaces on five warm and cloudless spring and summer days in 2015. Meanwhile, mobile equipment measured of air temperature (Ta), globe temperature (Tg), relative humidity (RH) and wind velocity (Va) during the survey.

5.2.1 Site and field survey description

Groningen has a mild maritime climate with a moderate level of rainfall and a sunshine duration of approximately six hours per day. Warmer weather starts in April and ends in early October. The average air temperature fluctuates between 19 ℃ and 23 ℃ within this warmer period (http://www.worldweatheronline.com). The total population of the University of Groningen is approximately 30,000 students and 5,000 staff. The Zernike Campus is currently under re-construction and many 'green projects' are in progress. A pilot survey with a small group of university students at the Zernike Campus was first conducted in the summer 2014 to check if the questionnaire (see Appendix 5.1) was appropriate and delivered the necessary data. Afterwards, the actual survey was carried out in five green spaces with different vegetation characteristics (see Figure 5.1) on five warm and cloudless days (May 11th, May 22nd, June 5th, June 12th, and July 4th 2015) from 12:00 pm–4:00 pm. The participants were randomly selected at the different survey locations and asked to fill out the two-page questionnaire. This questionnaire consisted of three sections:

- The first section gathered the demographical information of the respondents by asking their age, gender, nationality, weight and body-length. Additionally, to estimate the heat exchange rate, respondents' activity level and clothing were determined according to ISO 8996 (1990) and ISO 9920 (1995) standards respectively.

- The second section asked respondents to rate their current thermal comfort. Based on ASHRAE Standard 55 (ASHRAE 1992), a thermal sensation vote (TSV) was designed on a 7-point scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, and 3 hot), while a Bedford 7-point scale (Bedford 1936) was used for the thermal comfort vote (TCV). In addition, respondents were asked to indicate their thermal preference vote (TPV) on a 5-point scale ranging from 'much warmer'' to 'much cooler'. Using the humidity sensation vote (HSV) and the wind speed sensation vote (WSV), sensation and preference for humidity and air movement were also measured on a 7-point scale (HSV, -3 very dry, -2 dry, -1 slightly dry, 0 neither dry nor humid, 1 slightly humid, 2 humid, 3 very humid; WSV, -3 very low, -2 low, -1 slightly low, 0 neither low nor high, 1 slightly high, 2 high, 3 very high). Behavioural adjustment is also an important factor for evaluating the outdoor thermal comfort. Hence, respondents were asked to select what actions they would like to take if they feel too hot in this place.
- The last section asked non-Dutch respondents to indicate their residence time in The Netherlands. Subsequently, questions on the reason of coming to the survey location, frequency of visiting, and exposure time in the selected green spaces were given to all the respondents. Additionally, we asked them to describe the previous place where they were before coming to the survey location and activities 15–20 minutes before coming.



(a) (b)

Figure 5.1 The location of the study area.
(a) The blue star represents the location of Groningen city. (b) The blue circles represent the survey locations at the Zernike Campus, Groningen.
(Sources: German Kartenwerkstatt and Google Map).

Because responses for some open questions were subjective and described freely, we pragmatically categorized them into related answers to obtain as many values as possible. The responses to the **reason of coming** were grouped into: environment (e.g. enjoying the nice view, fresh air or less crowded), weather/sunshine (e.g. enjoying the sunshine, comfortable temperature or comfortable wind flow), relaxation/rest (e.g. relax, recover from intense work/study or break from class/work), study/work, transition (e.g. passing by or waiting for class), eat/drink and others. The **exposure time** in the study area was divided into six categories (i.e. less than 10 minutes, 10–15 minutes, 15–20 minutes, 20–60 minutes, and more than 60 minutes) and the visiting frequency was categorized into rarely visit, occasionally visit, often visit and very often visit. The **previous thermal environment** experienced 15–20 minutes before the survey (short-term memory) were classified as outdoor and indoor, while the **previous activity** in the last 15–20 minutes includes: resting, very light activity, light activity and medium activity (high activity was not mentioned by the respondents).

To investigate the effect of people's thermal history on their thermal perception, the **nationality** of the respondents was categorized under the different types of climate regions according to the Köppen climate classification (c.f. Peel et al. 2007), which are: tropical wet, tropical monsoon, tropical dry seasonal climate, arid, semi-arid, humid subtropical, oceanic, mediterranean, humid continental, subarctic, tundra, ice cap and alpine climates. The **residence time in The Netherlands** was categorized into: less than 0.5 year, 0.5–1 year, 1–2 years, 2–5 years, 5–20 years, a lifetime.

5.2.2 Physical measurements

Measurement items

Physical measurements were conducted to collect microclimatic data at the survey locations. A mobile meteorological station equipped with a globe thermometer (Heat Index WBGT Meter 2010SD) and anemometer (MS6252B Digital Anemometer) was continuously measuring the air and globe temperatures, relative humidity and air velocity during the survey. The measurement height was about 1.1 m above the ground surface level, corresponding to the average height of the centre of gravity for adults (Mayer and Höppe 1987). All measurements were simultaneously recorded and stored with a two seconds interval. As, in general, each respondent spent approximately five minutes to fill out the questionnaire, the average values in Ta, Tg, RH and Va during these five minutes were calculated and defined as the corresponding values for each respondent, then added to the database.

Mean radiant and operative temperatures

To estimate the thermal comfort, the mean radiant temperature (Tmrt) is required. Using the measurement data of Ta, Tg, RH, Va, we calculated Tmrt based on the standardized Tmrt equation from (Equation 5.1) ISO 7726 (1998).

$$Tmrt = \left[(Tg + 273.15)^4 + \frac{3.42\times10^9 Va^{0.119}}{\varepsilon D^{0.4}} \times (Tg - Ta)\right]^{0.25} - 273.15 \qquad \text{(Equation 5.1)}$$

Tg: Globe temperature (℃)
Va: Air velocity ($m\cdot s^{-1}$)
Ta: Air temperature (℃)
D: Globe diameter (75 mm)
ε: Globe emissivity (normally assumed as 0.95)

The operative temperature (T_{op}) as one metric that combines the effects of air and mean radiant temperature, was estimated to assess the effects of microclimatic conditions only. T_{op} can be defined as the average of the mean radiant and ambient air temperatures at the time of interview, weighted by their respective heat transfer coefficients (ASHRAE 1992).

$$T_{op} = \frac{[Tmrt + (Ta \times \sqrt{10Va})]}{1 + \sqrt{10Va}} \qquad \text{(Equation 5.2)}$$

$Tmrt$: Mean radiant temperature (℃)
Ta: Air temperature (℃)
Va: Air velocity ($m\cdot s^{-1}$)

5.2.3 Thermal comfort indices

Thermal comfort indices, such as physiological equivalent temperature (PhET) (Mayer and Höppe 1987), predicted mean vote (PMV) (Fanger 1972) and standard effective temperature (SET*) (Gagge et al. 1986) were used to examine the link between the thermal environment and human thermal comfort. In 1997, Matzarakis and Mayer translated PMV and PhET into equivalent grade of physiological stress on human beings (Fanger 1972). However, this relationship does not consider the thermal discrepancies of seasons and climate regions. De Dear and Brager (1998a) presented a solution by estimating equations to calculate adaptive PhET values for three climatic periods (cool, mild or warm). Table 5.1 presents the ranges of PMV, PhET and adaptive PhET during cool, mild and warm periods for different grades of thermal perception and stress (Matzarakis and Mayer 1997, De Dear and Brager 1998a).

Table 5.1 Ranges of PMV, PhET and adaptive PhET for different grades of thermal perception and physiological stress.
(Sources: according to Matzarakis and Mayer 1997, De Dear and Brager 1998a).

PMV	**PhET (℃)**	**Adaptive PhET**			**Thermal perception**	**Grade of thermal stress**
		Cool period	*Mild period*	*Warm period*		
					Very cold	Extreme cold stress
-3.5	4	4	6	8		
					Cold	Strong cold stress
-2.5	8	8	10	12		
					Cool	Moderate cold stress
-1.5	13	13	15	17		
					Slightly cool	Slight cold stress
-0.5	18	18	20	22		
					Neutral	No thermal stress
0.5	23	23	25	27		
					Slightly warm	Slight heat stress
1.5	29	27	29	31		
					Warm	Moderate heat stress
2.5	35	34	36	37		
					Hot	Strong heat stress
3.5	41	40	42	43		
					Very hot	Extreme heat stress

The RayMan model (Matzarakis et al. 2007) was utilized for estimating the thermal comfort indices. Ta, RH, Va, Tmrt together with other parameters that describe the heat exchange processes of the human body (personal data, clothing and activity) were the inputs required for running RayMan. Subsequently, the simulated PMV and PhET values were converted to the thermal perception and grade of thermal stress (see Table 5.1). Compared with PMV, PhET is more intuitive and comprehensive using a widely known unit (℃). This study, therefore, used the adaptive PhET model for warm climates, since our survey was performed on warm and cloudless days. We compared the adaptive PhET to the TSV derived from the survey to analyse if peoples' thermal perception differed from simulated results that were calculated according to objective variables.

5.2.4 Statistical analysis

Firstly, respondents' demographic characteristics, activity level and clothing were summarized. Afterwards, the correlation among thermal response votes, including TSV, HSV, WSV and TCV, was determined by applying the non-parametric Spearman Correlation test, as these thermal response votes were recorded at the ordinal scale and were not normally distributed.

Subsequently, a linear regression analysis determined the relationships of the subjective TSV derived from survey versus adaptive PhET and T_{op} derived from measurements, and to calculate the neutral temperature (comfort temperature). Because the variance of thermal sensations among individuals could be large, even in the same environment (De Dear and Brager 1998b), PhET and T_{op} were classified into different bins with an increment of 1 ℃ and 0.5 ℃. The mean thermal sensation vote (MTSV), weighted with the number of responses for each data bin, fell into the corresponding bin. The linear regression intercept determined the neutral operative temperature.

Profit analysis was applied to calculate the preferred temperature (the temperature people stated they would prefer) based on TPV, which was divided into groups for each 0.5 ℃ T_{op} intervals. The probit regression was applied for the votes of 'warmer' and 'cooler' temperatures against T_{op}. The goodness of the fit of these two probit regressions was assessed by Pearson chi-square (χ^2) tests. The intersection point of the two regressions indicated the preferred temperature at which people did not prefer either a cooler or warmer temperature (De Dear and Fountain 1994).

Finally, since a person is not a passive recipient of its ambient thermal environment, TSV is not only explained by local microclimatic conditions. TSV is also affected by various behavioural and psychological factors (e.g. adaptive behaviour, acclimatization and habituation or expectation) that are collectively referred to as thermal adaptation. To examine the effect of thermal adaptation (including both behavioural and psychological adaptation), we investigated the impact of thermal sensation based on the responses to seven questions on behaviour adjustment, purpose of coming, exposure time, visiting frequency, previous thermal environment and activity, and thermal history. The non-parameter Kruskal-Wallis H

Test was applied to evaluate the difference between the variables, because TSV in this study was not normally distributed.

All analyse were based on a 95% confidence interval at a significance level of 0.05.

5.3 Results

5.3.1 Statistical summary of personal parameters

The first section of the questionnaire was about the respondents' demographic characteristics, activity level and clothing worn. Table 5.2 presents a statistical summary of this information from the survey. In total, 389 valid questionnaires were obtained from students (70%), employees (20%) and other people (10%) at five locations. The survey involved respondents from 25 countries. Those countries were categorized into the Köppen climate regions. The respondents predominantly stemmed from the oceanic climate region (i.e. The Netherlands and Western Europe).

5.3.2 Thermal response votes and their correlation

The respondents were asked to vote for their thermal (TSV), humidity (HSV) and wind speed (WSV) sensation. Figure 5.2 illustrates the percentage distribution of TSV, HSV and WSV of all the respondents. The results showed that 'slightly warm' and 'warm' (+1 and +2) sensation were predominant for TSV, whereas people who felt 'cool' and 'cold' (-2 and -3) were rare. In terms of the humidity and wind speed sensation, people who voted 'neither dry nor humid' (0) and 'slightly high wind speed' (+1) represented the largest group.

The respondents' preferences regarding the thermal, humidity and wind speed conditions were assessed by statistically analysing their answer to the question about their desire for 'warmer/cooler', 'drier/more humid', 'less/more air movement' or 'no change' (see Appendix 5.2). The percentage of people who preferred 'no change' in the temperature was highest (48%), whereas the percentage of those who preferred 'warmer' and 'cooler' were respectively 32% and 20%. In addition, the percentage of people who voted 'no change' in humidity (69%) and wind speed (42%) was also higher than the other preference categories. Finally, 31% and 58% of the respondents were unsatisfied with the current humidity and wind speed respectively.

Table 5.2 A statistical summary of demographic characteristics, activity level and clothing worn.

Demographic characteristics

Gender		**Male**	**Female**	**Missing**						
	N	205	182	2						
	%	52.7	46.8	0.5						
Age		**15–25**	**26–35**	**36–45**	**46–55**	**> 55**	**Missing**			
	N	278	75	11	19	5	1			
	%	71.5	19.3	2.8	4.9	1.3	0.3			
Weight		**≤ 50**	**51–60**	**61–70**	**71–80**	**> 80**	**Missing**			
	N	20	57	108	103	86	15			
	%	5.1	14.7	27.8	26.5	22.1	3.9			
Height		**≤ 160**	**161–170**	**171–180**	**181–190**	**> 191**	**Missing**			
	N	20	95	116	117	37	4			
	%	5.1	24.4	29.8	30.1	9.5	1.0			
Categorical nationality		**Tropical wet**	**Tropical seasonal**	**Arid**	**Humid subtropical**	**Oceanic**	**Mediterranean**	**Humid continental**	**Subarctic**	**Missing**
	N	12	6	1	3	322	13	24	5	3
	%	3.1	1.5	0.3	0.8	82.8	3.6	6.2	1.3	0.8
Present activity level		**Reclining**	**Seat quiet**	**Standing relaxed**	**Light activity**	**Medium activity**	**High activity**			
	N	26	281	39	33	9	1			
	%	6.7	72.2	10.0	8.5	2.3	0.3			
Clothing		**Shorts**	**Casual clothing**	**Light summer cloths**	**Street suit**	**Suit and cotton coat**	**Winter suit and coat**	**Others**		
	N	42	221	105	7	4	1	9		
	%	10.8	56.8	27.0	1.8	1.0	0.3	2.3		

Table 5.3 shows the result of the Spearman Correlation test between TSV, HSV, WSV and TCV. Only WSV had significant influence on TSV with a correlation coefficient of -0.173. This reveals that TSV tended to decrease with the increase of WSV. Furthermore, TCV did not show a significant relationship with TSV, HSV and WSV. When comparing the distribution of the percentage of TSV, HSV and WSV with TCV (see Figure 5.2), people were more stringent on thermal sensation than on comfort perception. In general, around 95% of all respondents expressed that they felt 'comfortable' with all levels of comfort contained, whereas only 4% of the respondents felt generally 'uncomfortable' and 1% voted 'neutral' (See Figure 5.2).

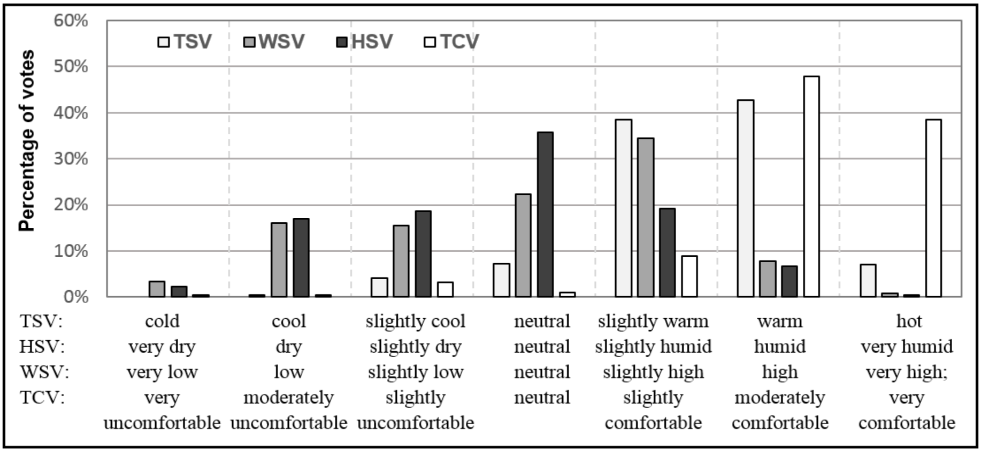


Figure 5.2 Distribution of the percentage of the thermal (TSV), humidity (HSV), and wind speed (WSV) sensation votes and the thermal comfort vote (TCV).

Table 5.3 Correlations analysis among thermal responses votes.

		TSV	HSV	WSV	TCV
TSV	Correlation Coefficient	1	-.019	-.173 [a]	.056
	Sig. (2-tailed)		.705	.001	.276
	N	389	389	389	386
HSV	Correlation Coefficient	-.019	1	.020	-.020
	Sig. (2-tailed)	.705		.689	.689
	N	389	389	389	386
WSV	Correlation Coefficient	-.173 [a]	.020	1	.013
	Sig. (2-tailed)	.001	.689		.802
	N	389	389	389	386
TCV	Correlation Coefficient	.056	-.020	.013	1
	Sig. (2-tailed)	.276	.689	.802	
	N	386	386	386	386

[a] *Correlation is significant at the 0.05 level (2-tailed).*

5.3.3 Neutral operative temperature

As mentioned above, the PhET value derived from the RayMan model was converted into the adaptive PhET values for warm period. We found that the adaptive PhET was mainly scored in the warm category (80%) with the highest percentage of 23% at 'hot' thermal sensation (+3). 14% of the PhET values was scored as 'neutral' sensation. The ratio of PhET in the cool category was very small, with <1% at 'slightly cool'. In terms of outdoor operative temperatures, the average T_{op} during the survey days ranged from approximately 30.5 ℃ on May 22nd to 40.1 ℃ on June 5th.

PhET and T_{op} were divided into a total of 33 and 31 bins with an increment of 1 ℃ and 0.5 ℃, then MTSV was calculated for the corresponding bin. Adaptive PhET was linearly regressed with MTSV (with 1 ℃ PhET interval) to understand how thermal sensation varied with thermal comfort based on the energy balance of the human body. In addition, linear regression was also applied to determine the strength of the relationship between MTSV and T_{op}. Figure 5.3 shows the scatter diagrams of MTSV versus PhET and T_{op}, with best-fitted lines. The simple correlation equations with 95% confidence limits are expressed as:

$$MTSV = 0.058PhET - 0.696\ (R^2 = 0.68, p < .0005) \qquad \text{(Equation 5.3)}$$

$$MTSV = 0.120Top - 2.659\ (R^2 = 0.82, p < .0005) \qquad \text{(Equation 5.4)}$$

The values of the t-statistic on the coefficient of the two linear regressions were respectively 8.224 and 11.692, and their significance level were both less than 0.0005 (Figure 5.3), indicating that the variability explained by the models are robust. From the above fitted Equation 5.3, we calculated that when PhET was equal to 24.5 (neutral sensation), MTSV from the survey was 0.725 (between 'neutral' and 'slightly warm'). Hence, people's subjective thermal sensation was in agreement with the estimated thermal comfort. The neutrality was derived by solving the Equation 5.4 with MTSV equals 0, the neutral operative temperature was then calculated to be 22.2 ℃.

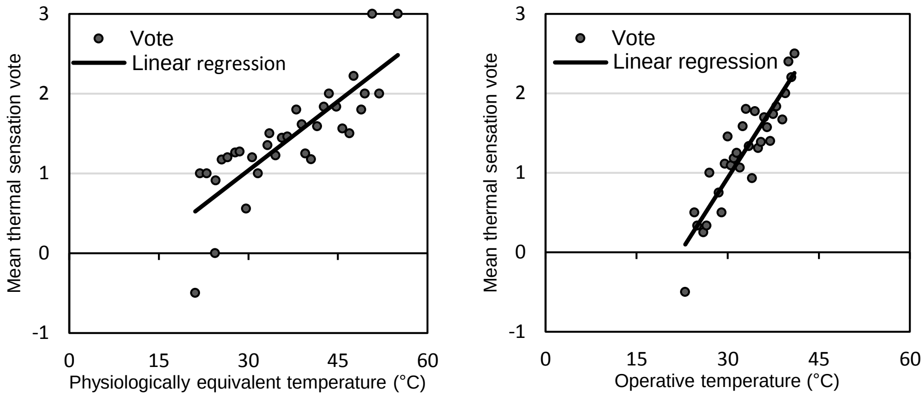


Figure 5.3 Correlation between adaptive physiologically equivalent temperature (PhET) and operative temperature (T_{op}) versus mean thermal sensation vote (MTSV).

5.3.4 Preferred temperature

Although the distribution of people's TSV revealed their perception to some extent for their current thermal comfort, the current thermal conditions may not yet reach their actual preference. Hence, people's TPV of 'warmer' or 'cooler' temperatures and the preferred temperature should also be used to define their thermal comfort perception. TPV was grouped into 31 bins for each 0.5 ℃ T_{op} intervals, and fitted within the probit models for 'warmer' and 'cooler' temperature votes against T_{op}. Figure 5.4 depicts the estimated probability values and area between upper and lower limits (95% confidence interval) for the preference to 'warmer' and 'cooler' temperatures versus T_{op}. The fits of both warmer and cooler models were good (warmer: $\chi^2 = 47.033,\ df = 29,\ p = 0.018;$ cooler: $\chi^2 = 53.752,\ df = 29,$ $p = 0.003$). The point at which both models intersect, was assumed as the preferred temperature. This was calculated to be 35.7 ℃ with a range between 34.1–37.8 ℃. Compared to the neutral operative temperature (22.2 ℃), this means an increase by more than 13.5 ℃. This implies that the respondents of this study preferred much higher temperatures than the neutral operative temperature in which they already felt comfortable (this is discussed in Section 5.4).

Figure 5.5 shows the frequencies of respondents' preferred temperature by different TSV. Generally, when TSV moves from 'cool' toward 'hot', the frequencies of the preferred 'warmer' temperatures declined, whereas 'cooler' preference increased. However, even at warm TSV (including ‘slightly warm’ and ‘warm’), considerable numbers of respondents still preferred a higher temperature (including ‘a bit warmer’ and ‘much warmer’).

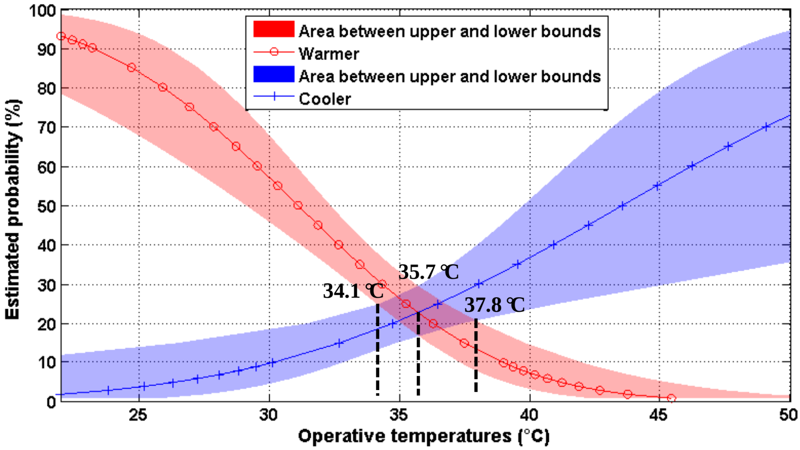


Figure 5.4 Preferred temperature based on probit analysis for ‘warmer’ and ‘cooler’ temperature votes against operative temperatures (T_{op}).
Estimated probability in y-axis stands for percentage of respondents preferring ‘warmer’ or ‘cooler’.

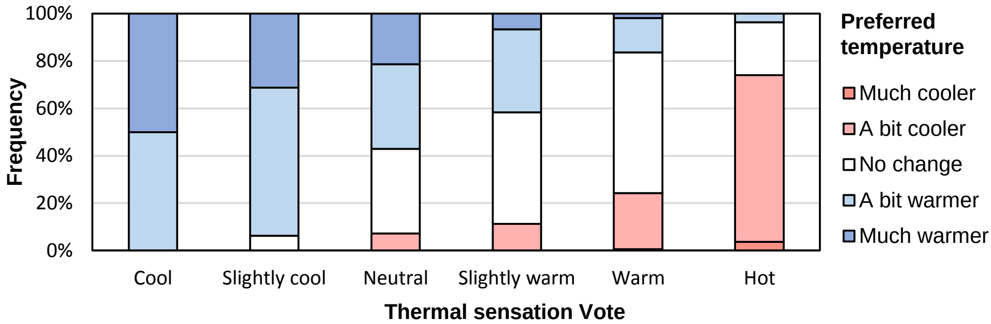


Figure 5.5 The frequencies of respondents’ preferred temperature by the thermal sensation vote (TSV).

5.3.5 Thermal adaptation

Since TSV from the survey was not normally distributed, the non-parameter Kruskal-Wallis H Test was applied to evaluate the difference between the variables. The results are described for the following five aspects:

Behavioural adjustment

The respondents were asked to choose the multiple adaptive actions that they prefer to take if they feel too hot or too cold. 'Move to a shaded place' was most preferred by respondents to deal with hot temperatures (48%). Other favoured adaptive actions were 'get more to drink' and 'reduce clothing' with 37% and 42% respectively. 'Open umbrella/wear hat' and 'nothing/go away' only occupied little percentages of 1% and 4%. These percentages of preferred actions indicate that moving to shaded areas in outdoor spaces were more popular than using personal shading equipment or apparel. Hence, the shade of trees in green spaces is preferred by most people to overcome their thermal discomfort.

Purpose of coming to the green space

The response to the open question on the respondent's motivation to come to the survey area was grouped into seven categories (environment, weather/sunshine, study/work, relaxation/rest, transition, eat/drink and others). The majority of the respondents (28%) visited the green space because of the nice weather/sunshine, whereas only few people (6%) came to enjoy the environment. The Kruskal-Wallis H test showed that TSV was not significantly different ($p = .291$) among the various purposes, indicating the reason for coming may not significantly affect thermal sensation.

Visiting frequency and exposure time

About 44% of the respondents rarely or for the first time visited this green space, and 55% of the respondents stayed more than 15 minutes. The results of the Kruskal-Wallis H test showed that the visiting frequency did not lead to significant differences in TSV ($p = .242$), whereas TSV was statistically different for respondents with different exposure time ($p = .012$). In general, TSV does not depend on the visiting frequency. Although the exposure time was a significant factor in explaining the TSV, the average TSV in the category of more than one hour was significantly higher than in the other four categories (less than 10 minutes, 10–15 minutes, 15–20 minutes or 20–60 minutes). This indicates longer an exposure time did not help people adapt to the hot conditions in this study.

Previous thermal environment and activity

About 41% of respondents changed their environment from indoor to outdoor within 15–20 minutes before filling out the questionnaire. Based on the Kruskal-Wallis H test, the difference in TSV between either staying outdoor or indoor in the last 15–20 minutes was significant ($p = .003$). Figure 5.6 shows the percentage distributions of the respondents who stayed outdoor and indoor in the last 15–20 minutes at a given TSV. The respondents, who had been in outdoor condition before the survey, tended to choose a higher TSV compared to those who had been indoor. In addition, the Kruskal-Wallis H test showed that respondents' previous activity level led to significant differences in TSV ($p = .031$). The average TSV was 1.52, 1.45, 1.20 and 1.08 (on a scale of 0 'neutral' to 2 'slightly warm') for resting, very light activity, light activity and medium activity respectively. In other words, a lower previous activity level resulted in higher average TSV. We also found that people, who were previously resting, stayed longer in the green space, while those, who were previously active, had stayed shorter. Hence, the differences in average TSV could be a result of synergism between previous activity and exposure time.

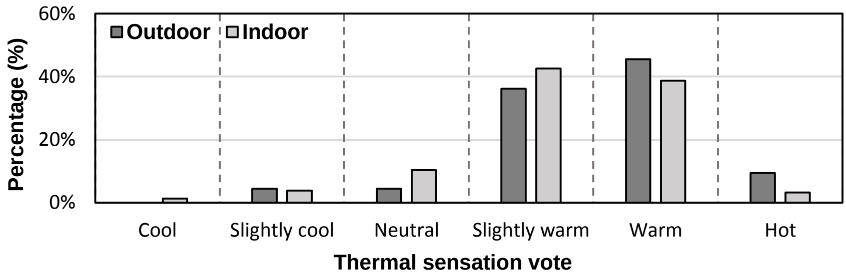


Figure 5.6 Comparison upon the percentage of thermal sensation vote (TSV) by the respondents who stayed outdoor and indoor in the last 15-20 minutes.

Thermal history

As mentioned earlier, people's thermal history could affect their expectations of thermal conditions in the survey area. The Kruskal-Wallis H test was first performed to evaluate the difference of TSV by the respondents from different regions with various types of climate. We found that TSV was statistically different ($p = .041$) for respondents with a different thermal history. This suggests that people's thermal history did significantly affect their thermal sensation and expectation in outdoor spaces. The average TSV of the respondents from tropical countries was the lowest (0.8, standard deviation (SD) = 1.1), while respondents from subarctic countries showed the highest average TSV (1.8, SD = 0.8). Although the climate in the home country did not significantly affect respondents' preferred temperature ($p > .05$), we found that respondents from tropical regions generally preferred 'cooler' temperatures, while those from temperate regions preferred 'warmer' temperatures.

Furthermore, the respondents were also asked how long they have been in The Netherlands. The statistical test results showed that TSV was not significantly influenced by the residence time in The Netherlands, with $p = .776$.

5.4 Discussion

5.4.1 Correlation between thermal responses votes

The result of the Spearman Correlation test confirmed the significant effect of WSV on TSV with a correlation coefficient of -0.173. The finding was generally in accordance with a study by Yang et al. (2013) in which the increase of WSV significantly decreased TSV with a correlation coefficient of -0.206. No significant relationship between TSV and HSV was found in our study. This finding contrasts with Yang et al. (2013), who showed that HSV had a significant effect on TSV (but with a very small correlation coefficient of -0.094). In fact, the range of RH in our study (29%–56%) was smaller than that was reported by Yang et al. (2013) (48%–91%) and the maximum RH was also much smaller. Although respondents subjectively voted HSV as 'dry' and 'humid', the absolute RH value was too low to significantly influence their TSV.

Furthermore, TCV did not show a significant relationship with TSV, HSV and WSV. People were more stringent on thermal sensation than on comfort perception, since 95% of the respondents expressed that they felt 'comfortable', but only 7%, 22% and 36% of the respondents voted 'neutral' for thermal, humidity and wind speed sensations, respectively. This indicates that they preferred a change in thermal condition, but were satisfied with the ambient environment in the green space. Therefore, it appears that people's assessment of their comfort is not only based on the current thermal condition in green spaces. Other environmental and non-physical factors, such as natural view, quiet environment and emotional condition, also affect people's comfort assessment (Feriadi and Wong 2004).

5.4.2 Neutral operative and preferred temperature

The neutral operative temperature and preferred temperature were assessed using linear regression and probit models based on the data from the survey (TSV and TPV) and corresponding measurements (T_{op}). The outcome of the analysis indicated that the neutral operative temperature of 22.2 ℃ had been interpreted by respondents as an acceptable temperature. This result is generally in line with previous studies carried out in other temperate European regions which reported a neutral operative temperature of approximately 21.5 ℃ (e.g. Nikolopoulou and Lykoudis 2006). Our neutral operative temperature is lower than those reported by studies in tropical regions: 26.5–27.9 ℃ in Taiwan (Hwang et al. 2010) and 28.7 ℃ in Singapore (Yang et al. 2013). Interestingly, based on our analysis, the respondents subjectively preferred a much higher operative temperature (35.7 ℃, ranging 34.1–37.8 ℃ in its 95% confidence interval) compared to their neutral operative temperature. This preferred temperature strongly differed from the study of Yang et al. (2013), who reported a preferred temperature of 26.5 ℃ in a tropical area in Singapore. They concluded that people in hot and humid climates dislike to describe their preferred state as ‘warm’ because that word implies an undesirable state. This conclusion could explain the extremely high preferred temperature derived in this study. Most respondents come from temperate regions with a relatively cool climate. These respondents, who rated their current thermal condition as ‘slightly warm’, still preferred ‘a bit warmer’ (35%) and ‘much warmer’ (7%). This probably influenced the result of the probit analysis. We therefore conclude that people from temperate regions instinctively like to describe their preferred state as ‘warmer’ instead of ‘cooler’, even if they already feel warm.

5.4.3 Thermal adaptation

The Kruskal-Wallis H test of subjective TSV and thermal adaptation confirms the effect of exposure time, previous thermal environment and activity, and thermal history on thermal comfort. People, who are engaged in high activities 15 to 20 minutes before the survey, expressed a cooler thermal sensation when filling the questionnaire than those with lower or no activity. A plausible explanation is that people with a relatively high previous activity might feel less hot due to their warmer body temperature. On the other hand, we found that people with a lower previous activity level had longer exposure time in the green space, resulting in non-causality between previous activity and TSV. Additionally, people from hot regions generally expressed a relatively cooler thermal sensation (‘slightly warm’) than those from cold regions who chose relatively warmer thermal sensation (‘warm’) under similar conditions. That people who live in hot regions are more tolerant to hot conditions would be a logical explanation. Although the climate in the respondents’ home country did not significantly affect their preferred temperature, respondents from tropical regions commonly preferred ‘cooler’ temperatures, while those from temperate regions preferred ‘warmer’ temperatures. Thus, people’s thermal experience and history influenced their preferred state and led them to prefer warmer or cooler temperatures.

Theoretically, a longer exposure time should allow people to better adapt to hot conditions and enhance their tolerance to these conditions (Yang et al. 2013). This phenomenon was, however, not found in this study as our results clearly indicate that the average TSV for the longest exposure time category (i.e. more than one hour) was higher than for the other four categories.

5.5 Conclusions

This study analysed people’s thermal comfort perception and preference in a local area, specified the combined effects between thermal environmental and personal factors on people’s thermal comfort, and established a quantitative relationship between the combined use of a social survey and field measurements to determine the role of UGI in microclimate regulation.

The data collected from surveys and measurements at the Zernike Campus of University of Groningen provide important information on how people perceive thermal comfort in local green spaces. Samples were randomly drawn from a group consisting of many different nationalities. This allowed us to examine the influence of people’s thermal history on their thermal perception and gave adequate statistical confidence to our assertions. We concluded that non-physical environmental and subjective factors (e.g. natural view, quiet environment, and emotional background) played more important roles in the comfort perception than the actual thermal conditions.

The subjective thermal sensation from the survey was in agreement with the estimated thermal comfort based on the measurements, and the comfort temperature was estimated to be 22.2 ℃. However, we found a considerably higher preferred temperature (i.e. 35.7 ℃) especially expressed by people from oceanic climates. The Kruskal-Wallis H test showed the effect of the previous thermal environment and activity experienced immediately prior to the survey and the influence of long-term thermal history on human thermal comfort. Including people's thermal preferences and adaptation factors is, therefore, necessary when interpreting results from human thermal comfort research in urban green spaces.

The combined use of a social survey and simultaneous measurements of weather conditions is essential to understand and quantify the combined effects of objective thermal environmental factors and subjective personal perception on people's thermal comfort. By providing evidence for the impacts of both objective and subjective factors on human thermal comfort, the relationship between UGI, microclimate and thermal comfort that was specified in this study, can assist urban planning to make better use of green spaces for microclimate regulation.

Images taken at four survey locations in the Zernike Campus, Groningen (latitude: 53 º24’ 0’’ N, longitude of 6º 53’ 00’’ E) on 5th and 12th June 2015.

CHAPTER 6

Synthesis, discussion and conclusion

6.1 Introduction

Rapid urbanization often leads to degradation of urban environmental quality. More awareness of this problem has led to increased interest in developing more sustainable urbanization paths. The concepts of 'Urban Green Infrastructure (UGI)' and 'Ecosystem Services (ESs)' have the potential to guide urban development in a more sustainable direction by linking conservation and restoration of urban ecosystems (parks, lakes etc.) with public health (Sandström 2002). Understanding and quantifying the impacts of different types of UGI on urban environmental quality and human comfort are, therefore, vital to achieve more sustainable urban development.

As described in Chapter 1, UGI affects human urban habitats mainly via regulating microclimate, air quality, sonic environment and aesthetic information (Wang et al. 2014). My study focused on microclimate regulation and its effects on human thermal comfort. Previous studies typically used models to simulate UGI's effects on local microclimate (e.g. Shahidan et al. 2012, Égerházi et al. 2013, Malys et al. 2014), or conducted field measurements in several representative but unconnected landscapes (e.g. Huang et al. 2008, Shahidan et al. 2012, Middel et al. 2014). The relationship between UGI and local microclimate is, however, complex and difficult to quantify using only a single modelling approach.

The core objective of my research therefore was to identify and quantify the influence of UGI on microclimate and human comfort in a local area by combining field measurements, modelling and social surveys. Four research questions were formulated to address this research objective:

RQ1. What are the ESs of UGI that influence human urban habitats?

RQ2. What factors influence the capacity of UGI to regulate microclimate?

RQ3. How can the effect of UGI on local microclimate and human thermal comfort be measured?

RQ4. How do people perceive thermal comfort in small urban green areas locally and how is this related to UGI planning and management?

For my thesis, I conducted an extensive literature review on the effects of UGI on human habitats and human comfort in urban areas, including different disciplines (e.g. ecology, environmental economics and epidemiology). I obtained microclimatic data from field measurements and modelling, and performed surveys of people's perception of the ambient thermal environment. The results provide new insights into the effects of UGI on human urban habitats and can be used to improve the design of UGI for enhancing urban microclimate and human thermal comfort.

This last chapter synthesises and reflects on my findings. The answers to the four RQs are presented in Sections 6.2, 6.3, 6.4 and 6.5 respectively. Finally, Section 6.6 discusses the strengths and limitations of my methodology, provides specific recommendations for future research and presents the key conclusions of my PhD study.

6.2 Influence of UGI's ecosystem services on human urban habitats

RQ1 aims to establish the relationship between UGI, thermal environmental condition, and human health and comfort. Based on a review of 148 studies, this relationship is described in detail in Chapter 2 and illustrated below in Figure 6.1. In my review I focussed on the regulation of microclimate, air quality, noise and aesthetics. The processes involved in the delivery of these four main services upon which human health and comfort depend are briefly summarized here.

First, the relevant ecosystem functions involved in **microclimate regulation** found in the literature include evapotranspiration, wind shielding and shading. These functions regulate the urban microclimate by blocking solar radiation and heat flow, altering temperature, adding moisture and lowering wind speed. Lowered incoming solar radiation and temperature reduce the solar exposure and thus moderate the urban thermal environment. However, reduced wind speed possibly impedes heat dissipation from sunlit surfaces and reduces the effectiveness of opening windows to regulate indoor environments. Hence, the influence of UGI on human thermal comfort could be both positive and negative depending on the situation.

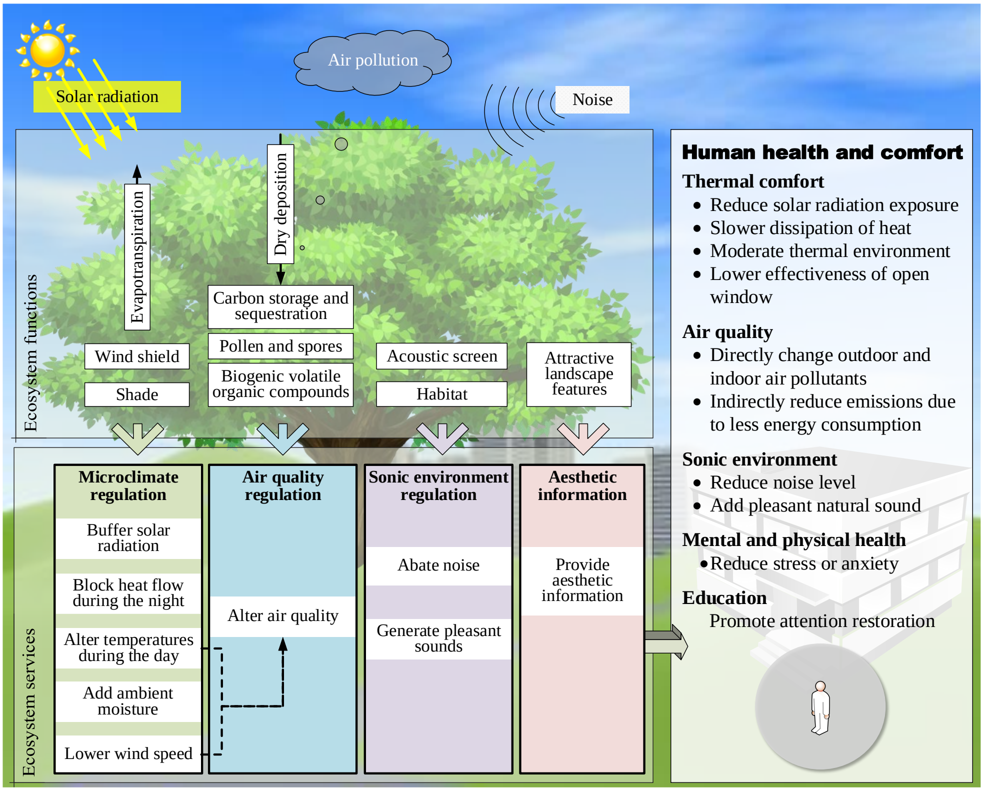


Figure 6.1 Overview of ESs of UGI in human urban habitats and its effects on human health and comfort.
Dash lines in ESs box correspond to UGI's indirect effects on air quality via regulating microclimate. See Chapter 2 for a detailed description.

Second, my review showed that UGI alters **air quality** mainly through biophysical processes, such as dry deposition, carbon storage and sequestration, release of pollen and spores, and emission of biogenic volatile organic compounds. In addition, UGI also has a potential indirect effect on air quality through microclimate regulation. For instance, lowered air temperature and air flow caused by UGI could reduce biogenic volatile organic compounds and carbon emission from power plants and influence pollutant dispersion.

Third, the foliage of UGI acts as an acoustic screen that can absorb the energy of sound waves and thereby contributes to **noise abatement**. In addition, UGI also generates pleasant sounds in the canopy. For instance, the sound of rustling leaves is considered as being pleasant for human beings. Furthermore, UGI provides habitats for diverse bird communities, and bird songs directly impact the quality of the soundscape.

Finally, scenic green landscapes in urban areas provide **aesthetic information** and other amenities to people, positively affecting both people's mental and physical health. Many studies demonstrated that views of green landscapes help people to cope with stress or anxiety and improve their attention span.

This systematic review of UGI's ESs clarifies the linkages between UGI and human comfort (see Figure 6.2) and provides guidance for measuring and modelling the role of UGI in supporting human health and comfort. The reviewed literature covers a broad range of spatial scales (from single to several trees or buildings, to one or several countries) and temporal scales (from days to years) (see Table 6.1). UGI's microclimate regulation was well studied especially at the scale of single and several trees or buildings (27 studies) and at the short time scale (24 studies) by both field measurements and modelling studies. However, information from the national and regional/local scale was fragmented and incomplete, and was mainly derived from modelling studies.

Table 6.1 The number of studies exploring four main ESs provided by UGI at different spatial and temporal scales.

ESs	METHODS	SPATIAL SCALE			TEMPORAL SCALE		
		National	Regional /local	Single/several tree(s) or building(s)	Day(s)	Month(s)	Year(s)
Microclimate	Measurements	0	2	19	13	8	0
	Modelling	4	8	8	11	2	7
Air quality	Measurements	0	9	1	0	2	8
	Modelling	9	14	0	3	3	17
Sonic environment	Measurements	0	3	2	5	0	0
	Modelling	1	1	0	2	0	0
Aesthetic information	Measurements	0	0	3	3	0	0
	Modelling	2	0	1	2	0	1

My review suggests that better integration of field measurements and modelling is needed when investigating UGI's effects on local microclimate and human comfort. The review also shows that information on UGI's economic effects is important to analyse its actual and potential role in reducing health expenditures (Tzoulas et al. 2007) and energy consumption (Saadatian et al. 2013). I assessed the economic effects of four main ESs using various methods (avoided cost, replacement cost contingent valuation and hedonic pricing). The results showed that the monetary annual value of an average tree for climate regulation is estimated to be worth up to US$250. For air quality regulation, monetary annual value ranges from US$0.1 to US$0.6 per m^2 tree cover, and for noise reduction and attractive landscape of urban green (e.g. parks and forests) up to US$20 and US$25, respectively (see Chapter 2).

6.3 Main factors influencing UGI's capacity to regulate microclimate

Based on my extensive literature review (Chapter 2 and Section 6.1), Table 6.2 lists the main factors and sub-factors that play important roles in microclimate regulation and alter the performance of four main ESs provided by UGI. The role of these factors is usually quantified through modelling studies with limited empirical support. Although the models are able to calculate many microclimatic parameters in detail, empirical evidence from field measurements is needed to validate their simulations. I therefore analysed the relative importance of these factors by combining field measurements with modelling (i.e. with the ENVI-met and RayMan models).

In Chapters 3 and 4, I analysed the role of **local morphology** (layout and geometry), **geographical conditions** (surface properties and weather conditions) and **vegetation characteristics** (vegetation abundance, plant area index (PAI) or leaf area index (LAI) and species composition) in microclimate regulation. The results are summarized below:

(1) **Local morphology**. Using the ENVI-met numerical model, I compared air temperature at 81 equidistant locations under current conditions (i.e. 5% total tree cover) with no-tree condition (see Chapter 3). The simulations showed significant spatial variations of trees' thermal effects due to the local morphology (i.e. layout and geometry) of the study area. During the summer, the spatial difference of air temperature reduction by trees was up to 1.5 ℃ on clear days and 0.3 ℃ on cloudy days. During the winter, these differences were smaller but still significant with a maximum of 0.5 ℃ on clear days and 0.1 ℃ on cloudy days. The effects of trees on the urban microclimate and human thermal comfort are thus significant and are strongly influenced by local morphology, even in close geographical proximity.

(2) **Geographical condition**. In Chapter 3, I discussed the effect of weather using a cluster methodology to characterize the sky conditions. This cluster method involves three features (clearness index, fluctuation of solar radiation, and maximum air temperature)

and was developed to classify weather conditions during field observation. I found that the cooling effect of trees on relatively clear and hot summer days was about twice as high as on cloudy and cold days (Chapters 3 and 4). This finding agrees with an earlier study by Morakinyo et al. (2013), showing that the influence of trees on outdoor air temperatures decreased with increasing cloudiness. My results also showed that winter weather conditions did not cause a notable change in the evergreen trees' performance to regulate microclimate (Chapter 3). The variation of incoming solar radiation under different weather conditions is likely too small because of the winter's low solar intensity.

(3) **Vegetation characteristics**. Chapter 4 describes the effects of vegetation characteristics on microclimate regulation by UGI. The model-based study by Shahidan et al. (2012) showed that the cooling effect is positively correlated to the quantity of UGI with a correlation coefficient of 0.0078–0.0091. My study quantified the cooling capabilities of three types of UGI: a multiple tree grove, a single deciduous tree, and a group of street trees. These three UGI-types reduced the daily average air temperature by 0.9 ℃, 0.8 ℃ and 0.6 ℃ respectively. The grove with the most trees yielded the best cooling capability compared to a single tree (above a green surface). However, a single tree above a green surface had a relatively stronger cooling effect than a group of street trees surrounded by asphalt paved surface. This is probably a consequence of the low-albedo of asphalt paved surface that offsets the temperature reductions by street trees (Shahidan et al. 2012).

Table 6.2 Main factors influencing microclimate regulation by UGI.
(See Chapter 2 for a detailed description.)

Main factors	Sub-factors
Local morphology	Configuration of building and vegetation Orientation of building and vegetation
Geographical conditions	Ground property (e.g. soil types, surface mulching) Local climate and weather condition
Vegetation characteristics	Vegetation quality and quantity PAI or LAI and Structure (height, width and crown property) Vegetation species (especially for deciduous or evergreen plants)
Building characteristics	Façade property (e.g. material, isolation, construction) Air ventilation and infiltration rate

To investigate the effects of densely vegetated areas on microclimate, PAI was quantified by measuring the gap fraction derived from upward-oriented fisheye photographs, instead of quantifying LAI (Chapter 4). This was done because the effect of stems and branch areas on the gap fraction overestimates LAI for these photographs. Estimating the PAI rather than LAI is, therefore, more suited. Such photographs must be taken under diffuse light conditions (Zhao et al. 2012). Unfortunately, Dutch daily weather changes quickly. Although I selected cloudy days to take these images, abrupt changes in solar intensity were inevitable and this probably caused some deviation between actual and measured values. Through linear regression analysis, I established that increasing PAI could considerably reduce mean radiant temperature (gradient coefficient = 2.054). Although PAI's effect on air temperature also occurred, the coefficient of this relationship (i.e. 0.059 ℃) was much smaller than the accuracy of my measurements (±0.5 ℃), indicating that this relationship is not fully reliable. Figure 6.2 illustrates the factors, parameters, methods and tools used to investigate the effects of UGI on microclimate regulation and thermal comfort.

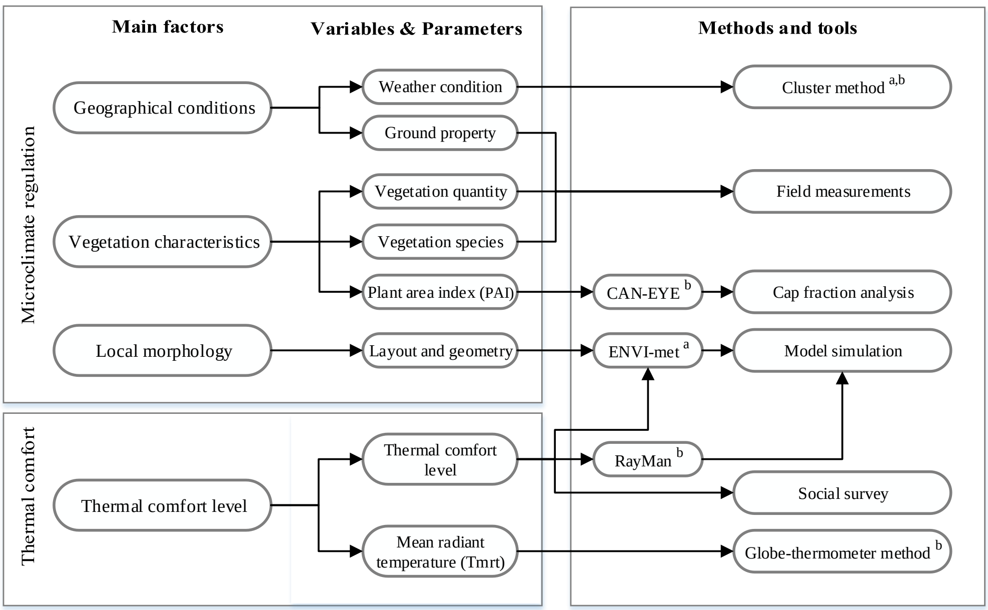


Figure 6.2 Overview of factors, parameters, methods and tools used to investigate the effects of Urban Green Infrastructure (UGI) on microclimate regulation and thermal comfort.
[a] Chapter 3 contains a detailed description; [b] Chapter 4 contains a detailed description.

6.4 Effect of UGI on microclimate and thermal comfort

To determine how strongly UGI affects the urban microclimate and human thermal comfort, I conducted field measurements of local microclimate in a small urban area in Assen, The Netherlands (see Figure 1.4).

(1) For the **local microclimate**, tree-shaded areas lowered average air temperature by approximately 1.0 ℃ at daytime during full leaf season compared to the unshaded areas (Chapters 3 and 4). This is in line with other studies (e.g. McPherson et al. 1989, Taha et al. 1991, Park et al. 2012), which reported a 0.9–2.0 ℃ average air temperature reduction within the canopy. Moreover, the peak temperature difference was observed to be 3.5 ℃ in my study on a hot sunny day (Chapter 4). The average relative humidity of shaded areas exceeded that of unshaded areas by 3% (Chapter 4). In addition, I found that the tree canopy reduced the daily air temperature change rate (a variable that changes over a day) and range (difference between the daily minimum and maximum values) by respectively 0.04 and 2.4 ℃ during daytime (Chapter 3). These reductions are due to the fact that the tree canopy protects the area from direct sunlight and reduces heat exchange. Literature data indicated that evergreen trees also reduce the air temperature in the winter which can potentially offset UGI’s energy-balance benefits (e.g. Akbari 2002, Mcpherson 1988). My measurements, which are consistent with the findings of these studies, showed that evergreen trees slightly reduced winter air temperature by about 0.5 ℃ (Chapter 3). At winter night, the change rate and the range of air temperature in shaded areas should be theoretically lower than that in unshaded areas, as evergreen trees can prevent vertical heat transfer and reduce the heat exchange between the areas below and above the canopy (Akbari 2002, Heisler and Grant 2000, Mcpherson 1988). This was not confirmed by my measurements (Chapters 3 and 4). A plausible explanation is that wind velocity during the winter observation periods was too high. This high wind velocity that was accompanied by high heat convection affected the temperature distribution. In short, evergreen trees lowered winter temperatures, while their prevention of heat loss at night was negligible in my study. Hence, deciduous trees that do not lower winter temperature have more benefits for human comfort compared to evergreen trees.

(2) To determine the effect on **human thermal comfort**, I simulated the predicted mean vote (PMV) and physiologically equivalent temperature (PhET) values with the ENVI-met (Chapter 3) and RayMan models (Chapter 4). The changes in the indices that resulted from the model simulations, showed that UGI enhanced summer thermal comfort locally by increasing 'comfortable' thermal condition by 16% and decreasing the condition of being 'hot' by 6% (Chapters 3 and 4). Although these thermal comfort indices integrate many environmental and personal variables (Fanger 1972, Mayer and Höppe 1987), human comfort levels highly depend on perceptions and preferences in a particular study context (Nikolopoulou et al. 2001, Lin 2009). Both social surveys and physical measurements are, therefore, necessary to investigate the influence of different physiological and psychological factors.

6.5 Subjective thermal perception and preference

An individual person is not a passive recipient of the ambient thermal environment and has a preferred temperature. Besides physical factors, behavioural factors (e.g. behavioural adjustment or previous activity) and psychological factors (e.g. experience based on 'thermal history' or expectations) also play an important role in the assessment of thermal environments (De Dear and Brager 1998b, Nikolopoulou et al. 2001, Lin 2009, Yang et al. 2013). To explore people's perception and preference of microclimatic conditions in green spaces during hot summer days and to elucidate the impact of thermal adaptation on thermal sensation, mobile physical measurements and a questionnaire survey were performed in five green spaces at the Zernike Campus of the Dutch University of Groningen on five warm and cloudless days (Chapter 5).

Based on the responses to the questionnaire about the thermal perception and the results from mobile measurements, the neutral operative temperature (i.e. comfort temperature) and the stated preferred temperature were derived from a linear regression and probit model, being 22.2 ℃ and 35.7 ℃ respectively. Comparing these findings with literature, I found that the neutral operative temperature of my study is in agreement with the results of, for example, Nikolopoulou and Lykoudis (2006) in other European temperate regions (approximately 21.5 ℃ on average) but lower than those reported by several studies in tropical regions (26.5–27.9 ℃ in Taiwan, Hwang et al. 2010; and 28.7 ℃ in Singapore, Yang et al. 2013). My estimated stated preferred temperature, however, was found to be much higher than that in Yang et al. (2013) in a tropical country – Singapore (26.5 ℃). I also found that around 42% of the respondents who felt ‘slightly warm’ under the current conditions during the survey, still preferred ‘warmer’ (i.e. higher) temperatures. This can be explained by the fact that most respondents in my study mainly stem from temperate regions. They have a natural tendency to describe their preferred state as ‘warmer’ even when feeling ‘warm’ already, since ‘cooler’ implies generally an emotionally undesirable state. This phenomenon was also found from tropical studies but in an opposite direction (Yang et al. 2013). They found that “people in hot and humid climates like to describe their preferred state as ‘cool’ because the word ‘warm’ implies an undesirable state”.

Although the effect of thermal adaptation has been discussed in many thermal comfort studies, behavioural adjustments are the main focus in most of these studies (e.g. Nikolopoulou and Lykoudis 2006, Lin 2009). My study explored the impacts of thermal adaptation, including both the effects of behavioural and psychological factors. I found that previous long-term thermal environment experiences (in short: thermal history) and physical activity shortly before the survey were the most significant factors in explaining the subjective TSV (by using the Kruskal-Wallis H test). People, who engaged in more intense physical activities during the last 15–20 minutes before they were surveyed, expressed a cooler thermal sensation when filling in the questionnaire than people who had been inactive. This is probably due to their higher body temperature and cooling effect of sweat evaporation of the first group. However, I also found that people who previously were active were in the green space for a shorter time. The differences of average TSV is likely also a result of synergism between previous activities and exposure time. Furthermore, people who originate from the world’s hotter regions expressed a cooler thermal sensation than people from temperate regions, even under the same weather conditions. This can be explained by the fact that people who normally live in hot regions, would be more tolerant to hotter conditions. In addition, I also observed that respondents from hot regions preferred ‘cooler’ temperatures, while those from temperate regions preferred ‘warmer’ temperatures. These findings strongly suggest that the design of UGI should take account of people’s thermal preferences (strongly affected by their ‘thermal history’) and adaptation possibilities, and will be different in different regions. Combining a social survey and simultaneous measurements of weather conditions, confirm the impacts of both objective and subjective factors on human thermal comfort. The relationship between UGI, microclimate and thermal comfort that was specified in this study can assist urban planning to make better use of green spaces.

6.6 Discussion and conclusions

6.6.1 Strengths and weaknesses of the methodology

The thermal effect of vegetation is well documented but its evidence is mainly based on modelling studies. However, no matter how complex the model is, model-simulations require empirical evidence for validation and trustworthy applications. Moreover, in the research field of urban ESs and human comfort, public perceptions and preferences are not yet sufficiently included. Therefore, the influence of UGI on human comfort should not be only modelled but also investigated through social surveys. An important strength and innovative aspect of my thesis is the combination of field measurements, modelling and social surveys.

Specific methods and tools were used to estimate the effects and relative contribution of the main factors influencing the capacity of UGI to regulate microclimate and thermal comfort (see Figure 6.2). For example, the ENVI-met model was used to simulate the spatial variations of trees' thermal effects in relation to the local morphology (Chapter 3); the RayMan model helped to estimate thermal comfort condition (Chapter 4); and CAN-EYE software was applied to analyse the PAI (Chapter 4). The utilisation of multiple tools in this thesis allows to investigate UGI's thermal effects in an integrated manner which enhances the necessary insights into the role of UGI in regulating urban microclimate.

With an integrated approach that combines model simulations, field measurements and social surveys, I was able to quantify the effects of UGI and demonstrate that urban microclimate and human thermal comfort vary significantly in close geographical proximity due to the presence of UGI. By combining objective physical measurements with people's subjective opinions related to UGI and thermal environments, my study contributes to the ongoing and increasing development of more human-oriented and localized urban design and planning.

Some weak points of my study were that data collection using wireless weather stations turned out to be problematic. The selection of the observation locations was limited by, among others, the range of the wireless signal, the power of the devices and close-by electrical interferences. Due to the limited accuracy of the used equipment, some findings in this thesis probably require further data or additional independent evidence to make them more robust. For instance, the coefficient of the relationship between PAI and air temperature was smaller than the measurement accuracy. This indicates that air temperature measurements with better resolution and accuracy are required. In addition, the survey study addressed people's perceptions and preferences but only five days could be selected due to the actual weather conditions in The Netherlands. The respondents were mainly active young people due to the selection of the university campus as the study area. This might reduce the reliability of the statistical outcomes.

6.6.2 Future perspectives and recommendations

This PhD project aimed to establish the quantitative relationship between UGI and outdoor microclimate. Originally, I planned to study the influence of UGI on indoor environments. The literature study presented in Chapter 2 shows that UGI can strongly affect indoor environments through both direct and indirect processes. However, quantifying this relationship is difficult and requires different data, such as the heat transfer coefficient of the building's façade, air ventilation and infiltration rates. Due to limited time, budget and suitable study locations, this part of my original research plan was not executed. However, since most people spend a substantial part of their life indoors, research on the influence of UGI on the indoor environment is important for human health and comfort. Additionally, building characteristics are one of the main factors influencing UGI's microclimate regulation but were not investigated because of the poor performance of ENVI-met V3 in building energy simulation. New or improved simulation models currently provide an opportunity to link UGI to the indoor thermal environment and to explore the effects of building characteristics on UGI's microclimate regulation. For example, the new version of ENVI-met (ENVI-met V4, http://www.model.envi-met/) can estimate the building energy balance and indoor temperature based on a building's properties and immediate outdoor thermal conditions.

To improve the social surveys aspect of my work, it is important to increase the number of survey days and include more respondents from different age groups and backgrounds. Ideally, surveys would be performed simultaneously in different green spaces and over longer time periods. This, however, requires much more effort in terms of human, material and financial resources.

The outdoor measurements can be improved by implementing automatized measurement networks. Including additional areas with more and different types of UGI is also recommended. A wireless sensor network of a hundred nodes is currently being established to measure outdoor air temperature and relative humidity at the Zernike Campus. These automated observation points cover several UGI types including gardens, parks, natural areas, playgrounds and green roofs. I intended to use this advanced sensor network for my PhD study but due to delays in its implementation the data only will become available at the end of 2015. With such fine-grained data from a clearly defined and described urban area, future studies will be able to capture more and better microclimatic information and lower the margin of error in the statistical analysis. This will certainly result in a better understanding of the role of different UGIs in microclimate regulation and human thermal comfort. Such a sensor network is also useful for designing green spaces by effectively highlighting the 'hot' and 'cold' spots and precisely navigating people to the most comfortable route or zone under different weather conditions.

6.6.3 Overall conclusion

My objective was to determine the effects of UGI on local microclimate and human thermal comfort. Although using UGI to reduce urban warming and enhance human comfort has been proposed by many studies, a comprehensive analysis of these effects was still lacking due to the complexity of urban ecosystems, the many environmental, physical and ecological processes involved, and the subjectivity of human perception on comforts. To achieve my objective, I therefore applied an integrated approach that combined model simulations, field measurements and social surveys. In my research, I succeeded in quantitatively analysing UGI's role in regulating local microclimate, examining the impacts of the main controlling factors and exploring the relative impact of various thermal adaptation factors on people's thermal comfort.

My comprehensive literature review showed that UGI regulates the local microclimate via altering temperature, adding moisture, buffering solar radiation, blocking heat flow and lowering wind speed. The results from my model simulations and field measurements revealed that local morphology (layout and geometry), geographical conditions (surface property and weather condition) and vegetation characteristics (vegetation quantity, PAI or LAI, and species) are the most important factors influencing UGI's performance to regulate microclimate. The quantitative analysis of these factors confirms the complexity and heterogeneity of urban ecosystems and highlights the need to perform urban studies locally. My field measurements showed that the local microclimate and human thermal comfort vary strongly spatially and temporally due to the presence of UGI. This suggests that adequate local field measurements are always required to model UGI's effects on microclimate and human comfort for a specific location. My social survey study highlighted the importance of non-physical factors on people's subjective perception of and preference for microclimate conditions, such as exposure time, the previous thermal environment and activity shortly before the survey, and their thermal history. Future UGI planning and management, therefore, should consider people's subjective thermal experiences and preferences to take full advantage of UGI to achieve the best possible thermal comfort, especially in view of increasing urbanization and ongoing climate change.

Cities are major contributors to greenhouse gas emissions, while urbanization causes changes in land-use. Both greenhouse gas emissions and land use change are the most important anthropogenic causes of climate change (Kalnay and Cai 2003). According to IPCC (2013), for example, global mean temperature will likely increase by more than 1.5 to 4.5 ℃ by the end of this century relative to the global mean temperature of the period 1850 to 1900. Although not all urban warming is necessarily a consequence of this anthropogenic climate change, urban temperatures will probably increase more compared to other regions in a warmer world. This temperature rise will aggravate environmental problems and further reduce urban human comfort. The results of my study show that UGI can effectively regulate local urban microclimate and enhance human comfort. My thesis provides an innovative approach to quantify UGI's effects on local microclimate and human thermal comfort. This integrated approach is essential to evaluate the influence of different types of UGIs on both physical microclimates and people's subjective thermal comfort. My findings contribute to better planning and management of UGI as an important instrument for sustainable urbanisation and climate change adaptation.

An example of 100 wireless sensor nodes equipped with air temperature and humidity sensors at the Zernike Campus, Groningen (latitude: 53 º24’ 0’’ N, longitude of 6º 53’ 00’’ E).

REFERENCES

Abdel-Ghany, A. M., Al-Helal, I. M., & Shady, M. R. (2013). Human Thermal Comfort and Heat Stress in an Outdoor Urban Arid Environment: A Case Study. *Advances in Meteorology*, *2013*, 1–7.

Akbari, H. (2002). Shade trees reduce building energy use and CO2 emissions from power plants. *Environmental Pollution*, *116*, 119–126.

Akbari, H., Kurn, D. M., Bretz, S. E., & Hanford, J. W. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings*, *25*, 139–148.

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, *70*, 295–310.

Akbari, H., & Taha, H. (1992). The impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities. *Energy*, *17*, 141–149.

Alberti, M., & Marzluff, J. M. (2004). Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. *Urban Ecosystems*, *7*, 241–265.

Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, *43*, 480–493.

ASHRAE. (1992). *Thermal environmental conditions for human occupancy*. *Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers*. Atlanta, ASHRAE Inc.

Babisch, W. (2005). Noise and Health. *Environmental Health Perspectives*, *113*, A14–A15.

Baik, J. J., Kim, J. J., & Fernando, H. J. S. (2003). A CFD model for simulating urban flow and dispersion. *Journal of Applied Meteorology and Climatology*, *42*, 1636–1648.

Baik, J.-J., Kwak, K.-H., Park, S.-B., & Ryu, Y.-H. (2012). Effects of building roof greening on air quality in street canyons. *Atmospheric Environment*, *61*, 48–55.

Barro, R., Regueiro, J., Llompart, M., & Garcia-Jares, C. (2009). Analysis of industrial contaminants in indoor air: part 1. Volatile organic compounds, carbonyl compounds, polycyclic aromatic hydrocarbons and polychlorinated biphenyls. *Journal of Chromatography. A*, *1216*, 540–566.

Baxter, L. K., Clougherty, J. E., Paciorek, C. J., Wright, R. J., & Levy, J. I. (2007). Predicting residential indoor concentrations of nitrogen dioxide, fine particulate matter, and elemental carbon using questionnaire and geographic information system based data. *Atmospheric Environment*, *41*, 6561–6571.

Bedford, T. (1936). *The warmth factor in comfort at work: A physiological study of heating and ventilation*. H. M. Stationery Office.

Benson, E. D., Hansen, J. L., Schwartz, A. L., & Smersh, G. T. (1998). Pricing Residential Amenities: The Value of a View. *Journal of Real Estate Finance and Economics*, *16*, 55–73.

Benson, F. B., Henderson, J. J., & Caldwell, D. E. (1972). *Indoor-Outdoor Air Pollution Relationship: A Literature Review*. Environmental Protection Agency, Research Triangle Park, NC. Office of Air Programs.

Berry, R., Livesley, S. J., & Aye, L. (2013). Tree canopy shade impacts on solar irradiance received by building walls and their surface temperature. *Building and Environment*, *69*, 91–100.

Bjørner, T. B. (2004). Combining socio-acoustic and contingent valuation surveys to value noise reduction. *Transportation Research Part D: Transport and Environment*, *9*, 341–356.

Blanusa, T., Vaz Monteiro, M. M., Fantozzi, F., Vysini, E., Li, Y., & Cameron, R. W. F. (2013). Alternatives to Sedum on green roofs: Can broad leaf perennial plants offer better "cooling service"? *Building and Environment*, *59*, 99–106.

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics*, *29*, 293–301.

Bonan, G. B. (2002). *Ecological climatology : concepts and applications*. Cambridge, U.K.: Cambridge University Press.

Bouvier-Brown, N. C., Schade, G. W., Misson, L., Lee, A., McKay, M., & Goldstein, A. H. (2012). Contributions of biogenic volatile organic compounds to net ecosystem carbon flux in a ponderosa pine plantation. *Atmospheric Environment*, *60*, 527–533.

Bréda, N. J. J. (2003). Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *Journal of Experimental Botany*, *54*, 2403–2417.

Brown, A. L., & Raghu, S. (1998). An overview of research on the effects of noise on animals. *Acoust. Aust.*, *26*, 63–68.

Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software 13*.

Campbell-Lendrum, D., & Corvalán, C. (2007). Climate change and developing-country cities: implications for environmental health and equity. *Journal of Urban Health : Bulletin of the New York Academy of Medicine*, *84*, 109–117.

Carver, A. D., Unger, D. R., & Parks, C. L. (2004). Modeling energy savings from urban shade trees: an assessment of the CITYgreen energy conservation module. *Environmental Management*, *34*, 650–655.

Castleton, H. F., Stovin, V., Beck, S. B. M., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, *42*, 1582–1591.

Chang, J., Ren, Y., Shi, Y., Zhu, Y., Ge, Y., Hong, S., … Fu, C. (2012). An inventory of biogenic volatile organic compounds for a subtropical urban–rural complex. *Atmospheric Environment*, *56*, 115–123.

Chen, L., & Ng, E. (2012). Outdoor thermal comfort and outdoor activities: A review of research in the past decade. *Cities*, *29*, 118–125.

Chen, W. Y., & Jim, C. Y. (2008). Assessment and Valuation of the Ecosystem Services Provided by Urban Forests. In M. M. Carreiro, Y. C. Song, & J. Wu (Eds.), *Ecology, Planning, and Management of Urban Forests: International Perspectives.* (pp. 53–83). Springer.

Claus, K., & Rousseau, S. (2012). Public versus private incentives to invest in green roofs: A cost benefit analysis for Flanders. *Urban Forestry & Urban Greening*, *11*, 417–425.

Colbeck, I., Nasir, Z. A., & Ali, Z. (2010). Characteristics of indoor/outdoor particulate pollution in urban and rural residential environment of Pakistan. *Indoor Air*, *20*, 40–51.

Cox, H. M. (2012). A sustainability initiative to quantify carbon sequestration by campus trees. *Journal of Geography*, *111*, 173–183.

Cutini, A., Matteucci, G., & Mugnozza, G. S. (1998). Estimation of leaf area index with the Li-Cor LAI 2000 in deciduous forests. *Forest Ecology and Management*, *105*, 55–65.

De Dear, R. J., & Brager, G. S. (1998a). Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans*, *104*, 145–167.

De Dear, R. J., & Brager, G. S. (1998b). Thermal adaptation in the built environment : a literature review. *Energy and Buildings*, *17*, 83–96.

De Dear, R. J., & Fountain, M. E. (1994). Field experiments on occupant comfort and office thermal environments in a hot-humid climate. *Ashrae Transactions*, *100*, 457–474.

De Groot, R. (1992). *Functions of Nature: Evaluation of Nature in Environmental Planning*. Amsterdam, The Netherlands: Wolters-Noordhoff.

De Groot, R., Wilson, M. A., & Boumans, R. M. J. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*, *41*, 393–408.

Dockery, D. W., & Spengler, J. D. (1981). Indoor-outdoor relationships of respirable sulfates and particles. *Atmospheric Environment*, *15*, 335–343.

Driver, B. L., Rosenthal, D., & Peterson, G. (1978). Social benefits of urban forests and related green spaces in cities. In *National Urban Forestry Conference* (pp. 98–111). SUNY College of Environmental USDA Forest Service, Syracuse.

Égerházi, L. A., Kovács, A., & Unger, J. (2013). Application of Microclimate Modelling and Onsite Survey in Planning Practice Related to an Urban Micro-Environment. *Advances in Meteorology*, *2013*, 1–10.

Elias, M., & Potvin, C. (2003). Assessing inter- and intra-specific variation in trunk carbon concentration for 32 neotropical tree species. *Forest Research*, *33*, 1039–1045.

Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J. McDonald, R. I., Parnell, S., … (Eds.). (2013). *Urbanization, biodiversity and ecosystem services: Challenges and opportunities*. Dordrecht: Springer Netherlands.

Emmanuel, R., Rosenlund, H., & Johansson, E. (2007). Urban shading – a design option for the tropics? A study in Colombo, Sri Lanka. *Journal of Climatology*, *27*, 1995–2004.

Escobedo, F. J., Wagner, J. E., Nowak, D. J., De la Maza, C. L., Rodriguez, M., & Crane, D. E. (2008). Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *Journal of Environmental Management*, *86*, 148–157.

Eumorfopoulou, E. A., & Kontoleon, K. J. (2009). Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. *Building and Environment*, *44*, 1024–1038.

Evans, G. W., Hygge, S., & Bullinger, M. (1995). Chronic Noise and Psychological Stress. *Psychological Science*, *6*, 333–338.

Fahmy, M., & Sharples, S. (2011). Urban form, thermal comfort and building CO2 emissions – a numerical analysis in Cairo. *Building Serv. Eng. Res. Technol.*, *32*, 73–84.

Fahmy, M., Sharples, S., & Eltrapolsi, A. (2009). Dual stage simulations to study the microclimatic effects of trees on thermal comfort in a residential building, Cairo, Egypt.

In *Eleventh International IBPSA Conference* (pp. 1730–1736). Glasgow, Scotland: Building Simulation.

Fanger, P. O. (1970). *Thermal Comfort Analysis and Applications in Environmental Engineering*. McGraw-Hill, Boulder, CO.

Fanger, P. O. (1972). *Thermal comfort*. McGraw Hill, Düsseldorf.

Feriadi, H., & Wong, N. H. (2004). Thermal comfort for naturally ventilated houses in Indonesia. *Energy and Buildings*, *36*, 614–626.

Finzel, J. A., Seyfried, M. S., Weltz, M. A., Kiniry, J. R., Johnson, M. V. V., & Launchbaugh, K. L. (2012). Indirect measurement of leaf area index in Sagebrush-Steppe Rangelands. *Rangeland Ecology & Management*, *65*, 208–212.

Folke, C., Jansson, A., Larsson, J., & Costanza, R. (1997). Ecosystem Appropriation by Cities. *Ambio*, *26*, 167–172.

Franck, U., Krüger, M., Schwarz, N., Grossmann, K., Röder, S., & Schlink, U. (2013). Heat stress in urban areas: Indoor and outdoor temperatures in different urban structure types and subjectively reported well-being during a heat wave in the city of Leipzig. *Meteorologische Zeitschrift*, *22*, 167–177.

Frelich, L. E. (1992). *Predicting dimensional relationships for twin cities shade trees*. *Methods*. Twin Cities 1530 N. Cleveland Avenue, St. Paul, MN 55108.

Fu, Y., & Liao, H. (2012). Simulation of the interannual variations of biogenic emissions of volatile organic compounds in China: Impacts on tropospheric ozone and secondary organic aerosol. *Atmospheric Environment*, *59*, 170–185.

Gagge, A. P., Fobelets, A. P., & Berglund, L. G. (1986). A standard predictive index of human response to the thermal environment. *ASHRAE Trans*, *92*, 709–731.

Garnier, E., Cortez, J., Billès, G., Navas, M., Roumet, C., Debussche, M., … Toussaint, J.-P. (2004). Plant functional markers capture ecosystem properties during secondary succession. *Ecology*, *85*, 2630–2637.

Garza, F. J. E. (2004). Reglamentos de ruido vs. naturaleza humana. *Ingenierías*, *VII*, 3–8.

Geron, C., Guenther, A., Greenberg, J., Karl, T., & Rasmussen, R. (2006). Biogenic volatile organic compound emissions from desert vegetation of the southwestern US. *Atmospheric Environment*, *40*, 1645–1660.

Geron, C., Guenther, A., Greenberg, J., Loescher, H. W., Clark, D., & Baker, B. (2002). Biogenic volatile organic compound emissions from a lowland tropical wet forest in Costa Rica. *Atmospheric Environment*, *36*, 3793–3802.

Gómez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics*, *86*, 235–245.

Gómez-Baggethun, E., Gren, A., Barton, D. N., Langemeyer, J., McPhearson, T., O'Farrell, P., … Kremer, P. (2013). Urban Ecosystem Services. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, … C. Wilkinson (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities.* (pp. 175–251). Dordrecht: Springer Netherlands.

González-Oreja, J. A., Bonache-Regidor, C., & De la Fuente-Díaz-Ordaz, A. A. (2010). Far from the noisy world? Modelling the relationships between park size, tree cover and noise levels in urban green spaces of the city of Puebla, Mexico. *Interciencia*, *35*, 486–492.

Gower, S. T., Kucharik, C. J., & Norman, J. M. (1999). Direct and indirect estimation of leaf area index , fAPAR , and net primary production of terrestrial ecosystems. *Remote Sens. Environm.*, *70*, 29–51.

Gratani, L., & Varone, L. (2006). Carbon sequestration by Quercus ilex L. and Quercus pubescens Willd. and their contribution to decreasing air temperature in Rome. *Urban Ecosystems*, *9*, 27–37.

Grimm, N. B., Grove, J. M., Pickett, S. T. A., & Redman, C. L. (2000). Integrated Approaches to Long-Term Studies of Urban Ecological Systems. *BioScience*, *50*, 571–584.

Grimmond, S. (2007). Urbanization and global environmental change: local effects of urban warming. *The Geographical Journal*, *173*, 83–88.

Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., & Fall, R. (1993). Isoprene and monoterpene emission rate variability: Model evaluations and sensitivity analyses. *Journal of Geophysical Research-Atmospheres*, *98*, 12609–12617.

Guenther, A., Geron, C., Pierce, T., Lamb, B., Harley, P., & Fall, R. (2000). Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. *Atmospheric Environment*, *34*, 2205–2230.

Guidotti, T. L. (2010). Health and Urban Ecosystems. *Archives of Environmental & Occupational Health*, *65*, 54–55.

Hayward, S. B. (1986). Source apportionment of indoor air pollution. *Atmospheric Environment*, *21*, 407–418.

He, H., & Jim, C. Y. (2010). Simulation of thermodynamic transmission in green roof ecosystem. *Ecological Modelling*, *221*, 2949–2958.

Hedquist, B. C., & Brazel, A. J. (2014). Seasonal variability of temperatures and outdoor human comfort in Phoenix, Arizona, U.S.A. *Building and Environment*, *72*, 377–388.

Heisler, G. M. (1986). Effects of individual trees on the solar radiation climate of small buildings. *Urban Ecology*, *9*, 337–359.

Heisler, G. M. (1990). Mean wind speed below building height in residential neighborhoods with different tree different tree densities. *Ashrae Transactions*, *96*, 1389–1396.

Heisler, G. M., & Grant, R. H. (2000). Ultraviolet radiation in urban ecosystems with consideration of effects on human health. *Urban Ecosystems*, *4*, 193–229.

Hien, W. N., Yok, T. P., & Yu, C. (2007). Study of thermal performance of extensive rooftop greenery systems in the tropical climate. *Building and Environment*, *42*, 25–54.

Hiramatsu, K., Matsui, T., Furukawa, S., & Uchiyama, I. (2008). The physical expression of soundscape: An investigation by means of Time Component Matrix Chart. In *Internoise 2008 from science to harmony - 37th International Congress and Exposition on Noise Control Engineering*. Shanghai, China.

Höppe, P. R. (1984). *Die Energiebilanz des Menschen*. Mittelungen Nr. 49.: Münchner Universitäts-Schriften, Wissenschaft.

Höppe, P. R. (1993). Heat balance modelling. *Experientia*, *49*, 741–746.

Howarth, A., Pearch, D. W., Ozdemiroglu, E., Seccomb-Hett, T., Wieringa, K., Streefkerk, C. M., & De Hollander, A. E. M. (2001). *Valuing the benefits of environmental policy: The Netherlands*.

Huang, L., Li, J., Zhao, D., & Zhu, J. (2008). A fieldwork study on the diurnal changes of urban microclimate in four types of ground cover and urban heat island of Nanjing, China. *Building and Environment*, *43*, 7–17.

Huang, Y. J., Akbari, H., Taha, H., & Rosenfeld, A. H. (1987). The potential of vegetation in reducing summer cooling loads in residential buildings. *Climate and Applied Meteorology*, *26*, 1103–1116.

Hugg, T., & Rantio-Lehtimäki, A. (2007). Indoor and outdoor pollen concentrations in private and public spaces during the Betula pollen season. *Aerobiologia*, *23*, 119–129.

Hwang, R. L., Lin, T. P., Cheng, M. J., & Lo, J. H. (2010). Adaptive comfort model for tree-shaded outdoors in Taiwan. *Building and Environment*, *45*, 1873–1879.

IPCC. (2013). Summary for Policymakers. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (pp. 1–29). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Irvine, K., Devine-Wright, P., Payne, S., Fuller, R., Painter, B., & Gaston, K. (2009). Green space, soundscape and urban sustainability: an interdisciplinary, empirical study. *Local Environment*, *14*, 155–172.

ISO 7726. (1998). *Ergonomics of the thermal environment — Instruments for measuring physical quantities*. *International Organization for Standardization*.

ISO 7730. (1994). *Moderate thermal environments—determination of the PMV and PPD indices and specification of the conditions for thermal comfort*. *International Organization for Standardization*.

ISO 8996. (1990). *Ergonomics -- Determination of metabolic heat production*. *International Organization for Standardization*.

ISO 9920. (1995). *Ergonomics of the thermal environment -- Estimation of the thermal insulation and evaporative resistance of a clothing ensemble*. *International Organization for Standardization*.

Jaffal, I., Ouldboukhitine, S. E., & Belarbi, R. (2012). A comprehensive study of the impact of green roofs on building energy performance. *Renewable Energy*, *43*, 157–164.

Jim, C. Y., & Chen, W. Y. (2006). Recreation–amenity use and contingent valuation of urban greenspaces in Guangzhou, China. *Landscape and Urban Planning*, *75*, 81–96.

Jim, C. Y., & Chen, W. Y. (2008). Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *Journal of Environmental Management*, *88*, 665–676.

Kalnay, E., & Cai, M. (2003). Impact of urbanization and land-use change on climate Eugenia. *Nature*, *423*, 528–531.

Kaplan, R. (1983). The role of nature in the urban context. *Human Behavior & Environment*, *6*, 127–161.

Kaplan, R. (2001). The nature of the view from home: Psychological benefits. *Environment and Behavior*, *33*, 507–542.

Kinney, P. L., Aggarwal, M., Northridge, M. E., Janssen, N. A. H., & Shepard, P. (2000). Airborne concentrations of PM2.5 and diesel exhaust particles on Harlem sidewalks: a community-based pilot study. *Environmental Health Perspectives*, *108*, 213–218. Retrieved from

Klemm, W., Heusinkveld, B. G., Lenzholzer, S., Jacobs, M. H., & Van Hove, B. (2014). Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands. *Building and Environment*, *83*, 120–128.

Knez, I., Thorsson, S., Eliasson, I., & Lindberg, F. (2009). Psychological mechanisms in outdoor place and weather assessment: Towards a conceptual model. *International Journal of Biometeorology*, *53*, 101–111.

Kommunförbundet, S. (1998). *Skönheten och oljudet (The Beauty and the noise)*. Handbok i trafikbuller skydd, Stokholm.

Kong, F., Yin, H., & Nakagoshi, N. (2007). Using GIS and landscape metrics in the hedonic price modeling of the amenity value of urban green space: A case study in Jinan City, China. *Landscape and Urban Planning*, *79*, 240–252.

Konopacki, S., & Akbari, H. (2000). *Energy savings calculations for heat island reduction strategies in Baton Rouge, Sacramento and Salt Lake City*. *Energy*.

Konopacki, S., & H. Akbari. (2002). *Energy savings for heat island reduction strategies in Chicago and Houston (including updates for Baton Rouge, Sacramento, and Salt Lake City*.

Kontoleon, K. J., & Eumorfopoulou, E. A. (2010). The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Building and Environment*, *45*, 1287–1303.

Koponen, I. K., Asmi, A., Keronen, P., Puhto, K., & Kulmala, M. (2001). Indoor air measurement campaign in Helsinki , Finland 1999 - the effect of outdoor air pollution on indoor air. *Atmospheric Environment*, *35*, 1465–1477.

Krüger, E. L., Minella, F. O., & Rasia, F. (2011). Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. *Building and Environment*, *46*, 621–634.

Kumar, R., & Kaushik, S. C. (2005). Performance evaluation of green roof and shading for thermal protection of buildings. *Building and Environment*, *40*, 1505–1511.

Kuye, A., & Jagtap, S. S. (1992). Analysis of solar radiation data for port harcourt, Nigeria. *Solar Energy*, *49*, 135–145.

Laband, D. N., & Sophocleus, J. P. (2009). An Experimental Analysis of the Impact of Tree Shade on Electricity Consumption. *Arboriculture & Urban Forestry, 35*, 197–202.

Lalic, B., & Mihailovic, D. T. (2004). An empirical relation describing Leaf-Area Density inside the forest for environmental modeling. *Journal of Applied Meteorology and Climatology*, *43*, 641–645.

Lee, T., Grinshpun, S. A., Kim, K. Y., Iossifova, Y., Adhikari, A., & Reponen, T. (2006). Relationship between indoor and outdoor airborne fungal spores, pollen, and (1→3)-β-D-glucan in homes without visible mold growth. *Aerobiologia*, *22*, 227–235.

Leung, D. Y. C., Tsui, J. K. Y., Chen, F., Yip, W.-K., Vrijmoed, L. L. P., & Liu, C.-H. (2011). Effects of urban vegetation on urban air quality. *Landscape Research*, *36*, 173–188.

Liao, C.-M., Luo, W.-C., Chen, S.-C., Chen, J.-W., & Liang, H.-M. (2004). Temporal/seasonal variations of size-dependent airborne fungi indoor/outdoor relationships for a wind-induced naturally ventilated airspace. *Atmospheric Environment*, *38*, 4415–4419.

Lin, B. S., Yu, C. C., Su, A. T., & Lin, Y. J. (2013). Impact of climatic conditions on the thermal effectiveness of an extensive green roof. *Building and Environment*, *67*, 26–33.

Lin, T.-P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, *44*, 2017–2026.

Lin, W., Wu, T., Zhang, C., & Yu, T. (2011). Carbon savings resulting from the cooling effect of green areas: A case study in Beijing. *Environmental Pollution*, *159*, 2148–2154.

Liu, B. Y. H., & Jordan, R. C. (1960). The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy*, *4*, 1–19.

Long, C. M., & Sarnat, J. A. (2004). Indoor-Outdoor Relationships and Infiltration Behavior of Elemental Components of Outdoor PM2.5 for Boston-Area Homes. *Aerosol Science and Technology*, *38*, 91–104.

Luttik, J. (2000). The value of trees, water and open space as reflected by house prices in the Netherlands. *Landscape and Urban Planning*, *48*, 161–167.

Magrab, E. B., & Jackson, F. J. (1973). Noise control. *C R C Critical Reviews in Environmental Control*, *3*, 61–83.

Maguire, D. A., & Bennett, W. S. (1996). Patterns in vertical distribution of foliage in young coastal Douglas-fir. *Canadian Journal of Forest Research*, *26*, 1991–2005.

Mäkelä, A., Virtanen, K., & Nikinmaa, E. (1995). The effects of ring width, stem position, and stand density on the relationship between foliage biomass and sapwood area in Scots pine (Pinus sylvestris). *Canadian Journal of Forest Research*, *25*, 970–977.

Malys, L., Musy, M., & Inard, C. (2014). A hydrothermal model to assess the impact of green walls on urban microclimate and building energy consumption. *Building and Environment*, *73*, 187–197.

Martin, N. A., Chappelka, A. H., Loewenstein, E. F., & Keever, G. J. (2012). Comparison of carbon storage, carbon sequestration, and air pollution removal by protected and maintained urban forests in Alabama, USA. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *8*, 265–272.

Matsui, T., Furukawa, S., Takashima, T., Uchiyama, I., & Hiramatsu, K. (2009). Time-component matrix chart as a tool for designing sonic environment having a diversity of sound sources. In *8th European Conference on Noise Control 2009, EURONOISE 2009 - Proceedings of the Institute of Acoustics* (PART 3, Vol. 31). Edinburgh, Scotland.

Matzarakis, A., & Amelung, B. (2008). Physiological Equivalent Temperature as Indicator for Impacts of Climate Change on Thermal Comfort of Humans. In M. C. Thomson, R. Garcia-Herrera, & M. Beniston (Eds.), *Seasonal Forecasts, Climatic Change and Human Health* (pp. 161–172). Springer Netherlands.

Matzarakis, A., & Mayer, H. (1997). Heat stress in Greece. *International Journal of Biometeorology*, *41*, 34–39.

Matzarakis, A., & Mayer, H. (1998). Investigations of urban climate's thermal component in Freiburg, Germany. In *Preprints Second Urban Environment Symposium - 13th Conference on Biometeorology and Aerobiology* (pp. 140–143). Albuquerque, USA: American Meteorological Society.

Matzarakis, A., Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology*, *43*, 76–84.

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International Journal of Biometeorology*, *51*, 323–334.

Mayer, H., & Höppe, P. (1987). Thermal Comfort of Man in Different Urban Environments. *Theor. Appl. Climatol.*, *38*, 43–49.

McPherson, E. G., Herrington, L. P., & Heisler, G. M. (1988). Impacts of vegetation on residential heating and cooling. *Energy and Buildings*, *12*, 41–51.

McPherson, E. G., & Simpson, J. R. (1999). *Carbon dioxide reduction through urban forestry: Guidelines for Professional and Volunteer Tree Planters*. *Forest Research*. Albany, California.

McPherson, E. G., Simpson, J. R., & Livingston, M. (1989). Effects of three landscape treatments on residential energy and water use in Tucson, Arizona. *Energy and Buildings*, *13*, 127–138.

Meng, Q. Y., Turpin, B. J., Korn, L., Weisel, C. P., Morandi, M., Colome, S., … Maberti, S. (2005). Influence of ambient (outdoor) sources on residential indoor and personal PM2.5 concentrations: analyses of RIOPA data. *Journal of Exposure Analysis and Environmental Epidemiology*, *15*, 17–28.

Middel, A., Häb, K., Brazel, A. J., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, *122*, 16–28.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Health synthesis*. *World Health*.

Miller, R. W. (1997). *Urban forestry: planning and managing urban greenspaces*. New Jersey: Prentice-Hall.

Morakinyo, T. E., Balogun, A. A., & Adegun, O. B. (2013). Comparing the effect of trees on thermal conditions of two typical urban buildings. *Urban Climate*, *3*, 76–93.

Nayar, T. S., & Jothish, P. S. (2012). An assessment of the air quality in indoor and outdoor air with reference to fungal spores and pollen grains in four working environments in Kerala, India. *Aerobiologia*, *29*, 131–152.

Ng, E., Chen, L., Wang, Y., & Yuan, C. (2012). A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment*, *47*, 256–271.

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., & Mihalakakou, G. (2001). Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings*, *33*, 719–729.

Nijland, H. A., Van Kempen, E. E. M. M., Van Wee, G. P., & Jabben, J. (2003). Costs and benefits of noise abatement measures. *Transport Policy*, *10*, 131–140.

Nikolopoulou, M., Baker, N., & Steemers, K. (2001). Thermal comfort in outdoor urban spaces: Understanding the human parameter. *Solar Energy*, *70*, 227–235.

Nikolopoulou, M., & Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment, 41,* 1455–1470.

Nizinski, J. J., & Saugier, B. (1988). A model of leaf budding and development for a mature quercus forest. *Journal of Applied Ecology*, *25,* 643–652.

Nowak, D., Crane, D., & Stevens, J. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, *4*, 115–123.

Nowak, D. J. (1994). *The effects of urban trees on air quality*. *New York*.

Nowak, D. J. (2006). Institutionalizing urban forestry as a “biotechnology” to improve environmental quality. *Urban Forestry & Urban Greening*, *5,* 93–100.

Nowak, D. J., & Crane, D. E. (2000). The urban forest effects (UFORE) model: Quantifying urban forest structure and functions. In M. Hansen & T. Burk (Eds.), *Integrated tools for natural resources inventories in the 21st century*. (pp. 714–720). IUFRO Conference, 16–20 August 1998, Boise, ID. General Technical Report NC-212. USDA Forest Service, North Central Research Station, St. Paul, MN.

Nowak, D. J., & Crane, D. E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution*, *116,* 381–389.

Nowak, D. J., Noble, M. H., Sisinni, S. M., & Dwyer, J. F. (2001). Assessing the US urban forest resource. *Journal of Forestry*, *99*, 37–42.

Onmura, S., Matsumoto, M., & Hokoi, S. (2001). Study on evaporative cooling effect of roof lawn gardens. *Energy and Buildings*, *33*, 653–666.

Ouldboukhitine, S.-E., Belarbi, R., Jaffal, I., & Trabelsi, A. (2011). Assessment of green roof thermal behavior: A coupled heat and mass transfer model. *Building and Environment*, *46*, 2624–2631.

Ouldboukhitine, S.-E., Belarbi, R., & Sailor, D. J. (2014). Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings. *Applied Energy*, *114*, 273–282.

Owen, S. M., MacKenzie, A. R., Stewart, H., Donovan, R., & Hewitt, C. N. (2003). Biogenic Volatile Organic Compound (VOC) Emission Estimates from an Urban Tree Canopy. *Ecological Applications*, *13*, 927–938.

Papadakis, G., Tsamis, P., & Kyritsis, S. (2001). An experimental investigation of the effect of shading with plants for solar control of buildings. *Energy and Buildings*, *33*, 831–836.

References

Parizotto, S., & Lamberts, R. (2011). Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. *Energy and Buildings*, *43*, 1712–1722.

Park, M., Hagishima, A., Tanimoto, J., & Narita, K.-I. (2012). Effect of urban vegetation on outdoor thermal environment: Field measurement at a scale model site. *Building and Environment*, *56*, 38–46.

Parra, R., Gassó, S., & Baldasano, J. M. (2004). Estimating the biogenic emissions of non-methane volatile organic compounds from the North Western Mediterranean vegetation of Catalonia, Spain. *The Science of the Total Environment*, *329*, 241–259.

Passchier-Vermeer, W., & Passchier, W. F. (2000). Noise exposure and public health. *Environmental Health Perspectives*, *108*, 123–131.

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.*, *11*, 1633–1644.

Peng, L. L. H., & Jim, C. Y. (2013). Green-roof effects on neighborhood microclimate and human thermal sensation. *Energies*, *6*, 598–618.

Poupkou, A., Giannaros, T., Markakis, K., Kioutsioukis, I., Curci, G., Melas, D., & Zerefos, C. (2010). A model for European Biogenic Volatile Organic Compound emissions: Software development and first validation. *Environmental Modelling & Software*, *25*, 1845–1856.

Rashid, R., & Ahmed, M. H. B. (2009). Thermal performance of rooftop greenery system at the tropical climate of malaysia: A case study of a 10 storied building R.C.C flat rooftop at UTM, Johor Bahru,Malaysia. *Journal of Architecture and Built Environment*, *37*, 41–49.

Redondo-Brenes, A. (2007). Growth, carbon sequestration, and management of native tree plantations in humid regions of Costa Rica. *New Forests*, *34*, 253–268.

Rees, W. E. (1997). Urban ecosystems : the human dimension. *Urban Ecosystems*, *1*, 63–75.

Ren, Y., Wei, X., Wei, X., Pan, J., Xie, P., Song, X., … Zhao, J. (2011). Relationship between vegetation carbon storage and urbanization: A case study of Xiamen, China. *Forest Ecology and Management*, *261*, 1214–1223.

Rich, P. M. (1988). Video image analysis of hemispherical canopy photography. In P. W. Mausel (Ed.), *First Special Workshop on Videography* (pp. 84–95). Terre Haute, Indiana.

Riley, W. J., McKone, T. E., Lai, A. C. K., & Nazaroff, W. W. (2002). Indoor particulate matter of outdoor origin: importance of size-dependent removal mechanisms. *Environmental Science & Technology*, *36*, 200–207.

Saadatian, O., Sopian, K., Salleh, E., Lim, C. H., Riffat, S., Saadatian, E., … Sulaiman, M. Y. (2013). A review of energy aspects of green roofs. *Renewable and Sustainable Energy Reviews*, *23*, 155–168.

Sander, H. A., & Haight, R. G. (2012). Estimating the economic value of cultural ecosystem services in an urbanizing area using hedonic pricing. *Journal of Environmental Management*, *113*, 194–205.

Sandström, U. F. (2002). Green Infrastructure Planning in Urban Sweden. *Planning Practice and Research*, *17*, 373–385.

Sawka, M., Millward, A. A., Mckay, J., & Sarkovich, M. (2013). Growing summer energy conservation through residential tree planting. *Landscape and Urban Planning*, *113*, 1–9.

Seto, K. C., & Reenberg, A. (2014). *Rethinking global land use in an urban era*. Cambridge, Massachusetts, US: The MIT Press.

Shahidan, M. F., Jones, P. J., Gwilliam, J., & Salleh, E. (2012). An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials. *Building and Environment*, *58*, 245–257.

Shashua-bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings*, *31*, 221–235.

Shashua-bar, L., & Hoffman, M. E. (2002). The Green CTTC model for predicting the air temperature in small urban wooded sites. *Building and Environment*, *37*, 1279–1288.

Shashua-bar, L., & Hoffman, M. E. (2004). Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: urban streets and courtyards with trees. *Building and Environment*, *39*, 1087–1099.

Simpson, J., & Mcpherson, E. (1997). The effects of roof albedo modification on cooling loads of scale model residences in Tucson, Arizona. *Energy and Buildings*, *25*, 127–137.

Skoulika, F., Santamouris, M., Kolokotsa, D., & Boemi, N. (2014). On the thermal characteristics and the mitigation potential of a medium size urban park in Athens, Greece. *Landscape and Urban Planning*, *123*, 73–86.

Smith, F. W., Sampson, A. D., & Long, N. J. (1991). Comparison of leaf area index estimates from tree allometrics and measured light interception. *Forest Science*, *37*, 1682–1688.

Sobotova, L., Jurkovicova, J., Stefanikova, Z., Sevcikova, L., & Aghova, L. (2010). Community response to environmental noise and the impact on cardiovascular risk score. *The Science of the Total Environment*, *408*, 1264–1270.

Stadt, K. J., & Lieffers, V. J. (2000). MIXLIGHT: a flexible light transmission model for mixed-species forest stands. *Agricultural and Forest Meteorology*, *102*, 235–252.

Stansfeld, S. A., & Matheson, M. P. (2003). Noise pollution: non-auditory effects on health. *British Medical Bulletin*, *68*, 243–257.

Sterling, D. A., & Lewis, R. D. (1998). Pollen and fungal spores indoor and outdoor of mobile homes. *Annals of Allergy, Asthma & Immunology*, *80*, 279–285.

Susca, T., Gaffin, S. R., & Dell'osso, G. R. (2011). Positive effects of vegetation: urban heat island and green roofs. *Environmental Pollution*, *159*, 2119–2126.

Susorova, I., Angulo, M., Bahrami, P., & Stephens, B. (2013). A model of vegetated exterior facades for evaluation of wall thermal performance. *Building and Environment*, *67*, 1–13.

Taha, H., Akbari, H., & Rosenfeld, A. (1991). Heat Island and Oasis Effects of Vegetative Canopies: Micro-Meteorological Field-Measurements. *Theoretical and Applied Climatology*, *44*, 123–138.

Taha, H., Douglas, S., & Haney, J. (1997). Mesoscale meteorological and air quality impacts of increased urban albedo and vegetation. *Energy and Buildings*, *25*, 169–177.

Taha, H., Konopacki, S., & Gabersek, S. (1996). *Modeling the Meteoro- logical and Energy Effects of Urban Heat Islands and their Mitiga- tion: A 10-Region Study*. Berkeley, CA.

Takakura, T., Kitade, S., & Goto, E. (2000). Cooling effect of greenery cover over a building. *Energy and Buildings*, *31*, 1–6.

Takano, T., Nakamura, K., & Watanabe, M. (2002). Urban residential environments and senior citizens' longevity in megacity areas: the importance of walkable green spaces. *Journal of Epidemiology and Community Health*, *56*, 913–918.

Taleghani, M., Sailor, D. J., Tenpierik, M., & Van den Dobbelsteen, A. (2013). Thermal assessment of heat mitigation strategies: the case of Portland State University, Oregon, USA. *Building and Environment*, *73*, 138–150.

Tallis, M., Taylor, G., Sinnett, D., & Freer-Smith, P. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, *103*, 129–138.

Taylor, A. F., Kuo, F. E., & Sullivan, W. C. (2002). Views of nature and self-discipline: Evidence from inner city children. *Journal of Environmental Psychology*, *22*, 49–63.

TEEB. (2010). *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. (P. Kumar, Ed.). London and Washington: Earthscan.

Thomas, S. C., & Winner, W. E. (2000). Leaf area index of an old-growth Douglas-fir forest estimated from direct structural measurements in the canopy. *Canadian Journal of Forest Research*, *23*, 1922–1930.

Thornes, J., Bloss, W., Bouzarovski, S., Cai, X., Chapman, L., Clark, J., … Randalls, S. (2010). Communicating the value of atmospheric services. *Meteorological Applications*, *17*, 243–250.

Townsend, A. R., Howarth, R. W., Bazzaz, F. A., Booth, M. S., Cleveland, C. C., Collinge, S. K., … Wolfe, A. H. (2003). Human health effects of a changing global nitrogen cycle. *Frontiers in Ecology and the Environment*, *1*, 240–246.

Tratsaert, K. (1998). *Stads(v)lucht maakt vrij. Analyse van de verhuisstromen en een bevraging van de verhuismotieven en woonwensen van jonge gezinnen in het Leuvense*.

Tyrvainen, L., & Miettinen, A. (2000). Property Prices and Urban Forest Amenities. *Journal of Environmental Economics and Management*, *39*, 205–223.

Tyrväinen, L., & Väänänen, H. (1998). The economic value of urban forest amenities : an application of the contingent valuation method. *Landscape and Urban Planning*, *43*, 105–118.

Tzoulas, K., Korpela, K., Venn, S., Ylipelkonen, V., Kazmierczak, A., Niemela, J., & James, P. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landscape and Urban Planning*, *81*, 167–178.

Ulrich, R. S. (1984). View through a Window May Influence Recovery from Surgery. *Science*, *224*, 420–421.

Ulrich, R. S. (1986). Human responses to vegetation and landscapes. *Landscape and Urban Planning*, *13*, 29–44.

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, *11*, 201–230.

Van den Berg, A. E., Maas, J., Verheij, R. A., & Groenewegen, P. P. (2010). Green space as a buffer between stressful life events and health. *Social Science & Medicine*, *70,* 1203–1210.

Van Renterghem, T., & Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. *Building and Environment*, *46*, 729–738.

Van Renterghem, T., Hornikx, M., Forssen, J., & Botteldooren, D. (2013). The potential of building envelope greening to achieve quietness. *Building and Environment*, *61*, 34–44.

VDI. (1998). *VDI 3787, Part I: Environmental Meteorology, Methods for the human biometeorological evaluation of climate and air quality for the urban and regional planning at regional level*. *Methods for the human-biometerological assessment of climate and air hygiene for urban and regional planning.* Beuth, Berlin.

Vos, P. E. J., Maiheu, B., Vankerkom, J., & Janssen, S. (2013). Improving local air quality in cities: To tree or not to tree? *Environmental Pollution (Barking, Essex : 1987)*, *183*, 113–122.

Walmsley, A. (2006). Greenways: multiplying and diversifying in the 21st century. *Landscape and Urban Planning*, *76*, 252–290.

Wang, Y., Bakker, F., De Groot, R., & Wörtche, H. (2014). Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Building and Environment*, *77*, 88–100.

Wang, Y., Bakker, F., De Groot, R., Wörtche, H., & Leemans, R. (2015a). Effects of urban trees on local outdoor microclimate: Synthesizing field measurements by numerical modelling. *Urban Ecosystems*. doi: 10.1007/s11252-015-0447-7

Wang, Y., Bakker, F., De Groot, R., Wörtche, H., & Leemans, R. (2015b). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. *Environmental Monitoring and Assessment*, *187*, 732–745.

Wang, Y.-C., & Lin, J.-C. (2012). Air quality enhancement zones in Taiwan: A carbon reduction benefit assessment. *Forest Policy and Economics*, *23,* 40–45.

Warren, P., Katti, M., Ermann, M., & Brazel, A. (2006). Urban bioacoustics: it's not just noise. *Animal Behaviour*, *71*, 491–502.

Watson, D. J. (1947). Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Annals of Botany*, *11*, 41–76.

Watson, I. D., & Johnson, G. T. (1987). Graphical estimation of sky view-factors in urban environments. *International Journal of Climatology*, *7*, 193–197.

Watson, R. T. (2005). Turning science into policy: challenges and experiences from the science-policy interface. *Philosophical Transactions of the Royal Society B*, *360*, 471–477.

Weiss, M., & Baret, F. (2010). *Can-eye v6.1 user manual*.

Welles, J. M., & Cohen, S. (1996). Canopy structure measurement by gap fraction analysis using commercial instrumentation. *Journal of Experimental Botany*, *47*, 1335–1342.

Willmott, C. J. (1981). On the validation of models. *Physical Geography*, *2*, 184–194.

Wilson, J. W. (1963). Estimation of foliage denseness and foliage angle by inclined point quadrats. *Australian Journal of Botany*, *11*, 95–105.

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities "just green enough." *Landscape and Urban Planning*, *125*, 234–244.

Wong, N. H., Chen, Y., Ong, C. L., & Sia, A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*, *38*, 261–270.

Wong, N. H., Tan, A. Y. K., Tan, P. Y., & Wong, N. C. (2009). Energy simulation of vertical greenery systems. *Energy and Buildings*, *41*, 1401–1408.

World Health Organization (WHO). (2009). *WHO Guidelines for Indoor Air Quality: Dampness and Mould*. (E. Heseltine & J. Rosen, Eds.). WHO Regional Office for Europe.

World Health Organization (WHO). (2013). *WHO centre for health development: Annual report 2013*. kobe, Japan.

Yang, F., Lau, S. S. Y., & Qian, F. (2010). Summertime heat island intensities in three high-rise housing quarters in inner-city Shanghai China: Building layout, density and greenery. *Building and Environment*, *45*, 115–134.

Yang, F., Lau, S. S. Y., & Qian, F. (2011). Urban design to lower summertime outdoor temperatures: An empirical study on high-rise housing in Shanghai. *Building and Environment*, *46*, 769–785.

Yang, J., McBride, J., Zhou, J., & Sun, Z. (2005). The urban forest in Beijing and its role in air pollution reduction. *Urban Forestry & Urban Greening*, *3*, 65–78.

Yang, W., Wong, N. H., & Jusuf, S. K. (2013). Thermal comfort in outdoor urban spaces in Singapore. *Building and Environment*, *59*, 426–435.

Yin, S., Shen, Z., Zhou, P., Zou, X., Che, S., & Wang, W. (2011). Quantifying air pollution attenuation within urban parks: An experimental approach in Shanghai, China. *Environmental Pollution*, *159*, 2155–2163.

Yli-Panula, E. (2012). Birch pollen allergen exposure: profiles, sources and characteristics. Settled dust and aeroallergens in indoor and outdoor environments of Finnish homes. *Aerobiologia*, *28*, 453–465.

Zhao, C., Fu, G., Liu, X., & Fu, F. (2011). Urban planning indicators, morphology and climate indicators: A case study for a north-south transect of Beijing, China. *Building and Environment*, *46*, 1174–1183.

Zhao, D., Xie, D., Zhou, H., Jiang, H., & An, S. (2012). Estimation of leaf area index and plant area index of a submerged macrophyte canopy using digital photography. *PloS One*, *7*, 1–10.

Zinzi, M., & Agnoli, S. (2012). Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. *Energy and Buildings*, *55*, 66–76.

Zipprich, J. L., Harris, S. A., Fox, J. C., & Borzelleca, J. F. (2002). An analysis of factors that influence personal exposure to nitrogen oxides in residents of Richmond, Virginia. *Journal of Exposure Analysis and Environmental Epidemiology*, *12*, 273–285.

APPENDICES

Appendix 2.1 Studies exploring the contribution of two major categories of urban green infrastructure (UGI), i.e. adjoining vegetation and roof & wall greens, to microclimate and energy use.

Types	Methodology	*SHADE*			*EVAPOTRANSPIRATION*		*WIND SHIELD*
		Buffer solar radiation	**Block heat flow**	**Alter temperature**		**Add moisture**	**Lower wind speed**
Adjoining vegetation	*Field measurement/ experimental study*	Heisler 1986, Akbari et al. 1997, Berry et al. 2013, Laband and Sophocleus 2009, McPherson et al. 1989, Morakinyo et al. 2013, Papadakis et al. 2001, Park et al. 2012, Taha et al. 1991	Akbari et al. 1997, Berry et al. 2013, McPherson et al. 1989, Morakinyo et al. 2013, Papadakis et al. 2001, Park et al. 2012, Taha et al. 1991	Akbari et al. 1997, Berry et al. 2013, Laband and Sophocleus 2009, McPherson et al. 1989, Morakinyo et al. 2013, Papadakis et al. 2001, Park et al. 2012, Taha et al. 1991		Akbari et al. 1997, Berry et al. 2013, Papadakis et al. 2001	Akbari et al. 1997, Berry et al. 2013, Morakinyo et al. 2013, Papadakis et al. 2001, Park et al. 2012, Taha et al. 1991, Heisler 1990
	Modelling	Akbari and Taha 1992, Mcpherson et al. 1988, Sawka et al. 2013, Shahidan et al. 2012, Shashua-bar and Hoffman 2000, Shashua-bar and Hoffman 2002, Shashua-Bar and Hoffman 2004	Akbari and Taha 1992, Mcpherson et al. 1988, Sawka et al. 2013, Shahidan et al. 2012, Shashua-bar and Hoffman 2000, Shashua-bar and Hoffman 2002, Shashua-Bar and Hoffman 2004	Akbari and Taha 1992, Mcpherson et al. 1988, Sawka et al. 2013, Shahidan et al. 2012, Shashua-bar and Hoffman 2000, Shashua-bar and Hoffman 2002, Shashua-Bar and Hoffman 2004	Akbari and Taha 1992, Sawka et al. 2013, Shahidan et al. 2012, Shashua-bar and Hoffman 2000, Shashua-bar and Hoffman 2002, Shashua-Bar and Hoffman 2004	Akbari and Taha 1992, Sawka et al. 2013, Shahidan et al. 2012, Shashua-bar and Hoffman 2000, Shashua-bar and Hoffman 2002, Shashua-Bar and Hoffman 2004	Akbari and Taha 1992, Mcpherson et al. 1988, Shahidan et al. 2012,
Roof & wall greens	*Field measurement/ experimental study*	Eumorfopoulou and Kontoleon 2009, Hien et al. 2007, Onmura et al. 2001, Parizotto and Lamberts 2011, Rashid and Ahmed 2009, Susca et al. 2011, Wong et al. 2003	Eumorfopoulou and Kontoleon 2009, Hien et al. 2007, Onmura et al. 2001, Parizotto and Lamberts 2011, Rashid and Ahmed 2009, Susca et al. 2011, Wong et al. 2003, Niachou et al. 2001	Shashua-Bar and Hoffman 2004, Eumorfopoulou and Kontoleon 2009, Hien et al. 2007, Onmura et al. 2001, Parizotto and Lamberts 2011, Rashid and Ahmed 2009, Susca et al. 2011, Wong et al. 2003, Niachou et al. 2001, Blanusa et al. 2013, Lin et al. 2013		Eumorfopoulou and Kontoleon 2009, Hien et al. 2007, Onmura et al. 2001, Parizotto and Lamberts 2011, Rashid and Ahmed 2009, Wong et al. 2003	Eumorfopoulou and Kontoleon 2009, Hien et al. 2007, Parizotto and Lamberts 2011, Susca et al. 2011

Modelling	Alexandri and Jones 2008, Castleton et al. 2010, He and Jim 2010, Jaffal et al. 2012, Kontoleon and Eumorfopoulou 2010, Kumar and Kaushik 2005, Ouldboukhitine et al. 2011, Ouldboukhitine et al. 2014, Peng and Jim 2013, Susorova et al. 2013, Takakura et al. 2000, Wong et al. 2009, Zinzi and Agnoli 2012	Alexandri and Jones 2008, Castleton et al. 2010, He and Jim 2010, Jaffal et al. 2012, Kontoleon and Eumorfopoulou 2010, Kumar and Kaushik 2005, Ouldboukhitine et al. 2011, Ouldboukhitine et al. 2014, Peng and Jim 2013, Susorova et al. 2013, Takakura et al. 2000, Wong et al. 2009, Zinzi and Agnoli 2012	Alexandri and Jones 2008, Castleton et al. 2010, He and Jim 2010, Jaffal et al. 2012, Kontoleon and Eumorfopoulou 2010, Kumar and Kaushik 2005, Ouldboukhitine et al. 2011, Ouldboukhitine et al. 2014, Peng and Jim 2013, Susorova et al. 2013, Takakura et al. 2000, Wong et al. 2009, Zinzi and Agnoli 2012	Alexandri and Jones 2008, Castleton et al. 2010, He and Jim 2010, Jaffal et al. 2012, Kontoleon and Eumorfopoulou 2010, Kumar and Kaushik 2005, Ouldboukhitine et al. 2011, Ouldboukhitine et al. 2014, Peng and Jim 2013, Susorova et al. 2013, Takakura et al. 2000, Wong et al. 2009, Zinzi and Agnoli 2012	Alexandri and Jones 2008, Kontoleon and Eumorfopoulou 2010, Ouldboukhitine et al. 2011, Ouldboukhitine et al. 2014, Peng and Jim 2013, Susorova et al. 2013	Alexandri and Jones 2008, Kontoleon and Eumorfopoulou 2010, Ouldboukhitine et al. 2014, Peng and Jim 2013, Susorova et al. 2013

Appendix 2.2 Studies exploring the contribution of urban green infrastructure on air quality for both direct and indirect processes.

	Dry deposition	Carbon Storage and Sequestration	Pollen and spores of fungi
Direct effects	Escobedo et al. 2008, Jim and Chen 2008, Martin et al. 2012, Nowak et al. 2006, Nowak 2006, Tallis et al. 2011, Yang et al. 2005, Yin et al. 2011	Martin et al. 2012, Yang et al. 2005, Cox 2012, Elias and Potvin 2003, Gratani and Varone 2006, Nowak and Crane 2002, Redondo-Brenes 2007, Ren et al. 2011, Wang and Lin 2012	Hugg and Rantio-Lehtimäki 2007, Liao et al. 2004, Nayar and Jothish 2012, Sterling and Lewis 1998, Yli-Panula 2012
	Biogenic Volatile Organic Compound (BVOC) Emissions	**Effects on air quality by micro climate regulation**	**Potential energy saving benefits**
Indirect effects	Bouvier-Brown et al. 2012, Chang et al. 2012, Fu and Liao 2012, Geron et al. 2006, Geron et al. 2002, Owen et al. 2003, Parra et al. 2004, Poupkou et al. 2010	Baik et al. 2012, Vos et al. 2013	Akbari 2002, Fahmy and Sharples 2011, Lin et al. 2011

Appendix 2.3 Summary of the findings from the literature review related to the cooling effect and energy saving by UGIs.

References	Location	UGI	Cooling effect (℃)			Energy saving	Wind reduction
			Air	Surface	Indoor		
Heisler 1986 [a]	USA	Trees	0.9 ℃–1.2 ℃				
Mcpherson et al. 1988 [b]	Madison, Salt Lake City, Tucson and Miami, USA	All vegetation				53–61% cooling	50%
McPherson et al. 1989 [a]	Tucson, Arizona, USA	Green space	1.5 ℃	14.0 ℃		20–30% cooling	
Heisler 1990 [a]	USA	Forest					65% in the winter; 70% in the summer
Taha et al. 1991 [a]	Davis, California, USA	Green space (isolated orchard)	2.0 ℃				2 $m \cdot s^{-1}$–6.7 $m \cdot s^{-1}$
Akbari and Taha 1992 [b]	Toronto, Edmonton, Montreal, and Vancouver, Canada	Green space				10%–40% in urban; 20%–30% in rural	
Akbari et al. 1997 [a]	Sacramento, California, USA	Trees		11.0–25.0 ℃		30% cooling	2–16%
Takakura et al. 2000 [b]	Japan	Green roof		15.0 ℃			
Niachou et al. 2001 [a]	Greece	Green roof			1.0 ℃	2–48%	
Onmura et al. 2001 [a]	Japan	Roof lawn garden		30.0–60.0 ℃			
Wong et al. 2003 [a]	Singapore	Rooftop garden	4.3 ℃	30.0 ℃			
Kumar and Kaushik 2005 [b]	Yamuna Nagar, India	Green roof				3.02 $kWh \cdot day^{-1}$	
Alexandri and Jones 2008 [b]	London, UK Montreal, Canada Moscow, Russia Athens, Greece Riyadh, Saudi Arabia Hong Kong, China Mumbai, India Brasilia, Brazil	Green roof		9.1–19.3 ℃			

Eumorfopoulou and Kontoleon 2009 [a]	Greece	Green wall		1.9–8.3 ℃	0.5 ℃		
Laband and Sophocleus 2009 [a]	Beauregard, Alabama, USA	All vegetation				13%	
Rashid and Ahmed 2009 [a]	Malaysia	Green roof			4.0–5.0 ℃		
Wong et al. 2009 [b]	Singapore	Green roof and wall	0.3 ℃				
Castleton et al. 2010 [b]	UK	Green roof				13-45%	
Kontoleon and Eumorfopoulou 2010 [b]	Greece	Green wall		1.6–19.0 ℃		20.08%	
Ouldboukhitine et al. 2011 [b]	France	Green roof		30.0 ℃			
Parizotto and Lamberts 2011 [a]	Florianópolis, Brazil	Green roof		18.0 ℃			
Susca et al. 2011 [a]	New York City, USA	Green roof	2.0 ℃				
Jaffal et al. 2012 [b]	La Rochelle, France	Green roof			2.0 ℃	6%	
Shahidan et al. 2012 [b]	Putrajaya, Malaysia	Green space	0.9–1.2 ℃			10–29%	
Park et al. 2012 [a]	Saitama Prefecture, Japan	Trees (mobile shade trees)					51%
Zinzi and Agnoli 2012 [b]	Barcelona, Spain Cairo, Egypt Palermo, Italy	Green roof				30%	
Berry et al. 2013 [a]	Melbourne, Australia	Trees (mobile shade trees)		9.0 ℃			
Blanusa et al. 2013 [a]	UK	Green roof	1.0 ℃	12.0 ℃			
Lin et al. 2013 [a]	Taipei and Chiayi, Taiwan	Green roof		12.1–22.5 ℃			
Peng and Jim 2013 [b]	Hong Kong, China	Green roof	0.4–1.7 ℃				
Sawka et al. 2013 [b]	Toronto, Canada	All vegetation				3.4–54%	
Susorova et al. 2013 [b]	USA	Green wall		0.7–13.1 ℃			
Morakinyo et al. 2013 [a]	Akure, Nigeria	All vegetation		5.0–7.0 ℃	3.0 ℃		
Ouldboukhitine et al. 2014 [b]	Poitou–Charentes region, France	Green roof	0.8 ℃	20.0–30.0 ℃			

[a] Field measurements/experimental study
[b] Modelling study

Appendix 2.4 Summary of applied models from the literature review.

Model	Description	Reference	Source
MICROPAS	Building energy simulation program	Mcpherson et al. 1988	MICROPAS users manual. (1985). ENERCOMP, Davis, CA.
SPS	A shadow pattern simulator		
DOE-2.1D	A building energy simulation program	Park et al. 2012	Huang, Y. J., Akbari, H., Taha, H., Rosenfeld, A. H. (1987). The potential of vegetation in reducing summer cooling loads in residential buildings. *Climate and Applied Meteorology*, *26*, 1103–1116.
ENVI-met	A three dimensional non hydrostatic micro climate model	Shahidan et al. 2012, Peng and Jim 2013, Fahmy and Sharples 2011	http://www.envi-met.com/
DesignBuilder	An energy analysis package	Fahmy and Sharples 2011	http://www.designbuilder.co.uk/
HTB2	A dynamic energy consumption software	Shahidan et al. 2012	http://www.cardiff.ac.uk/archi/computermodelling.php
Sacramento Municipal Utility District's (SMUD) Tree Benefits Estimator	An energy conservation benefits of a utility-sponsored shade-tree-planting programme in	Sawka et al. 2013	Sarkovich, M. (2009). Sacramento Municipal Utility District's (SMUD) urban heat island mitigation efforts. *2nd International Conference on Countermeasures to Urban Heat Islands*.
CSMP models	A one-dimensional non-steady model	Takakura et al. 2000	Takakura, T., Kitade, S., Goto, E. (2000). Cooling effect of greenery cover over a building. *Energy and Buildings*, *31*, 1–6.
RayMan	A micro climate model	Peng and Jim 2013	Matzarakis, A., Rutz, F., Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments - application of the RayMan model. *International Journal of Biometeorology*, *51*, 323–334.
Screening Tool for Estate Environment Evaluation (STEVE) model	An air temperature prediction model	Wong et al. 2009	Jusuf, S. K., Hien, W. N. (2009) Development of empirical models for an estate level air temperature prediction in Singapore. *The second international conference on countermeasures to urban heat islands.* Berkeley, California.

A TRaNsient SYstems Simulation Program (TRNSYS)	An building energy programs	Jaffal et al. 2012, Ouldboukhitine et al. 2014	http://sel.me.wisc.edu/trnsys/
Energy Plus	A whole building energy simulation program	Zinzi and Agnoli 2012	http://apps1.eere.energy.gov/buildings/energyplus/
#	A climatological model	Susorova et al. 2013	Susca, T., Gaffin, S. R., Dell'osso, G. R. (2011). Positive effects of vegetation: urban heat island and green roofs. *Environmental pollution*, *159*, 2119-2126
#	A two-dimensional, prognostic (dynamic) micro-scale model	Alexandri and Jones 2008	Alexandri, E., Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, *43*, 480-493.

no specification on the names

Appendix 2.5 The main indoor pollutants from outdoor sources.

Main pollutants	Description	References

PM	Particulate matter
	- Categorizied by sizes (referred to as fractions)
	  ○ PM_1
	  ○ $PM_{2.5}$
	  ○ PM_{10}
	- The sources of them can be artificial or natural
		Colbeck et al. 2010,
		Riley et al. 2002

NO_X	Nitrogen oxide
	- Nitrogen Dioxide (NO_2)
	  ○ Mainly produced through industrial processes
	- Nitric Oxide (NO)
	  ○ The sources of them can be artificial (industry, transport and agriculture) or natural (lightning)
		Baxter et al. 2007,
		Zipprich et al. 2002

EC	Elemental carbon - The sources of them can be artificial or natural	Fahmy and Sharples 2011, Baxter et al. 2007, Kinney et al. 2000, Benson et al. 1972
SO_2	Sulfur dioxide - The main important source is industry	Benson et al. 1972
BVOC	Volatile organic compounds - Mainly emitted by vegetation	Owen et al. 2003, Guenther et al. 2000
Pollen and spores of fungi	A fine to coarse powder - Mainly emitted by vegetation	Hugg and Rantio-Lehtimäki 2007, Sterling and Lewis 1998, Lee et al. 2006

Appendix 2.6 Summary of the annual air pollutant removal from the literature review.

References	Location	UGI	Year	Pollutants removal									
				NO_2		O_3		SO_2		PM_{10}		CO	
				($g \cdot m^{-2} \cdot yr^{-1}$)	(%)	($g \cdot m^{-2} \cdot yr^{-1}$)	(%)	($g \cdot m^{-2} \cdot yr^{-1}$)	(%)	($g \cdot m^{-2} \cdot yr^{-1}$)	(%)	($g \cdot m^{-2} \cdot yr^{-1}$)	(%)
Yang et al. 2005	Central part of Beijing, China	Forest	2002	2.45		4.46		1.78		13.61			
Nowak et al. 2006	11 selected cities, USA	Trees and shrubs	2006	0.4–6.3	0.1–0.5	1.1–7.6	0.1–0.8	0.2–2.4	0.1–0.7	1.1–8.0	0.2–1.0	0.1–1.2	0.001–0.003
Nowak 2006	New York, NY	Forest	2000	2.18		3.21		1.19		2.12		0.4	
	Atlanta, GA			1.44		5.35		0.71		4.2		0.31	
	Beijing, China			2.88		5.58		2.2		16.83			
	Toronto, Canada			1.54		3.13		0.59		2.19		0.25	
	Baltimore, MD			1.78		4.23		1.04		2.69		0.17	
	Philadelphia, PA			1.73		3.44		0.76		3.6		0.19	
	Washington, DC			1.1		3.33		1.12		2.34		0.39	
	Boston, MA			1.51		3.4		0.73		2.3		0.19	
	Woodbridge, NJ			2.37		3.73		0.85		3.51		0.34	
	San Francisco, CA			1.76		3.31		0.49		2.95		0.49	
	Moorestown, NJ			1.32		4.06		0.85		3.59		0.19	
	Syracuse, NY			0.8		3.67		0.47		1.53		0.13	
	Morgantown, WV			0.63		3.25		1.13		2.25		0.13	
	Jersey City, NJ			2.04		2.95		1.14		2.04		0.45	
	Freehold, NJ			1.71		5.13		0.57		3.42		0.57	
	Fuenlabrada, Spain			2.65		3.98				3.98			
Escobedo et al. 2008	Santiago, Chile	Forest	July 2000–June 2001							14.8–17.3			
Jim and Chen 2008	Guangzhou, China	Trees	2000	2.64				2.73		10.9			
Tallis et al. 2011	London, UK	Trees	2006							2.47–6.15	0.7–1.4		

Appendix 2.7 Summary of carbon storage and annual gross sequestration per square meter from the literature review.

References	Location	UGI	Year	Carbon storage (g C·m^{-2})	Gross carbon sequestration (g C·m^{-2}·yr^{-1})
Nowak and Crane 2002	Sacramento, CA	Forest	1996–1999	36,100	85
	Atlanta, GA			9,700	123
	Baltimore, MD			10,000	71
	Syracuse, NY			9,400	73
	Boston, MA			9,100	67
	New York, NY			7,300	48
	Chicago, IL			12,900	67
	Philadelphia, PA			9,000	43
	Oakland, CA			5,200	
	Jersey City, NJ			4,400	21
Yang et al. 2005	Central part of Beijing, China	Forest	2002	3,964	202
Ren et al., 2011	Xiamen, China	Forest	1972–2006	414±93–1, 373±208	
Cox, 2012	Los Angeles, USA	Forest	2006		134 (40,000 g·tree^{-1}·yr^{-1})
Wang and Lin 2012	Taiwan	Forest and green spaces	2010	839	122

Appendix 3.1 Summarized table on daytime Ta and RH between cloudy and cool and clear and hot days in the daytime of summer.

Weather	**No. of days**	**Features**	**Features on daily basis** [a]		**Mean differences** (Site one minus Site four)	
			Site one (no trees)	Site four (beneath tree)	*Value*	*Std. Deviation*
Cloudy and cool	17	Max. Ta (℃)	18.9–28.0	18.3–25.5	1.8	0.7
	17	Min. Ta (℃)	9.7–20.1	9.7–19.9	0.1	0.2
	17	Ave. Ta (℃)	16.0–22.9	15.5–21.9	0.8	0.2
	17	Max. RH (%)	79–97	79–98	-1	0.8
	17	Min. RH (%)	43–83	48–84	-4	2.4
	17	Ave. RH (%)	62–92	64–94	-3	0.8
Clear and hot	7	Max. Ta (℃)	28.3–36.8	25.2–33.7	3.2	0.5
	7	Min. Ta (℃)	13.3–19.0	13.4–18.7	0.0	0.3
	7	Ave. Ta (℃)	22.6–29.3	21.3–27.8	1.5	0.2
	7	Max. RH (%)	81–96	82–98	0	1.4
	7	Min. RH (%)	28–50	33–57	-6	1.3
	7	Ave. RH (%)	49–70	51–75	-3	1.4
TOTAL	43	Max. Ta (℃)	18.9–36.8	17.9–33.7	2.4	0.9
	43	Min. Ta (℃)	9.7–20.1	9.7–19.9	0.1	0.2
	43	Ave. Ta (℃)	16.0–29.3	15.2–27.8	1.0	0.4
	43	Max. RH (%)	79–97	79–98	0.0	1.2
	43	Min. RH (%)	28–83	33–84	-5	2.3
	43	Ave. RH (%)	49–92	51–94	-3	1.2

[a] $\frac{1}{K}\sum_{d=1}^{K}(Features\ on\ daily\ basis)$

Where: d is the index of observation day (d=1,…, K), K= 17 for cloudy and cool days and 7 for clear and hot days

Appendix 3.2 Summarized table on daytime Ta and RH between cloudy and cold and clear and mild days in the daytime of winter.

Weather	No. of days	Features	Features on daily basis [a]		Mean differences	
			Site one (no trees)	Site four (beneath tree)	(Site one minus Site four)	
					Value	*Std. Deviation*
Cloudy and cold	11	Max. Ta (℃)	-2.2–4.6	-2.7–3.9	0.6	0.1
	11	Min. Ta (℃)	-4.2–2.0	-4.9–1.6	0.5	0.2
	11	Ave. Ta (℃)	-3.2–3.3	-3.9–2.8	0.6	0.1
	11	Max. RH (%)	89–96	90–98	-1.8	0.4
	11	Min. RH (%)	79–94	81–96	-2.2	0.6
	11	Ave. RH (%)	83–95	85–97	-2.0	0.4
Clear and mild	6	Max. Ta (℃)	7.6–13.4	7.4–12.7	0.5	0.2
	6	Min. Ta (℃)	0.2–4.4	0.4–4.3	0.1	0.2
	6	Ave. Ta (℃)	5.1–10.3	4.9–9.6	0.5	0.2
	6	Max. RH (%)	86–96	87–96	-1	0.6
	6	Min. RH (%)	55–78	58–80	-3	1.4
	6	Ave. RH (%)	66–83	69–84	-3	0.9
TOTAL	58	Max. Ta (℃)	-2.2–13.4	-2.7–12.9	0.5	0.2
	58	Min. Ta (℃)	-4.2–10.3	-4.9–10.2	0.2	0.2
	58	Ave. Ta (℃)	-3.2–11.4	-3.9–11.2	0.5	0.2
	58	Max. RH (%)	68–97	69–98	-1	0.6
	58	Min. RH (%)	55–94	58–96	-2	1.0
	58	Ave. RH (%)	62–95	63–97	-3	0.6

[a] $\frac{1}{K}\sum_{d=1}^{K}(Features\ on\ daily\ basis)$

Where: d is the index of observation day (d=1,…, K), K= 11 for cloudy and cool days and 6 for clear and hot days

Appendix 3.3 Summary on the comparison of 24 hours Ta and wind between the CU and NT conditions of selected days.

Days	**Features**	**Values** (Range of receptors)		**Differences** [a]
		Current (CU)	No tree (NT)	NT minus CU (SD) [b]
2nd Aug, 2013	Max Ta (℃)	33.6–34.9 [c]	34.7–36.0	1.1 *(0.23)*
clear and hot	Min. Ta (℃)	19.6–20.3 [c]	19.6–20.3	0.0 *(0.03)*
	Ave. Ta (℃)	26.4–26.9 [c]	26.9–27.4	0.5 *(0.04)*
3rd Aug, 2013	Max Ta (℃)	24.7–26.2 [c]	24.8–26.3	0.2 *(0.05)*
cloudy and cool	Min. Ta (℃)	20.5–21.1 [c]	20.5–21.1	0.0 *(0.03)*
	Ave. Ta (℃)	22.4–23.2 [c]	22.5–23.3	0.1 *(0.03)*
18th Jan, 2014	Max Ta (℃)	8.5–9.4 [d]	8.6–9.5	0.2 *(0.05)*
clear and mild	Min. Ta (℃)	5.8–6.3 [d]	5.8–6.3	0.0 *(0.05)*
	Ave. Ta (℃)	6.7–7.2 [d]	6.7–7.2	0.1 *(0.02)*
21st Jan, 2014	Max Ta (℃)	2.3–2.7 [d]	2.3–2.7	0.0 *(0.02)*
cloudy and cold	Min. Ta (℃)	1.2–1.5 [d]	1.2–1.5	0.0 *(0.02)*
	Ave. Ta (℃)	1.7–2.1 [d]	1.7–2.1	0.0 *(0.01)*

[a] $\frac{1}{M}\sum_{j=1}^{M}\left(DFcu_j - DFnt_j\right)$

Where: j is the index of receptors (j=1,…, M); M = 68

[b] SD (SD) is given in parenthesis

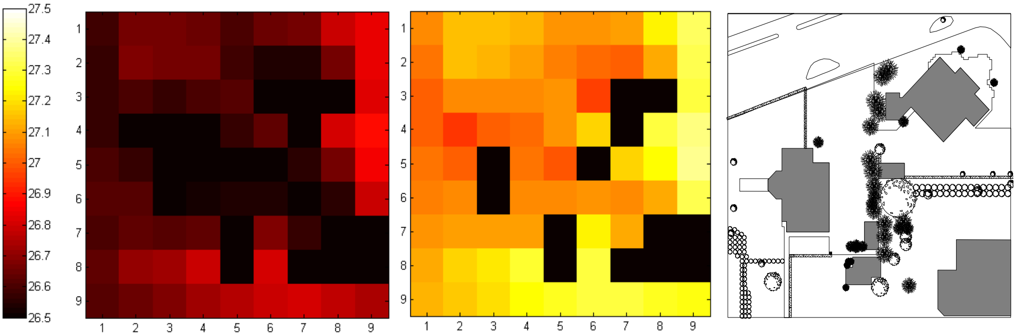
[c] 5% mixed tree cover in the summer

[d] 3% evergreen tree cover in the winter

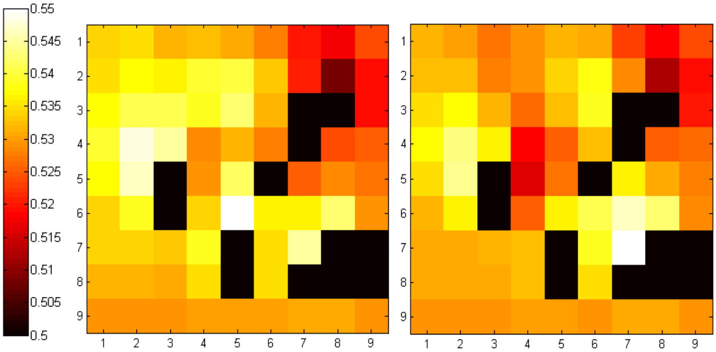
Appendix 3.4 Comparisons of average value (a), CR (b) and TR (c) of Ta between CU and NT conditions on 2nd August, 2013.

	CU condition	NT condition	Sitemap

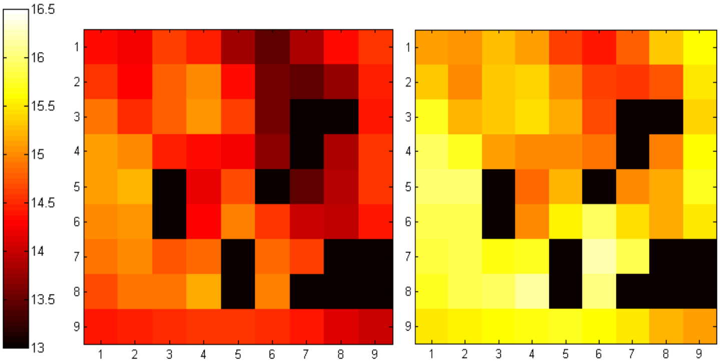
(a)



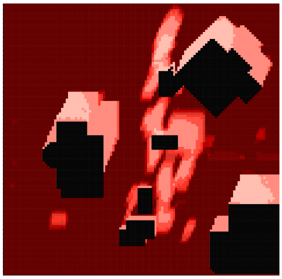
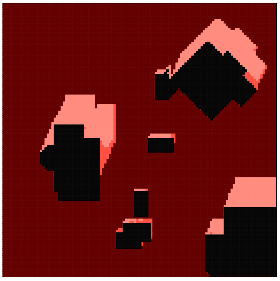
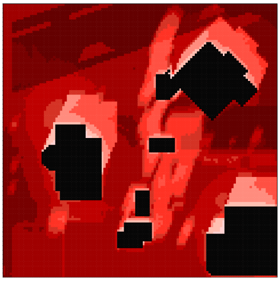
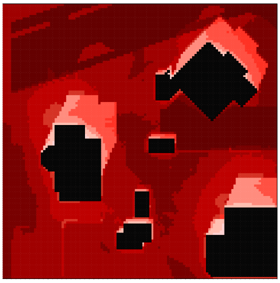
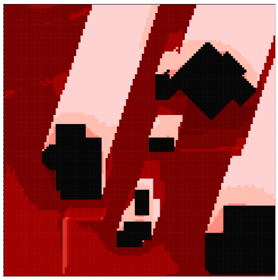
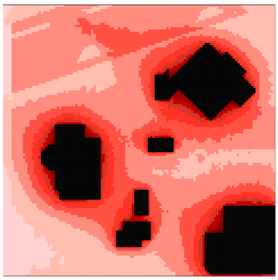
(b)



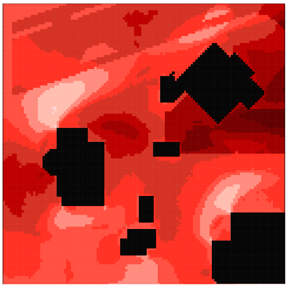
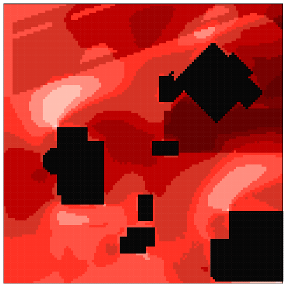
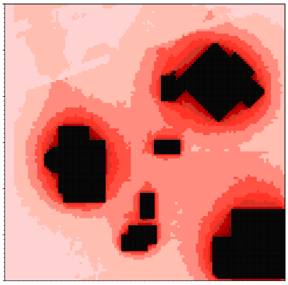
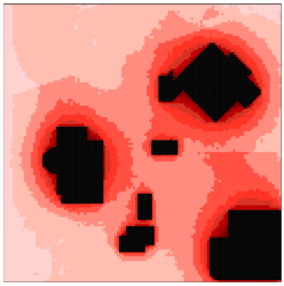
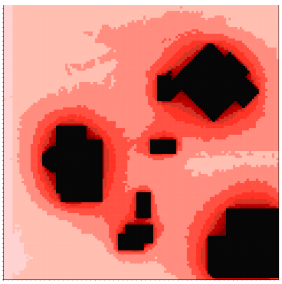
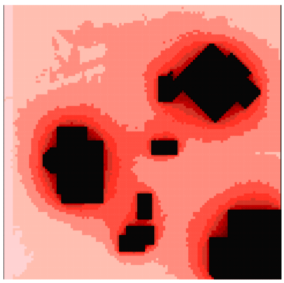
(c)



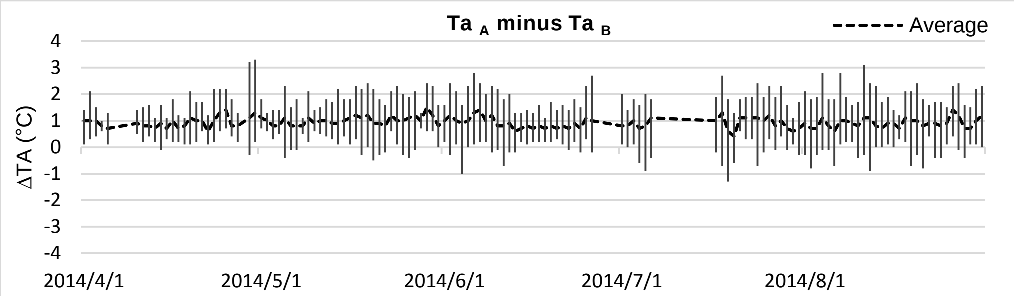
Appendix 3.5 PMV value (at 1.5m height) at 14:00 on 2nd and 3rd August, 2013 under CU (left) and NT (right) conditions.

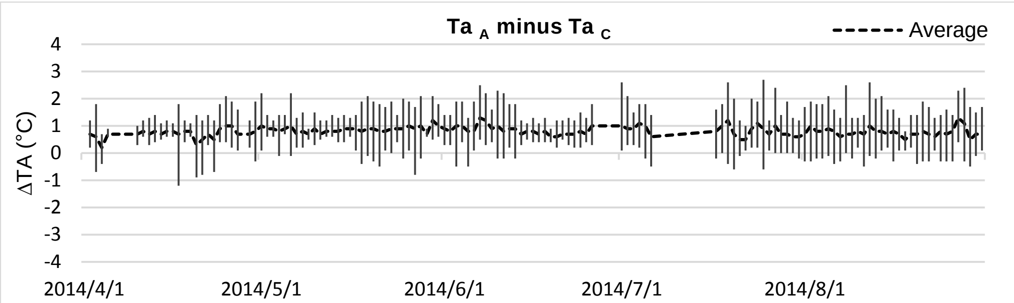
Days	Current (CU)	No tree (NT)	PMV
2nd August, 2013 *clear and hot*			***PMV Value*** below 2.60 2.60 to 2.96 2.96 to 3.33 3.33 to 3.69 3.69 to 4.05 4.05 to 4.41 4.41 to 4.77 4.77 to 5.14 5.14 to 5.50 above 5.50
3rd August, 2013 *cloudy and cool*			***PMV Value*** below 1.40 1.40 to 1.60 1.60 to 1.80 1.80 to 2.00 2.00 to 2.20 2.20 to 2.40 2.40 to 2.60 2.60 to 2.80 2.80 to 3.00 above 3.00
18th January, 2014 *clear and mild*			***PMV Value*** below 0.45 0.45 to 0.55 0.55 to 0.65 0.65 to 0.75 0.75 to 0.85 0.85 to 0.95 0.95 to 1.05 1.05 to 1.15 1.15 to 1.25 above 1.25
21st January, 2014 *cloudy and cold*			***PMV Value*** below -0.16 -0.16 to -0.15 -0.15 to -0.14 -0.14 to -0.13 -0.13 to -0.12 -0.12 to -0.11 -0.11 to -0.10 -0.10 to -0.09 -0.09 to -0.08 above -0.08

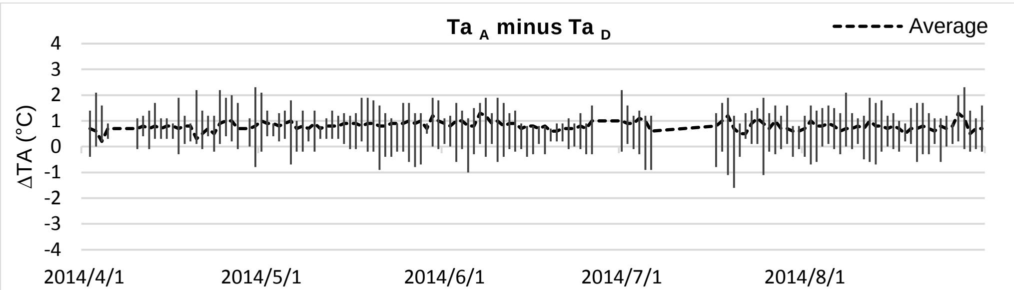
Appendix 3.6 PMV value (at 1.5m height) at 22:00 on 2nd and 3rd August, 2013 under CU (left) and NT (right) conditions.

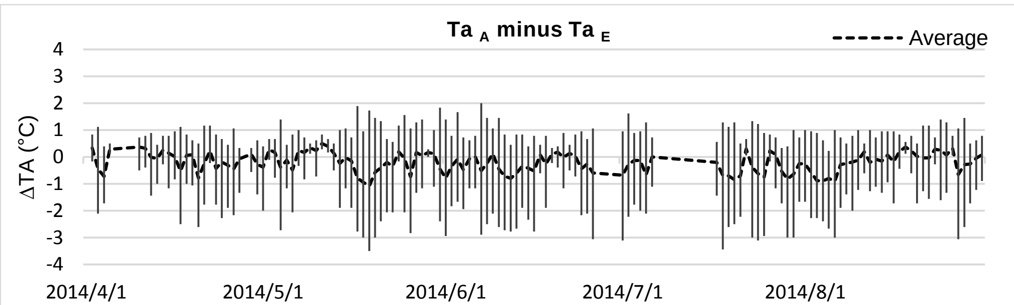
Days	Current (CU)	No tree (NT)	PMV
2nd August, 2013 *clear and hot*			***PMV Value*** below -0.16 -0.16 to -0.15 -0.15 to -0.14 -0.14 to -0.13 -0.13 to -0.12 -0.12 to -0.11 -0.11 to -0.10 -0.10 to -0.09 -0.09 to -0.08 above -0.08
3rd August, 2013 *cloudy and cool*			***PMV Value*** below 0.08 0.08 to 0.12 0.12 to 0.16 0.16 to 0.20 0.20 to 0.24 0.24 to 0.28 0.28 to 0.32 0.32 to 0.36 0.36 to 0.40 above 0.40
18th January, 2014 *clear and mild*			***PMV Value*** below 0.12 0.12 to 0.14 0.14 to 0.15 0.15 to 0.17 0.17 to 0.19 0.19 to 0.21 0.21 to 0.23 0.23 to 0.24 0.24 to 0.26 above 0.26
21st January, 2014 *cloudy and cold*			***PMV Value*** below -0.22 -0.22 to -0.20 -0.20 to -0.19 -0.19 to -0.18 -0.18 to -0.16 -0.16 to -0.15 -0.15 to -0.13 -0.13 to -0.12 -0.12 to -0.11 above -0.11

Appendix 4.1 Ta differences between Sites A and B; Sites A and C; Sites A and D; and Sites A and E.









Note: The vertical line on the chart shows the range of Ta differences (the highest and lowest values) over one day

Appendix 4.2 Summarized table on differences of daytime Ta and RH between Site A (open space) and Site B (grove).

Months	No. of days (N)	Features	Differences of Ta (℃) A minus B			Differences of RH (%) A minus B		
			Value per day	*Mean*	*Std. Deviation*	*Value per day*	*Mean*	*Std. Deviation*
April	25	Maximum	1.0–3.3	1.7	0.6	0–6	2	1
	25	Minimum	-0.3–0.7	0.3	0.2	-15–-1	-5	3
	25	Average	0.6–1.4	0.9	0.2	-4–1	-1	1
May	31	Maximum	1.1–2.4	1.9	0.4	-1–9	3	3
	31	Minimum	-0.5–0.7	0.2	0.4	-10–-3	-6	2
	31	Average	0.8–1.5	1.0	0.2	-3–1	-1	1
June	26	Maximum	1.1–2.8	1.8	0.5	1–8	3	2
	26	Minimum	-1.0–0.3	-0.0	0.3	-9–-2	-5	2
	26	Average	0.6–1.4	0.9	0.2	-2–0	-1	1
July	21	Maximum	1.1–2.7	1.9	0.4	0–11	4	3
	21	Minimum	-1.3–0.6	-0.2	0.5	-9–-2	-5	2
	21	Average	0.4–1.3	0.9	0.2	-3–2	-1	1
August	31	Maximum	1.2–3.1	2.0	0.5	-1–8	3	2
	31	Minimum	-0.9–0.4	-0.2	0.4	-14–-1	-6	3
	31	Average	0.6–1.4	0.9	0.2	-4–2	-1	1
TOTAL	134	Maximum	1.0–3.3	1.9	0.5	-1–11	3	2
	134	Minimum	-1.3–0.7	-0.0	0.4	-15–-1	-5	3
	134	Average	0.4–1.5	0.9	0.2	-4–2	-1	1

Appendix 4.3 Summarized table on differences of daytime Ta and RH between Site A (open space) and Site B (single deciduous tree).

Months	No. of days (N)	Features	Differences of Ta (℃) A minus C			Differences of RH (%) A minus C		
			Value per day	*Mean*	*Std. Deviation*	*Value per day*	*Mean*	*Std. Deviation*
April	25	Maximum	0.7–2.2	1.4	0.4	0–8	3	1
	25	Minimum	-1.2–0.6	0.1	0.6	-11–1	-4	2
	25	Average	0.2–1.0	0.7	0.2	-3–1	-0	1.1
May	31	Maximum	0.9–2.2	1.6	0.4	-1–8	2	2
	31	Minimum	-0.8–0.6	0.2	0.4	-11–-2	-5	2
	31	Average	0.7–1.2	0.9	0.1	-4–0	-1	1
June	26	Maximum	0.9–2.6	1.6	0.5	0–5	3	1
	26	Minimum	-0.5–0.5	0.2	0.3	-9–-2	-5	2
	26	Average	0.6–1.3	0.8	0.2	-3–1	-1	1
July	21	Maximum	1.0–2.7	1.7	0.5	1–9	4	2
	21	Minimum	-0.6–0.3	-0.1	0.3	-8–-1	-5	2
	21	Average	0.5–1.2	0.8	0.2	-2–2	-0	1
August	31	Maximum	0.8–2.6	1.7	0.4	1–6	4	1
	31	Minimum	-0.5–0.4	-0.1	0.2	-10–-1	-5	2
	31	Average	0.5–1.3	0.8	0.2	-3–2	0	1
TOTAL	134	Maximum	0.7–2.7	1.6	0.4	-1–9	3	2
	134	Minimum	-1.2–0.7	0.1	0.4	-11–-1	-5	2
	134	Average	0.2–1.3	0.8	0.2	-4–2	-1	1

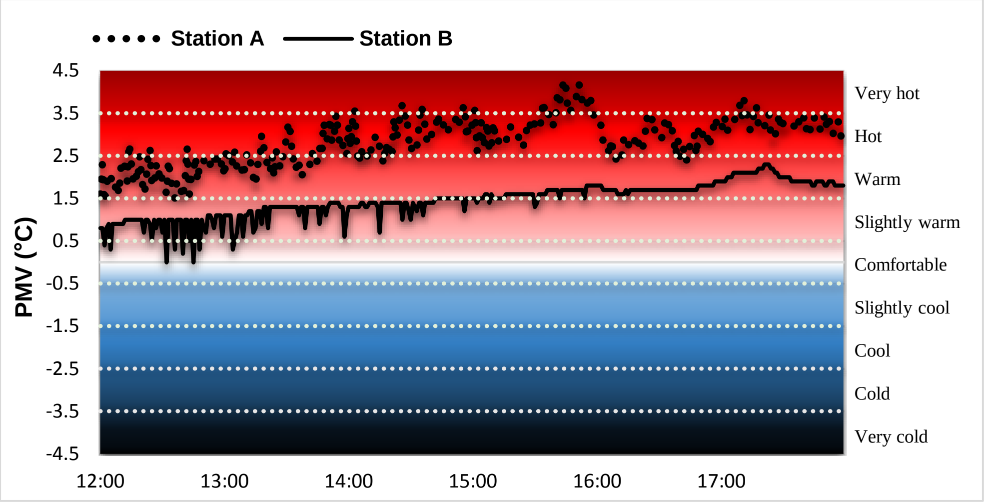
Appendix 4.4 Summarized table on differences of daytime Ta and RH between Site A (open space) and Site D (street trees).

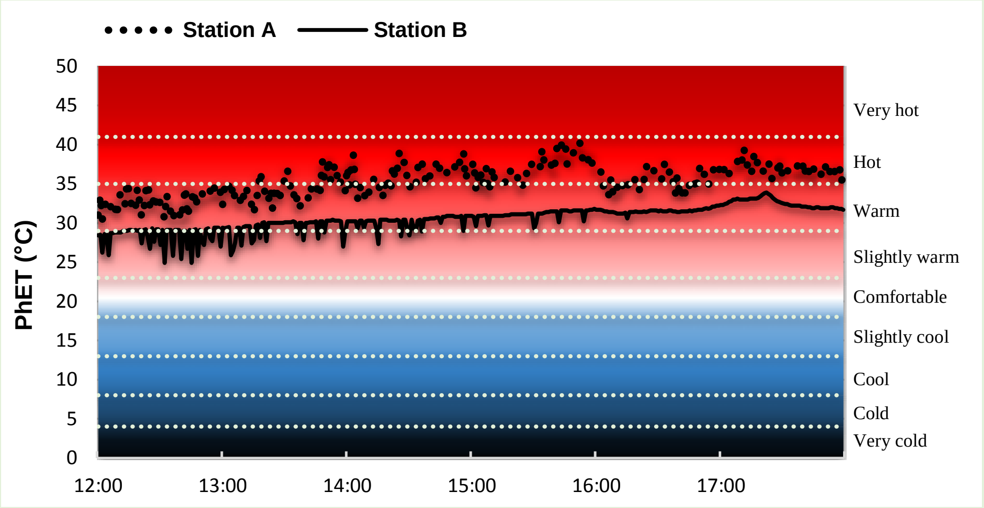
Months	No. of days (N)	Features	Differences of Ta (℃) A minus D			Differences of RH (%) A minus D		
			Value per day	*Mean*	*Std. Deviation*	*Value per day*	*Mean*	*Std. Deviation*
April	25	Maximum	0.9–2.3	1.5	0.5	0–6	3	1
	25	Minimum	-0.8–0.4	0.0	0.3	-10–0	-3	2
	25	Average	0.5–1.1	0.7	0.2	-2–1	-0	1
May	31	Maximum	0.7–1.9	1.4	0.3	-1–8	3	2
	31	Minimum	-0.9–0.5	-0.1	0.4	-7–-2	-3	0
	31	Average	0.4–0.9	0.6	0.1	-2–1	0	1
June	26	Maximum	0.6–2.2	1.3	0.4	1–10	4	2
	26	Minimum	-1.0–0.2	-0.2	0.3	-7–-1	-3	1
	26	Average	0.3–0.8	0.5	0.1	-1–1	0	0
July	21	Maximum	0.8–1.9	1.4	0.3	0–12	4	3
	21	Minimum	-1.6–0.3	-0.4	0.5	-7–-1	-4	2
	21	Average	0.2–0.8	0.5	0.2	-3–2	0	1
August	31	Maximum	0.9–2.3	1.5	0.3	1–8	3	2
	31	Minimum	-0.7–0.2	-0.2	0.3	-8–-2	-4	2
	31	Average	0.4–1.1	0.6	0.1	-2–2	0	1
TOTAL	134	Maximum	0.6–2.3	1.4	0.4	-1–12	4	2
	134	Minimum	-1.6–0.5	-0.1	0.4	-10–0	-3	2
	134	Average	0.2–1.1	0.6	0.1	-3–2	0	1

Appendix 4.5 Summarized table on differences of daytime Ta and RH between Site A (open space) and Site E (building façade).

Months	No. of days (N)	Features	Differences of Ta (℃) A minus E			Differences of RH (%) A minus E		
			Value per day	*Mean*	*Std. Deviation*	*Value per day*	*Mean*	*Std. Deviation*
April	25	Maximum	0.3–1.2	0.7	0.3	3–13	8	3
	25	Minimum	-2.6–0.1	-1.3	0.8	-6–1	-1	1
	25	Average	-0.8–0.4	-0.1	0.3	1–5	3	1
May	31	Maximum	0.3–1.9	1.0	0.4	2–13	8	4
	31	Minimum	-3.5–0.3	-1.5	1.1	-8–2	-3	3
	31	Average	-1.1–0.5	-0.2	0.4	0–6	2	2
June	26	Maximum	0.3–2.0	0.9	0.4	3–13	8	3
	26	Minimum	-3.1–-0.2	-1.9	0.9	-9–0	-2	2
	26	Average	-0.8–0.2	-0.3	0.3	1–4	3	1
July	21	Maximum	0.3–1.6	0.9	0.3	2–12	9	3
	21	Minimum	-3.4–0.1	-2.0	0.9	-5–1	-2	2
	21	Average	-0.9–0.3	-0.4	0.4	0–5	3	1
August	31	Maximum	0.2–1.4	0.9	0.3	2–13	8	3
	31	Minimum	-3.1–0.1	-1.4	0.8	-4–1	-2	1
	31	Average	-0.9–0.4	-0.1	0.4	1–6	3	1
TOTAL	134	Maximum	0.2–2.0	0.9	0.4	2–13	8	3
	134	Minimum	-3.5–0.3	-1.6	1.0	-9–2	-2	2
	134	Average	-1.1–0.5	-0.2	0.4	0–6	3	1

Appendix 4.6 Diurnal PhET and PMV values from 10:00 to 18:00 on 18th July.





Appendix 5.1 The questionnaire for the thermal comfort survey at the Zernike Campus.

Thermal comfort survey at the Zernike Campus

Survey Date: ……………… Time: ……………… Location: ……………… No: …………

Current activity:

□ Reclining □ Seated quiet □ Standing relaxed □ Light activity □ Medium activity □ High activity

SECTION ONE

Age: …………………………; **Nationality:** ………………..; **Gender:** Male/Female

Weight (kg): ……………….; **Height (cm):** ……………….;

What is your clothing now?

□ Shorts □ Casual clothing □ Light summer cloths □ Street suit

□ Suit and cotton coat □ Winter suit and coat □ Other……………….....................................;

SECTION TWO

1a. How do you experience/feel the present temperature?

□ Cold □ Cool □ Slightly cool □ Neutral □ Slightly warm □ Warm □ Hot

1b. How would you prefer the temperature to be?

□ Much warmer □ A bit warmer □ No change □ A bit cooler □ Much cooler

2a. How do you experience the air movement (windiness)?

□ Very high □ High □ Slightly high □ Neither high nor low
□ Slightly low □ Low □ Very low

2b. How would you prefer to have the air movement?

□ Much more air movement □ A bit more air movement □ No change
□ A bit less air movement □ Much less air movement

3a. How do you experience the humidity (wetness fraction)?

□ Very humid □ Humid □ Slightly humid □ Neither humid nor dry
□ Slightly dry □ Dry □ Very dry

3b. How would you prefer the humidity to be?

□ Much drier □ A bit drier □ No change □ A bit more humid □ Much more humid

4. How would you rate your overall comfort at this moment?

□ Very comfortable □ Moderately comfortable □ Slightly comfortable □ Neutral
□ Slightly uncomfortable □ Moderately uncomfortable □ Very uncomfortable

5. What measures would you prefer to take if you felt it is too hot?

□ Move to shaded place □ Open umbrella/wear hat □ Get more to drink □ Reduce clothing
□ Nothing/go away

SECTION THREE

1. If you are not Dutch, how long have you been in *__The Netherlands__*?

………………………………………………………………………………………………………

2. Why do you come to this *__specific location__* at the campus?

………………………………………………………………………………………………………

3. How long have you been to this *__specific location__*?

………………………………………………………………………………………………………

4. How often do you come to this *__specific location__*?

………………………………………………………………………………………………………

5. Where have you been in the *__last 15/20 minutes__*?

………………………………………………………………………………………………………

6. What activities have you done in the *__last 15/20 minutes__*?

………………………………………………………………………………………………………

Appendix 5.2 The respondents' preferences regarding the thermal, humidity and wind speed condition.

Respondents' preferences	-2		-1		0		1		2	
	N	%	N	%	N	%	N	%	N	%
Thermal	much cooler		a bit cooler		no change		a bit warmer		much warmer	
	2	0.5	77	19.8	186	47.8	99	25.4	25	6.4
Humidity	much drier		a bit drier		no change		a bit more humid		much more humid	
	9	2.3	58	14.9	268	69.1	52	13.4	1	0.3
Wind speed	much less air movement		a bit less air movement		no change		a bit more air movement		much more air movement	
	41	10.5	98	25.2	163	41.9	77	19.8	10	2.6

Summary

Urban areas cover less than 5% of the world's land surface, but more than half of the world population lives in cities, and this will likely increase. Urban sprawl and rapid population growth causes many environmental problems such as air pollution, urban warming and noise. During the last few decades, many studies have shown that natural elements in urban areas (e.g. trees, parks and small lakes) play an important role in mitigating these problems and improving urban quality under both rapid population growth and climate change. In the 1990s, the concept of 'Urban Green Infrastructure (UGI)' was introduced to support an ecosystem-based approach in urban planning instead of a purely technological approach. Due to the heterogeneity of the urban environment, the effect of UGI varies spatially and temporally. To better plan UGI and account for its heterogeneity, the effects of UGI on human comfort are investigated locally in this thesis.

Within in this broad question, my research analyses the effects of UGI on local microclimate and human thermal comfort. The rapid development of urban infrastructure causes changes in surface geometry and materials, releases heat and reduces natural land cover. These processes lead to urban warming and deteriorate thermal comfort conditions. Using UGI to mitigate urban warming and promote human health has been proposed by various earlier studies. Yet finding feasible urban designs that take full advantage of UGI, is a big challenge for researchers and urban designers. UGI has many complex interlinkages with local microclimate and human thermal comfort. Thus investigating UGI should be done in an integrated manner and combine various methods from different disciplines.

In my thesis I therefore identified and quantified the influence of UGI on microclimate and human comfort in a local area by combining field measurements, modelling and social surveys. Four research questions were formulated to achieve this objective: 1) What are the ESs of UGI that influence human urban habitats; 2) What factors influence the capacity of UGI to regulate microclimate; 3) How can the effect of UGI on local microclimate and human thermal comfort be measured; and 4) How do people perceive thermal comfort in small urban green areas locally and how is this related to UGI planning and management.

To address the first research question, I conducted an extensive literature review of 148 publications on urban ecosystem services and the underlying processes and functions. In Chapter 2 the state-of-the-art research on urban ecosystem services and their effects on environmental quality in outdoor and indoor spaces is described. The most important ecosystem functions involved in the link between UGI and microclimate regulation were found to be shading, evapotranspiration, and wind shielding. During the daytime, trees and tall bushes provide shades that buffer solar radiation, whereas at night, they block heat flow and reduce heat exchange. The ambient air temperature and humidity are influenced by evapotranspiration and wind speed is reduced by vegetation. The wind shielding effect influences human thermal comfort both positively and negatively. Based on the literature review, I identified four main factors and sub-factors that show how UGI affect microclimate regulation through local morphology (configuration of building and vegetation, orientation of building and vegetation), geographical conditions (ground property, local climate and weather condition), vegetation characteristics (vegetation quality and quantity, plant area index (PAI) or leaf area index (LAI), vegetation structure and species composition), and building characteristics (façade property, air ventilation and infiltration rate). My results show that some quantitative information on the climate-effect of individual factors was found in the literature but the combined effects of these four factors on vegetation's microclimate regulation and seasonal influence remain unclear. My literature review revealed that most published data are based on model-studies and that empirical research on urban ecosystem services is rare. I also found that the information on UGI's microclimate regulation at the national, regional and local level is fragmented and incomplete. Hence, better integration of modelling with empirical research and field measurements is required to improve our understanding of the effects of UGI on local microclimate and human comfort.

To observe the microclimatic differences between shaded and unshaded areas, and to examine the impact of local morphology and weather conditions on UGI's microclimate regulation, I conducted field measurements and numerical modelling (with the ENVI-met model) in a small urban area (3,600 m^2) in Assen (NL) (Chapter 3). Assen enjoys a typical oceanic climate with mild winters and cool summers with evenly distributed precipitation over the year. July and August are the warmest months and January and February are the coldest months. During both summer and winter periods, air temperature and relative humidity were continuously measured at five selected sites with clearly different environmental characteristics of UGI. In the summer, urban microclimate and human thermal comfort varied significantly in close geographical proximity and both were strongly affected by the presence of trees. Shaded areas showed lower air temperature (approximately 1.0 ℃) and higher average relative humidity (approximately 3%), compared to unshaded areas. These differences reached 3.5 ℃ and 5% on a hot sunny day. In the winter, the evergreen trees slightly lowered the average air temperature by approximately 0.5 ℃. This could increase energy costs and potentially offset the energy benefits of trees in the winter. The biological and physical processes (evapotranspiration, wind shielding and shading) involved in microclimate regulation were affected by the surrounding temperature, humidity and solar radiation. I found that the trees' performance on influencing microclimate in the summer was strongly influenced by prevailing weather conditions: the cooling effect of trees on clear and hot days was approximately two times higher than on cloudy cold days.

To study the impact of vegetation density and PAI on microclimate regulation by different UGIs in more detail, follow-up field measurements were done in the same area in Assen (Chapter 4). During the growing season (April to August), microclimatic data were acquired at five different locations: an open space, a grove, a single deciduous tree, street trees and a building façade. Gap fraction analysis and the globe-thermometer method were used to quantify PAI and thermal comfort, respectively. The cooling capabilities of the different observed UGIs in terms of reductions of daily average air temperature were 0.9 ℃ for a multiple tree grove, 0.8 ℃ for a single deciduous tree and 0.6 ℃ for a group of street trees. These results show that higher tree density reduced the temperature only slightly more than a single tree while street trees surrounded by asphalt paved surface were much less effective. Due to the low-albedo (i.e. asphalt paved surface and building materials), building façades increased the daily maximum air temperature by 1.6 ℃. This offsets the temperature reductions by UGI. A positive correlation was found between PAI and the differences of mean radiant temperature (between shaded and unshaded areas) with a 2.054 gradient coefficient. This indicates that a gain in the PAI value by one unit would reduce the mean radiant temperature increase by 2.0 ℃.

Although the improvement of human thermal comfort by UGI was confirmed by both modelling and empirical measurements (Chapters 3 and 4), people's subjective thermal perception and preferences should also be studied because each individual is not simply a passive recipient of the ambient thermal environment. In addition to physical environmental factors, behavioural factors and psychological factors are also important in the assessment of thermal environments. To explore people's subjective thermal perception and preference in a small urban area, thermal comfort was studied at the Zernike university campus of Groningen (Chapter 5). Groningen is about 25 km north from Assen and enjoys a similar climate and houses one of the oldest and largest universities in The Netherlands. Students represent one third of the whole city population. Mobile measurements of weather-conditions and a survey were performed in five green spaces at the Zernike Campus on five warm and cloudless days (the outdoor operative temperatures on these days ranged between 22.4 ℃ to 40.4 ℃). In spite of these high temperatures, approximately 95% of respondents were satisfied with their environment and felt 'comfortable' in the green space during the survey days. Higher wind speed led to a cooler thermal sensation with a correlation coefficient of -0.173. Based on the response votes and the physical measurements, the neutral operative temperature (i.e. comfort temperature) and preferred temperature (the temperature people stated they would prefer) were 22.2 ℃ and 35.7 ℃ respectively according to a linear regression with a probit model. The neutral operative temperature was in accordance to the literature and our expectations. The stated preferred temperature was, however, remarkably high. Of the respondents who felt 'slightly warm' and 'warm', respectively 42% and 17% still preferred 'warmer' temperatures. This was partly explained by the respondents' origin. Most come from temperate regions and are inclined to describe their preferred state as 'warmer', since 'cooler' usually implies an undesirable state to them. Based on the Kruskal-Wallis H Test, I found that people's actual current thermal sensation was both significantly influenced by their thermal experience shortly before the survey and by their longer-term history (i.e. the thermal environment and climate in their home country). Respondents from hot regions expressed a relatively cooler thermal sensation, while those from cold regions expressed relatively warmer thermal sensation under the same conditions. This can be explained by the fact that people who normally live in hot regions, are more used to hot conditions. Interestingly, although my survey was done on hot days most respondents from tropical regions preferred 'cooler' temperatures, while those from temperate regions preferred 'warmer' temperatures.

To gain more comprehensive insight into the effects of UGI on microclimate and human thermal comfort Chapter 6 integrates the findings from Chapters 2, 3, 4 and 5. Strengths and weaknesses of my methodology are discussed and recommendations for UGI planning and use in urban areas are provided. The need for better integration of field measurements, modelling and social survey studies locally is emphasized in order to better understand the effects of UGI on local microclimate and human comfort.

I conclude that well-planned and managed UGI substantially buffers local urban warming and enhances summer thermal comfort. This effect is influenced by local morphology, geographical conditions and vegetation characteristics. Besides these physical factors, the behavioural/psychological factors (e.g. exposure time, previous thermal environment and activity shortly before the survey, and thermal history) also play important roles in human thermal sensation. The results of my study imply that future research should pay more attention to the heterogeneity in the urban context and that the planning of UGI should consider people's thermal preferences and adaptation factors. An integrated approach is therefore essential to evaluate the influence of different types of UGI on both physical microclimate and people's subjective thermal comfort. The approach presented in my research make it possible to quantitatively analyse UGI's role in regulating local microclimate, examine the impacts of the main controlling factors, and explore the relative impact of thermal adaptation factors on people's thermal comfort. My findings can contribute to better planning and management of UGI as an important instrument for sustainable urbanisation and climate change adaptation.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characteristics
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winter
unshaded
subjective
influenced
operative
respondents
physical
average

Samenvatting

Ondanks het feit dat stedelijke gebieden slechts 5% van de landoppervlakte op aarde beslaan, leeft meer dan de helft van de wereldbevolking in steden. De trek van mensen uit landelijke gebieden naar steden (ook wel urbanisatie genoemd) is een trend die zich wereldwijd door lijkt te zetten. De combinatie van deze stadsuitbreiding en de snelle toename van de wereldbevolking veroorzaakt diverse milieuproblemen, zoals luchtvervuiling, stedelijke opwarming en geluidsoverlast. In de afgelopen decennia hebben vele onderzoeken laten zien dat natuurlijke elementen in steden (e.g. bomen, parken en vijvers) een belangrijke rol spelen in het beperken van deze milieuproblematiek en in het verbeteren van het stedelijk leefklimaat, ondanks snelle bevolkingsgroei en klimaatveranderingen. Het concept ‘Stedelijk Groene Infrastructuur (UGI)’ werd in de jaren 90 van de vorige eeuw geïntroduceerd om stadsplanning vanuit het perspectief van ecosystemen te benaderen in plaats van uit puur technologisch oogpunt. Als gevolg van de heterogeniteit van de stedelijke omgeving varieert het effect van UGI aanzienlijk afhankelijk van de locatie en het tijdstip. Om de UGI beter te kunnen plannen, rekening houdend met deze heterogeniteit, worden in dit proefschrift de lokale effecten van UGI op het menselijk comfort onderzocht.

Dit proefschrift beschrijft de effecten van de UGI op het lokale microklimaat en het menselijke thermisch comfort. De snelle ontwikkeling van de stedelijke niet-groene infrastructuur veroorzaakt veranderingen in de oppervlaktetopologie en –samenstelling, draagt bij aan de vorming van hitte-eilanden en zorgt voor een afname van natuurlijke bodembedekking. Deze processen leiden tot lokale opwarming en verslechteren het thermisch comfort. Het inzetten van UGI om stedelijke opwarming tegen te gaan en de gezondheid van inwoners te verbeteren is aangedragen in diverse wetenschappelijke studies. Het vinden van praktisch haalbare oplossingen waarbij UGI in al zijn potentieel wordt gebruikt is echter een grote uitdaging voor wetenschappers en stadsontwerpers. Omdat de UGI vele complexe relaties heeft met het lokale microklimaat en menselijk thermisch comfort dient het onderzoek naar UGI zodanig te worden opgezet dat verschillende methoden uit meerdere disciplines worden gecombineerd.

In dit onderzoek is de lokale invloed van de UGI op het microklimaat en menselijk thermisch comfort geïdentificeerd en gekwantificeerd door een combinatie van veldmetingen, modellen

en enquêtes. Er zijn vier onderzoeksvragen geformuleerd ten behoeve van deze doelstelling: 1) Wat zijn de ecosysteemdiensten van de UGI die invloed hebben op de stedelijke leefomgeving van de mens; 2) Welke factoren beïnvloeden de capaciteit van de UGI om het microklimaat te reguleren; 3) Hoe kan het effect van de UGI op het lokale microklimaat worden gemeten; 4) Wat is de perceptie van thermisch comfort in klein stedelijk groene zones en hoe is dit gerelateerd aan UGI planning en management.

Om de eerste onderzoeksvraag te kunnen beantwoorden is een uitgebreide literatuurstudie uitgevoerd onder 148 publicaties over stedelijke ecosysteemdiensten en de onderliggende processen en functies. Hoofdstuk 2 geeft een overzicht van het recente onderzoek naar stedelijke ecosysteemdiensten en de effecten hiervan op de milieukwaliteit in binnen- en buitenruimten. De belangrijkste ecosysteemfuncties van de UGI die zijn betrokken bij regulatie van het microklimaat zijn het bieden van schaduw, evapotranspiratie en de afscherming van de wind. Overdag bieden bomen en hoge struiken bescherming tegen zonnestraling, terwijl ze 's nachts juist de warmtestroom blokkeren en warmtewisseling met de atmosfeer tegengaan. De omgevingstemperatuur en –luchtvochtigheid worden beïnvloed door evapotranspiratie-processen en de windsnelheid wordt verlaagd door de aanwezigheid van vegetatie. De verlaging van windsnelheid heeft zowel positieve als negatieve effecten op het menselijk comfort. Uit het literatuuronderzoek blijkt dat er vier hoofdfactoren en sub-factoren zijn die de relatie tussen UGI en microklimaatregulatie karakteriseren: de lokale morfologie (configuratie van bebouwing en vegetatie, oriëntatie van gebouwen en vegetatie), geografische condities (grondsoort, lokaal klimaat en weersomstandigheden), vegetatiekarakteristieken (kwaliteit en kwantiteit, plantoppervlakte-index (PAI) of bladoppervlakte-index (LAI), structuur van de vegetatie en samenstelling van de plantsoorten), en bebouwingskarakteristieken (eigenschappen van de gevels, luchtventilatie en infiltratiesnelheid). Kwantitatieve relaties tussen de individuele factoren en het microklimaat zijn in verschillende studies reeds onderzocht. Echter, de combinatie van bovenstaande vier factoren en hun seizoensafhankelijkheid blijkt onvoldoende geadresseerd in eerdere studies. Uit het literatuuronderzoek blijkt dat de meeste studies zijn gebaseerd op modellen en dat empirisch onderzoek op het gebied van stedelijke ecosysteemdiensten schaars is. Daarnaast is de informatie over microklimaatregulatie door UGI op nationaal, regionaal en lokaal niveau erg gefragmenteerd en incompleet. Daarom is een verdere en betere integratie van modellering, empirisch onderzoek en metingen essentieel om het begrip van de effecten van UGI op het lokale microklimaat en menselijk comfort te verhogen.

De microklimaatverschillen tussen schaduwrijke en schaduwloze gebieden en de invloed van de lokale morfologie en weersomstandigheden op de regulatie van het microklimaat zijn onderzocht door middel van veldmetingen en numerieke modellering (ENVI-met model) in een klein stedelijk gebied (3,600 m^2) in Assen (NL) (Hoofdstuk 3). Assen geniet een typisch zeeklimaat met milde winters en koele zomers en heeft een neerslaghoeveelheid die gelijkmatig over het gehele jaar gespreid is. Juli en augustus zijn de warmste maanden en januari en februari zijn de koudste maanden. Gedurende de zomer- en winterperiode zijn zowel de luchttemperatuur als luchtvochtigheid continu gemeten op vijf geselecteerde plekken met duidelijk verschillende UGI karakteristieken. De resultaten laten zien dat het stedelijk microklimaat en het menselijk thermisch comfort tijdens de zomer significante verschillen kent binnen een klein gebied en dat beide sterk beïnvloed worden door de aanwezigheid van bomen. Op schaduwrijke plekken werd een lagere luchttemperatuur (gemiddeld −1.0 ℃) en een hogere gemiddelde relatieve luchtvochtigheid geconstateerd (+3%). Deze verschillen bereikten zelfs maximaal −3.5 ℃ en +5% op een warme zonnige dag. Tijdens de winter zorgden de groenblijvende bomen slechts voor een geringe lokale temperatuurdaling van −0.5 ℃. Dit laatste kan leiden tot extra verwarmingskosten in de winter en op die manier de voordelen van de aanwezigheid van bomen mogelijk tenietdoen. Biofysische processen (i.e. schaduw, evapotranspiratie en de afscherming van de wind) die betrokken zijn bij microklimaatregulatie worden beïnvloed door de omgevingstemperatuur, -luchtvochtigheid en zonnestraling. Daarnaast bleken de ‘prestaties’ van bomen – de uitwerking van bomen op het lokale microklimaat - sterk afhankelijk te zijn van de heersende weeromstandigheden in de zomer: het afkoelingseffect van bomen op heldere warme dagen was bijvoorbeeld twee keer groter dan op bewolkte koude dagen.

Voor het bestuderen van de impact van vegetatiedichtheid en de PAI op de regulatie van het microklimaat zijn vervolgmetingen uitgevoerd in hetzelfde stedelijk gebied in Assen (Hoofdstuk 4). Tijdens de vegetatieperiode (van april tot augustus) zijn gegevens over het microklimaat verzameld op vijf verschillende locaties: in open veld, tussen de bomen, onder een enkele loofboom, nabij straatbomen en langs een gebouwgevel. Gap fraction analyse en globe-thermometer metingen zijn gebruikt voor het kwantificeren van respectievelijk de PAI en het thermisch comfort. De koelcapaciteit, in termen van verlaging van gemiddelde dagelijkse luchttemperatuur (ten opzichte van het open veld), voor de verschillende type UGI's was 0.9 ℃ tussen de groep bomen, 0.8 ℃ voor een enkele loofboom en 0.6 ℃ nabij de straatbomen. Deze resultaten laten zien dat binnen een klein gebied een verhoogde dichtheid van bomen slechts zorgt voor een geringe extra temperatuurverlaging ten opzichte van een enkele boom. Daarnaast blijkt dat straatbomen wanneer omringd door asfalt en bestrating veel minder effectief zijn. Als gevolg van het lage albedo (i.e. lage reflectiecoëfficiënt kenmerkend voor asfalt, bestrating- en bouwmaterialen) en hoge warmteopslagcapaciteit leidt de aanwezigheid van een gebouwgevel juist tot en toename van de dagelijkse maximum temperatuur met 1.6 ℃. Daarnaast is een positieve relatie geconstateerd tussen de PAI en de verschillen in globetemperatuur (tussen schaduwrijke en schaduwloze gebieden), zodanig dat een toename van één eenheid in PAI leidt tot een afname van 2.0 ℃ in globetemperatuur.

Ondanks dat zowel modellering als empirisch onderzoek aantonen dat de UGI het menselijk thermisch comfort kan verbeteren (Hoofdstuk 3 en 4) is het ook van belang om de subjectieve thermische perceptie van mensen en hun persoonlijke voorkeur voor het omgevingsklimaat te bestuderen. Naast fysische omgevingsfactoren spelen gedragsfactoren en psychologische factoren namelijk ook een rol van betekenis in de beoordeling van de thermische omgeving. Om deze subjectieve thermische perceptie en voorkeuren in kaart te brengen is het thermisch comfort van mensen onderzocht op de Zernike Universiteitscampus in Groningen (Hoofdstuk 5). Groningen ligt ongeveer 25 km ten noorden van Assen, heeft een overeenkomstig klimaat en herbergt één van de oudste en grootste Nederlandse universiteiten. Studenten vertegenwoordigen er ongeveer een derde van het totaal aantal inwoners. In vijf groene zones op de Zernike Campus zijn mobiele meetstations gebruikt om het lokale microklimaat te meten en zijn er enquêtes afgenomen gedurende vijf warme en zonnige dagen (de operatieve buitentemperatuur lag tijdens deze dagen tussen de 22.4 ℃ en 40.4 ℃). Ondanks de relatief hoge buitentemperatuur gaf ongeveer 95% van de respondenten aan de groene omgeving als 'prettig en comfortabel' te ervaren. Een toename in windsnelheid resulteerde in een koelere thermische sensatie met een correlatiecoëfficiënt van −0.173. Op basis van de reacties van respondenten en de fysische metingen werd de neutrale operatieve temperatuur (i.e. de comfort temperatuur) en de voorkeurstemperatuur (de temperatuur die men aangaf te prefereren) vastgesteld op respectievelijk 22.2 ℃ en 35.7 ℃. Dit werd berekend aan de hand van lineaire regressie met een probitmodel. Het neutrale operatieve model komt goed overeen met de literatuur en verwachtingen. De vastgestelde voorkeurstemperatuur was echter opmerkelijk hoog. Respondenten die aangaven het ‘enigszins warm’ en ‘warm’ te vinden (42% en 17%) prefereerden nog steeds een hogere temperatuur. Dit effect kan deels worden toegeschreven aan de herkomst van de respondenten. Het merendeel van de respondenten kwam uit landen met een gematigd klimaat en zij neigen wellicht naar een sterke voorkeur voor warmere condities, omdat koelere condities normaal gesproken een ongewenste situatie is voor deze groep. Daarnaast is middels een Kruskal-Wallis H Test een significante relatie aangetoond tussen de actuele thermische sensatie en zowel hun thermische ervaring vlak voor de enquête alsook hun thermische lange termijn geschiedenis (i.e. de voorkomende temperaturen en het klimaat in hun thuisland). Respondenten uit warmere landen gaven onder gelijke condities aan gemiddeld een koelere thermische sensatie te ervaren dan respondenten uit koelere gebieden. Dit kan worden verklaard door het feit dat mensen die leven in warme regio’s gewend raken aan warmere condities. Opmerkelijk genoeg blijkt uit de resultaten van de enquête tijdens warme dagen dat de meeste respondenten uit tropische gebieden een voorkeur hadden voor lagere temperatuur, terwijl respondenten uit een gematigd klimaat juist een voorkeur hadden voor een hogere temperatuur.

In Hoofdstuk 6 worden de uitkomsten van de voorgaande hoofdstukken bijeen gebracht om meer inzicht in de effecten van UGI op het microklimaat en menselijk thermisch comfort te verwerven. Sterke en zwakke punten van de methodologie worden bediscussieerd en aanbevelingen voor UGI planning en gebruik in stedelijk gebied worden gemaakt. Hieruit blijkt dat een betere integratie van metingen, modellen en sociale studies essentieel is om de effecten van UGI op het lokale microklimaat en menselijk thermisch comfort te kunnen begrijpen.

Concluderend kan gezegd worden dat het goed plannen en managen van UGI substantieel kan bijdragen aan het bufferen van lokale stedelijke opwarming en het thermisch comfort in de zomer kan doen toenemen. Deze effecten van UGI zijn afhankelijk van de lokale morfologie, geografische condities en vegetatiekarakteristieken. Naast fysische factoren spelen ook gedrags- en psychologische factoren (e.g. duur van de blootstelling, activiteiten net voor de enquête en thermische geschiedenis) een rol van betekenis voor de menselijk thermische sensatie. De resultaten van dit proefschrift geven aan dat toekomstig onderzoek zich meer zou moeten richten op de heterogeniteit van de stedelijke omgeving en het effect hiervan op het microklimaat. Daarnaast zou voor het plannen van UGI ook de thermische voorkeur van mensen moeten worden meegenomen. Een geïntegreerde aanpak is daarom essentieel om de invloed van de verschillende typen UGI op zowel het fysische microklimaat als het subjectieve thermisch comfort te evalueren. De aanpak en de methodologie beschreven in dit proefschrift maken het mogelijk om de rol van de UGI in microklimaatregulatie te kwantificeren, de impact van de verschillende controlerende factoren te onderzoeken en de effecten op het menselijk comfort te verkennen. De bevindingen kunnen bijdragen aan betere planning en management van de UGI als onderdeel van een belangrijk instrument voor duurzame verstedelijking en de aanpassing aan de gevolgen van klimaatverandering.


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Groene
opwarming
voorkeur
onderzocht
koelere
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Ondanks
essentieel
verbeteren
afhankelijk
subjectieve

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About the Author

Yafei Wang was born on August 10th, 1983 in Zhangjiakou, Hebei Province China. She completed her primary and secondary school in her hometown. In 2002, she travelled to Beijing to start an international BSc program on Environmental Sciences in China Agricultural University (CAU). She spent the first two years in CAU, then travelled abroad to the Netherland for finishing the second half of her BSc. From September 2005, she continued with a Land and Water Management a BSc program in Van Hall Larenstein (VHL), University of Applied Sciences. In VHL, she completed a BSc thesis entitled "Controlling factors of greenhouse gas emission in fen meadow ecosystems and the possibility of using water level manipulation as a tool for emission reduction", which was a sub-topic of a PhD project in Wageningen University. In September 2007, she started an MSc program on Environmental Sciences in the Environmental System Analysis (ESA) group in Wageningen University. During her MSc, she was one of the commissioners of education in the study association "Aktiefslip" for the Environmental Science Major. After finishing her MSc thesis entitled "The role of green space in reducing air, water and noise pollution in Dongguan city, China", she worked as a teaching assistant for ESA group, meanwhile as a researcher in Foundation for Sustainable Development (FSD) for the international report "The Economics of Ecosystems and Biodiversity (TEEB) study". Between March and August 2011 she has been working as pre-doctor in INCAS^3 institute, where she wrote a PhD research proposal by herself. With this proposal, she successfully built up cooperation between INCAS3 and ESA group of Wageningen University. Soon later, this PhD project dealing with the relationship between "urban green infrastructure" and "local microclimate & human comfort" was granted and officially started in September 2011. During her PhD, she was also involved in one of the on-going projects in FSD, the Ecosystem Services Partnership. Within this project, she was one of the leading members in the Biome Working Group where she made contributions in various activities. In Costa Rica 2014, she co-organized the "Urban Ecosystem Services" working group session in the 7th ESP conference where she also gave an overview presentation of working group at the end of the conference.

List of Publications

Wang, Y., Bakker, F., de Groot, R., & Wörtche, H. (2014). Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Building and Environment*, *77*, 88–100.

Wang, Y., Bakker, F., de Groot, R., Wörtche, H. & Leemans, R. (2015). Effects of urban trees on local outdoor microclimate: Synthesizing field measurements by numerical modelling. *Urban Ecosystems*, 1-27. doi: 10.1007/s11252-015-0447-7.

Wang, Y., Bakker, F., De Groot, R., Wörtche, H., & Leemans, R. (2015). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. *Environmental Monitoring and Assessment*, *187*, 732–745.

Wang, Y., Bakker, F., de Groot, R., Wörtche, H. & Leemans, R. Thermal comfort in urban green spaces: A survey on a Dutch university campus. *International Journal of Biometeorology*, submitted.

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- SENSE writing week (2012)
- Research in Context Activity: 'Co-organising the Urban Ecosystem Services working group session in the 7th Ecosystem Services Partnership (ESP) in Costa Rica (2014) and leading member of Biome Working Group (since 2012)'
- Basic Statistics (2013)

Other PhD and Advanced MSc Courses

- Groningen Energy Summer School, Groningen University (2013)

Management and Didactic Skills Training

- Supervising MSc student with thesis entitled 'Estimating the perceived socio-economic value of micro-climate regulation by urban green infrastructure in a local area: A case study on Zernike campus, Groningen, The Netherlands' (2014)
- Supervising MSc internship student with thesis entitled 'Cooling effect of the urban green infrastructure improving microclimate and human comfort: Pilot study of Zernike campus, Groningen' (2014)

Oral Presentations

- Effects of urban trees on local outdoor microclimate: Synthesizing field measurements by numerical modelling. The 7th Ecosystem Services Partnership (ESP) Conference, 8-12 September 2014, San José, Costa Rica

SENSE Coordinator PhD Education

Dr. ing. Monique Gulickx

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