Cooling effects of urban green spaces on residential neighbourhoods: a review and empirical study

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vorgelegt von
Frau Madhumitha Jaganmohan,
geb am 29.03.1988 in Coimbatore, Indien

1. Gutachter/-in: Prof. Dr. Ralf Seppelt

2. Gutachter/-in: Prof. Dr. Boris Schröder-Esselbach

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Summary

With increasing human populations and rising temperatures, cities are growing warmer, and there is a dire need for local climate regulation. Urban green spaces (UGS) provide an important ecosystem service, namely local climate regulation: a cooling effect, which extends into the surroundings of UGS. Vegetation cover in UGS is being increased in many cities globally for the purpose of lowering the temperatures. Thus, UGS play a vital role in mitigating urban heat problems. To understand the relationship between the design aspect (size, shape) and tree diversity of UGS, and local climate regulation in urban areas, the quantification of the cooling effects of UGS is the main focus of this study. The research presented in this dissertation was conducted in two steps: a comprehensive literature review on studies that calculated cooling effects of UGS over a temperature gradient and an empirical study to quantify the indicators of cooling and the influence of variables that were found to be missing in other studies. Therefore, the main research questions were to

i. review the current studies that quantify cooling effects calculated over temperature gradients of UGS globally (Chapter 2);
ii. analyse the influence of different UGS characteristics on the cooling effect, between different types of UGS (parks and forests) based on data collected for a case study (Chapter 4, 5);
iii. assess the diversity of trees in the UGS and its influence on cooling effects to understand the role that UGS design, biodiversity, and characteristics of residential surroundings play using statistical models for the same case study (Chapter 4, 5).

To substantiate the choice of indicators and variables for the empirical study, and to see the various methods involved in the quantification of cooling effects calculated over temperature gradients, a review study was done focusing on the research question i. From the review (including 23 publications) it was evident that the common indicators of cooling were difference in temperature (21 indicators) and the extent of cooling (26 indicators). The literature review also provided an overview of the variables that have an influence on the cooling effects. As biodiversity as a variable was not considered in any of the studies that were reviewed, I included this variable in the statistical analysis for the empirical study. Also, it was observed that the literature lacked studies specifically for urban ecosystems.

The empirical study was conducted in the city of Leipzig in Germany in two parts. The first part (temperature analysis) mainly aimed at quantifying and comparing the strength of the cooling effects of 62 UGS (parks and forests), to determine how far the cooling effects extended into the surrounding residential area, and to better understand how these indicators of cooling effect are affected by the physical characteristics, vegetation cover and the surroundings of the green space. This temperature analysis of the empirical study provides answers for the research question ii. For this, the change in temperature (ΔT) at the park-width distance (PWD), the fitted maximum ΔT and the cooling distance were the three indicators of cooling that were calculated from daytime air temperature measurements. Multiple regression models were used to analyse the relationships of the indicators of cooling on to the physical characteristics of the UGS and the surroundings. Cooling effects were found to be larger in urban forests than in parks. The characteristics of the green spaces were found to be more important than the characteristics of the residential surroundings in explaining the cooling effects. The influence of the area and shape of the park was found to be complex, hinting at a trade-off between maximizing temperature differences and the distance at which cooling is still noticeable. Since it was found that the percentage of tree/shrub cover did not aid in cooling, detailed investigations of vegetation cover were performed.

In the second part (biodiversity analysis) of the empirical study that focusses on the research question iii, tree sampling was carried out in a subsample of 54 UGS that were accessible; and results showed that specific aspects of tree diversity play a stronger role in temperature mitigation, such as functional diversity and mean traits rather than taxonomic diversity. Therefore, it was important to look at the influence of various diversity variables such as taxonomic diversity, functional diversity and mean traits (height and diameter at breast height - DBH) of tree vegetation on cooling effects in different types of UGS. The explanatory power of the model increased with the inclusion of diversity variables.

The main result of this dissertation from the methodological point is that transect measurements of temperature data are found to be more reliable than point measurements in assessing the cooling effects. It is to be noted that not all UGS provide cooling effects, and the cooling effects differ based on the type of UGS as forests were found to be better than parks for providing a cooling effect. The intensity of temperature difference and the spatial extent of cooling cannot be both achieved together. Larger and more structurally diverse UGS provide better cooling distance, with the size of the UGS being most important. The effects of tree diversity were found to be less important compared to that of physical characteristics of the UGS (size and type of UGS). Diverse vegetation structure in terms of tree height, rather than species diversity, improved the cooling effects of parks. Large irregularly shaped green spaces and especially forests in urban areas have a stronger cooling effect than small green spaces and parks. Thus, this study also provides insights regarding the importance of species diversity vs. functional diversity and mean traits of tree vegetation on the cooling effect in UGS, which may guide effective management and conservation strategies in urban environments.

Therefore, to improve local climate regulation in cities, it can be said that it is important to recognize the need to either have higher intensity cooling or a longer distance along which cooling is noticeable. The indicators that are quantified over a transect are better in assessing the cooling effects. In terms of the design of the UGS, the bigger the area, the better is the cooling, with tree diversity being diverse in terms of structural variation in tree heights rather than species diversity.

Zusammenfassung

Durch steigende menschliche Bevölkerung und Temperaturen werden Städte immer wärmer, sodass ein dringender Bedarf an lokaler Klimaregulierung besteht. Urbane Grünflächen (UGS) bieten als wichtige Ökosystemleistung lokale Klimaregulierung: eine abkühlende Wirkung, die bis in die Umgebung der UGS reicht. Daher wird die Vegetationsbedeckung in UGS in vielen Städten weltweit erhöht, um Temperaturen zu senken. Somit spielen UGS eine wichtige Rolle, um städtische Hitzeprobleme zu lindern. Um die Beziehung zwischen dem Designaspekt (Größe, Form) und der Diversität der Baumarten von UGS und der lokalen Klimaregulierung in städtischen Gebieten zu verstehen, steht die Quantifizierung der Kühlungseffekte von UGS im Mittelpunkt dieser Studie. Die in dieser Dissertation vorgestellte Forschungsarbeit wurden in zwei Schritten durchgeführt: eine umfassende Literaturrecherche zu Studien, in denen Kühlungseffekte von UGS über einen Temperaturgradienten berechnet wurden, und eine empirische Studie, um die Kühlungsindikatoren zu quantifizieren und ihr Einfluss auf Variablen zu untersuchen, die bisher in anderen Studien nicht berücksichtig wurden.

Deshalb sind die Hauptziele dieser Studie:

i. eine Zusammenstellung aktueller Studien, die Kühlungseffekte über Temperaturgradienten von UGS global quantifizieren (Kapitel 2);
ii. die Analyse des Einflusses verschiedener UGS-Eigenschaften und verschiedener Typen von UGS (Parks und Wälder) auf den Kühlungseffekt (Kapitel 4, 5);
iii. die Bestimmung der Baumdiversität in UGS und ihres Einflusses auf die Kühlungseffekte, um die Rolle, die die Gestaltung von UGS, ihre Biodiversität und Charakteristika der Wohnumgebung spielen, unter Zuhilfenahme statistischer Modelle zu verstehen (Kapitel 4, 5).

Um die Auswahl der Indikatoren und Variablen für die empirische Studie zu konkretisieren und die verschiedenen Methoden zur Quantifizierung von Kühlungseffekten über Temperaturgradienten zu erfassen, wurde eine Review-Studie durchgeführt, die sich auf Frage i bezog. Aus diesem Review (von insgesamt 23 Veröffentlichungen) ging hervor, dass üblicherweise die Temperaturdifferenz (21 Indikatoren) und das räumliche Ausmaß der Kühlung (26 Indikatoren) als Indikatoren für die Kühlung verwendet werden. Dieses Review gibt auch einen Überblick über die Variablen, die einen Einfluss auf die Kühlung haben. Da Biodiversität bisher in keiner der Studien als Variable berücksichtigt wurde, wurde diese Variable in die statistische Analyse der empirischen Studie mit einbezogen. Zudem wurde beobachtetet, dass in der Literatur ein Mangel an Studien speziell für urbane Ökosysteme vorliegt.

Die empirische Studie wurde in der Stadt Leipzig, Deutschland, in zwei Teilen durchgeführt. Im ersten Teil (Temperatur-Analyse) quantifizierte und verglich ich die Stärke der Kühlungseffekte von 62 UGS (Parks und Wälder). So konnte ich feststellen, wie groß die Temperaturdifferenz ist und wie weit die Abkühlungseffekte in das umliegende Wohngebiet reichen. Ich tat diesum besser zu verstehen, wie diese Indikatoren für den Kühlungseffekt von den räumlichen Eigenschaften, der Vegetationsbedeckung und der

Umgebung der Grünfläche beeinflusst werden. Diese Temperatur-Analyse der empirischen Studie beantwortet Frage ii. Die Temperaturänderung (ΔT) der jeweiligen „park-width distance“ (PWD), das gefittete Maximum ΔT und die Distanz, in der eine Abkühlung messbar war, waren drei Indikatoren für die Kühlung, die aus Messungen der Tageslufttemperatur berechnet wurden. Mittels multipler Regression wurden die Beziehungen der Kühlungs-Indikatoren zu den räumlichen Eigenschaften des UGS sowie ihrer Umgebung analysiert. Die statistische Analyse der Indikatoren zeigte, dass die Kühlungseffekte städtischer Wälder größer sind als die von Parks. Die Charakteristika der Grünflächen haben dabei einen stärkeren Effekt auf die Kühlungswirkung als die Eigenschaften der Umgebung. Der Einfluss der Fläche und der Form des Parks erwies sich als komplex, was auf eine Wechselwirkung zwischen der Maximierung der Temperaturunterschiede und der Entfernung, bei der die Abkühlung noch spürbar ist, hinweist. Da ich feststellte, dass der Anteil der Baum- und Strauchdeckung nicht zur Kühlung beiträgt, wurden detaillierte Untersuchungen zur Vegetationsbedeckung durchgeführt.

Im zweiten Teil (Biodiversitäts-Analyse) der empirischen Studie, der sich auf Frage iii bezieht, wurde die Baumdiversität in einer Teilprobe (54 UGS) bestimmt, die zugänglich waren. Die Ergebnisse zeigten, dass spezifische Aspekte der Baumdiversität, wie z. B. funktionelle Diversität und mittlere Ausprägung von Merkmale, eine stärkere Rolle bei der Temperaturreduktion spielen als andere Aspekte, wie z. B. taxonomische Diversität. Daher war es wichtig, den Einfluss verschiedener Variablen, wie taxonomischer Diversität, funktioneller Diversität und Merkmalen (Höhe und Durchmesser in Brusthöhe - DBH) der Baumvegetation auf die Kühlungseffekte bei verschiedenen UGS-Typen zu untersuchen. Die Erklärungskraft des Modells stieg, wenn Diversitätsvariablen miteinbezogen wurden.

Das Hauptergebnis aus methodischer Sicht dieser Dissertation ist, dass Temperaturmessungen zur Bewertung der Kühlungseffekte zuverlässiger waren, wenn sie entlang von Transekten, anstatt als Punktmessungen gemessen wurden. Es ist anzumerken, dass nicht alle UGS Kühlung liefern, da die Kühlungseffekte sich je nach UGS-Typ unterscheiden. Wälder eignen sich besser als Parks, um einen Kühlungseffekt bereitzustellen. Die Intensität der Temperaturdifferenz und die räumliche Ausdehnung der Kühlung können nicht beide zusammen erreicht werden. Größere und strukturell vielfältigere UGS bieten eine bessere Kühlungsdistanz, wobei die Größe des UGS den wichtigsten Faktor darstellt. Die Auswirkung der Baumdiversität war, im Vergleich zu dem Effekt der Eigenschaften des UGS (Größe und Art des UGS), weniger wichtig. Diversere Vegetationsstrukturen, insbesondere in Bezug auf die Baumhöhe, zeigten einen besseren Kühlungseffekt als die Artenvielfalt. Große, unregelmäßig geformte Grünflächen und vor allem Wälder in städtischen Gebieten haben eine stärkere kühlende Wirkung als kleinere Grünflächen und Parks. Somit liefert diese Studie auch Einblicke in die Bedeutung der Artenvielfalt gegenüber der funktionellen Diversität und der mittleren Ausprägung von Merkmalen der Baumvegetation für die Kühlungseffekte von UGS. Dadurch können effektivere Management- und Erhaltungsstrategien in städtischen Gebieten eingesetzt werden.

Um die lokale Klimaregulierung in Städten zu verbessern, kann entweder eine höhere Intensität der Kühlung, oder eine längere Strecke, entlang derer sich eine Abkühlung bemerkbar macht, genutzt werden. Dabei ist es ratsam, Indikatoren entlang eines Transektes zu quantifizieren, um die Kühlungseffekte zu bewerten. Um UGS effektiver zu planen, sollten größere Flächen mit Bäumen angelegt werden, wobei die Variation in der Höhe der Bäume eine wichtigere Rolle spielt als deren Diversität.

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List of articles published as result of this dissertation

The following article was published before submission of this dissertation and originates from work and results of this dissertation.

Jaganmohan, M., Knapp, S., Buchmann, C.M. & Schwarz, N. (2016) The bigger, the better? The influence of urban green space design on cooling effects for residential areas. Journal of Environmental Quality, 45, 134-145.

From Jaganmohan et al., (2016) figures 8, 9, 11, 14, 15, 16 & 17 and tables 7 &11 are taken and paragraphs originally published were labeled with the reference (Jaganmohan et al., 2016).

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Abbreviations

AIC	Akaike Information Criterion
CBD	Central Business District
CII	Cool Island Intensity
CIR	Color-infrared aerial imagery
CWM	Community-Weighted Mean
DBH	Diameter at Breast Height
GPS	Global Positioning System
LST	Land Surface Temperature
MCA	Maximum Cooling Area
MSI	Mean Shape Index
NDVI	Normalized Difference Vegetation Index
PCHI	Local cool/heat island intensity of a park
PCI	Park Cooling Intensity
PWD	Park-Width Distance
RS	Remote Sensing
UCI	Urban Cooling Intensity
UGS	Urban Green Spaces
UHI	Urban Heat Island
WRF	Weather Research and Forecasting
ΔT[FIT]	maximum temperature difference between UGS boundary and the surrounding area

1 Introduction

Cities are home to a large proportion of the world's population, and UGS play a critical role in maintaining ecological, economic and social wellbeing of urban residents. UGS like urban forests and parks are maintained largely for recreational purposes, and have an impact on residential prices and provide social and ecological benefits for the urban residents (Oleyar et al., 2008). Ecosystem services are the benefits that humans derive from nature (Millennium Ecosystem Assessment, 2005; TEEB, 2010). Cities as such are heterogeneous environments that provide a wide range of ecosystem services (Bolund and Hunhammar, 1999) where UGS are biodiversity hotspots (Cornelis and Hermy, 2004; Li et al., 2006) and significant ecosystem service providers (Gaston et al., 2013). Ecosystem functions and processes in cities differ compared to rural or natural ecosystems (Gaston, 2010) and cities form a complex ecological entity (Alberti, 2005) with urban ecosystems being highly dynamic (Ripplinger et al., 2016). By assessing some of the various ecosystem services, the value and benefits of UGS can be quantified, which will help in better conservation and management of these spaces for the well-being of the city's residents.

Maintaining and improving ecosystem services in urban areas for human well-being is essential for sustainable development and therefore ecosystem services are an important topic in urban ecological research. A change in provisioning services, regulating services or cultural services can have strong impacts on human health (Millennium Ecosystem Assessment, 2005). Cities with a high proportion of built up areas particularly inhibit regulating services like the regulation of temperature, especially where there is dearth of open spaces and sections of green cover. Climate regulation is thus an important ecosystem service for urban inhabitants, as cities can influence the local climate and weather conditions. A review study on urban ecosystem services reported that local climate regulation is one of the most frequently assessed services (Haase et al., 2014).

There is evidence of high biodiversity in various cities (Kent et al., 1999; Maurer et al., 2000; Li et al., 2006; Davies et al., 2008) and urban plant distributions are strongly impacted by urban development, history, city structure, socioeconomic status (Martin et al., 2004; Kinzig et al., 2005; Hope et al., 2003) and legacy effects of land use (Cook et al., 2012; Johnson et al., 2015). The natural environments such as vegetation, open spaces and water bodies play a vital role in maintaining lower temperatures in city areas. Evidence suggests that vegetation might be related to the provision of ecosystem services (climate regulation), such as trees in parks were significantly cooler than trees surrounded by sealed ground (Leuzinger et al., 2010). The provision of habitat for species diversity can be viewed as a supporting service provided by UGS (TEEB, 2010) along with climate regulation. It is therefore essential to understand the relationship between biodiversity and climate regulation, at the level of finer habitat units such as UGS, for cities specifically as in the process of urbanization, parts of the native vegetation are either destroyed or altered and new habitats are created. Such UGS in the midst of the high population density and high resource consumption are very essential to enhance human well-being. Therefore, local climate regulation provided by different types of UGS (forests and parks) and the influence of various characteristics of UGS and their residential surroundings, including biodiversity, on to the cooling effect is the main focus of the dissertation.

1.1 The urban heat island effect: state of research

Urban regions are very distinct from surrounding rural regions, with more built-up areas and fewer open spaces. For instance, urban built-up structures exacerbate heat waves due to the urban heat island (UHI) effect (Oke, 1982) and induce heat stress (Harlan et al., 2006) in urban residents. Studies (Li and Bou-zeid, 2013; Li et al., 2015) also indicate that synergies between heat waves (excessively hot periods during which the air temperature increases significantly) and UHI can lead to higher health risks to urban residents, especially those who do not have means to cool their residences, who are often the elderly and the poor (Grimmond, 2007). An UHI can develop through a difference between the urban temperature and the temperature in the rural surroundings. Simulated results for a change in the nocturnal heat island in response to atmospheric CO_2 for a global climate model showed an increase of 30 % in some locations with high population growth and a global area averaged nocturnal heat island reduction of 6 % (McCarthy et al., 2010). Global climate simulations for urban surfaces (Oleson et al., 2011) showed that the present day annual mean air temperatures are higher than for rural areas by up to 4°C. Results from climate change scenarios (Oleson, 2012) showed that urban and rural areas respond differently to climate change, with urban areas having more warm nights. (Jaganmohan et al., 2016).

Water bodies and other vegetated areas, such as forests, parks and gardens, provide fresh, cool air for urban populations (Tratalos et al., 2007). Vegetation helps to moderate the microclimate and cools the environment mainly through evapotranspiration, shading, a low thermal storage capacity and re-radiation of less heat compared to non-vegetated structures (Spronken-Smith and Oke, 1998). Local climate regulation is a valuable ecosystem service provided by green spaces for urban residents because it reduces the UHI effect and therefore is important for maintaining the quality of life and adapting to climate change (Gill et al., 2007; Bowler et al., 2010). The cooling effect of green spaces, which is easily perceived by urban residents, is a regulating ecosystem service (TEEB, 2010) that can help mitigate heat stress (Lafortezza et al., 2009) (Jaganmohan et al., 2016).

The UHI not only affects the thermal comfort and health of residents (Harlan et al., 2006; Grimmond, 2007), but it also influences vegetation. For example, UHIs may shift tree phenology to earlier dates (Shustack et al., 2009) or alter the taxonomic and functional composition of species assemblages (Knapp et al., 2008). Knapp et al. (2009) showed that plant species that prefer higher temperatures are more frequent in Germany if they are adapted to urban areas. The type, structure and spatial distribution of green cover can influence the amount of cooling provided by vegetation (Dimoudi and Nikolopoulou, 2003) thereby determining the local climate regulation ability of UGS. Increasing vegetation cover is a strategy for moderating regional climate changes in urban areas that provides multiple ecosystem services (McPherson et al., 2011). Thus, urban tree planting programs are becoming popular in many cities; for example, in New York (Rosenzweig et al., 2009), Los Angeles (McPherson et al., 2011) and Chicago (City of Chicago, 2009). In Leipzig, "Baumstarke Stadt" is a tree campaign which was started in the year 1997, as an initiative to allow citizens and companies to plant trees in public parks, streets, squares and cemeteries (Leipzig (n.d)).

Although research on UHI has been carried out for a few decades now, only in recent years there has been a concern about it. This increased awareness to heat-related environment and health issues has brought about heat reduction strategies, mainly in the form of trees and vegetation, green roofs, and green walls.

1.2 Quantifying micro climate regulation: cooling effects

Local climate regulation is mostly quantified using air temperatures or land surface temperatures (LST). Air temperatures and LST in urban areas show some similarities in terms of their relationship to land cover/use (Schwarz et al., 2012) but are different with respect to lawns (Yilmaz et al., 2008), exhibit different diurnal patterns (Roth et al., 1989) and are perceived differently by the urban population. For the air temperature measurements, direct assessments using mobile (Arnfield, 2003; Chang et al., 2007) and fixed (Yu and Hien, 2006; Hamada and Ohta, 2010) temperature probes have been commonly used in the literature. Mobile measurements have been performed either by walking (Lu et al., 2012) or by using an automobile (Saito et al., 1991; Upmanis et al., 1998) to collect a temperature reading at various intervals along a defined transect during the day or night. Saaroni et al., (2000) found air temperature variations of 3-5°C between the city center and the surrounding areas in Tel Aviv. Studies that looked at the seasonal temperature gradients have primarily used fixed sensors placed inside a green space and in reference stations in built-up areas (Hamada and Ohta, 2010) (Jaganmohan et al., 2016).

1.3 Indicators of cooling effects

The cooling effects of UGS are often calculated as the difference in the temperature of the reference station versus the green space. This thermal contrast has multiple names in the literature; for example, it has been referred to as a “park cool island” (Spronken-Smith and Oke, 1998), the “park cooling intensity” (Lu et al., 2012; Feyisa et al., 2014), the ‘‘cool-island’’ effect (Hamada and Ohta, 2010), and the “local cool/heat island intensity” (Chang et al., 2007). Often, the reference point is chosen at a meteorological site (Cohen et al., 2012), the city center or central business district (CBD) (Lee et al., 2009), or at the park-width distance (PWD) from the boundary of the green space (Chang et al., 2007). The PWD is defined as a distance that is the square root of the area of the green space. This is because studies have shown that the cooling effect of the green space is extended beyond the boundary, and its impact is extended to roughly one PWD (Jauregui, 1991; Spronken-Smith, 1994). Another indicator used to quantify the cooling effect is the cooling distance (Chen et al., 2012; Feyisa et al., 2014), which uses a polynomial fitted to the temperature data points, and is mainly a measure of the maximum distance of the detected cooling effect. One study also obtained average temperatures at different locations using temperature probes fixed at various equidistant locations throughout the green and built-up areas (Yu and Hien, 2006) (Jaganmohan et al., 2016).

Following the definition of UHI, urban cooling intensity (UCI) is defined as the mean air temperature difference between the green space and the urban center. With surface temperatures, it can be defined as the difference between the mean LST in a greenspace and the mean temperature in a specific buffer area as by Cao et al. (2010) where the fixed buffer of 500 m was used to evaluate the cooling effect of a city park. Also, the UCI can also be affected by boundary effects of the surrounding land use and land cover (Kong et al. 2014).

1.4 Strength of cooling effects and factors affecting it

Many studies have shown that UGS can mitigate the UHI effect considerably; a maximum nocturnal air temperature difference of 5.9°C was observed over a distance of approximately 1.5 km in Gothenburg, Sweden (Upmanis et al., 1998). In Seoul, there was a cooling effect of 2°C/100 m between a green space and the CBD area (Lee et al., 2009). In Israel, 11 different wooded sites were examined in summer, and the cooling effects of the wooded areas, which were attributed to shading at noon, averaged 2.5°C within a distance of 100 meters (Shashua-Bar and Hoffman, 2000). A large park in Mexico was found to be 2-3°C cooler than its surroundings, and the cooling effect extended to approximately 2 km, which equates to approximately one PWD (Jauregui, 1991). The presence of a water body in an urban park in Tel Aviv (Saaroni and Ziv, 2003) was found to show a cooling effect up to 40 m downwind of the pond during daytime hours under dry and humid hot weather conditions within the urban park. However, regardless of the number of studies, most studies on the cooling effects of UGS only considered a single green space (Jauregui, 1991; Lee et al., 2009; Chow et al., 2011; Skoulika et al., 2014), and a limited number of studies considered the characteristics of the surrounding areas (Hamada and Ohta, 2010; Bowler et al., 2010; Chen et al., 2012; Feyisa et al., 2014) (Jaganmohan et al., 2016).

1.5 The relationship of cooling effects and vegetation: A synthesis

Trees and vegetation in general, lower surface and air temperatures mainly by shading and evapotranspiration. The presence of leaves drastically reduces the amount of incoming solar radiation that could heat up the ground surface and thereby reduces the intensity of heat transferred to nearby surfaces. Evapotranspiration is a phenomenon which encompasses two processes, firstly transpiration, a process in which the water absorbed by the roots is expelled through its stomatal pores on the leaves. Secondly evaporation, the process of conversion of liquid water to water vapour from soil as well as vegetation.

The cooling effects of UGS were found to be related to certain characteristics of a green space such as the vegetation cover and the vegetation structure (trees, shrubs, grass) (Spronken-Smith and Oke, 1998; Chang et al., 2007; Shashua-Bar et al., 2009). Additionally, the effects of the individual tree species can differ, as indicated by a study on surface temperatures below the crowns of different tree species in the city of Basel, Switzerland. Lower crown temperatures were associated with trees with smaller leaves (Leuzinger et al., 2010). Grass was found to have a negative impact on the cool island intensity (Cao et al., 2010) and in the Mediterranean climate, lawns were warmer during the daytime than tree parks, but they were cooler during the night (Cohen et al., 2012). Deciduous trees have a better cooling effect, and this effect is more pronounced in summer than in winter (Hamada and Ohta, 2010; Cohen et al., 2012) (Jaganmohan et al., 2016).

1.6 Role of biodiversity

In general, biodiversity is considered important for the enhancement of both ecosystem services and ecosystem processes (Millennium Ecosystem Assessment, 2005). "Biodiversity is the variety of life, including variation among genes, species and functional traits. It is often measured as: richness a measure of the number of unique life forms; evenness a measure of the equitability among life forms; and heterogeneity the dissimilarity among life forms" (Cardinale et al. 2012, p.60).

A review on the links between ecosystem service provision and biodiversity, which did not focus on urban areas, found that regulating services were more often associated with biodiversity attributes than provisioning or cultural services (Harrison et al., 2014). A positive, negative or no relationship existed between biodiversity and ecosystem service provisioning, even though biodiversity was more likely to be positively related to ecosystem services than negatively related (Harrison et al., 2014; Ziter, 2016; Schwarz et al., 2017). The mechanisms between biodiversity and the provisioning of ecosystem services are highly complex and involve many uncertainties (Balvanera et al. 2014; Harrison et al. 2014; Cardinale et al. 2012). Biodiversity is often measured as species richness, reflecting the number of species in a given area, and several diversity indices include information on the relative abundance of the different species (e.g. the Shannon index, evenness). However, functional traits, i.e., the characteristics of an organism having links to the organism's function (de Bello et al., 2010), are gaining attention in discussion of the role of biodiversity in ecosystem services and ecosystem functioning across habitats and spatial scale (de Bello et al. 2006; Petchey and Gaston 2007, Harrison et al. 2014, Ziter 2016). Two different aspects of functional traits have been discussed (Ricotta and

Moretti, 2011), with supporting evidence for (i) functional diversity, as the diversity of traits in a community (Petchey and Gaston, 2006), and (ii) the dominant, or mean trait value in a community (de Bello et al., 2010).

The cooling effects of UGS were also related to the cover and structure of vegetation. For example, in Taipei, the cooling intensity was related to park characteristics such as park size and park cover; and paved coverage affected park temperatures and increased tree and shrub cover resulted in cooler parks at noon (Chang et al., 2007). Trees were the most efficient means of reducing outdoor air temperature in a study in a hot-arid region of southern Israel (Shashua-Bar et al., 2009), and the combination of shade trees over grass was predictably found to be the most effective for cooling effect. A study in the city of Basel, Switzerland (Leuzinger et al., 2010) also found that the surface temperatures below tree crowns of different tree species differed, which suggests that the cooling effect may be species-dependent and demonstrates the importance of species selection for cooling. This suggests that tree traits will be important for local climate regulation. Although cooling is related to specific tree species, most of the studies do not test or report any relationship between biodiversity and local climate regulation, or report a non-significant relationship (Lundholm et al., 2010). Until now, studies on the cooling effects of UGS have considered only the amount of vegetation cover differentiated into turf, trees, shrubs, species groups (Feyisa et al., 2014) or species composition (Lundholm et al., 2010). However, studies on the cooling effects of UGS have historically considered only the amount of different land uses or land covers as well as vegetation cover but have not accounted for their spatial configuration in the urban landscape. Additionally, little research has been conducted to compare the different types of green spaces with different indicators for the cooling effects or to include the characteristics of both UGS and their surroundings in explaining it (Jaganmohan et al., 2016).

It is thus necessary to also explore various traits of trees, and their cooling effect in different UGS. Identifying relationships between biodiversity and local climate regulation will help in managing and designing urban ecosystems for human wellbeing and conservation.

1.7 Motivation and aims of the dissertation

The aim of this dissertation is to increase the knowledge of how UGS should be designed in urban neighbourhoods in order to help in effectively reduce temperatures by providing a cooling effect. The review study thus focusses on studies that measure cooling effects from temperature gradients of specific UGS. The objective of the empirical study is to focus mainly on air temperature measurements to quantify the cooling effects of different types of green spaces in residential areas. The specific aims of the research and the research questions are:

I. Review the current studies that quantify cooling effects calculated over temperature gradients of UGS globally; the research needs and gaps: What are the different methods used to derive the cooling effect indicator? What are the different variables that were considered in the studies? Which variables influenced the cooling effect?

II. Analyze the influence of different UGS characteristics on the cooling effect, a case study from Leipzig, Germany: Are the indicators used to quantify the cooling effects strongly related to each other? Do all UGS have a cooling effect on the surrounding residential areas? What are the variables that influence the cooling effect? Do urban forests have a larger cooling effect than urban parks? Does the cooling effect increase with an increasing area and complexity of the shape of an UGS?

III. Assess the diversity of trees in the UGS of Leipzig and its influence on cooling effects: How do different aspects of tree diversity (taxonomic vs. functional aspects) affect cooling? Do the measures of tree diversity have a positive influence on cooling effect?

As cities are growing in size and number to accommodate and meet the needs of a growing urban population, huge areas are urbanized, the built-up structure not only changes natural landscapes but also alters their climatic characteristics. Such man-made changes have a direct effect on the local climate of urban spaces and bring about increases in air and surface temperatures compared to their rural surroundings. It is important to understand one of the essential services provided by UGS, i.e. local climate regulation. Many studies have been carried out to quantify the local climate regulation in terms of quantifying the intensity of cooling effects of UGS. This dissertation firstly presents a systematic review (last updated on 18th April 2016) on all the studies that quantify cooling effect over a gradient analysis. The objective is to review the state of knowledge and current research to quantify cooling effects over transects/gradients that provide information on the techniques and indicators used for measuring cooling effects in various climatic regions. It identified all the different indicators of cooling and the variables used to explain them. This review included the publication Jaganmohan et al., (2016) that focused on the temperature analysis of the empirical study and the results informed the variable selection for biodiversity analysis of empirical study.

The dissertation then focusses on the details of the empirical study conducted in the city of Leipzig, Germany based on air temperature measurements to quantify the cooling effects of UGS on adjacent residential areas. Leipzig was chosen as a case study because it represents a compact central European city with distinct housing types and considerably large amounts of green space within the city. This case study is one of the very few studies globally to sample a large number of sites and also carry out statistical analysis. The first part of the empirical study focused on temperature analysis and was mainly conducted to quantify and explain the influences of various factors on the cooling effect taking into consideration two different types of UGS (parks and forests), using air temperature measurements. The analysis also examines the performances of and relationships between the different indicators of the cooling effect. The second part of the empirical study focused on biodiversity analysis and was conducted mainly to look at the importance of tree biodiversity in providing cooling effects. Therefore, along with other variables of the UGS and surroundings, the different measures of biodiversity (taxonomic diversity, functional diversity and mean traits of tree vegetation) and their interactions were examined using regression models to understand the relationship with the indicators of cooling effect that were measured during the temperature analysis.

1.8 Structure of the dissertation

This dissertation consists of 6 chapters (Fig.1). While chapter 1 is the general introduction; chapter 2 contains the details of the review study and is mainly aimed at research question I. Apart from the general literature review presented in chapter 1, chapter 2 focusses only on those studies that looked at cooling effects calculated over a temperature gradient. Since both temperature analysis and biodiversity analysis of the empirical study were conducted in the same location, Chapter 3 describes the study area of the empirical work and the methodology which was carried out. Chapter 4 has its emphasis on the answers to questions II and III followed by discussion in chapter 5. Hence the methodology, results and discussions are combined for both analysis of the empirical study. Chapter 6 synthesizes and concludes what has been achieved in this dissertation. References for all chapters can be found at the end of the dissertation.

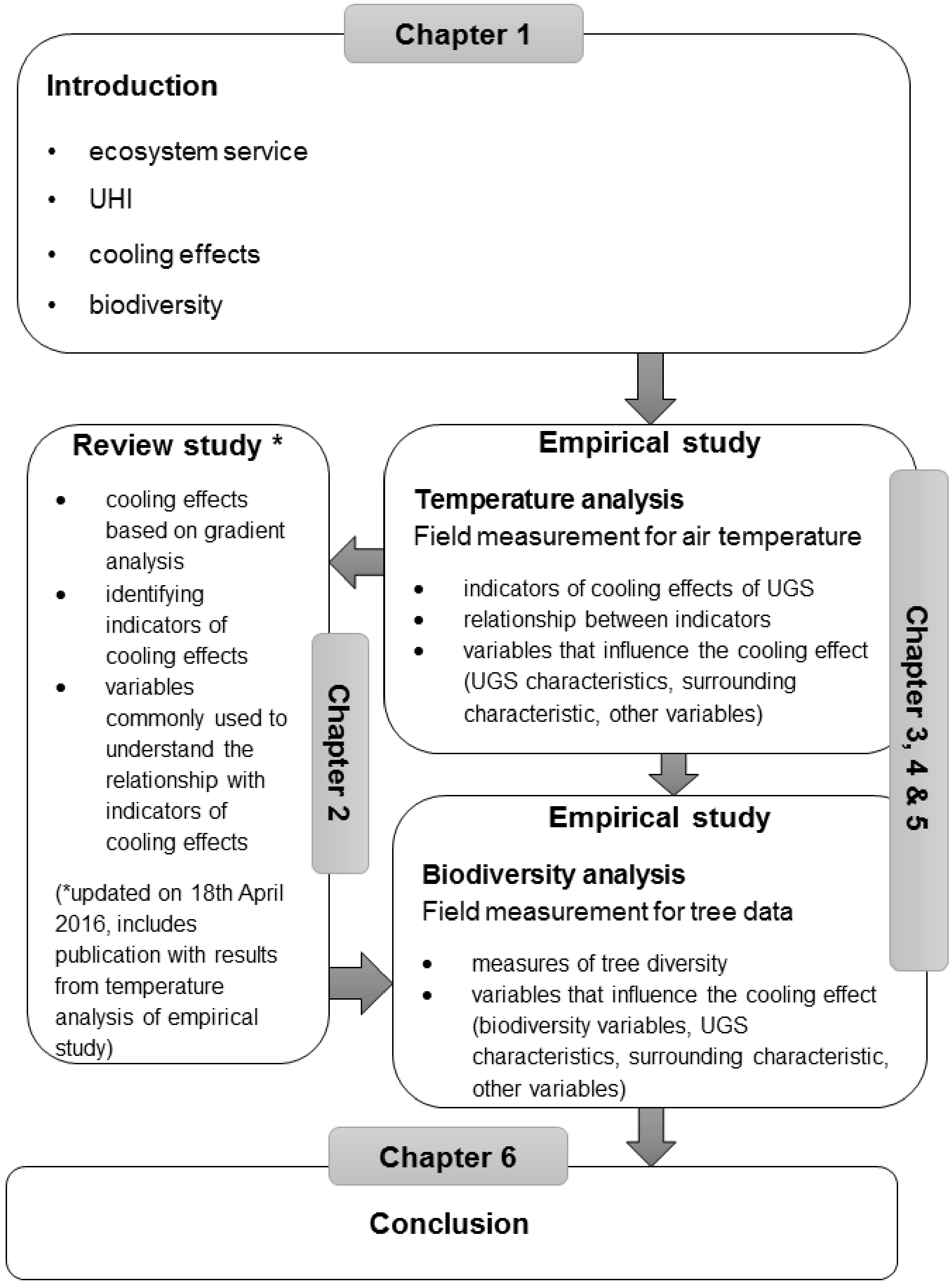

Figure 1. The research framework of the dissertation. The boxes contain information on different chapters and the arrows represent how the information from the various chapters are related.

2 Review on cooling effects of UGS over a gradient analysis

This chapter provides information on the studies present in the literature that quantify cooling effects calculated over temperature gradients of UGS globally, addressing the research question I (Section 1.7).

In literature, various techniques have been applied for analyzing the cooling effects of UGS. Choosing an appropriate method to define the extent and intensity of the cooling effect is critical. The measurement of the extent of the cooling effect beyond the UGS has been carried out using different methods such as measurement of the prevalent air temperatures (using thermometers at stationary fixed observation points or through mobile measurements), remote sensing (RS) based surface temperatures and modelling. The methods are based on the principle that the cooling effect will decline while moving away from the boundary into the surrounding areas to a distance at which the effect is no longer observed. Therefore, by locating the constant point mostly where the temperature difference levels off, it is possible to identify the limits of the cooling extent either in one direction or at different directions around the UGS. Also, during the empirical study of temperature analysis (Section 4.1.2 & 4.4) one of the indicators of cooling ($\Delta T[PWD]$) which was a difference between two points, was found to be a commonly used indicator of cooling although the results were not as good as the other indicators of cooling. Thus, the review looks at those studies which have calculated cooling effects including a transect to get an overview of the methods currently used to differentiate the indicators of assessing the cooling effect of individual UGS over specific UHI indicators. Some of the methods have already been mentioned in Chapter 1 (Section 1.4), but this systematic review will contribute to the understanding of the cooling effect of vegetation on the urban surface and air temperature measured over separate UGS.

Questions answered within the review study are:

1. What are the different methods used to derive the cooling effect indicator?
2. What are the different variables that were considered in the studies?
3. Which variables influenced the cooling effect?

The main outcome of this step is to assess the different indicators of cooling and their relationship to various indicators analysed in the literature from transect measurements. The results (indicators and variables) of the temperature analysis of the empirical study (Jaganmohan et al., 2016) are included in the review and results of the missing variables from the review will be included in the biodiversity analysis of the empirical study.

2.1 Selection of studies and methodology

Literature has shown that UGS can provide cooler microclimates and other ecosystem services, and play an important role in mitigating UHI. Along with the magnitude of cooling provided by UGS, it is also necessary to understand the variables that influence these effects with different methodological and experimental approach. Here, I conduct a quantitative review of cooling effect studies in literature, synthesizing the methods, extent and other variables that lead to the results. Thus, the main focus of the study is the impact of UGS on air/surface temperature and UHI intensity calculated over a temperature gradient.

I was mainly interested in studies that looked at UGS as a separate entity and the cooling effects that were measured and not those described on a city level or urban patch level. The articles needed to focus on a patch of vegetation and not individuals (e.g. studies measuring temperature under single tree species were excluded).

My review is based on peer-reviewed publications indexed in ISI Web of Science that were included in the search string with the following keywords “((urban OR city OR metropolis OR megalopolis) AND (greenery OR vegetat* OR tree* OR "green space*" OR "open space*" OR "green roof*" OR "open area*" OR park* OR wood* OR forest* OR garden* OR playground* OR cemeter* OR "brown field*" OR grass* OR shrub* OR allotment* OR yard* OR lawn*) AND ("cool* distance*" OR "temperature regulation" OR "temperature gradient" OR "climate regulation" OR "heat mitigation" OR "cool* effect*" OR "cool* intensit*" OR "cool* island*"))” for all years up to 18th April 2016. The use of the terms for UGS and cooling effect was carefully selected so as to encompass all the possible urban studies. This intended to capture studies that are part of the weather and climate-related regulating services in literature. Only English-language full-text research articles were included. My initial search identified 205 studies, the titles and abstracts of which were screened to retain only those that actually measured at least one UGS within an urban area and the related temperature.

The articles were subjected to selection criteria at various stages (Fig. 2). After they were retrieved from the database, at first, the selection criteria were applied to title and abstract only in order to efficiently remove irrelevant studies. At this stage to have an unbiased selection, two other individuals’ opinions on whether to include a study or not were taken into account. This was done to eliminate discrepancies in inclusion decisions and in order to strengthen consistency. Articles remaining were then further looked at their full text, to reach the final list of relevant articles. Further information on methodology, study characteristics, measurement details and results were recorded from each study.

The five studies that were not included in the review although their full text at first seemed relevant did not specify the extent of the cooling effect in terms of a measurable value over a gradient, rather used the values in the surroundings at a particular distance to calculate the temperature value of the urban environment and used this to obtain the cooling intensity value.

A total of 23 publications identified in ISI Web of Science was analysed that included the following information: 1. bibliographic information; 2. geographic region and climatic zone; 3. the UGS measured – number, category, size description; 4. Temperature measurement – period and season of measurement, type of indicator of cooling and methods to derive it, the values of the indicator and indicators with positive or negative influence; 5. the measure used to quantify biodiversity (if included).

Figure 2. PRISMA flow diagram for the number of articles passing each stage of the selection process. Adapted from Moher et al., (2009).

2.2 Sampling details of the cooling effects study analysed in the literature review

While studies were conducted on all of the inhabited continents except South America and Australia, the Asian and European studies dominated the literature (Fig. 3). The highest number of studies were carried out in China (5 studies, 22 %) followed by Japan (4 studies, 17 %).

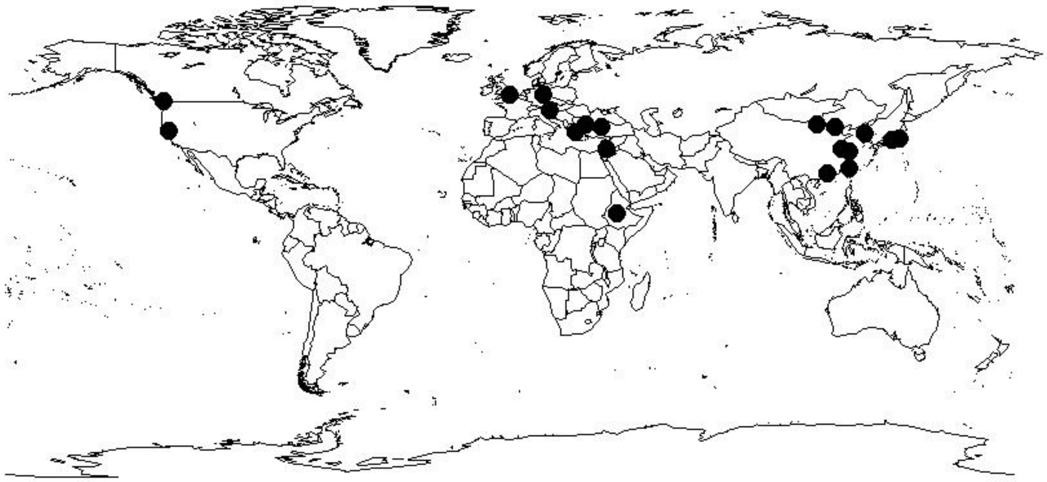

Figure 3. The locations of cities where the studies were analysed in the literature review.

For the articles that used observational data, out of the 13 studies 8 of them sampled a single UGS, while only two studies had above 60 UGS sampled (Fig. 4). The 8 articles that used RS data had a varied number of UGS sampled. The number of articles that published the cooling effects of UGS calculated over a gradient is seen to be increasing over the years (Fig. 5).

UGS are an essential component of urban green infrastructure and are known for their multiple ecosystem services that they provide to the residents in the cities. The ecosystem services of UGS have been explicitly acknowledged in 4 studies; 17 % of the studies. Urban ecosystem disservices are also a growing concern and there are also a number of articles which recognize disservices (Von Döhren and Haase, 2015) but this concept was not mentioned in any of the studies in this review that quantified the cooling effects of UGS.

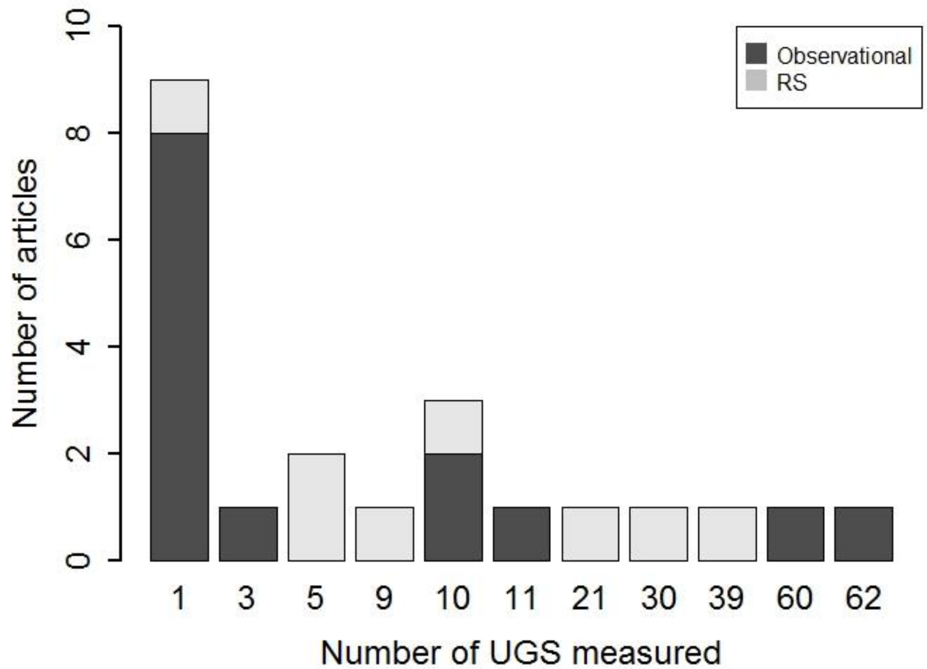

Figure 4. Total number of UGS measured per article. The black bars represent the studies that used observational data for calculating the cooling effect and the grey bars represent the studies that used RS data.

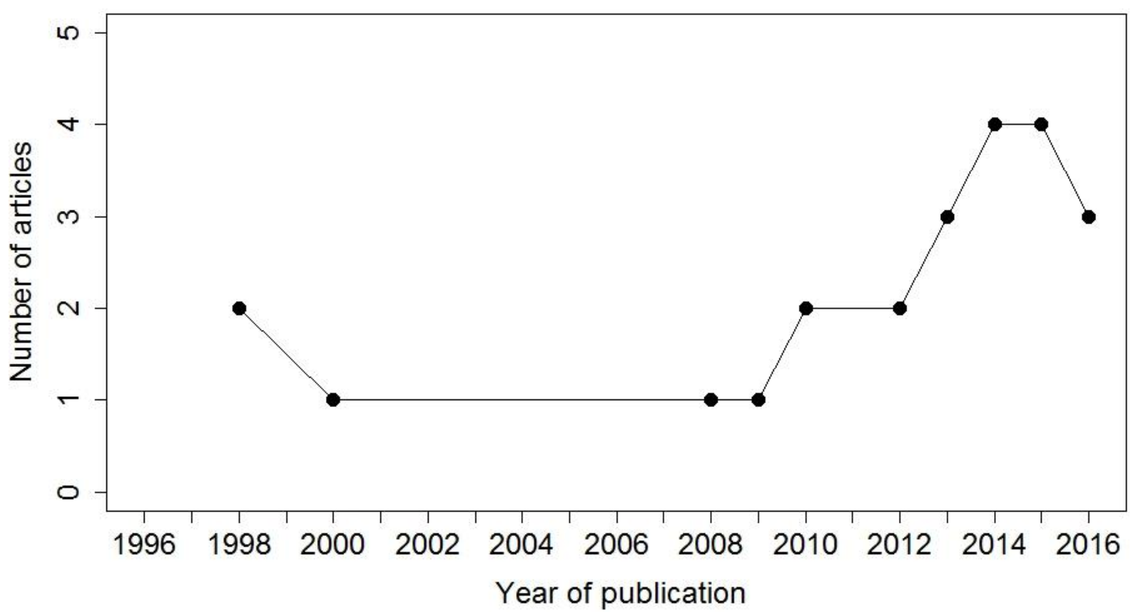

Figure 5. Number of articles published in over two decades up to 18th April 2016.

The UGS that are considered in studies on cooling effects are mainly public parks, gardens, forests, botanical gardens and wooded sites. A total of 7 studies (30 %) were conducted during the day and 2 studies (8 %) in the night, while 13 (56 %) presented both day and night measurements, and 2 studies had not mentioned the time of obtaining temperature data (Table 1). Temperature data (used to quantify cooling effects) is mostly collected from RS (8 studies, 35 %) and observational methods (13 studies, 56 %) and then used for measuring the cooling effect. However, modelling is used in 2 studies (9 %) to quantify the cooling effect. In latter studies, the cooling effect is modelled by using thermal response models of park elements for the determination of space dependent boundary conditions of park elements in computational fluid dynamics modelling (Vidrih and Medved, 2013) and also the Weather Research and Forecasting model, coupled to a single layer urban canopy model on various land use scenarios (Papangelis et al., 2012). Studies from Bao et al. 2016, Chen et al. 2012, Jaganmohan et al. 2016, and Myeong 2010 (4 studies, 17 %) looked at temperatures outside the UGS, while all others measured temperatures within and outside the UGS. Comparing UGS in different cities with varied climatic conditions within a research paper was rare, while only one study (Spronken-Smith and Oke, 1998) looked at temperature differences between urban parks and their surroundings and found a similar influence of cooling. All the other studies predominantly looked at either a single UGS or compared various UGS within a single city but not between cities.

Table 1. UGS and sampling details of the review study.

Sl.no	Citation	City, Country	Climate	UGS Category	No. of UGS	Size (ha)	Reference site	Year	Period	Season
1	Bao et al. 2016	Baotou, China	temperate continental	park, botanical garden	9	9.00 - 494.00	300 m around UGS	2000, 2004, 2007, 2011, 2014 (5 time period images)	-	July - August [o,r]
2	Bilgili et al. 2013	Ankara, Turkey	mediterranean	park	3	12.00 - 64.00	-	2008[1], 2007 - 2008[2]	day[1](morning and noon), day and night[2]	July, August – June[io,ob]
3	Ca et al. 1998	Tokyo, Japan	subtropical and humid	park	1	60	commercial center	1994	day and night[1,2]	August – September[io,ob]
4	Chang and Li 2014	Taipei, Taiwan	subtropical monsoon	park	60	0.01 - 39.7	slightly larger than one park width	August - September 2003, December - February 2004	day and night[1,io,ob]	-
5	Chen et al. 2012	Guangdong province, China	subtropical monsoon maritime	park	10	1.81 - 138.35	-	October 2009, June 2011	day[o,r]	-
6	Cheng et al. 2015	Shanghai, China	northern subtropical monsoon	park	39	0.96 - 140.22	surrounding buffer zone	2001	day	July[io,r]
7	Doick et al. 2014	London, England	temperate oceanic	royal park	1	111	rural reference point	2011	night[2]	August – December [io,ob]
8	Feyisa et al. 2014	Addis Ababa, Ethiopia	subtropical highland	parks, green spaces	21	0.85 - 22.3	-	2010	day[2]	October[io,r]
9	Hamada and Ohta 2010	Nagoya, Japan	temperate humid	park	1	147	urban site	August 2006-July 2007	day and night[2]	one year[io,ob]

10	Hamada et al. 2013	Nagoya, Japan	temperate humid	park	1	147	surrounding urban area	(10 July 2000, 25 May 2004, 3 August 2006,4 September 2006, and 9 September 2008)[d] (September 2010 and July 2011)[n]	day and night	July – September[io,r]
11	Huang et al. 2008	Nanjing, China	humid subtropical	forest	1	2970	microscale: bare concrete near the woods, mesoscale: city center	2005	day and night[1,2]	July – September[io,ob]
12	Jaganmohan et al. 2016	Leipzig, Germany	sub continental	park, forest	62	0.2 - 35.6	-	2013	day[1]	June – August[o,ob]
13	Lee et al. 2009	Seoul, South Korea	humid continental	park	1	24.2	CBD	November 2007- November 2008	day and night[2]	one year[2], 3 days[1,io,ob]
14	Lin et al. 2015	Beijing, China	humid continental	park	30	1842.00 (total area)	-	2009	day[2]	September[io,r]
15	Myeong 2010	Seoul, South Korea	humid continental	park	5	-	-	2006	-	September[o,r]
16	Özyavuz et al. 2015	Tekirdağ, Turkey	mediterranean	forest natural park	1	26.6	-	2013	day	July[io,ob]
17	Papangelis et al. 2012	Athens, Greece	mediterranean	proposed park	2	400, 800	-	2007	day and night[2]	September[io,m]
18	Rotem-Mindali et al. 2015	Tel Aviv, Israel	mediterranean	public park	5	2.6 - 42.4	residential area	2000-2010	night	June – August[io,r]
19	Shashua-Bar and Hoffman 2000	Tel Aviv, Israel	mediterranean	wooded sites	11	0.04 - 1.10	site without vegetation effects 50 - 100 m away	1996	day and night[1]	July – August[io,ob]
20	Skoulika et al. 2014	Athens, Greece	mediterranean	park	1	6	various urban areas	2012	day and night[1,2]	July – September[io,ob]

21	Spronken-Smith and Oke 1998	Vancouver, Canada	mediterranean type with cool summer	park	10	3.0 - 53.0	rural reference point	1992	day and night[1,2]	July – August[io,ob]
22	Spronken-Smith and Oke 1999	Sacramento, USA	oceanic	park	10	2.0 - 15.0	rural reference point	1993	day and night[1,2]	August[io,ob]
23	Sugawara et al. 2016	Tokyo, Japan	subtropical and humid	park	1	20	three urban sites in surrounding town, 1.5 km from UGS	2009 to 2012(4 summer period), all year	day and night[2]	July–September[io,ob]
24	Vidrih and Medved 2013	Ljubljana, Slovenia	subtropical and humid	park	1	1.96	-	2010	day[2]	July[m]

[1]mobile measurement, [2]stationary measurement,

temperature measurement: [io]inside and outside, [o]outside

method of sampling:[r]remote sensing, [ob]observational,[m]modelling

the rows marked in grey are from own publication (Jaganmohan et al. 2016).

2.3 Indicators of cooling: measurement and values

In total, 47 different indicators were used in the 23 studies. The main indicators of cooling are difference in temperature (21 indicators, 45%) (Table 2) and the extent of cooling either measured as distance (23 indicators, 49%) (Table 3) or area (3 indicators, 6%) (Table 4). The indicator for difference in temperature: temperature difference (15 indicators, 72 %) was measured differently as cool island intensity (CII) (Sugawara et al., 2016), maximum park cooling intensity (PCI) (Spronken-Smith and Oke, 1998), or Local cool/heat island intensity of a park (PCHI) (Chang and Li, 2014) to name a few (Table 2) and maximum difference in temperature using models (6 indicators, 28 %). For example, the indicator PCI has been used in 4 studies but has been calculated differently either by using models to calculate the maximum temperature difference (Skoulika et al. 2014) or by taking the temperature difference at two points; therefore, the indicators do not have a specific definition.

The park microclimate extends into its surrounding built-up areas because of air movement and heat exchange up to a limit where the cooling effect is weaker and then it finally becomes insignificant (Lin et al., 2015). This cooling extent could be identified by the temperature differences shown on LST maps directly (Lin et al., 2015) or by converting the retrieved LST to air temperatures (Chen et al., 2012). The most commonly used method for calculating the cooling distance is to fit the decay trend of temperature (9 indicators, 40 %) in either the linear, second or third order polynomial. Another method is to see the influence of parks on air temperatures in the surrounding and use contour mapping (3 indicators, 13 %) or visual analysis of temperature distribution to see the extent of influence (9 indicators, 40 %).

An example of calculating the cooling distance by a third order polynomial (Jaganmohan et al., 2016) is described in detail in the following chapter 3 (Section 3.2.4).

Only 3 studies (13 %) looked at the extent of cooling in terms of area (Table 4). It can be calculated as the maximum cooling area (MCA), defined as the largest area where the park's cooling effect can extend. This is the sum of all pixels in the buffer zones with their LST between the mean value of the park and maximum LST corresponding to the maximum cooling distance (Cheng et al., 2015). The cooling extent of the green park can also be depicted as the influence areas of the green parks (Lin et al., 2015), which are calculated similar to the catchment area of a lake, in this study the green park is considered a lake and the cooling extent as the catchment area.

Table 2. Details of the studies in the literature review using difference in temperature as an indicator of cooling.

Citation	Type of indicator of cooling	Method used to derive indicator	Value of indicator
Bao et al. 2016	cooling temperature	temperature semi-variance curve	1.9 °C - 3.1 °C
Bilgili et al. 2013	temperature difference	temperature differences of the park with surrounding area	1 °C
Ca et al. 1998	temperature difference	temperature difference between the park and the hottest area in the town	1.5 °C (noon)
Chang and Li 2014	PCHI	temperature difference between park and PWD	average –0.17 °C (noon)
Chen et al. 2012	ΔTmax	cubic polynomial fit	1.59 °C - 4.62 °C
Cheng et al. 2015	MLCII	MLCII =Ts – Tp	3 K on average (5.2 K – 1.0 K)
Doick et al. 2014	the maximum cooling effect	asymptotic model	1.1 °C - 4 °C (nocturnal)
Feyisa et al. 2014	max park cooling intensity	segmented non-linear model including a second-order polynomial	6.72 °C
Hamada and Ohta 2010	temperature difference	temperature difference between urban and green areas	- 0.3 °C to - 1.9 °C
Huang et al. 2008	cooling effect	temperature difference between city center and green area	5.3 °C (nocturnal)
Jaganmohan et al. 2016	ΔT[FIT]	cubic polynomial fit	on average 0.8K (0.0–3.3K) was observed for forests, and 0.5K
Jaganmohan et al. 2016	ΔT[PWD]	temperature difference between UGS boundary and PWD	on average 0.3K (-0.7 to 1.9K) for forests and for parks 0.1K (-0.7 to 3.2K)
Lee et al. 2009	temperature difference	temperature difference between park and a CBD area	4.7 °C (nocturnal)
Lin et al. 2015	ΔTmax	curve line model	2.3 °C – 4.8 °C
Özyavuz et al. 2015	temperature difference	temperature difference between the research area and its surroundings	3–3.5 °C (morning), 5–5.5 °C (noon)
Papangelis et al. 2012	PCI	scenarios, PCI =Tu−Tp*	6.4 °C -9.5 °C (nocturnal)
Shashua-Bar and Hoffman 2000	cooling effect	temperature difference between observation point and reference point	On average 2.8 K (noon)
Skoulika et al. 2014	PCI	second order polynomial	3.3 K - 3.8 K
Spronken-Smith and Oke 1998	PCI	temperature difference between the minimum park temperature and maximum urban temperature	4.9 °C (nocturnal), 1.3 - 2.7 °C (noon)
Sugawara et al. 2016	CII	temperature difference between the park and the surrounding town	1.5 K - 3 K (daytime)
Vidrih and Medved 2013	PCI	temperature difference between pedestrian zone and the reference point	−1.2°C and − 4.8 °C

Ts = maximum mean land surface temperature of the surrounding buffer zones; Tp = mean land surface temperature within the park; Tu= maximum urban air temperature; Tp*= minimum park air temperature, MLCII = maximum local cool island intensity, the rows marked in grey are from own publication (Jaganmohan et al. 2016)

Table 3. Details of the studies in the literature review using cooling distance as an indicator of cooling.

Citation	Type of indicator of cooling	Method used to derive indicator	Value of indicator
Bao et al. 2016	cooling distance	temperature semi-variance curve	within 300 m, the maximum cooling distance was between 120 and 300 m. From the centroid of green space, the maximum directional cooling distance was between 150 and 454 m, while the minimum directional cooling distance was between 106 and 333 m.
Bilgili et al. 2013	cooling distance	distances where the temperature is 1°C different	200,50, 50
Ca et al. 1998	cooling effect	contour mapping	1 km downwind
Chang and Li 2014	cooling effect	graphical analyses: relationship between relative distance and LCHI	10-20 m for <0.5 ha, 50-70 m for 0.5 to 1 ha parks, and 60-300 m for > 1ha parks
Chen et al. 2012	cooling distance	cubic polynomial fit	46.4 m - 447.23 m
Cheng et al. 2015	maximum cooling distance	cubic polynomial fit	mean 276.7 m (64 m – 1405 m)
Doick et al. 2014	cooling distance	asymptotic curvilinear model	20-400 m
Feyisa et al. 2014	maximum park cooling distance	a segmented non-linear model including a second-order polynomial	240 m
Hamada and Ohta 2010	cooling effect	distance from the edge of Heiwa Park to each measurement point, and the correlation between distance and temperature	night 200–300 m, day 300 - 500 m
Hamada et al. 2013	extent of a park's cooling effect	prewitt gradient filter	350 m (day)
Huang et al. 2008	maximum decay rate	air temperature distribution over distance	0.9 °C/100m and 0.4 °C/km
Jaganmohan et al. 2016	cooling distance	cubic polynomial fit	maximum of 469 m for forests and 391 m for parks
Lin et al. 2015	cooling extent	curve line model, limits of the cooling extent	35 m – 805 m, median values between 85 m and 284 m
Lee et al. 2009	temperature distribution	distance of highest temperature observed from park	240 m
Myeong 2010	cooling effect distance	where the relative temperature is lower than surrounding areas from temperature maps	240m to 360m, averaging about 300m
Özyavuz et al. 2015	effective temperature difference	experimental semivariogram model	400 m radius
Papangelis et al. 2012	cooling effect	contour mapping	4.2 km
Rotem-Mindali et al. 2015	cooling distance	difference between the LST at distance x and at distance x-30 m (ΔLST)	30 m

Shashua-Bar and Hoffman 2000	cooling effect on the site surroundings	the point at which cooling effect vanishes	100 m
Skoulika et al. 2014	climatic influence of the park	second order polynomial	300–350 m
Spronken-Smith and Oke 1998	influence of parks	contour mapping	PCI influences extends to a distance of one park width
Sugawara et al. 2016	thermal extent	distribution of normalized temperatures along the transect line	an average of 200 m, 450m downwind and 65 m upwind
Vidrih and Medved 2013	length of the park cooling effect	numerical simulations	PCI increases with the length of the park

LCHI = local cool/heat-island intensity, the rows marked in grey are from own publication (Jaganmohan et al. 2016)

Table 4. Details of the studies in the literature review using cooling area as an indicator of cooling.

Citation	Type of indicator of cooling	Method used to derive indicator	Value of indicator
Cheng et al. 2015	MCA	on the LST map, all pixels in the buffer zones with their LST between T_p and T_{max} were identified, and the sum of these pixels is the maximum cooling area	Mean 46.5 ha (2.19 ha – 350.15 ha)
Lin et al. 2015	extent of a park's cooling effect	overlaying slope data of LST map with basin (water-shed) data	0.14 km^2 to 10.09 km^2
Papangelis et al. 2012	extent of influential cooling	topography contours at 100 m intervals	10.5 km^2

T_p = the mean LST of the park, T_{max} = corresponding to the maximum cooling distance

The most frequently used indicator for difference in temperature of the cooling effect is the thermal contrast (14 studies; 60 %) between urban and green spaces ($\Delta T_{u\text{-}p}$). The maximum temperature difference or the point at which the temperature stabilizes is another indicator and it is mostly derived by fitting the data points in a model (7 studies; 30%). Another indicator is the measure of the point until which the cooling effect is experienced (23 studies; 100 %). It has been termed differently in usage as the extent of cooling effect, thermal extent and cooling distance which is the most commonly used terminology. The papers looked at the local scale mostly, but UHI is also calculated in the studies in addition to UCI that look at a temperature on a mesoscale level. Studies also looked at the influence of park size on UHI intensity and the role of surrounding landscape patterns on park cooling effect in Shanghai (Cheng et al., 2015), the temperature profile of a large UGS in London was assessed along with the extent to which the nocturnal UHI intensity is brought about (Doick et al., 2014). The spatial pattern of UHI intensity has been carried out along with the cooling effects also in Batao (Bao et al., 2016), Vancouver and Sacramento (Spronken-Smith and Oke, 1998), Tel Aviv (Rotem-Mindali et al., 2015) and Nanjing (Huang et al., 2008) that looked at larger study areas.

Based on the review study, the selection of indicators of cooling for the dissertation was to include those that are calculated using transects where by using a model to extract the values of the indicators and also using just observational values using point measurements.

2.4 Variables that explain the cooling effects

A total of 7 studies (30 %) did not perform any analysis between the indicators of cooling and the variables of UGS and surrounding but variables were mentioned in the article for e.g., the details of the area, type of vegetation, forest type, and dominant tree species. However, 16 studies (70%) used at least one variable or more to explain the cooling effects. The variables that influenced the cooling effects can be broadly classified as characteristics of the UGS (area/size, shape, Normalized Difference Vegetation Index (NDVI), green area, water area, ratio of length and width, ratio of forest cover, vegetation characteristics of canopy cover) and characteristics of the surrounding environment (percentage of built-up area and green area, buffer NDVI, distance from park boundary/ city center, wind speed). The main variables that influenced the cooling effects were area, vegetation cover, shape and the vegetation characteristics (NDVI) of the UGS. The area of UGS was the most common variable used in 8 studies (34 %) to indicate a relationship with the indicators of cooling effect, and vegetation cover was used in 5 studies (21%) followed by shape and NDVI of UGS in 3 studies (13 %) each (Fig. 6).

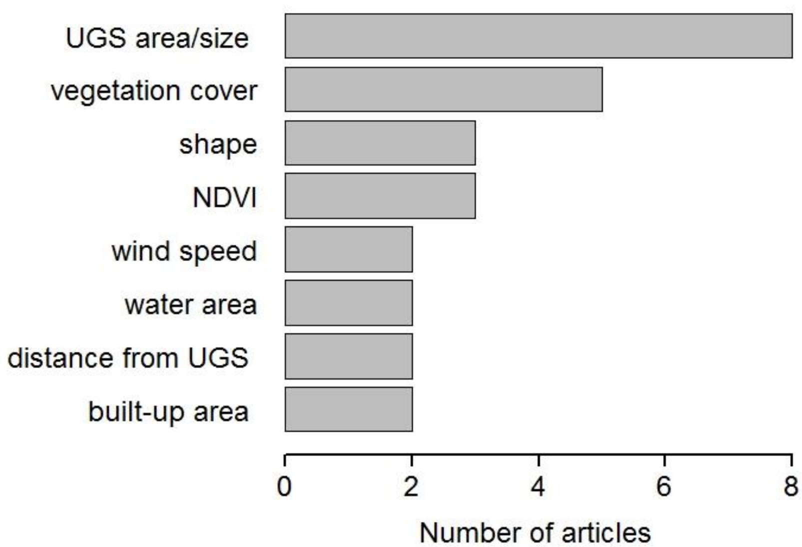

Figure 6. Variables used in the articles to indicate a relationship with the indicators of cooling. The variable vegetation cover includes green area, ratio of forest cover, vegetation characteristics of canopy cover, percentage of tree/shrub cover and proportion of trees, shrubs, turf.

In a study of 30 parks in Beijing (Lin et al. 2015), the area around a park that benefits from the cooling effect increased with park size and was influenced by the conditions of surrounding built-up areas; and the cooling extents in different directions of the same park varied greatly with larger area of green park leading to a greater cooling effect. The influence of the area and shape of the park was complex in the study conducted at Leipzig (Jaganmohan et al., 2016), hence it can either be maximizing temperature differences or the distance at which cooling is still noticeable (see Section 4.4.2 for details). A logarithmic relationship between area and shape index with cooling was observed in Baotou (Bao et al., 2016). A study in Shanghai, with 39 parks with varying sizes found that the LST decreases logarithmically with park size but eventually reaches an asymptote (Cheng et al., 2015). It also showed that the larger parks do not have an advantage in cooling efficiency when compared with the smaller ones. Lin et al. (2015) regard the calculation of the cooling extent of a green park as the calculation of the basin of a lake. The cooling extent of the park is similar to the catchment area of the lake where the UCI effect is defined as the phenomenon of lower temperature within a greenspace patch, compared to the surrounding built-up area. The UCI effect of urban greenspace patches decreases with distance from the boundary of the patch and disappears at a certain distance. A linear relationship between mean NDVI and cooling distance was observed in Batao (Bao et al., 2016). PCI was positively related to the size of the park and NDVI (within UGS) and negatively related to NDVI in 30 m ring buffer (outside UGS) in Addis Ababa (Feyisa et al. 2014).

Since the temperature difference indicator depends not only on the air temperature/LST but also strongly on the temperature of the surrounding landscape, the presence of the other greenery and water bodies could influence the indicator. Studies by Chen et al. (2012), Hamada et al. (2013) and Feyisa et al. (2014) found that the green space's cooling distance was influenced by the surrounding environment and thus the UCI intensity is affected by the land-use pattern surrounding a UGS. It was also seen that parks with larger green areas (>37163.61 m^2) or large water bodies (>128889 m^2) have more significant temperature cooling effects in summer (Chen et al., 2012). One of the ways to understand the intensity of the cooling effect is by understanding the role of confounding variables. As seen in this review, most commonly used variables were that of the UGS that are easily available and quantifiable. Since not all variables affect the cooling effect in the same manner, it is essential to statistically analyse them. Many studies failed to look at the variables and only described the conditions of the study area in the methodology. It is therefore suggested to carefully select the variables that could potentially affect the cooling intensity and accounted for with statistical analysis.

Since area of the UGS was the most commonly used variable that was found in the review studies, this dissertation looks in detail into investigating other additional variables of the UGS such as the type of UGS (park/forest), area of waterbody, the percentage of vegetation cover, shape and its interaction with area. The influence of the variables of the surrounding and the other confounding variables on to the cooling effects will also be explored.

2.5 Inclusion of biodiversity variables

As seen in Sections 1.5 and 1.6 vegetation plays an important role in providing cooling effects. Spronken-Smith and Oke (1998) found that the type of park is also important as there was a difference in maximum PCI observed at different times of the day for parks with substantial tree cover and open grass parks. Hence it is important to look at the different aspects of biodiversity variables that are related to cooling. It was found that 14 studies (60 %) included information on the type of vegetation or dominant or commonly found tree species present in the UGS that were considered for estimating the cooling effect. It was mainly descriptive information such as the type of tree cover and the dominant species, for e.g., a study in Japan considered two sites where observations were carried out. The first was a mixed secondary forest consisting of 40 % deciduous and 60 % evergreen trees without tree maintenance provided with the names of the tree species, along with stand density and range of DBH and height measurements (Hamada and Ohta, 2010). A study in Turkey at the Tekirdag Ataturk Forest Nature Park had a vegetation cover of coniferous and evergreen trees with Pinus sp. being the dominant tree species (Özyavuz et al., 2015). The Shirogane Park in Japan was covered with 90 % deciduous forest with a mean canopy height of 14m (Sugawara et al., 2016). A modelling study (Vidrih and Medved, 2013) derived a specific dimensionless leaf area index (LAIsp) from tree age and tree planting density and modelled the vegetation impact on a park's cooling effect relative to park size. A study in Nanjing (Huang et al., 2008) on a mesoscale study looked at the influence of vegetation indices (canopy coverage; basal coverage; length diameter of canopy coverage; width diameter of canopy coverage; diameter at breast height; LAI) on air temperature at different time points in vegetation corridors. Tree species category (*Eucalyptus, Acacia, Cupressus, Grevillea, Olea*) and percentage of canopy cover were used in Addis Ababa (Feyisa et al. 2014) on mean hourly temperature averaged across 15 days. Shannon’s Evenness Index was one of the biodiversity index as part of landscape-metrics calculated to describe the pattern of UHI intensity in Batao for five different time periods (Bao et al., 2016). Apart from this, no study described or used a specific biodiversity variable in explaining the cooling effects. Since the specific biodiversity variables are lacking in all studies, one of the main outcomes of the review was to include various measures of biodiversity in further studies.

2.6 Conclusions

In the review study the number of published papers that refer to cooling effect measured over a transect is very small, which indicates that this concept is quite new with the use of models to fit the data. However, the increasing number of papers since 2009 suggests a growing recognition of this method to calculate the indicators of cooling. The cooling effect of diverse UGS has been carried out in very few geographical regions. The cooling effects provided by other greenery than UGS were not considered in this review. Since each study was unique in study design and measuring conditions, having a typology of cooling effects was not possible.

Research on cooling effects of UGS over a transect generally measured air temperature of points in and around the city. However, the temperature data extracted from RS data captured more details on the surrounding area of the study sites. As seen in Fig. 4 most studies only measured a small number of UGS, for instance, a single park with measurements within and outside the UGS. It is also suggested to have comparable sites within a study area to look at the cooling effects in different parts of the city, as in this review most of the articles looked at a single UGS. A review on the urban heat/cool island specifically by RS (Rasul et al., 2017) also suggested looking at study sites at different locations in the city. This could be a limitation for observational studies but with RS and modelling this could be easily achieved. All the studies covered in this review on temperature gradients supported the fact that the cooling effect of a UGS extends into the surrounding and provides the strength of the effect. Studies like the one conducted in Nanjing (Huang et al., 2008) analysed air temperature differences from different types of ground cover and from the different observation sites including the temporal and spatial scales. Thus, articles on cooling effect also looked at other aspects mentioned above including UHI intensity in some cases.

The term "indicator of cooling effects" is not widely recognized and hence there is no single specific terminology to address the cooling effects of UGS, but the effect of cooling is measured as difference in temperature, distance or area up to which the cooling effect is experienced. Using models to fit the temperature data to determine the cooling effects can easily quantify at least 2 of the 3 indicators namely difference in temperature and the distance. Looking at studies that evaluated and compared different types of UGS, based on the vegetation type and cover, it is seen that only quantitative descriptions of the UGS for e.g., area of grass, shrub and tree cover, along with information on height, DBH and dominant species (Lee et al., 2009; Doick et al., 2014; Feyisa et al., 2014; Özyavuz et al., 2015) were mentioned albeit corroborating it with statistical analysis for their influence on cooling effect specifically of biodiversity variables. Apart from just describing the vegetation or calculation in terms of percentage cover, more details on vegetation (measurable indices) should be considered for a holistic understanding of the cooling effects. The variables that influenced cooling was mainly that of the physical aspects of UGS and the most common variable to explain cooling effect was area of the UGS. The indicators chosen for cooling effects are mainly temperature difference, the extent of cooling in terms of distance and area. These results suggest that UGS is a very important component for UHI mitigation and provision of cooling effect, but the role of variables that influence the cooling effect is not so certain in many studies. Biophysical characteristics of vegetation were used to determine the cooling efficiency only in Addis Ababa (Feyisa et al., 2014) and Nanjing (Huang et al., 2008). Thus, the role of the physical characteristics of the UGS and the role of vegetation is well acknowledged in most of the studies, but not all of the variables are included for statistical analysis.

Based on the insights provided by the review study, this dissertation aims at exploring the different indicators of cooling and understanding the role of the different variables (physical and biodiversity) that could influence the cooling effect of the UGS.

3 Empirical case study: Leipzig

An empirical study on temperature analysis and biodiversity analysis was conducted in two different types of UGS (parks and forests) in the city of Leipzig, to quantify and explain the influences of various factors on the cooling effect. Using existing maps, the UGS were delineated and their physical features were extracted. The UGS selected were then sampled for temperature trends and tree vegetation.

Questions to be answered under temperature analysis are:

- Are the indicators used to quantify the cooling effects strongly related to each other?
- Do all UGS have a cooling effect on the surrounding residential areas?
- What are the variables that influence the cooling effect?
- Do urban forests have a larger cooling effect than urban parks?
- Does the cooling effect increase with an increasing area and complexity of the shape of an UGS?

In order to understand different UGS at different locations of the city, a total of 62 UGS were chosen and the UGS characteristics and characteristics of each UGS' residential surroundings were included for statistical analysis.

Some of the questions to be answered under biodiversity analysis are:

- How do different aspects of tree diversity (taxonomic vs. functional aspects) affect cooling?
- Do the measures of tree diversity have a positive influence on cooling effect?

The following chapters describe the study design, results and discussion of both temperature analysis and biodiversity analysis of the empirical study combined.

3.1 Study area

Leipzig (51°20'north latitude and 12°22'east longitude) is a city in the federal state of Saxony, Germany, with an administrative area of 297.4 km² and approximately 532,000 inhabitants in the year 2013. Leipzig lies at the confluence of the rivers White Elster, Pleisse, and Parthe with its characteristic riparian forest running south through the city. The city landscape is mostly flat and is approximately 118 m above sea level. Leipzig has many forests and parks within the administrative region, but the area surrounding the city is largely unforested. Other prominent landscape elements in the city are agricultural sites, allotment gardens, and wetlands. The case study region has a temperate climate with a mean annual air temperature of 9.3°C, an absolute high air temperature of 35.4°C and a low temperature of -15.3°C, and the mean annual precipitation was approximately 670 mm for the year 2013. The number of days observed in 2013 with maximum air temperature ≥

30°C (hot days) was 11, and with maximum air temperature ≥ 25°C (summer days) was 41 days. (Stadt Leipzig, 2014) (Jaganmohan et al., 2016).

3.2 Methodology

3.2.1 Habitat and land-use types map for selection of UGS

Green spaces here are defined as delineated urban open spaces that are generally accessible to the public with the presence of vegetation and are selected from the map of habitat and land-use types of Leipzig from the year 2005. These maps are derived from aerial photographs showing land use at the time of recording. In Germany, such photographs are made regularly, and the habitat categories and land-use types derived from these photographs are commonly applied. The categories “forest” and “park” (Fig. 7) were chosen as the types of green spaces to be used in the study. Leipzig is a very green city (Table 5) with many green spaces scattered around (29.1 km² of forests and 1.5 km² of parks in total).

Table 5. Different land use types that are of importance for empirical study in Leipzig.

Land use type	Description	Total Area (ha)
Forests	Areas where trees with a DBH > 40 cm are present with or without lawn or sports field	2913.7
Parks	Small parks with or without play area	154.7
Residential area	Areas containing open and compact mid-rise housing units	6162.5

Therefore, the study sites were carefully selected as a stratified random sampling to obtain an unbiased distribution of UGS with respect to the size, the complexity of their shape (quantified as the mean shape index (MSI); i.e., the perimeter divided by the square root of the area, see below) and the distance to the city center. The MSI of each individual UGS, which indicates regularity, was calculated using Spatial Analyst of ArcGIS (version 10.1). It equals 1 for circular or square patches and increases with irregularity. In total, 37 parks and 25 forests were selected (Fig. 8). Because the land use differs from city center to the outskirts, the distance to the city center was chosen as a stratum to have the sample sites evenly distributed geographically. As the focus of this study is on the cooling effects of green spaces in residential areas, only those green spaces with more than 30 % residential area in a 300-m buffer were selected. The types of residential areas covered in the study are categorized as “open mid-rise” and “compact mid-rise” for the semi-detached housing type and the dense housing type, respectively, according to the building types for the local climate zones (Stewart and Oke, 2012). The size, shape, distance to the city center and distance between the boundary of the green space and the subsequent locations for the temperature measurements were calculated from the map of the habitat and land-use types (Jaganmohan et al., 2016).

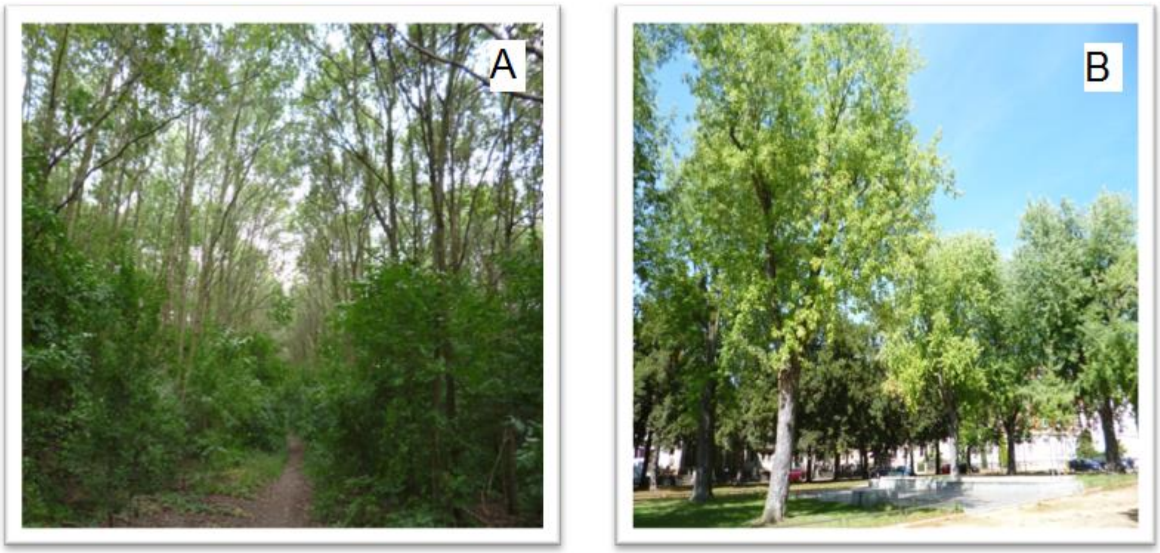

Figure 7. Example of the two different UGS in the study area, Leipzig. A: urban forest, B: urban park.

3.2.2 Calculation of tree/shrub cover: Remote Sensing

The amount of tree/shrub cover within the green spaces and surroundings was calculated using Color-infrared imagery (CIR) from the years 2012/13 with a 60 cm resolution. CIR-imagery provides information on the location of every individual tree and shrub in the city, which is a level of precision that could not be gained from the map of the habitat and land-use types (Jaganmohan et al., 2016). ArcGIS was used to superimpose CIR onto the habitat and land-use type map, and the areas for UGS and a 25m buffer around each UGS were demarcated and the percentage of tree/shrub cover was calculated for both UGS and buffer.

3.2.3 Temperature analysis: Air temperature sampling

The mobile temperature measurements were taken in the months of June to August 2013 on clear sunny days. The air temperature and humidity were measured using a Q-Trak 8552 monitor (company TSI Inc.) with an accuracy of ±0.6K for air temperature and ±3.0 % for relative humidity. The sensor was placed in a cylindrical tube and covered with silver foil to protect it from direct sunlight. Battery operated ventilators at the bottom of the cylinder provided air circulation. The sensors, along with a data logger, were placed on a backpack at the height of 1 m from the ground (Schwarz et al., 2012). The transect routes and measurement times were recorded using a Global Positioning System (GPS) device (Garmin GPSmap 60CSx). Wind measurements were performed using a Kestral 4000 Pocket Weather Tracker, which was also held at approximately 1 m from the ground.

Each green space was visited once during the sampling period. All of the temperature measurements were taken at an interval of 10 seconds. A transect of approximately 500 meters (Lu et al., 2012) was chosen randomly, running from the boundary of a green space into the adjacent residential area along a street. The measurements along the entire transect took less than 20 min. The mean transect length was 547 m and 505 m for the parks and forests, respectively. All of the measurements were performed during the day between 9 am and 5 pm. One stationery sampler (Fig. 8) equipped with a temperature and humidity sensor and a data logger (OPUS10 TIC, Lufft company, Germany, accuracy±0.3K and ±2.5 % relative humidity) was mounted at a 1.5 m height in a ventilated shelter that protected against solar radiation and precipitation (Schwarz et al., 2012). The mobile air temperature measurements were corrected to compensate for warming/cooling during the traverse by using the stationary temperature measurements collected at the time of the mobile measurements. The correction was done by subtracting the difference in air temperatures of the stationery measurement from the mobile measurement at that specific time (Jaganmohan et al., 2016).

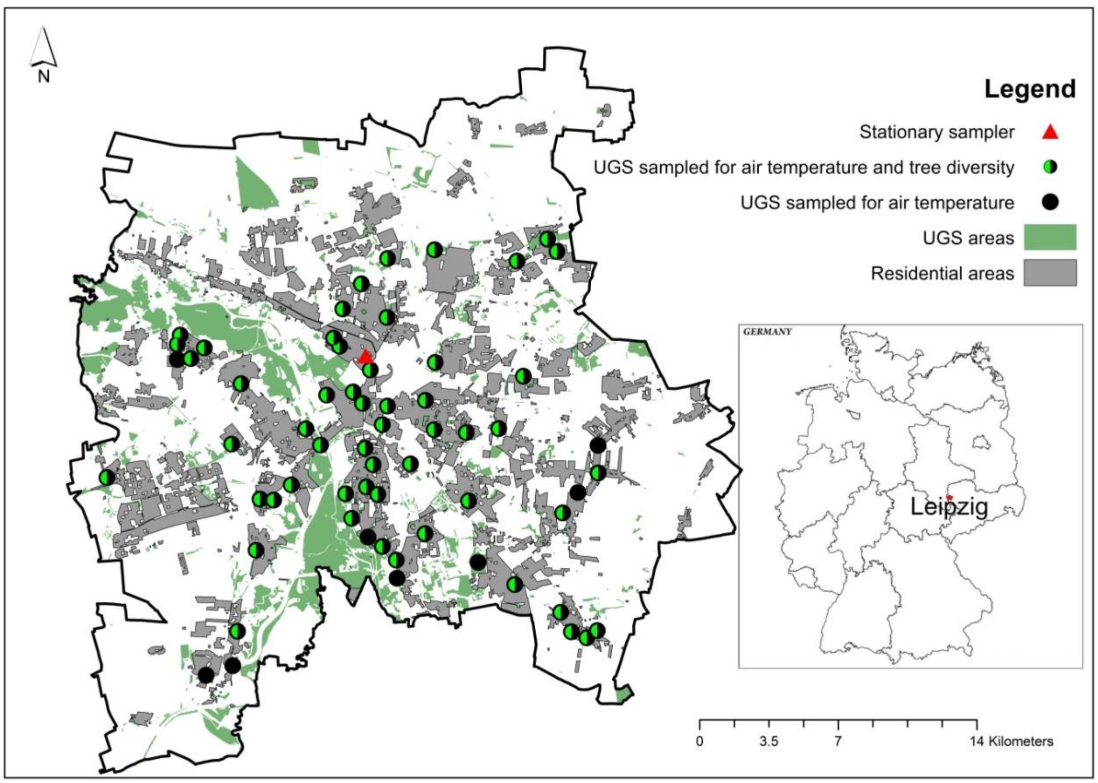

Figure 8. Map of the habitat and land-use types in the city of Leipzig, Germany, showing the UGS that were sampled.

3.2.4 Calculation of the indicators of cooling

Various indicators of the cooling effects of specific green spaces (n=62) were identified, which were also found to be commonly used (cf. Chapter 2). From the measurements mentioned before, a total of three indicators were derived and used in the analysis as dependent variables: The three indicators were:

(1) ΔT[PWD] (K): calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the PWD along the transect (with PWD being the square root of the area of the green space) (Jauregui, 1991);
(2) ΔT[FIT] (K): the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route. This was calculated from the transect by a fitted polynomial function (see below);
(3) Cooling distance (m): The distance at which the maximum cooling is experienced from the boundary of the green space when fitted with a polynomial function (see below).

From the temperature measurements for each green space, the temperature difference (ΔT**)** was calculated by subtracting the temperature measurement taken at the boundary of a green space from each subsequent temperature measurement along the whole transects.

The temperature trends found in the green spaces were of three main types: linear (Fig. 9A), flat (Fig. 9B) and increasing only up to a certain distance before flattening or decreasing again (Fig. 9C, D). The ΔT[FIT] and the cooling distance were fitted only for the third trend, namely the increase from the boundary to a maximum value (i.e., ΔT[FIT]), and the distance where ΔT reaches a maximum (i.e., the cooling distance) before flattening or decreasing again (Fig. 9C and 9D). The following procedure was performed: from the positive ΔT(K) values, a third-order polynomial was fitted to each transect dataset (equation 1); the coefficients of the model were used to obtain values for the ΔT[FIT] (equation 2) and the cooling distance (equation 3) following the procedure proposed by Chen et al. (2012).

Delta T (distance) = a*distance^3 + b*distance^2 + c*distance (equation 1),

$$\Delta \mathrm{T[FIT]} = \frac{2b^3+2b^2\sqrt{b^2-3ac}-6ac\sqrt{b^2-3ac}-9abc}{27a^2} \text{ (equation 2),}$$

$$\text{Cooling distance} = \frac{-b-\sqrt{b^2-3ac}}{3a} \text{ (equation 3),}$$

where a, b and c are the fitting coefficients of the fitted polynomial.

To obtain the values specific to a particular sample site, selected small green spaces (n=21) were fitted for the polynomial function only up to twice the PWD to prevent the influence of a temperature decrease due to other vegetated areas in the surroundings. For the green spaces that exhibited a negative or flat trend, the values of ΔT[FIT] and the cooling distance were set to zero (n=11). The green spaces that showed a linear temperature trend (n=3) were ignored for the calculation of the cooling effect for ΔT[FIT] and the cooling distance. The green spaces that were so large that PWD was not reached within the 500 m transect (n=2) were ignored for the cooling effect of ΔT [PWD] (Jaganmohan et al., 2016).

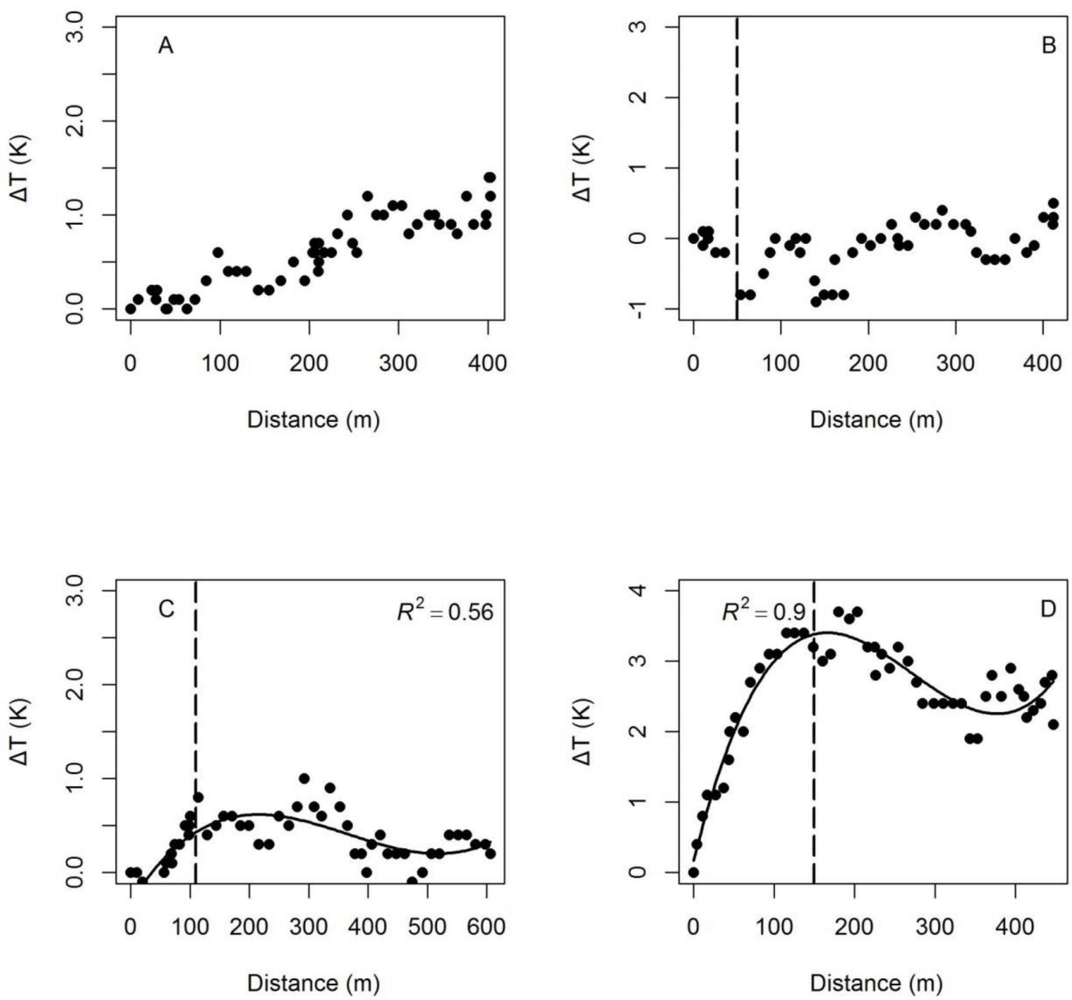

Figure 9. The temperature difference (ΔT) for four green spaces, distinctively showing the high heterogeneity of the temperature gradients found for green spaces in Leipzig (the curve is a polynomial fit and its R^2 value; the dashed line is the park-width distance [PWD]). For (A) (linear) and (B) (flat), no polynomial was fitted. For (A), the transect did not reach up to the PWD.

3.2.5 Biodiversity analysis: Tree diversity sampling

Data collection for the trees was carried out in May and June of 2014. Due to limited access into some UGS, of the 62 UGS sampled for air temperature, only 54 UGS (33 parks and 21 forests) were sampled for tree diversity characteristics. Random plots of 10 by 10 m were created using ArcGIS software, with a minimum distance of 50 m between plots. The number of plots depended on the area of the UGS, ensuring that on average, 2.5 % of the total area of the UGS was covered or a maximum of 15 plots for large green spaces.

A total of 254 (174 had trees, 69 had lawn/shrub, 7 had waterbody and 4 had playground) random plots were surveyed across the city and their location was identified on the ground using a GPS. The center of the plot was identified, and the boundaries were marked, with the upper side of the plot always facing north. Within a plot, all trees above 5 cm DBH; (i.e., at 1.30 m (Stohlgren, 2007)) were identified to the species level, and DBH was recorded using a measuring tape. The height of trees was estimated with a dendrometer. A total of 610 trees were sampled in 174 plots (mean number of plots = 4.7, min number of plots = 1, max number of plots = 15) in 54 UGS.

3.2.6 Calculation of the measures of biodiversity

Eight measures of biodiversity were calculated: taxonomic diversity (species richness, Shannon diversity, Pielou's evenness), functional diversity (functional richness, functional evenness, and functional divergence) and mean traits (height and DBH). Measures of taxonomic and functional diversity were calculated for each plot based on species relative abundance and functional trait data for each tree species. Taxonomic diversity was represented by species richness (the number of tree species), the Shannon index of diversity at the species level (Shannon diversity, equation 4) and Pielou's evenness index (equation 5).

The Shannon index of diversity, H is one of the most popular indices used in community ecology to quantify biodiversity, and is defined as

$H = - \sum_{i=1}^{S} p_i log_b \ p_i$ (equation 4),

where p_i is the abundance of species i, and S is the number of species so that $\sum_{i=1}^{S} p_i = 1$, and b is the base of the logarithm. This index, ranging in theory from 0 to infinity, combines aspects of species richness and evenness, increasing under conditions where the number of species increases, or the equitability of distribution of individuals belonging to different species increases, or both (Stohlgren, 2007).

The evenness of a community can be represented by Pielou's evenness index, J and is defined as

$J = H/\log(S)$ (equation 5),

where H is Shannon diversity and S is the number of species. This index ranges between 0 and 1, with higher values representing less variation in abundance between the species.

Functional diversity is considered as an important feature of biological assemblages, enabling prediction of the rate and reliability of ecosystem processes and functions (Mason et al., 2005). Functional diversity was represented as functional richness, functional evenness (equation 6), and functional divergence (equation 7) using the life-history traits (Wagner et al., 2014): maximum height and maximum DBH of trees. The functional richness (Villéger et al., 2008) indicates the volume of the functional space occupied by the community; it is calculated by convex hull algorithm after Villéger et al. (2008).

The functional evenness is the evenness of abundance distribution in a functional trait space, it quantifies the regularity with which traits are distributed across a community, weighted by species abundance. Functional evenness decreases either when abundance is less evenly distributed among species or when functional distances among species are less regular (Villéger et al., 2008)

$FEve = \frac{\sum_{l=1}^{S-1} min\left(PEW_{l}, \frac{1}{S-1}\right) - \frac{1}{S-1}}{1 - \frac{1}{S-1}}$ (equation 6),

where partial weighted evenness (PEW) and S species computed using minimum spanning tree (MST) for the S-1 branches between the S species. PEW is based on EW i.e. weighted evenness, which is calculated by dividing dist (*i, j*) i.e. the Euclidean distance between species *i* and *j*, by the sum of w_i and w_j, being the relative abundance of species *i,* and *j*, respectively. PEW is then obtained by dividing EW of all species in a branch by the sum of EW values for the MST.

Villéger et al. (2008) state that the “Functional divergence relates to how abundance is distributed within the volume of functional trait space occupied by species”. This index varies between 0 and 1. High functional divergence indicates large functional differences among species, and thus indicates low resource competition. Mason et al (2005) state that “the communities with high functional divergence may have increased ecosystem function as a result of more efficient resource use “.

$FDiv = \frac{\Delta d + \overline{dG}}{\Delta |d| + \overline{dG}}$ (equation 7)

where the sum of abundance-weighted deviances (Δd) and absolute abundance-weighted deviances (Δ|d|) for distances from the center of gravity of trait values across the given species assemblage are calculated across the species and mean distance of the S species to the center of gravity ($\overline{dG}$).

For mean traits, community-weighted mean values (CWM) were calculated for the tree height and DBH. This is the mean of trait values in a plot weighted by the relative abundances of species.

In order to calculate these indicators, a data base of traits per species is needed. First, the mean value for the traits maximum height and maximum DBH across all species per plot was calculated. These values were used to look at differences in trait values among the species. The approach used here was to calculate the trait values from own sampling data. Being aware of the traditional methods of acquiring the trait values from trait data bases and by calculating them from mature individuals, a different approach was used to look at existing vegetation in UGS that not only contain mature stand but also young individuals. Therefore, the traits can be calculated as found in reality, as these would be influencing the cooling effect. Thus, considering mature trees (DBH > 10 cm) as defined in literature, and the 95th percentile diameters was used as estimates of maximum DBH and the respective heights were used to calculate maximum height for all species per plot. The

95th percentile diameters were used as estimates of maximum DBH to minimize the weight of outliers (King et al., 2006). Hence all trees per plot were considered, and then computed for the indices including CWMs for both traits height and DBH (Díaz et al., 2007; Violle et al., 2007). For computing the indices of functional diversity per UGS, the mean indices per plot were calculated. This was done with the function 'dbFD' in the software R (version 2.14.2; R Development Core Team 2014), using package "FD" (Laliberté et al., 2015). Functional diversity indices of Villéger et al. 2008 – functional richness, functional evenness, functional divergence and the community-level weighted means of trait values e.g. CWM; (Lavorel et al., 2008) per UGS – were used for all of the following analyses.

3.2.7 Data analysis

All of the analyses of the microclimate data used the corrected temperature differences, rather than the actual temperature values. All statistical analyses were performed using the R language environment for the statistical computing version 3.1.2 (R Development Core Team, 2014).

To examine the influence of the characteristics of green spaces and their residential surroundings on the observed cooling effect (i.e., ΔT [FIT], ΔT [PWD] and cooling distance), multiple linear regressions model 1-3 (Table 6) were used. A comparative summary of the minimum adequate models for ΔT [FIT], ΔT[PWD] and cooling distance is given in Table 11 (temperature analysis, Section 4.4).

Hierarchical partitioning was performed for the tree diversity variables with the 'hier.part. package (Walsh and Nally, 2015). All the independent variables (species richness, Shannon diversity, Pielou's evenness index, functional richness, functional evenness, functional divergence, CWM DBH and CWM height) were calculated and were checked for multicollinearity, which determined their inclusion for regression analysis. To examine the influence of the different measures of biodiversity on the observed cooling effect (i.e., ΔT [FIT] and cooling distance), multiple regressions model 4-7 (Table 6) were used with a subset of the sampled UGS, and due to very low R^2 values (0.05) of the indicator ΔT[PWD] (model 3) was not further analysed. The models ΔT[FIT] and ΔT[FIT] without diversity variables are similar in the variables as well as models cooling distance and cooling distance without diversity variables except for the number of UGS included in the model. The comparison of models with and without diversity variables was done to check if the effect and the values are similar. While models with measures of biodiversity variables contained all independent variables; this was done to understand the influence of specific measures of biodiversity variables and their interaction with the type of green space onto the respective cooling effect. The interaction terms (Table 13) in the analysis were included to determine whether the effects of taxonomic diversity, functional diversity and mean traits on cooling differ among the two UGS categories: parks and forests. (Biodiversity analysis, Section 4.5)

The initial models included all of the independent variables, but they were reduced to a minimal adequate version according to the Akaike's information criterion (AIC) (Mac Nally, 2000). AIC is used to compare models; the lower the AIC, the better is the fit of the model. The automated model simplification is done using "step" function in R.

For ease, the variables were categorized into different categories

i. UGS characteristics: area, area of waterbody, percentage of tree/shrub cover within green space, shape (calculated as mean shape index, MSI), type of green space

ii. Surrounding characteristics: distance to city center, percentage of tree/shrub cover in 25-m buffer, type of housing

iii. Other variables: month of sampling, average wind speed of transect

iv. Biodiversity variables: Species richness, Shannon diversity, Pielou's Eveness, functional richness, functional divergence, functional eveness, CWM height, CWM DBH.

Table 6. An overview matrix summarizing all the models used for the analysis.

Model no.	Model name	No. of UGS	Dependent variable	Independent variables
1	ΔT[FIT]	62	ΔT[FIT]	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect Interaction: type of green space x area x shape
2	Cooling distance	62	Cooling distance	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect Interaction: type of green space x area x shape
3	ΔT[PWD]	62	ΔT[PWD]	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect Interaction: type of green space x area x shape
4	ΔT[FIT] without diversity variables	54	ΔT[FIT]	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect Interaction: type of green space x area x shape
5	ΔT[FIT] with diversity variables	54	ΔT[FIT]	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect, CWM DBH, species richness, functional richness Interactions: type of green space x area x shape, type of green space x functional richness, type of green space x species richness + type of green space X CWM DBH
6	Cooling distance without diversity variables	54	Cooling distance	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect Interaction: type of green space x area x shape
7	Cooling distance with diversity variables	54	Cooling distance	type of green space, area, shape, percentage of tree/shrub cover within green space, area of waterbody, distance to city center, type of housing, percentage of tree/shrub cover in 25-m buffer, month of sampling, average wind speed of transect, CWM height, Pielou's Eveness, functional divergence Interactions: type of green space x area x shape, type of green space x functional divergence, type of green space x CWM height, type of green space x Pielou's Eveness

4 Results of empirical case study

4.1 Descriptive statistics of temperature analysis: air temperature sampling

4.1.1 Independent variables of UGS and surroundings

An overview of all independent variables of UGS and surroundings used in the analysis and regression models 1-3 is provided in Table 7. Since none of the variables were highly correlated, they were all used for the analysis.

Table 7. Independent variables (n=62) that are used in the models (1-3) with their minimum, maximum, and median values.

	Forests			**Parks**		
	Min	**Median**	**Max**	**Min**	**Median**	**Max**
Area, ha	0.4	2.2	35.6	0.2	0.8	3.4
Shape (MSI)	1.1	1.4	2.5	1.1	1.2	1.9
Percentage of tree/shrub cover	56.0	96.5	99.6	39.1	74.0	99.8
Total area of waterbody, ha	0.08	0	1.2	0.07	0	0.8
Distance to city center, m	1876	5589	9885	359	3928	9778
Percentage of tree/shrub cover in 25m buffer	12.31	39.11	52.76	11.04	28.62	53.00
Average wind speed of transect, ms^{-1}	0.2	0.82	2.26	0.06	0.8	1.54

4.1.2 Descriptive statistics of indicators of cooling effect

On average, for the ΔT[FIT], a cooling effect of 0.8 K (ranging from 0.0 to 3.3 K) was observed for forests (n=22) and 0.5 K (ranging from 0.0 to 3.2 K) was observed for parks (n=37). A maximum cooling distance of 469 m for forests and 391 m for parks was estimated. The ΔT[PWD] for forests (n=23) was averaged at 0.3 K (ranging from -0.7 to 1.9 K) and for parks (n=37) it was averaged at 0.1 K (ranging from -0.7 to 3.2 K). The values were the same for the UGS sampled for tree diversity sampling (n=54), with an exception of maximum cooling distance for parks which was 342 m.

The distribution of cooling effects (ΔT[FIT], ΔT[PWD] and cooling distance) for forests and parks is depicted in Fig 10. It was observed that few UGS had low cooling effects. Approximately 50.0 % of forests and 67.6 % of the parks showed a temperature difference of 0 - 0.5 K for ΔT[FIT]. Similarly, 13.6 % of the forests and 29.7 % of the parks had a cooling distance of 0 - 50 m, of which 2 forests and 9 parks had a ΔT[FIT] and cooling distance = 0. For ΔT[PWD] 26.1 % of forests and 29.7 % of parks had values below zero and about 65 % of both forest and parks had values within the range of 0 -1.0 K (Jaganmohan et al., 2016).

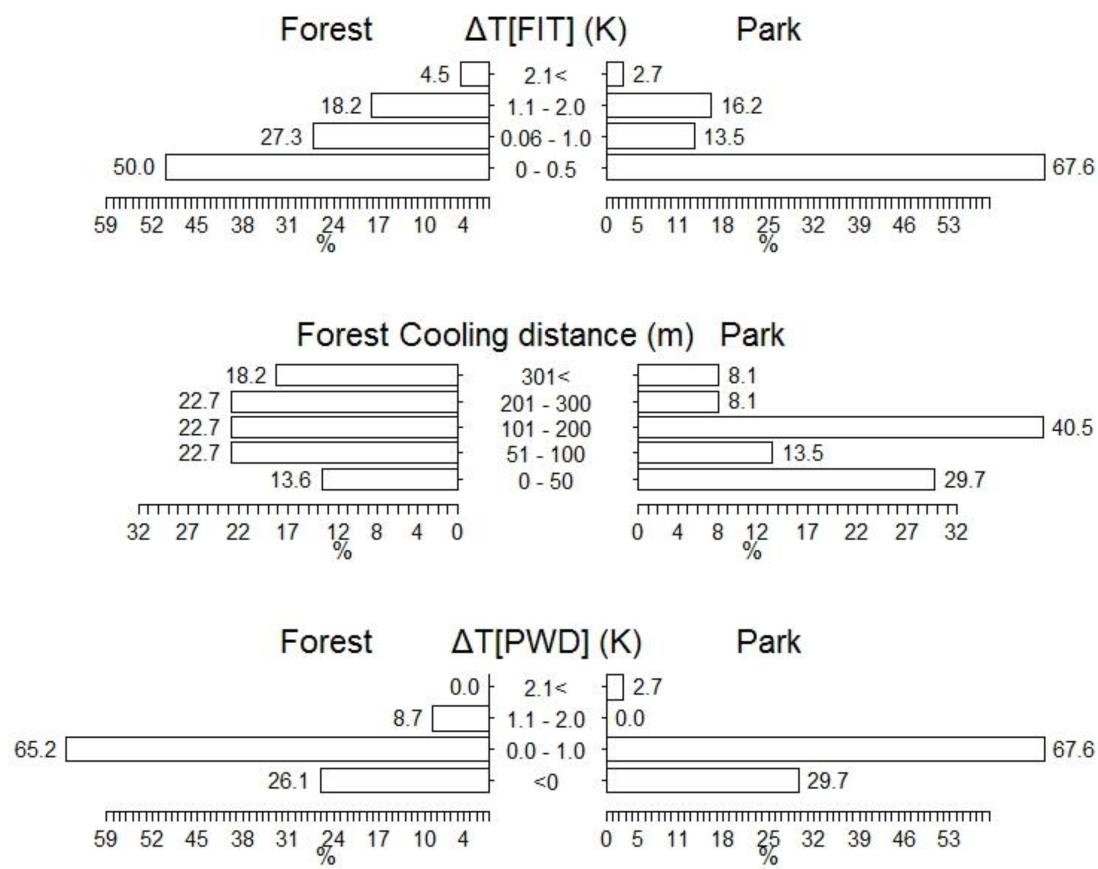

Figure 10. Distribution of sampled UGS (forests and parks) in various classes for temperature difference (ΔT[FIT]) and cooling distance in Leipzig.

4.1.3 Correlation of indicators of cooling effect

Spearman correlations between the different indicators for quantifying the cooling effect indicate significant positive correlations (r_s=0.8, $p<0.001$ for both the ΔT[PWD] and the ΔT[FIT] as well as for the ΔT[FIT] and cooling distance). An increase in the ΔT[FIT] is related to increases in the ΔT[PWD] (Fig. 11A) and the cooling distance (Fig. 11B), but the differences for forests and parks, as indicated with the separate fitted lines, are not strong. However, there is a remarkable degree of scatter, indicating that the two variables cannot simply be replaced by each other. Therefore, the scatter plots imply that the three different indicators do not exactly measure the same aspects of the cooling effect, and a broad variety in the relationship between the indicators and the effects is present. This holds especially true for the cooling distance versus the temperature differences (Fig. 11B). A comparison of the PWD and the cooling distance shows considerable differences (Fig.

11C), especially for parks; the PWD strongly overestimates the cooling distance as fitted from the observed temperatures (Jaganmohan et al., 2016).

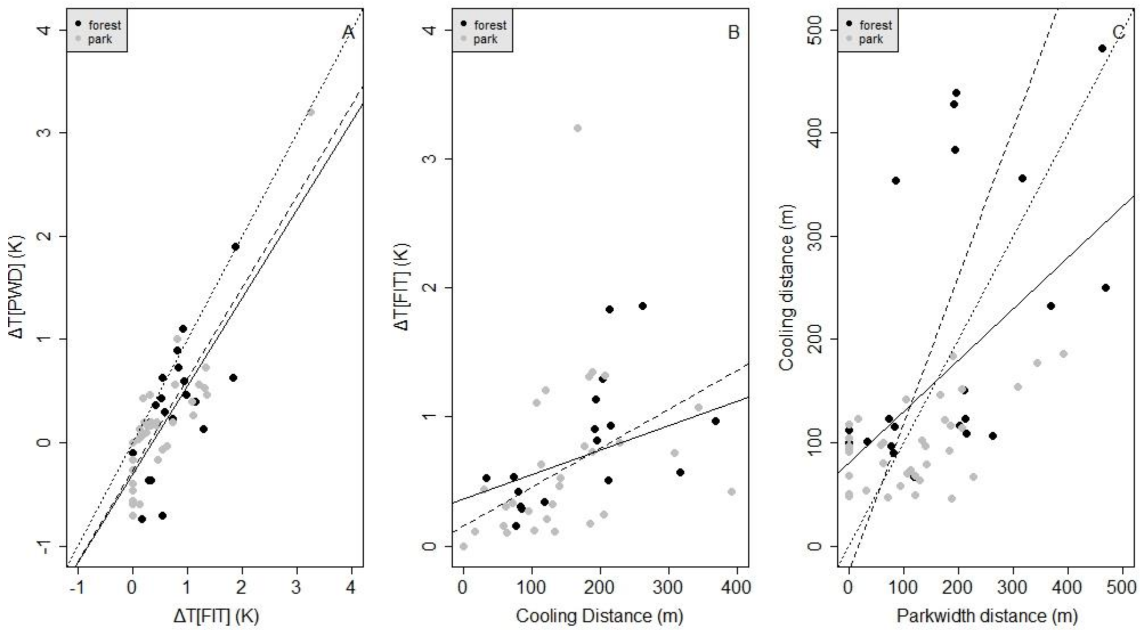

Figure 11. The relationships between the various indicators for quantifying the cooling effect. In A and C, the bisecting line (dotted line) demonstrates perfect agreement of the two different measures of the temperature difference and distances. The lines represent the slopes for the forests (bold line) and the parks (dashed line). B is the calculated cooling effects from cubic polynomial fit. ΔT[FIT] is the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route. ΔT[PWD] is calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at PWD along the transect, with PWD being the square root of the area of the green space.

4.2 Descriptive statistics of biodiversity analysis: tree diversity sampling

4.2.1 Aggregate distributions of trees

The composition of plots was dominated by deciduous trees. There were 36 species belonging to 14 families encountered in all UGS. The most dominant tree species across all plots were *Fraxinus excelsior* (14.3 %), *Salix caprea* (12.8 %) and *Betula pendula* (12.3 %). Together, the three dominant species accounted for approximately 40 % of all sampled trees (Table 8). Approximately 70 % of the tree species that occurred in the study plots are native to Europe.

Table 8. Attributes of all tree species encountered during sampling in 54 UGS of Leipzig.

Scientific name	Common name	Family	Percentage of trees (%)	Origin	Phenology
Acer campestre	Field Maple	Aceraceae	1.3	Native to Europe	Deciduous
Acer griseum	Paper-back Maple	Aceraceae	3.4	Non-native, China	Deciduous
Acer platanoides	Norway Maple	Aceraceae	9.0	Native to Europe	Deciduous
Acer pseudoplatanus	Sycamore	Aceraceae	9.8	Native to Europe	Deciduous
Acer saccharum	Sugar Maple	Aceraceae	0.5	Non-native, E Canada	Deciduous
Aesculus x carnea	Red Horse Chestnut	Hippocastanaceae	0.3	Native to Europe	Deciduous
Aesculus hippocastanum	Horse Chestnut	Hippocastanaceae	3.6	Native to Europe	Deciduous
Alnus glutinosa	Common Alder	Betulaceae	3.1	Native to Europe	Deciduous
Betula pendula	Silver Birch	Betulaceae	12.3	Native to Europe	Deciduous
Carpinus betulus	Common Hornbeam	Betulaceae	4.8	Native to Europe	Deciduous
Corylus avellana	Common Hazel	Betulaceae	0.2	Native to Europe	Deciduous
Crataegus monogyna	Common Hawthorn	Rosaceae	0.5	Native to Europe	Deciduous
Fagus sylvatica	Common Beech	Fagaceae	1.0	Native to Europe	Deciduous
Fraxinus excelsior	Common Ash	Oleaceae	14.3	Native to Europe	Deciduous
Gleditsia triacanthos	Honey locust	Leguminosae	0.3	Non-native, Central N America	Deciduous
Juglans regia	Common Walnut	Juglandaceae	0.2	Native to Europe	Deciduous
Picea sitchensis	Sitka Spruce	Pinaceae	0.5	Non-native, Alaska to N California	Coniferous Evergreen
Pinus nigra ssp. nigra	Austrian Pine	Pinaceae	0.3	Native to Europe	Coniferous Evergreen
Platanus x hispanica	London Plane	Platanaceae	1.1	Non-native, N America and Asia	Deciduous
Populus x canadensis	Hybrid Black Poplars	Salicaceae	0.8	Hybrid	Deciduous
Populus nigra ssp. betulifolia	Wild Black Poplar	Salicaceae	0.8	Native to Europe	Deciduous
Prunus avium	Wild Cherry	Rosaceae	0.5	Native to Europe	Deciduous
Quercus palustris	Pin Oak	Fagaceae	0.2	Non-native, Ontario to N Carolina and Kansas	Deciduous
Quercus robur	English Oak	Fagaceae	4.1	Native to Europe	Deciduous
Quercus rubra	Red Oak	Fagaceae	1.1	Non-native, E North America	Deciduous
Robinia pseudoacacia	False Acacia	Leguminosae	4.9	Non-native, E USA	Deciduous
Salix alba	White Willow	Salicaceae	0.5	Native to	Deciduous

				Europe	
Salix caprea	Goat Willow	Salicaceae	12.8	Native to Europe	Deciduous
Salix fragilis	Crack Willow	Salicaceae	0.2	Native to Europe	Deciduous
Sambucus nigra	Elder	Adoxaceae	0.3	Native to Europe	Deciduous
Sophora japonica	Pagoda Tree	Leguminosae	0.2	Non-native, China, Korea	Deciduous
Tilia cordata	Small-leaved Lime	Tiliaceae	2.0	Native to Europe	Deciduous
Tilia x petiolaris	Silver Pendent Lime	Tiliaceae	0.3	Hybrid	Deciduous
Tilia platyphyllos	Broad-leaved Lime	Tiliaceae	4.3	Native to Europe	Deciduous
Tilia tomentosa	Silver Lime	Tiliaceae	0.2	Native to Europe	Deciduous
Ulmus minor	Field Elm	Ulmaceae	0.3	Native to Europe	Deciduous

4.2.2 Correlation of DBH and height

The correlation between DBH and height was positive ($r_{pearson} = 0.65$; $p<0.001$), for all the sampled trees. There was a significant difference in the mean DBH between forests (m=23.0, sd= 20.8) and parks (m= 42.0, sd = 23.3) but not for the mean height between forests (m=15.2, sd=6.1) and parks (m=16.0, sd=5.1) using paired Student’s t-tests with the p-value indicated in Fig. 12. Overall, forests contained approximately 86 % of trees with a DBH below 45 cm (Fig. 13). Parks contained trees with a larger DBH compared to forests; only 60 % of trees in parks had a DBH below 45 cm. Average tree height was similar in both forests and parks; approximately 80 % of trees were below 20 m.

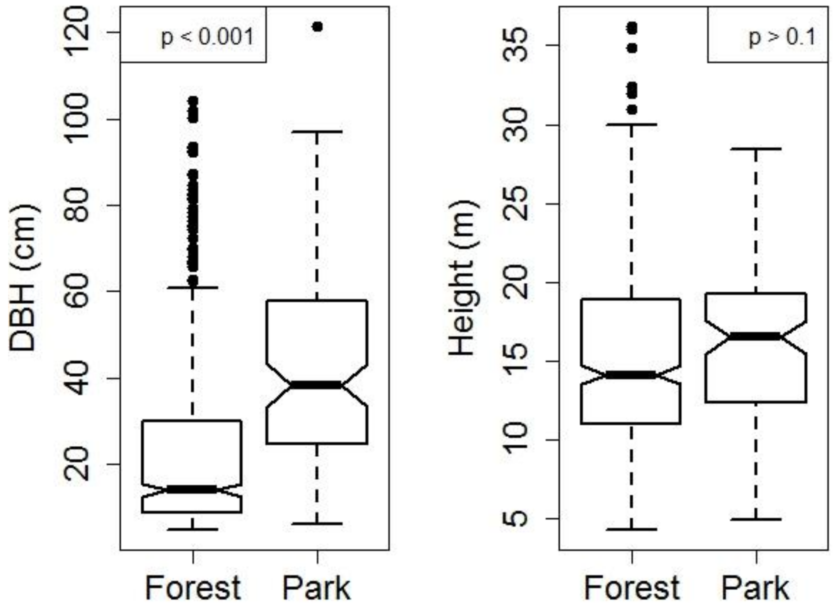

Figure 12. Boxplots showing a comparison of the parks and forests with respect to DBH and height. The boxes represent the quartiles (25-75 %); horizontal line indicates the median; the notch marks the 95 % confidence interval for the medians; and the circles beyond whiskers indicate outliers with extreme values.

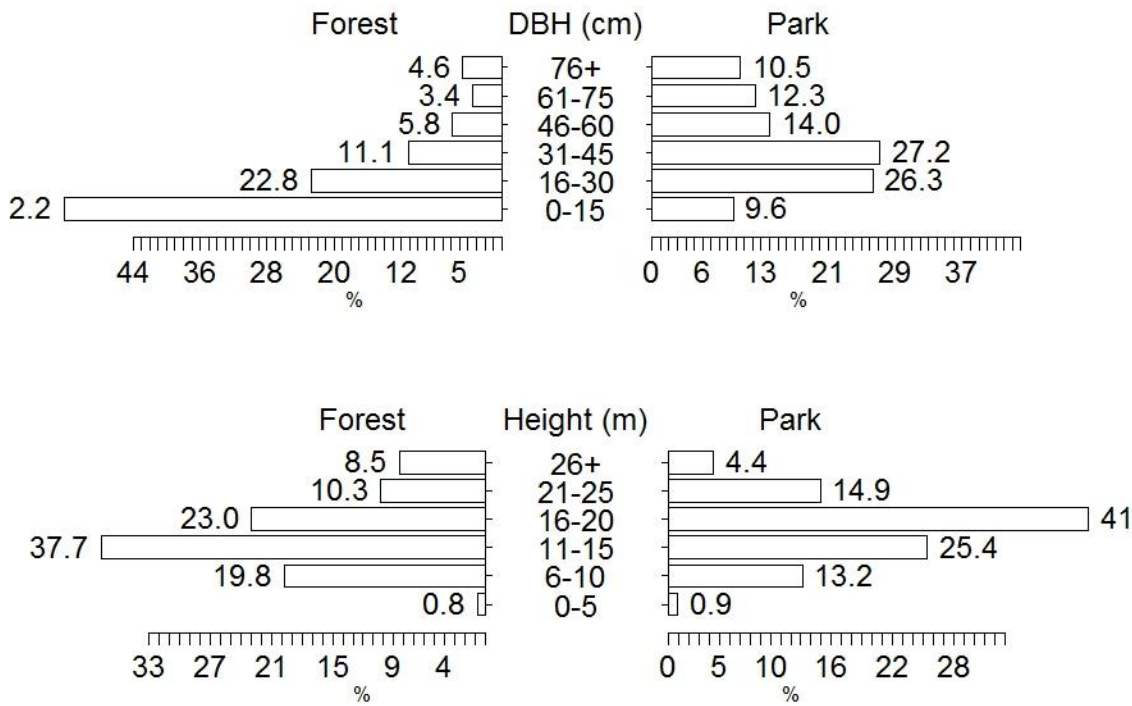

Figure 13. Distribution of sampled trees in various classes for tree DBH and height across different UGS (forests and parks) in Leipzig.

4.2.3 Descriptive statistics of measures of biodiversity

On average, forests were richer in species, and had higher Shannon diversity and Pielou's Evenness compared to parks (Table 9). These differences were statistically significant based on a paired Student's t-test. Functional richness and divergence were higher for forests while functional evenness was higher for parks. For mean traits, the CWM DBH of trees was significantly higher in parks than forests with no significant difference in CWM height. Parks are dominated by larger trees, whose planting is planned to allow ample space for tree growth.

Table 9. Attributes of UGS and trees sampled in 54 UGS in Leipzig.

Attributes of UGS of sampled trees	**Forests**	**Parks**	**Significance**
Number of green spaces sampled	21	33	
Number of plots with trees	111	63	
Size (ha)	7.2 ± 9.5	1.1 ± 0.8	
No. of individuals per plot	4.4 ± 4.7	1.8 ± 1.3	
Tree density	4.4 ± 3.6	1.8 ± 1.4	
Taxonomic diversity			
Species richness	1.9 ± 0.9	1.3 ± 0.5	forests > parks*
Species Shannon diversity	0.4 ± 0.4	0.2 ± 0.3	forests > parks*
Pielou's Evenness	0.4 ± 0.3	0.2 ± 0.3	forests > parks**
Functional diversity			
Functional richness	0.70 ± 0.57	0.40 ± 0.65	forests > parks**
Functional Evenness	0.14 ± 0.21	0.37 ± 0.15	forests < parks**
Functional divergence	0.19 ± 0.25	0.03 ± 0.12	forests > parks*
Mean traits			
CWM DBH (cm)	37.0 ± 20.5	48.5 ± 18.3	forests < parks*
CWM height (m)	16.7 ± 4.6	17.1 ± 4.3	forests < parks

Mean ± standard deviation given whenever appropriate.

* Significant at the 0.05 probability level.

** Significant at the 0.1 probability level.

*** Significant at the 0.001 probability level.

4.2.4 Correlations among biodiversity variables

Among all of the calculated independent biodiversity variables, some were highly correlated (absolute Pearson correlation of > 0.7) (Table 10). It thus becomes difficult to use them in a regression model directly due to multicollinearity. Species richness was highly correlated with Shannon diversity, Pielou's Evenness, Functional Evenness and Functional Divergence while Shannon diversity was highly correlated with all variables except with mean traits.

Table 10. Correlation coefficients of the independent variables of tree diversity calculated from 54 UGS in the city of Leipzig.

		Taxonomic diversity			**Functional diversity**			**Mean traits**	
		Species richness	**Shannon diversity**	**Pielou's eveness**	**Functional richness**	**Functional evenness**	**Functional divergence**	**CWM height**	**CWM DBH**
Taxonomic diversity	Species richness	1.00	0.96***	0.85***	0.66***	0.81***	0.91***	-0.45***	-0.57***
	Shannon diversity		1.00	0.95***	0.74***	0.79***	0.82***	-0.44***	-0.56***
	Pielou's eveness			1.00	0.86***	0.60***	0.61***	-0.42*	-0.54***
Functional diversity	Functional richness				1.00	0.24**	0.33*	-0.35*	-0.53***
	Functional evenness					1.00	0.88***	-0.37*	-0.38*
	Functional divergence						1.00	-0.38*	-0.44***
Mean traits	CWM height							1.00	0.71***
	CWM DBH								1.00

* Significant at the 0.05 probability level.

** Significant at the 0.1 probability level.

*** Significant at the 0.001 probability level.

4.3 Descriptive results for warming and cooling effects

The values of the calculated indicators of temperature difference (ΔT[FIT], ΔT[PWD]) had a wide range from positive, zero and negative values. It was thus necessary to separate those UGS that have a cooling effect in either one of the indicators since every UGS has one value for each indicator (ΔT[FIT] and ΔT[PWD]). The cooling distance indicator has no negative values; hence no warming effect can be concluded for this specific indicator. For those UGS where the ΔT[FIT] equals to zero, the corresponding cooling distance value is also zero. A green space is considered to have a cooling effect if the indicator has a positive value; if the value is 0 (ΔT[FIT], ΔT[PWD]) or negative (ΔT[PWD]), the green space has a warming effect. Out of the 58 UGS with complete datasets (with values for both indicators ΔT[FIT] and ΔT[PWD]), 39 were considered to have a cooling effect for both indicators, and 8 had a cooling effect only for the ΔT[FIT] indicator; meanwhile, the ΔT[PWD] indicated a warming effect for the same green spaces. None of the green spaces showed any warming indicated by ΔT[FIT] and cooling by ΔT[PWD]. In total, 11 UGS were found to have a warming effect for both indicators. Thus, a considerable portion of the UGS did not provide a cooling effect that extended into the surrounding residential areas. This indicates, first, that there are differences in the cooling and warming effects between different UGS, and second, that the assessment depends on the calculation method. The different characteristics of the UGS and their surroundings may be the main factors influencing their cooling effects. However, in this study a significant influence on the warming/cooling effect only from the size (Fig. 14, 15) was found. The warmer green spaces were generally smaller in size and did not have any bodies of water in them (Jaganmohan et al., 2016).

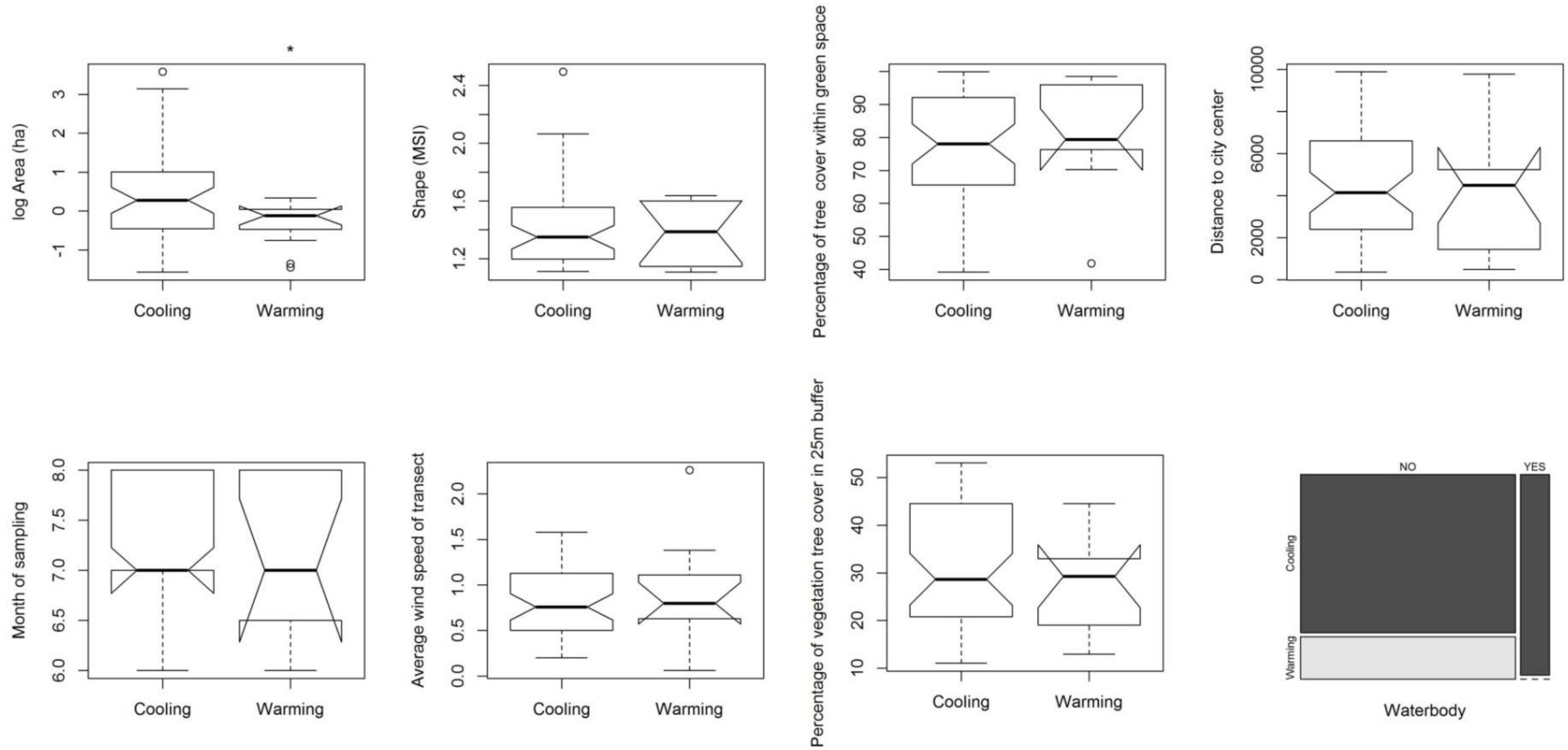

Figure 14. Boxplots and mosaic plot showing a comparison of the cooling and warming green spaces using the ΔT[FIT] indicator (i.e., the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route) with respect to various independent variables. The boxes represent the quartiles (25-75 %); horizontal line indicates the median; the notch marks the 95 % confidence interval for the medians and the circles beyond whiskers indicate outliers with extreme values. The asterisk above a boxplot indicates a statistically significant difference between cooling and warming green spaces. MSI, mean shape index.

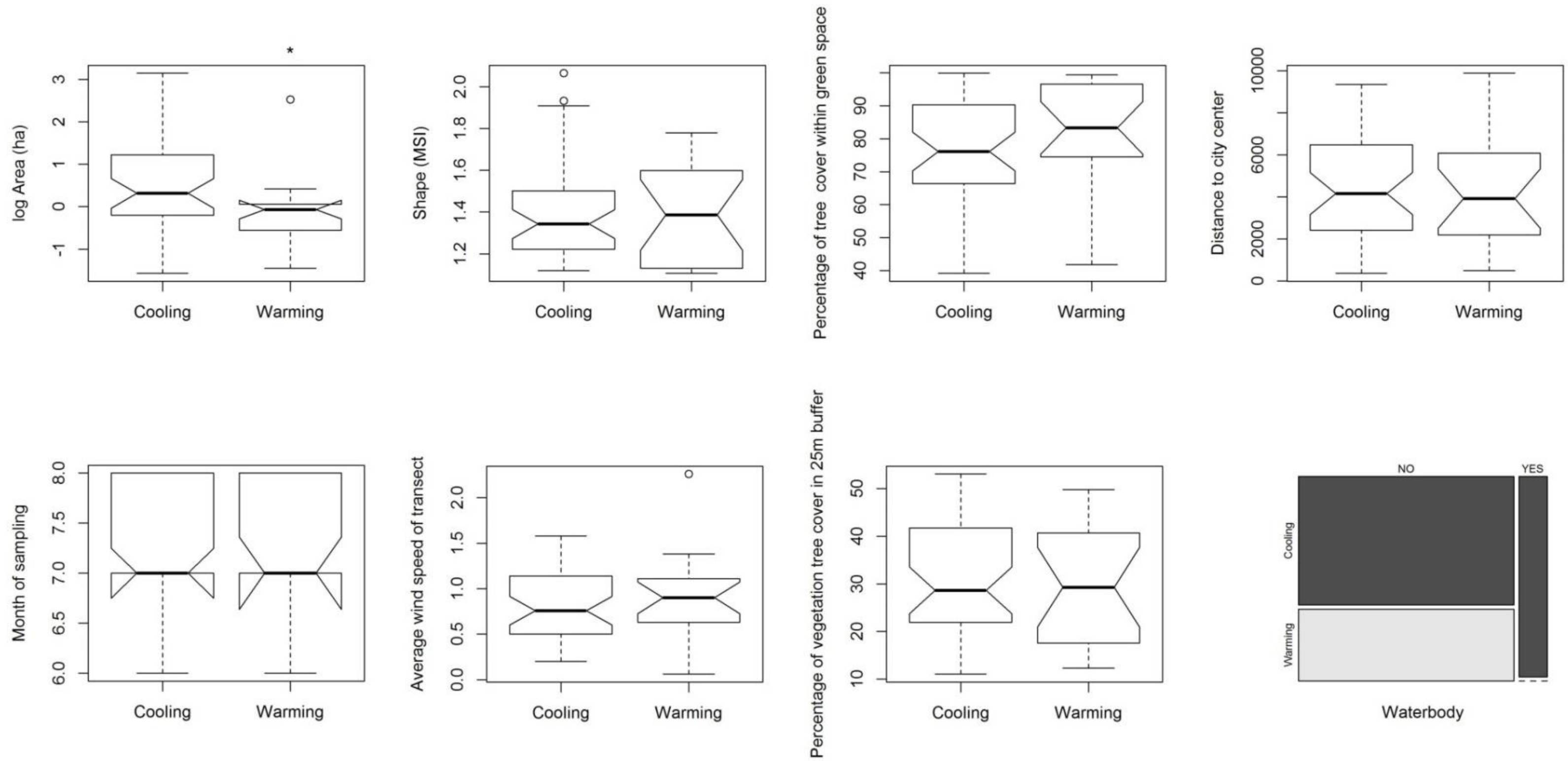

Figure 15. Boxplots and mosaic plot showing a comparison of the cooling and warming green spaces using the ΔT[PWD] indicator (calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance [PWD] along the transect, with PWD being the square root of the area of the green space) with respect to various independent variables. The boxes represent the quartiles (25-75 %); horizontal line indicates the median; the notch marks the 95 % confidence interval for the medians and the circles beyond whiskers indicate outliers with extreme values. The asterisk above a boxplot indicates a statistically significant difference between cooling and warming green spaces. MSI, mean shape index.

4.4 Regression analysis to examine the influence of the characteristics of green spaces and their residential surroundings on the observed cooling effect

A comparative summary of the minimum adequate models after a stepwise reduction is given in Table 11 for all the three indicators. The R^2 values are highest for the cooling distance (0.51) and lower for the temperature differences (ΔT[FIT]= 0.35 and ΔT[PWD]= 0.05, respectively). Because the R^2 values of the ΔT[PWD] model was found to be very low, the results of this model are not discussed below.

The residential surroundings of UGS are characterized by their distance to the city center, the type of housing and the percent tree/shrub coverage within a 25-m buffer around the measurement transects. Table 11 indicates that the characteristics of the surroundings are of medium importance for the cooling effects. The distance to the city center was never included in the minimal adequate models. The type of housing was only included for the cooling distance. Compared with dense housing, semi-detached housing implies a cooling distance that is approximately 50 m shorter. Tree/shrub cover in the 25-m buffer was found to be important for both the cooling distance and the ΔT[FIT] model, whereby the increased tree/shrub coverage on streets indicates a larger cooling effect. Furthermore, the measurement-specific variable sampling month was not included in any of the final models. With regard to wind speed in the ΔT[FIT] model, a higher wind speed implied a lower temperature difference between the green spaces and the surroundings. Other green space characteristics, namely the percent tree/shrub coverage within the green space and the size of the body of water, slightly decreased the cooling distance (Jaganmohan et al., 2016).

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Table 11. A multiple linear regression (final models) showing the relationship between the ΔT[FIT], the cooling distance, and the ΔT[PWD] and the variables characterizing the green spaces, their residential surroundings, and the measurement specifics in the city of Leipzig.

	Model ΔT[FIT]†	**Model cooling distance**	**Model ΔT[PWD]‡**
R^2	0.35	0.51	0.05
Adj. R^2	0.26	0.42	0.04
Intercept	1.04	313.35**	0.14
UGS characteristics			
Type of green space (park)	−0.40	−159.30***	–
Area	−0.07	17.96*	0.03¶
Shape (mean shape index)	−0.28	45.13	–
Percentage of tree/shrub cover within green space	–	−2.90**	–
Area of waterbody	–	−131.15*	–
Interactions			
Type of green space (park): area	0.20¶	72.48***	–
Type of green space (park): shape	–	–	–
Area: shape	0.05*	−7.2¶	–
Type of green space (park): area: shape	–	–	–
Surrounding characteristics			
Distance to city center	–	–	–
Type of housing (semi-detached)	–	−51.74	–
Percentage of tree/shrub cover in 25-m buffer	0.01	1.92	–
Other variables			
Month of sampling	–	–	–
Average wind speed of transect	−0.31	–	–

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

¶ Significant at the 0.1 probability level.

† Maximum temperature difference between the green space boundary and the surrounding area measured within the transect route.

‡ Calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance (PWD) along the transect, with PWD being the square root of the area of the green space.

-- Variable not included in the final model. The model included the interaction between the type of green space $\times$ area $\times$ shape, and the coefficients indicate how different the parks are from the forests.

4.4.1 Cooling effect of parks versus forests

For all three indicators, the cooling effect was higher in the forests than in the parks (Fig. 16). This finding was also confirmed using the multiple regression model (Table 11), where the slope given for the cooling effect of the parks was smaller than the slope for the forests in both the ΔT[FIT] and cooling distance models. This shows that forests provide greater cooling effects with higher mean ΔT[FIT] values and larger cooling distances than parks. Thus, forests have a larger cooling effect than parks (Jaganmohan et al., 2016).

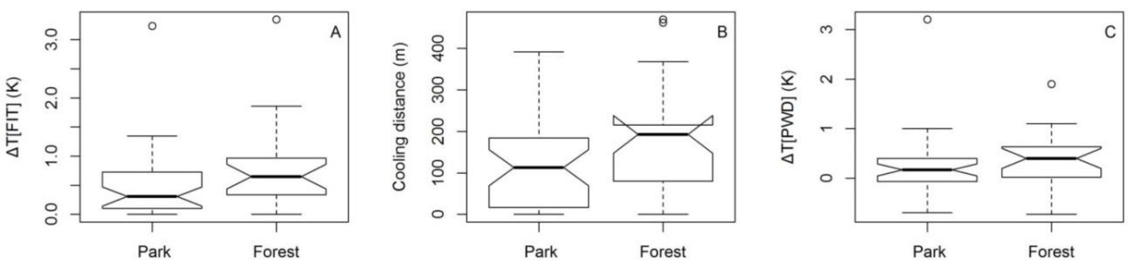

Figure 16. Boxplots showing a comparison of the parks and forests with respect to cooling distance and the temperature differences Δ T[FIT] (i.e., the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route) and Δ T[PWD] (calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance [PWD] along the transect, with PWD being the square root of the area of the green space). The boxes represent the quartiles (25-75 %); horizontal line indicates the median cooling effect for each type of vegetation; the notch marks the 95 % confidence interval for the medians and the circles beyond whiskers indicate outliers with extreme values.

4.4.2 Size and shape of green spaces

The interaction between the size and shape shows a positive effect on the ΔT[FIT] and a negative effect on the cooling distance regardless of whether a green space is a forest or park. However, this interaction alone does not tell us whether the area and shape of a green space has a positive or negative effect on the ΔT[FIT] or the cooling distance. To test this and to refine visual interpretation (Fig. 17), simple slopes (cf. (Bauer and Curran, 2005)) was considered. These showed that the increasing complexity of a green space has a negative effect on the ΔT[FIT] for green spaces smaller than 5.6 ha, but it has a positive effect on the ΔT[FIT] for green spaces larger than 5.6 ha (cf. the minimal adequate model; Table 11: the simple slope for the MSI in the model ΔT[FIT] equals -0.28 + 0.05*area, which is > 0 for areas > 5.6 and < 0 for areas < 5.6). This suggests that a complex green space provides a smaller cooling effect when it is small but not for larger green spaces. The opposite relationship is shown for cooling distance, with a positive effect from the complexity for green spaces smaller than 6.27 ha and a negative effect for green spaces larger than 6.27 ha (cf. the minimal adequate model; Table 11: the simple slope for the MSI in the model cooling distance equals 45.13 - 7.2*area, which is > 0 for area < 6.27 and < 0 for area > 6.27). Thus, a more complex pattern of relationships with increase in size and shape was found (Jaganmohan et al., 2016).

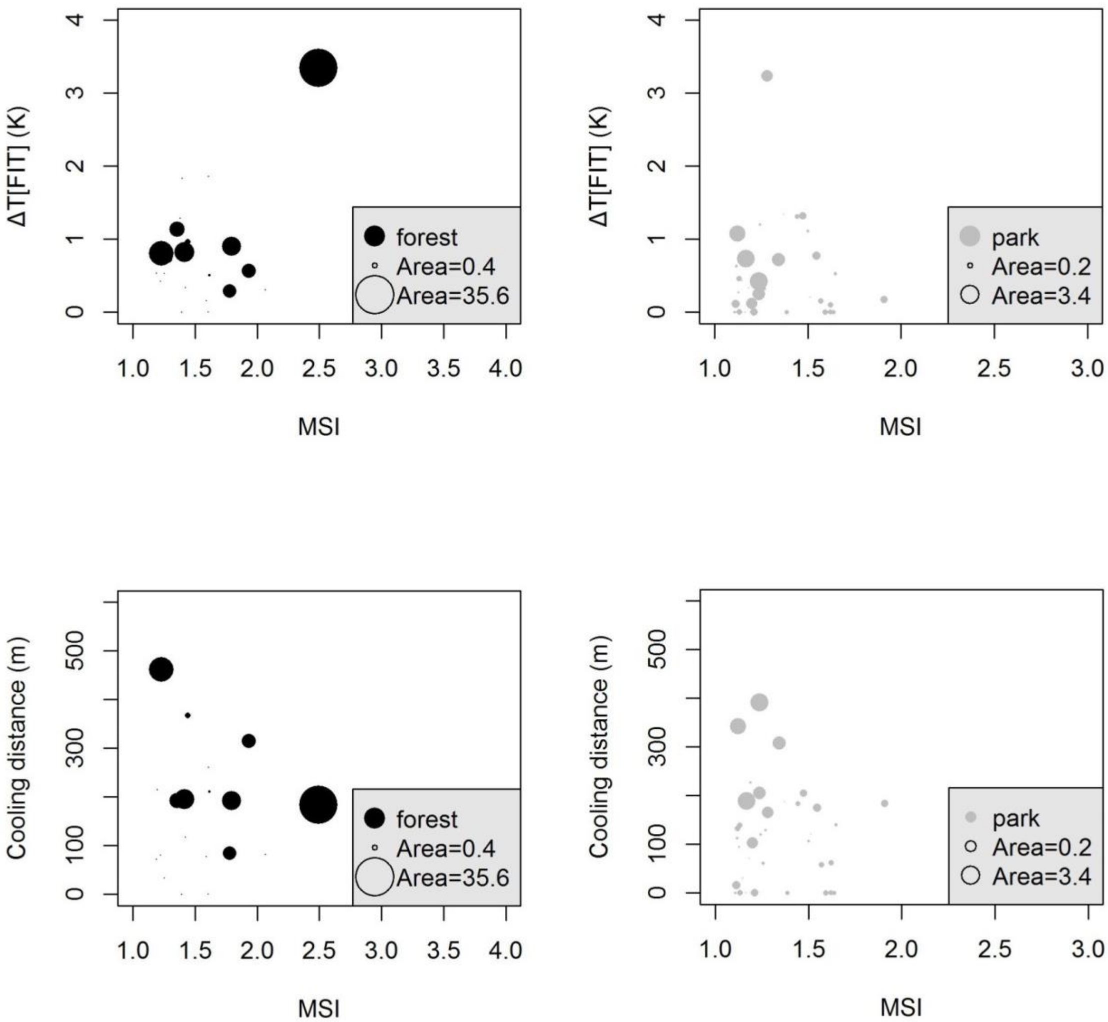

Figure 17. Scatter plots showing the relationship of ΔT[FIT] (i.e., the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route) and cooling distance with the mean shape index (MSI) of green spaces. The larger the points, the larger the area, indicating increasing size.

4.5 Cooling effects and biodiversity

4.5.1 Hierarchical partitioning

Due to high correlations between the independent variables, hierarchical partitioning was performed (Olea 2010) for the tree diversity variables (Table 12). The cooling effects, i.e. ΔT[FIT] and cooling distance (the indicators derived from transect measurements), were independent variables, and the biodiversity variables were dependent variables. Hierarchical partitioning then provides for each independent variable a value of importance for explaining both dependent variables. For a given independent variable, hierarchical partitioning provides the explanatory power of the independent contribution of that specific variable (Independent) on the dependent variable, and the joint contribution that is not specific to that individual variable but the contribution due to joint effect with other variables (Joint) (Mac Nally, 2002). Independent % is the percentage of total explained variance for that specific variable. Based on their individual effects, one variable from each type of measures of biodiversity is used in multiple linear regressions to further explain the cooling effects. In order to understand the difference between parks and forests, interaction terms were included. Furthermore it is interesting to see the direction of the effects of the variables on to cooling which is obtained after a multiple regression analysis, as hierarchical partitioning only gives the importance of variables, but not their direction.

4.5.2 Regression analysis to examine the measures of biodiversity on the observed cooling effect

Even though model ΔT[FIT], and model ΔT[FIT] without diversity variables, as well as model cooling distance, and model cooling distance without diversity variables, have the same dependent and independent variables, it was necessary to carry out these two additional models with varying number of UGS (since biodiversity data was not available for all the 62 UGS). It is to be noted that model ΔT[FIT], and model cooling distance, had 62 UGS and model ΔT[FIT] without diversity variables, and model cooling distance without diversity variables, had 54 UGS values fed in to the model (Table 6).

Thus, model ΔT[FIT] with diversity variables, included mean values of the variables species richness, functional richness, CWM DBH and their interaction with the variable type of green space (park/forest), in addition to the variables included in model ΔT[FIT] without diversity variables. Similarly, model cooling distance with diversity variables, had Pielou's evenness, functional divergence, CWM height and their interaction with the variable type of green space (park/forest) compared to model cooling distance without diversity variables. As shown in Table 13, in both models ΔT[FIT] with diversity variables, and cooling distance with diversity variables, adding biodiversity variables improved model performance based on AIC scores which were lower (-47.43 and 487.02 respectively) compared to ΔT[FIT] without diversity variables, and cooling distance without diversity variables (-47.05 and 491.49 respectively). Improved model performance is also indicated by a higher adj. R^2 for model ΔT[FIT] with diversity variables (0.30) and cooling distance with diversity variables (0.50) in comparison to ΔT[FIT] without diversity variables (0.27) and cooling distance without diversity variables (0.41).

Table 12. Hierarchical partitioning: Independent, joint and total contribution of each variable to ΔT[FIT] and cooling distance. The values in bold are the highest among each measure of biodiversity and were chosen for regression analysis.

		ΔT[FIT]				Cooling distance			
	Variable	**Independent**	**Joint**	**Total**	**Independent %**	**Independent**	**Joint**	**Total**	**Independent %**
Taxonomic diversity	Species richness	0.01	-0.003	0.007	**11**	0.008	-0.008	0	10.6
	Shannon diversity	0.006	-0.001	0.005	6.3	0.008	-0.005	0.003	10.3
	Pielou's Evenness	0.008	-0.004	0.004	8.2	0.014	-0.006	0.008	**18.5**
Functional diversity	Functional richness	0.011	-0.001	0.01	**12.4**	0.003	0	0.003	4.1
	Functional Evenness	0.002	-0.001	0.001	2.2	0.002	-0.001	0.001	2.2
	Functional divergence	0.006	-0.003	0.003	6	0.007	-0.007	0	**9.5**
Mean traits	CWM DBH	0.044	-0.03	0.014	**48**	0.004	0.003	0.008	5.5
	CWM height	0.005	-0.004	0.001	5.9	0.03	0.003	0.034	**39.2**

For ΔT[FIT], species richness, functional richness and CWM DBH had the highest values for variable importance, while for cooling distance, the three biodiversity measures are best represented by Pielou's evenness, functional divergence and CWM height (Table 12). When looking at the individual variable importance of the three measures, there is always at least one variable other than taxonomic diversity with higher importance for explaining the cooling effect.

Table 13. Results of four multiple linear regressions (minimal adequate models) showing the relationship between ΔT[FIT], cooling distance and the independent variables of 54 UGS in the city of Leipzig, Germany.

	Model 4 ΔT[FIT] without diversity variables	**Model 5 ΔT[FIT] with diversity variables**	**Model 6 cooling distance without diversity variables**	**Model 7 cooling distance with diversity variables**
R^2	0.35	0.40	0.49	0.62
adj. R^2	0.27	0.30	0.41	0.50
AIC	-47.05	-47.43	491.49	487.02

(Intercept)	0.52	1.316	299.17 *	476.6 **
Biodiversity variables:				
CWM DBH	–	-6.852e-03	–	–
Species richness	–	-0.26 ¶	–	–
Functional richness	–	–	–	–
Interaction -Type of green space (Park): Functional richness	–	–	–	–
Interaction -Type of green space (Park): Species richness	–	–	–	–
Interaction -Type of green space (Park): CWM DBH	–	–	–	–
CWM height	–	–	–	-12.51 *
Pielou's Eveness	–	–	–	–
Functional divergence	–	–	–	-253.4 **
Interaction -Type of green space (Park): Functional divergence	–	–	–	473 **
Interaction -Type of green space (Park): CWM height	–	–	–	12.67 *
Interaction -Type of green space (Park): Pielou's Eveness	–	–	–	–
UGS characteristics:				
Type of green space (Park)	-0.21	-0.31	-153.55 ***	-406.2 **
Area	-0.04	-0.04	21.01 **	16.25 *
Shape (MSI)	-0.21	-0.21	82.47	72.14
Interaction -Type of green space (Park): Area	0.22	0.22	65.02 **	66.37 **
Interaction -Type of green space (Park): Shape	–	–	–	–
Interaction - Area: Shape	0.05 ¶	0.05 ¶	-8.62 *	-5.76
Interaction -Type of green space (Park): Area: Shape	–	–	–	–
Percentage of tree/shrub cover within green space	–	–	-3.01 **	-2.00 *
Area of waterbody	–	–	-122.87 *	-128 *

Surrounding characteristics:			
Distance to city center	6.69E-05 ¶	0.00006519 ¶	0.009
Type of housing (semi-detached)	–	–	-57.29 ¶
Percentage of tree/shrub cover in 25m buffer	–	–	
Other variables:			
Month of sampling	–	–	–
Average wind speed of transect	–	–	–

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

¶ Significant at the 0.1 probability level.

-- Variable not included in the final model. The model included the interaction between the type of green space × area × shape and type of green space x measures of biodiversity, and the coefficients indicate how different the parks are from the forests.

4.5.3 Similarity among the variables retained in the models

As compared to the model ΔT[FIT] (Table 11), it is seen that the other UGS variables that remained in the model are the same, except that in this regression with a subset of 54 UGS the previously important variables, such as percentage of tree/shrub in 25-m buffer and average wind speed of transect are discarded and instead the variable distance to city center remains in models 4 and 5 (Table 13).

For cooling distance, model 6 did not include the previously important variables Type of housing (semi-detached) and percentage of tree/shrub in 25 m buffer, while model 7 only excluded percentage of tree/shrub in 25 m buffer and retained Type of housing (semi-detached) and distance to city center. The direction of the UGS characteristics variables (area, MSI, type of green space (park), percentage of tree/shrub cover within green space, area of water body, and the interactions) are same as those in Table 11.

For both models 4 and 5, the interaction between the area and shape has a positive effect on ΔT[FIT], which means that the effect of area on temperature difference increases if UGS are more irregular (consistent with results presented in Table 11). Considering the simple slopes (cf. (Bauer and Curran, 2005)) it is again seen that the increasing complexity of a green space has a negative effect on ΔT[FIT] for green spaces smaller than 4.2 ha, but it has a positive effect on ΔT[FIT] for green spaces larger than 4.2 ha (cf. the minimal adequate model; Table 13: the simple slope for the MSI in the model ΔT[FIT] equals -0.21 + 0.05*area, which is > 0 for areas > 4.2 and < 0 for areas < 4.2). This suggests that smaller green space should have simpler shapes for achieving temperature difference and larger green spaces can have complex shapes. For the cooling distance, models 6 and 7, the effect of the percentage of tree/shrub coverage within the green space and the effect of area of the body of water were negative. The cooling effect is smaller for parks than forests. The interaction between the area and shape of UGS shows a negative effect on cooling distance, meaning that the effect of area on cooling distance decreases as UGS became more irregular. Considering the simple slopes (cf. (Bauer and Curran, 2005)) for cooling distance, a positive effect from the complexity for green spaces smaller than 9.5 ha (model 6) and 12.52 ha (model 7) and a negative effect for green spaces larger than 9.5 ha (model 6) and 12.52 ha (model 7) was shown (cf. the minimal adequate model; Table 13: the simple slope for the MSI in the model cooling distance equals 82.47 - 8.62*area, which is > 0 for area < 9.5 and < 0 for area > 9.5, 72.14 – 5.76*area, which is > 0 for area < 12.52 and < 0 for area > 12.52). This suggests that smaller green space can have complex shapes for achieving longer cooling distance and larger green spaces should have simpler shapes.

Additionally, the cooling effect increases for parks, with increasing area, but not for forests, suggesting that the effect of area on cooling depends on the type of green space. In addition, the cooling effect (ΔT[FIT] and cooling distance) is greater in UGS that are farther from the city center. The regression results (Table 13) also demonstrate that an increase in the percentage of tree/shrub cover within green space leads to a decrease in cooling distance (consistent with results presented in Table 11).

4.5.4 Effects of measures of biodiversity

For temperature difference (ΔT[FIT]), model ΔT[FIT] with diversity variables, the effect of only species richness and CWM DBH was negative, while the other biodiversity variable functional richness was discarded along with their corresponding interactions. The minimal adequate model cooling distance with diversity variables contained more biodiversity-related variables such as CWM height, functional divergence and their interactions with type of green space compared to model ΔT[FIT] with diversity variables. The interaction between types of green space and functional divergence shows a positive effect on cooling distance, meaning that the effect of functional divergence on the cooling effect is stronger for parks than forests. This is the same in the interaction of type of green space and CWM height for cooling distance. To understand these interactions better, the previously described simple slope approach (see Section 4.4.2) was used to check if the slope will be always positive, or if negative values are also possible.

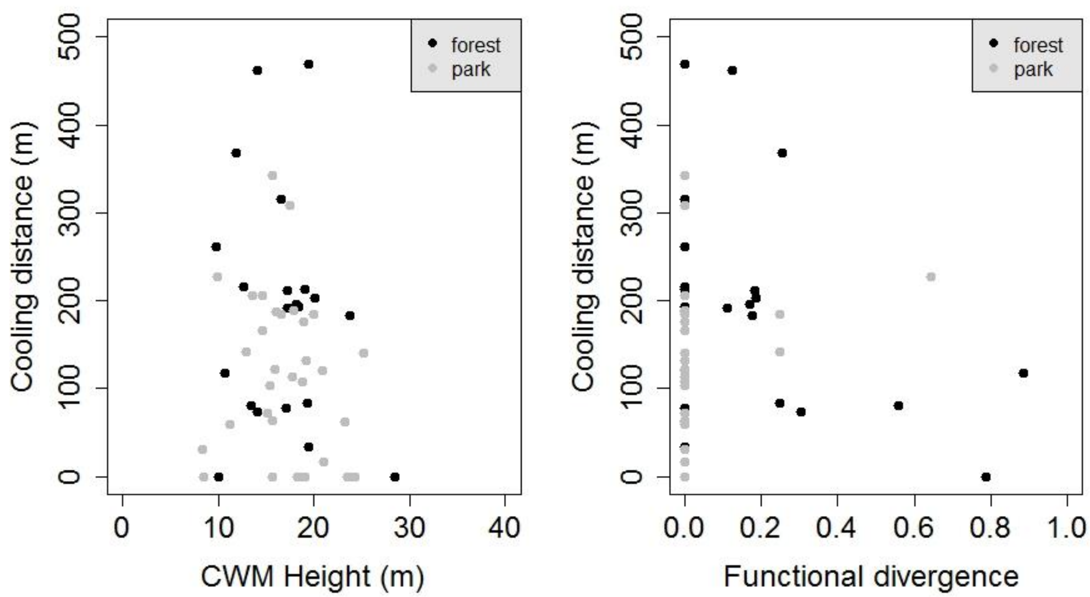

Figure 18. Scatter plots showing the relationship of cooling distance with the CWM height and functional divergence of trees in different types (forests, parks) of UGS.

At first, looking at the interaction of type of green space and functional divergence (Table 13) for the minimal adequate model of cooling distance, the simple slope (cf. (Bauer and Curran, 2005)) for forests is 476.6 – 253.4 * functional divergence. Since the values of functional divergence are between 0 and 1, the slope will always remain positive, although more functional divergence leads to less cooling distance for forests than parks. The simple slope for parks is 70.4+219.6 * functional divergence, where the slope is also positive and increases to have a maximum value when functional divergence is 1.

Secondly, regarding the interaction of type of green space and CWM height (Table 13) for the minimal adequate model of cooling distance, the simple slope (cf. (Bauer and Curran, 2005)) for forests is 476.6 – 12.5 * CWM height. While solving this equation for the values of height, it is seen that the cooling distance tends to be positive for values of height up to 38.1 m and then it tends to be negative. For parks, the simple slope is 70.4 + 0.2 * CWM height, it always remains positive, with a lower cooling effect to begin with and this increases with increasing height of trees. Figure 18 shows the visual representation of the relation of CWM height and functional divergence with cooling distance.

5 Discussion

5.1 Indicators of cooling effect

In this study, the focus was to use the following different measures: the temperature difference at PWD and the green space boundary, a calculated fitted maximum temperature difference and cooling distance calculated from the mobile air temperature measurements. The derivation of the cooling distance is attempted in very few studies (Chen et al., 2012; Feyisa et al., 2014) even though it is an important indicator of the cooling effect as seen in Chapter 2. Most observational studies investigated the difference in temperature between green sites (tree or grass) and a reference site (non-green) within the same urban area on a microscale analysis. As seen in the review study (Chapter 2) the reference site or the point at which the transects have to be measured was different for each study. The indicators thus identified and included ($\Delta T[PWD]$, $\Delta T[FIT]$ and cooling distance) in the empirical study are well known and have been in use for calculating the cooling effects of UGS. As seen from the results, the $\Delta T[PWD]$ and the $\Delta T[FIT]$ varied among green spaces. Furthermore, the cooling distance (i.e., the distance from the boundary of the green space with the maximum temperature difference) is not identical to the PWD, which is a strong indication that focusing only on the $\Delta T[PWD]$ misses important information on the actual cooling effect of an UGS. Additionally, the regression analysis revealed that the $\Delta T[PWD]$ cannot be explained with the characteristics of the green space and its surroundings, which was also found by Chang et al. (2007) for the characteristics of the green space alone. Comparing the three indicators of cooling for a large sample size (n=62) is very unique to this empirical study conducted in Leipzig, which was not carried out in any other study considered in Chapter 2.

With the fitted indicators, it can be seen that some of the green spaces with larger cooling distances had low $\Delta T[FIT]$ and vice versa (Fig. 11B). This demonstrates that there is a considerable amount of variation in the relationship between the cooling distance and the temperature differences, indicating the necessity for evaluating both aspects for the proper quantification of the cooling effects. This is attributed to the heterogeneity and complexity of urban environments, which results in the varied temperature profiles shown above (Fig. 9). In an attempt to tackle this urban complexity, the various factors that could influence the cooling effects were included in this study (Jaganmohan et al., 2016).

5.2 Influence of UGS design

The results show that UGS are cooler than their surroundings in most cases and thus they provide a cooling effect. However, the study confirms the finding of other studies (Potchter et al., 2006; Chang et al., 2007) that not all green spaces provide cooling effects, as 11 small UGS that lacked water bodies showed warming effects for all three indicators of cooling. The regression analysis revealed the following aspects that are considered important for UGS design: first, forests provide a higher cooling effect than parks, and second, the influence of area on the cooling effect is complex. Further, the effect of area on cooling is depending on the type of green space, (i.e., for parks, an increase in the cooling effect as area increases is stronger than for forests as also seen in Fig. 16). In addition, the area variable interacts with the shape variable regarding the cooling effect. The increasing complexity of smaller green spaces has a negative effect on the ΔT[FIT] but a positive effect for green spaces larger than 5.6 hectares. The relationship of area and shape is opposite for the cooling distance, with a slightly different threshold of 6.3 hectares, meaning that the increasing complexity for small green spaces has a positive effect on the cooling distance and vice versa. A trade-off exists when designing UGS: one can either increase the absolute temperature difference between the green space and the residential surroundings at the cost of a smaller area of influence (i.e., a shorter cooling distance); or, one can increase the distance to which a temperature reduction is noticeable, at the cost of an overall decrease in the temperature difference. This trade-off for smaller green spaces is likely because an increase in the shape irregularity provides a longer interface between a green space and its surroundings. This provides more opportunities for cooler air to influence the residential surroundings; however, it also means that more cool air can be transported away from the green space, thus reducing the maximum temperature difference. Why this process is opposite for larger green spaces needs to be investigated in future studies. Similar studies have found the area of the green space to be the primary factor influencing the cooling intensity, and the effect is obvious when the area exceeds 14 ha (Lu et al., 2012); green spaces above 3 ha were more consistently cooler than their surroundings (Chang et al., 2007). Third, an increase in tree/shrub coverage within a green space reduces the cooling distance, which is quite surprising. This could be due to a lower albedo of vegetation in the green space compared to the surroundings during the daytime. Also, with the increasing area of waterbody within green spaces the cooling distance decreases (Jaganmohan et al., 2016).

5.3 Influence of surrounding variables

The distance to the city center was insignificant for explaining the cooling effects for regression model 1-3. Therefore, regardless of the location of a green space in the city, green spaces provide a cooling effect. This is interesting, as the UHI of Leipzig (Schwarz et al., 2012) indicates a decrease of absolute temperatures from the city center, which apparently does not affect the cooling function of UGS. But the variable, distance to city center is important in the models 4, 5 and 7 suggesting that cooling effect is greater when the UGS is farther from the city center when only 54 UGS were considered, thus the results regarding this variable is not so consistent with all models.

There was a decrease in the cooling distance for residential areas characterized as semi-detached housing type compared to areas characterized by densely compacted housing. In the semi-detached housing locations, the composition of the residential area varies. The houses are apart from each other and have open spaces or residential gardens around them, and these residential open spaces should have a cooling effect themselves. This implies that the distance where the maximum temperature is measured is not close to the residential open spaces but might be affected by large streets or buildings close to the green space. This result differs from that of a comparative study in California between a neighborhood with varied tree cover; that study found that temperatures were slightly higher in neighborhoods with higher tree cover (Grimmond et al., 1996) (Jaganmohan et al., 2016).

The increase in percentage of trees/shrubs in a 25 m buffer around the transects increased the cooling distance as well as the thermal contrast between green space boundary and the surrounding. Thus, linear vegetation structures such as trees and bushes along roads enhance the cooling effect. When the models included the measures of biodiversity however the percentage of trees/shrubs in a 25 m buffer around the transects was kicked out of the model, indicating that tree diversity might be more important for cooling than the sole presence of green. The influence of wind speed on the temperature and humidity is highlighted in studies in Mexico (Jauregui, 1991) and Turkey (Yilmaz et al., 2008). In our study, the results show that an increase in wind speed decreases the difference in the temperature of a green space boundary and its surroundings, as expected (Watkins, 2002), because higher wind speeds cause turbulence, which mixes the air and reduces temperature gradients. The sampling month did not influence any of the cooling effect indicators, suggesting that during the summer season, June to August 2013, the results were stable, on clear, sunny days, regardless of any slight variations in the wind speed (Jaganmohan et al., 2016).

5.4 Influence of measures of biodiversity

One of the main reasons to retain the previously used variables of UGS characteristics, surrounding characteristics and other variables along with the biodiversity variables is to see whether the diversity of trees has an additional effect on temperature difference and on cooling distance. Based on the results obtained from the models 4 to 7 (models ΔT[FIT] without diversity variables, ΔT[FIT] with diversity variables, cooling distance without diversity variables, cooling distance with diversity variables), it is evident that the previously obtained relationships for UGS characteristics mainly do not change. Only the variable distance to city center is important in the model ΔT[FIT] without diversity variables, ΔT[FIT] with diversity variables and cooling distance with diversity variables suggesting that cooling effect is greater when the UGS is farther from the city center.

For cooling distance, more biodiversity variables were retained in the final model, and the amount of explained variance was higher, which suggests that the relationship between the cooling effect and biodiversity variables in UGS was stronger for cooling distance rather than for the temperature difference. The results also suggest that the effects of biodiversity variables are less important than UGS characteristics such as area or type of green space for cooling effects in general.

The biodiversity – ecosystem service relationship in urban areas has emerged as a critical issue in ecological research in the last few years (Ziter, 2016; Schwarz et al., 2017) where biodiversity was most often assessed at the species level, followed by functional diversity, community diversity and structural diversity. Studies have provided insights into the role of biodiversity in ecosystem service delivery and explored the links between functional traits and ecosystem services (de Bello et al., 2010) and examined how biodiversity influences the functioning of ecosystems as a result providing ecosystem services (Cardinale et al., 2012). Not just urban ecosystems, but all ecosystems are valued for their ability to maintain multiple functions. For example in grassland biodiversity experiments, results showed that the level of ecosystem multifunctionality was promoted by functional identity of species and functional divergence among species, rather than species diversity per se (Mouillot et al., 2011). A global empirical study relating plant species richness (perennial vascular plants) and abiotic factors (climate, slope, elevation, and soil texture) to multifunctionality (such as carbon storage, productivity, and the buildup of nutrient pools) in drylands, showed that multifunctionality was positively and significantly related to species richness (Maestre et al. 2012). Many studies of species richness and ecosystem function have focused on productivity (Chisholm et al., 2013) through niche complementarity, facilitation and sampling effects. The positive relationship between richness or diversity and productivity are supported by small scale experimental designs in grasslands, and in natural communities (Chisholm et al., 2013) scale-dependent relationships were found with positive relationship for smaller scales (0.04 ha). In this research on UGS of Leipzig, it was found that other biodiversity measures than the taxonomic diversity had higher influence on the cooling distance of UGS (Table 13). Here, I measured the taxonomic diversity with three biodiversity metrics (Shannon diversity, species richness and Pielou's evenness) to consider alternatives to species richness. However, Shannon diversity did not have a higher value of importance in comparison to species richness and Pielou's evenness in the hierarchical partitioning analysis. And when species richness and Pielou's evenness were considered in the regressions, Pielou's evenness was kicked out of the models while species richness was found to be important for temperature difference but had a negative effect on cooling. In general, neither the percentage of tree/shrub cover nor species richness within UGS did favor cooling intensity. As seen with the results of the study, it is recommended to use other measures of biodiversity in addition to species diversity. Also a review on the evidence of relations between ecosystem processes and different components of plant diversity (Díaz and Cabido, 2001) shows that the "studies that have jointly addressed species richness, functional richness and functional composition suggest that the components of variance for functional composition and functional richness tend to be larger than the component of variance for species richness in influencing ecosystem processes" (Díaz and Cabido 2001, p. 647).

For $\Delta T[FIT]$, a negative regression coefficient was estimated for CWM DBH, which suggests that there is a decrease of 0.007 °C for 1 cm increase in DBH. This suggests that large tree trunks could hinder the movement of wind through the green space for facilitating cooling in its surrounding. If planting densities are higher, the tree crowns are close together and evaporative cooling is less intense due to lower transpiration rate of shaded leaves as compared to sunlit leaves (Konarska et al., 2016). An increase in species richness also decreases temperature difference by 0.2 °C. The mean species richness of UGS was highly correlated with the total number of trees sampled within the UGS (rs=0.7; $p < 0.001$). Also the cooling effect in this study was assessed by the air temperatures taken during day; it is likely that those UGS that had a lower cooling effect also had high tree density that inhibited air circulation, the results could be different if cooling was considered after sunset since the transpiration rate of trees could increase cooling effects (Konarska et al., 2016).

For the cooling distance, it is seen that there is a negative slope for height above 38.1 m on average (Section 4.5.4), thus this is the optimum height up to which the cooling effect is measurable in terms of distance for forests whereas for parks, it is seen that the cooling effect increase with height of trees. And it is also found that parks had larger trees with DBH (Fig.12) and height values higher than the forests. An increase in functional divergence increases cooling distance for parks while there is a decrease in cooling effect for forests. Since park communities had a lower functional divergence than forests (Table 9), but forests had a larger cooling effect, it can be said that the forests were thus more efficient in providing cooling effects.

To summarize, these results emphasize the importance of the functional aspect, taxonomic aspect and means traits of tree cover. In that respect, it is important not only to choose trees over grass cover or green roofs/wall structures to mitigate heat but also to create structural variation with respect to height of trees in UGS. This is particularly important now, given the increase in urban greening programs in many cities. In landscape design and planning, the ecological and environmental effects of different UGS are important to consider (Bilgili et al., 2013). The results also indicate that an increase in tree heights is better for the cooling effect in UGS (cooling distance) suggesting that taller trees are beneficial for parks whereas only up to a certain threshold for forests.

This dissertation supports previous recommendations that UGS should contain discontinuous canopy, for proper ventilation and outgoing long-wave radiation to occur (Spronken-Smith and Oke, 1998; Spronken-Smith and Oke, 1999; Dimoudi and Nikolopoulou, 2003), so that UGS do not experience heat trapping in the vegetation canopy. A mix of tree species, with different canopy architectures was also suggested in a study on successful urban street tree plantings (Pauleit, 2003). Since most of the UGS are maintained by civic authorities the trees can be well managed to receive optimum cooling effect.

The results of the regression analysis without diversity variables (model ΔT[FIT] without diversity variables and model cooling distance without diversity variables) were similar to the results of models 1 and 2 on the characteristics of UGS, which revealed that the size and shape of UGS is important and that forests have a better cooling effect than parks. As seen in previous studies, increasing the total area of green space within a city may significantly reduce temperatures at the city scale (Bowler et al., 2010; Lu et al., 2012) but UGS are difficult to implement in most cities where land resources are limited. However, some studies also show that smaller green spaces can benefit city residents, as the cooling effect though relatively small can be experienced up to a certain distance (Shashua-Bar and Hoffman 2000; Chang et al. 2007; Feyisa et al. 2014). The influence of area on the cooling effect was complex, as it also depended on the type of green space. Parks with increasing area had a stronger effect on cooling than forests. In addition, the area variable also interacts with the shape variable, for temperature difference (ΔT[FIT]) as well as cooling distance. The increase in area of habitat patches and corridors has also been suggested to maintain high levels of urban biodiversity (Beninde et al., 2015). As the size of UGS positively affects cooling (as shown by results), by having large green spaces, both biodiversity and local climate regulation can be achieved.

5.5 Limitations

The empirical study on air temperature was conducted during a period of three months, and the green spaces were sampled on different days and at different times of the day. The simultaneous collection of synchronized air temperature measurements would be helpful to better compare the data. This, however, is not usually feasible with respect to manpower, because large number of green spaces were sampled in the study. A study with the diurnal, seasonal and annual variations of the cooling effect could be more helpful in explaining the importance of the shape and size of the green spaces. However, as it is very difficult to record air temperatures on a large scale at the same time using traditional site-measurement methods using probes; RS could be employed as an alternative (Schwarz et al., 2012). Furthermore, other parameters such as the sky view factor, architectural design and other buildings characteristics could be included in further studies.

In this study, the measurements were not performed up to their potential cooling distances for some of the large forests, and the ΔT[PWD] was not computed for this reason. Therefore, the findings for very large forests are limited for this indicator. I included mobile routes along transects in residential areas assuming that the data collected would represent a gradient within the built-up area and would accurately illustrate any meaningful influence from the characteristics of residential surroundings on the cooling effect of the green spaces. The study might not have accounted for all facets of the urban environment; however, it is the first to understand the effects of green space design using various cooling indicators.

The measures of biodiversity were calculated from very basic traits (DBH and height). Other traits such as leaf area, foliage density, leaf texture and leaf thickness that could affect cooling should be considered in future studies.

6 Conclusion

With the knowledge that UGS play a vital role in mitigating urban heat problems, this dissertation aims to understand the quantification of micro climate regulation, specifically cooling effects of UGS. To increase the knowledge on how UGS should be designed in urban neighbourhoods in order to help effectively reduce temperatures by providing a cooling effect, the various indicators of cooling and their relationship between the different independent variables that could influence the cooling effects were studied. The research presented in this dissertation was conducted in two steps: a comprehensive literature review on studies that calculated cooling effects of UGS over a temperature gradient to assess indicators and their relationships and an empirical study to quantify three indicators of cooling effects and analyse their relationship with different independent variables. The proposed questions are tackled in the various parts of the dissertation:

i. Chapter 2 provides details on a review of the current studies that quantify cooling effects calculated over temperature gradients of UGS globally;

ii. Sections 4.1, 4.3 and 4.4 provide details on the influence of different UGS characteristics on the cooling effect, between different types of UGS (parks and forests) based on data collected for a case study (Leipzig);

iii. Sections 4.2 and 4.5 provide details on the diversity of trees in the UGS and its influence on cooling effects to understand the role that UGS design, biodiversity, and characteristics of residential surroundings for the same case study (Leipzig).

The research findings derived from this dissertation identify the common methods used in assessing cooling effects that are prevalent in the literature. The studies using statistical analysis to look at the influence of variables on to the indicators of cooling in the literature were very few and lacked investigation of effects of important variables such as biodiversity. This research is the first of its kind that has investigated the comparisons of parks and forests with three different indicators for the cooling effects, along with the statistical analysis in explaining the influence of the physical and vegetation characteristics of both urban green spaces and their surroundings. An empirical study in the city of Leipzig was conducted in 62 UGS (parks and forests) and three different indicators of cooling were calculated: the change in temperature (ΔT) at the park-width distance (PWD), the fitted maximum ΔT, and the cooling distance. These were calculated from air temperature measured over a transect during the day. Multiple regression models were used to analyse the relationships of these indicators of cooling on to the physical characteristics of the UGS and the surroundings along with various measures of biodiversity. The indicators used to quantify the cooling effects are not strongly related to each other and cannot be replaced by one another. The temperature differences between the boundaries of the green spaces and the temperatures at the park-width distance do not reliably illustrate the temperature gradient in the surroundings. It is thus suggested to analyse the temperature patterns along an entire transect from a green space into the surroundings and calculating the maximum temperature and the distance at which this is perceivable.

In conclusion, the main findings of the dissertation are:

- The literature review revealed that cooling effects of UGS extend into the surroundings and can be measured in various ways.
- 70% of the studies in the review used at least one variable or more to explain the cooling effects, with area of the UGS being the most common variable.
- The empirical study for Leipzig showed that some of the smaller UGS without water bodies were found to exhibit warming effects.
- Each indicator of cooling measures cooling effects differently; and indicators are not strongly related to each other.
- The cooling effects depended on the type of UGS; and forests had larger cooling effects than parks.
- The independent variables area of water body, percentage of trees/shrubs within UGS and type of housing were found to be important in explaining only the cooling distance and not the temperature difference.
- A complex relationship was found in UGS variables - size and shape; and the biodiversity variables - functional divergence and CWM height.
- Inclusion of the various measures of biodiversity increased the model performances.
- Taxonomic diversity was not as important as functional diversity and mean traits.
- The characteristics of the green spaces were found to be more important than the characteristics of the residential surroundings in explaining the cooling effects.

Some implications for urban planning can be concluded from these findings. First, the influence of the area and shape of the park is complex, therefore only one maximum indicator of cooling can be achieved, either higher temperature differences or longer cooling distance. Urban planners will have to clearly specify the aim of any measure that should be taken with respect to cooling. Second, in most cases, an increase in area leads to an increase in the cooling effect. This suggests that a number of small green spaces distributed throughout a city may not individually have a greater cooling effect on their surroundings, but it still remains to be clarified whether they, in sum, might have a stronger or lesser cooling effect than a few larger green spaces. This indicates that urban planning for heat mitigation might not work along the same lines as urban planning for environmental justice (with many people having access to green spaces close to their homes, as discussed by Kabisch and Haase, (2014). Third, forests in general were found to provide higher maximum temperature differences and cooling distances than parks. The fact that urban forests provide better cooling than urban parks should be taken into account in urban planning. Shrinking cities, for example, often contain a number of brownfields. Because Leipzig had been a shrinking city after German re-unification, the city administration aimed at developing urban brownfields into urban forests, to improve their recreational value (Arndt and Rink, 2013). Fourth, while planning UGS, it is important to identify the proposed site area and decide on the respective shape to benefit local climate regulation. For achieving higher temperature difference, if the UGS is smaller it is better to have simpler shapes but in contrast complex shapes for the larger UGS. If the aim is to achieve longer cooling distances from UGS, then complex shapes for smaller and simpler shapes for larger UGS would be more efficient. Fifth, prioritizing to have UGS further away from the city center would benefit in providing both temperature difference and cooling distance. Sixth, the results of the tree biodiversity study showed that functional variability of the tree vegetation within UGS is an important aspect to consider for optimum cooling effects. Results also showed that specific aspects of tree diversity play a stronger role in temperature mitigation, such as functional diversity (functional divergence) and mean traits (mean height) rather than taxonomic diversity for the different indicators of cooling. The main recommendation, in terms of maximizing cooling effects of UGS based on tree species, is to increase variance in tree heights based on the type of UGS.

Since most of the cities are highly populated due to the scarcity of land, an important question for future research is how to allocate new UGS in existing residential areas to benefit the urban residents. Apart from parks and forests, other non-conventional green spaces such as brownfields, open spaces with trees or biodiversity-rich green roofs should be considered for future research. Also, future research should specifically investigate the role of large UGS and the interactions between the area and shape with respect to cooling effects. The possibilities for improving the ecosystem service provisioning of existing and temporary green space should be explored. Future research should more profoundly investigate the importance of biodiversity in UGS. Biodiversity alone cannot enhance all ecosystem services, but it affects multifunctionality which is also influenced by other biotic and abiotic factors in the UGS. Hence, it is suggested to carry out experiments in non-experimental communities such as UGS to understand the role of biodiversity in enhancing cooling effect as a specific ecosystem service at different locations that represent a wide range of spatial variability in both biotic and abiotic composition. Biodiversity can thus be seen as an additive effect in the provision of climate regulation. The ecosystem services of UGS should be studied and compared in different cities since the urban development is different in different parts of the world in collaboration with various organisations that are involved in urban planning.

Since humans play a very important role in urban ecosystems, managing ecosystems in urbanizing and human-dominated, socio-ecological contexts and resilient research is the need of the hour. With changing temperatures and precipitation due to climate change, monitoring these changes that could impact the ability of tree vegetation to cool the environment is needed, that mainly includes the designing of UGS to meet the optimum requirements to mitigate some of these effects most efficiently. UGS should be planned in a holistic way at the scale in which both the physical characteristics and the vegetation give optimal cooling effects. With the growing recognition of urban ecology in ecological research, the integrated view of social-ecological systems in sustainable urban development is essential. With the numerous challenges that exist with the concept of urban ecosystem services and biodiversity, understanding their relationships is essential in future research.

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Curriculum vitae

Name Madhumitha Jaganmohan

Date of birth 29.03.1988

Place of birth Coimbatore, Tamil Nadu

Nationality Indian

Education

10/2013 – 11/2018 PhD Student, Martin Luther University Halle Wittenberg, Institute of Geosciences and Geography, Halle, Germany

09/2009 - 06/2011 Master of Science, Bangalore University, Department of Environmental Science, Bangalore, India

06/2005 - 04/2008 Bachelor of Science, St. Joseph's College (Autonomous), Bangalore, India

Experience

02/2013 – 09/2016 Scientific staff, Department of Computational Landscape Ecology, Helmholtz Centre for Environmental Research GmbH – UFZ, Leipzig, Germany

05/2008 – 01/2013 Research Associate, Department of Urban Ecology, Ashoka Trust for Research in Ecology and Environment, Bangalore, India

01/2008 – 03/2008 Intern, Centre For Environment Education, Bangalore, India

05/2007 – 06/2007 Intern, World Wide Fund for Nature – India, Bangalore, India

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Selbstständigkeitserklärung / Declaration under Oath

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

Bayreuth Madhumitha Jaganmohan