Dissertation

GREEN INFRASTRUCTURE FOR CLIMATE RESILIENT DENSIFICATION: FROM EVIDENCE TO ACTION

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“First life, then spaces, then buildings – the other way around never works.”

Jan Gehl

Contents

Summary

The increase in urban population and the rising demand for housing per capita lead to high pressure on the housing market. In order to avoid urban sprawl, denser cities and urban infill have been promoted as more sustainable planning solutions. However, highly densified urban areas show a lack of urban green space and are prone to increased levels of outdoor heat stress. Large-scale and small-scale green spaces fulfil an important role in regulating the urban climate through evaporative cooling, shading and provision of fresh air corridors. In the course of ongoing climate change, the intensity and frequency of heat waves and storm water events will further increase, calling for smart solutions in city planning and an early incorporation of urban green in development processes.

In this context, this cumulative thesis investigates the interrelations between densification and urban green space using a multi-method approach in order to identify possible courses of action for climate-adapted urban planning. Microclimate modelling and scenario based analyses are used to quantify the influence of densification on outdoor human thermal comfort and climate regulation capacities of urban green infrastructure (UGI). Quantitative and qualitative research methods are combined to compare the subjective perception of density and heat with objective assessments. Expert interviews and document analysis are employed to analyse key factors for the integration of urban green infrastructure in urban planning of densifying municipalities.

The thesis is based on four articles. In the first two studies, several densification scenarios were developed to analyse the effects on outdoor thermal comfort and ventilation using microclimate modelling. A redevelopment area in the northwest of Munich with typical row buildings serves as a study example. The results from study I emphasise that the preservation of large trees is the most important factor to avoid negative climatic effects of densification. The study also considers associated effects of densification that have been little studied so far, such as increased parking space demand generated by the new housing units. Reducing the amount of stationary traffic and promotion of alternative mobility concepts are important approaches to diminish the impact of densification on existing greenery and preserve mature trees. Study II combined ventilation analysis at the neighbourhood and outdoor comfort analysis at the block scale to identify interrelations between the two and the compensation potential of UGI. UGI can reduce heat stress in the medium term, but cannot compensate for losses of cold air volume flow through densification. A climate-optimised neighbourhood design takes into account shading of heat islands, cold air flows and open spaces for nocturnal cooling.

The third paper contrasts the objective assessment of density and heat with the subjective perception through a combination of GIS analyses, microclimate modelling and expert interviews. Different aspects of spatial design and green amenities in two contrasting neighbourhoods in Munich were compared. The results indicate that the existence and the amount of UGI per se are not decisive for people’s perception of urban heat, density, and neighbourhood attractiveness. It is rather the perceived accessibility of green spaces, their design, quality, and contextual factors like traffic or the presence of other people that define its value for urban dwellers.

Finally, the fourth study examines the structural conditions that decide upon the integration of climate change adaptation and green space preservation in urban development processes by analysing planning documents and expert interviews. Four growing municipalities in Bavaria serve as case studies, the Policy Arrangement Approach (PAA) provides the analytical framework. The results underline the importance of looking at system interdependencies to understand the interactions between individual factors and the causes of barriers to implementation. Key factors include cooperation between politics and administration, the establishment of guiding principles with public participation and a strategic use of external resources.

This thesis reveals potential conflicts between urban densification and the conservation of green spaces and provides guidelines for improving the integration of green infrastructure in planning processes of growing cities. The availability of reliable information on the climate regulation performance of green spaces and the impact of densification on the urban microclimate and ventilation is an important basis for planners in consideration processes, but also for their communication with different target groups. This also applies to the consideration of residents' perspectives on density, heat and green space. To support this, further research should be directed towards tools that facilitate urban climate assessments on different scales. In addition, instruments and approaches should be developed that support the involvement of different actors and collaborative efforts in the early phases of urban planning processes and support trans- and interdisciplinary research. Application-oriented research projects with integration of external stakeholders represent a promising approach.

Keywords: green infrastructure, outdoor thermal comfort, densification, climate change adaptation, urban planning

Kurzfassung

Der Anstieg der städtischen Bevölkerung und der zunehmende Flächenverbrauch pro Kopf führen zu Flächenkonkurrenzen und einem hohen Druck auf den Wohnungsmarkt. Um die Zersiedelung der Landschaft zu vermeiden, wurde Nachverdichtung als nachhaltigere Planungslösung propagiert. Stark verdichtete städtische Gebiete weisen jedoch eine hohe Hitzebelastung im Sommer und einen Mangel an Grünflächen auf. Sowohl große als auch kleine Grünflächen regulieren das Stadtklima durch Verdunstungskühlung, Beschattung und die Bereitstellung von Frischluftschneisen. Im Zuge des fortschreitenden Klimawandels werden die Intensität und Häufigkeit von Hitzewellen und Starkregenereignissen weiter zunehmen, was intelligente Lösungen in der Stadtplanung und eine frühzeitige Einbeziehung von Stadtgrün in Entwicklungsprozesse erfordert.

Vor diesem Hintergrund untersucht diese kumulative Doktorarbeit das Spannungsfeld zwischen Nachverdichtung und urbanen Grünflächen, um Handlungsmöglichkeiten für eine klimaangepasste Stadtplanung aufzuzeigen. Mikroklimamodellierung und Szenarienanalysen werden verwendet, um den Einfluss von Nachverdichtung auf den menschlichen thermischen Komfort im Außenraum und die Klimaregulationsleistung von urbaner grüner Infrastruktur zu quantifizieren. Quantitative und qualitative Forschungsmethoden werden kombiniert, um die subjektive Wahrnehmung von Dichte und Hitze mit objektiven Messungen zu vergleichen. Experteninterviews und Dokumentenanalysen dienen dazu, die Schlüsselfaktoren zur Integration von grüner Infrastruktur in Stadtplanungsprozesse von wachsenden Kommunen zu analysieren.

Die Arbeit baut auf vier Untersuchungen auf. In den ersten beiden Studien werden verschiedene Nachverdichtungsmöglichkeiten und ihre Auswirkungen auf den thermischen Komfort im Außenraum und die Durchlüftung mithilfe von Modellierungen untersucht. Als Untersuchungsbeispiel dient ein Sanierungsgebiet im Nordwesten von München mit typischer Zeilenbebauung. Die Ergebnisse aus Studie I unterstreichen, dass der Erhalt von Großbäumen der wichtigste Faktor ist, um negative klimatische Auswirkungen von Nachverdichtung zu vermeiden. Die Studie berücksichtigt zudem bislang wenig untersuchte Nebeneffekte wie Parkplatzbedarfe. Die Reduzierung des ruhenden Verkehrs und alternative Mobilitätskonzepte sind wichtige Ansätze, die Auswirkungen von Nachverdichtung auf das Bestandsgrün zu verringern und den Großbaumerhalt zu fördern. Studie II kombiniert eine Betrachtung von Durchlüftung auf Quartiers- und Außenraumkomfort auf Wohnungsblockebene. UGI kann erhöhten Hitzestress im Quartier mittelfristig kompensieren, aber nicht Verluste an Kaltluftvolumen durch Nachverdichtung ausgleichen. Eine klimaoptimierte Quartiersgestaltung berücksichtigt Verschattung von Hitzeinseln, übergeordnete Kaltluftströme und offene Flächen für die nächtliche Abkühlung.

Die dritte Forschungsarbeit stellt durch eine Kombination von GIS-Analysen, Mikroklimamodellierungen und Befragungen, die objektive Bewertung von Dichte und Hitze der subjektiven Wahrnehmung gegenüber. Verglichen werden verschiedene Aspekte der Raumgestaltung und Grünausstattung in zwei gegensätzlichen Stadtvierteln in München. Die Ergebnisse weisen darauf hin, dass das Vorhandensein und die Menge von Grün an sich nicht ausschlaggebend für die Wahrnehmung der städtischen Hitze, Dichte und Attraktivität des Viertels durch die Menschen sind. Vielmehr sind es die wahrgenommene Zugänglichkeit von Grünflächen, ihre Gestaltung, Qualität und kontextuelle Faktoren wie Verkehr oder die Anwesenheit anderer Menschen, die ihren Wert für Stadtbewohner:innen definieren.

Schließlich wertet die vierte Studie Planungsdokumente und Expert:inneninterviews aus, um die strukturellen Bedingungen, die über die Integration von Klimawandelanpassung und Grünflächenerhalt in städtischen Entwicklungsprozessen entscheiden, zu untersuchen. Vier wachsende Kommunen in Bayern dienen hierfür als Fallstudien, der Policy Arrangement Approach (PAA) wird als analytischer Rahmen verwendet. Die Ergebnisse unterstreichen die Wichtigkeit der Betrachtung von Systemzusammenhängen, um Wechselwirkungen zwischen einzelnen Faktoren und die Ursprünge von Hindernissen zu verstehen. Zu den Schlüsselfaktoren gehört die Zusammenarbeit zwischen Politik und Verwaltung, die Aufstellung von Leitbildern unter Öffentlichkeitsbeteiligung und eine strategische Nutzung externer Ressourcen.

Diese Doktorarbeit zeigt potentielle Zielkonflikte zwischen Nachverdichtung und Grünflächenerhalt auf und gibt Planungshinweise für eine verbesserte Integration von grüner Infrastruktur in die Stadtentwicklung wachsender Städte. Die Verfügbarkeit von belastbaren Informationen zur Klimaregulationsleistung von Grün und der Auswirkung von Nachverdichtung auf das städtische Mikroklima und die Durchlüftung stellen für Planer:innen eine wichtige Grundlage in Abwägungsprozessen, aber auch für die Kommunikation mit verschiedenen Zielgruppen dar. Dies gilt auch für Berücksichtigung von Bewohner:innenperspektiven auf Dichte, Hitze und Grünraum. Um dies zu fördern, besteht weiterer Forschungsbedarf in der Entwicklung von Modellen, die Klimaanalysen auf verschiedenen räumlichen Ebenen erleichtern. Zudem sollten Instrumente und Ansätze entwickelt werden, die eine Einbindung von verschiedenen Akteuren und die Zusammenarbeit in frühen Phasen von Stadtplanungsprozessen sowie inter- und transdisziplinäre Forschung unterstützen. Anwendungsorientierte Forschungsprojekte mit Reallaboren stellen dafür einen vielsprechenden Ansatz dar.

Schlagwörter: Grüne Infrastruktur, Außenraumkomfort, Klimawandelanpassung, Nachverdichtung, Stadtplanung

List of Figures

List of Tables

List of Abbreviations

BMBF	German Ministry for Education and Research (Bundesministerium für Bildung und Forschung)
CAVF	Cold air volume flow
CFD	Computational fluid dynamics
DWD	German Weather Service (Deutscher Wetterdienst)
FITNAH	Flow over Irregular Terrain with Natural and Anthropogenic Heat sources
IPCC	International Panel on Climate Change
LHM	State Capital Munich (Landeshauptstadt München)
LCZ	Local climate zone
LfStat	Bavarian State Office for Statistics (Bayerisches Landesamt für Statisik)
PAA	Policy arrangement approach
PET	Physiologically equivalent temperature
Rh	Relative Humidity
T_a	Air temperature
T_{mrt}	Mean radiant temperature
UBA	German Environmental Agency (Umweltbundesamt)
UN	United Nations
UGI	Urban green infrastructure
UHI	Urban heat island
VDI	Association of German Engineers (Verein deutscher Ingenieure)
ZSK	Centre for Urban Ecology and Climate Adaptation (Zentrum für Stadtnatur und Klimaanpassung)

List of Original Articles

This doctoral thesis is based on the following four articles, which will be referred to in the text by Roman numerals. At the time of submission, three articles were published in internationally peer-reviewed journals and one was in review. The articles are attached in the appendix and reproduced with the permission of the publishers, if applicable.

Paper I

Erlwein, S. and Pauleit, S. (2021): **Trade-Offs between Urban Green Space and Densification: Balancing Outdoor Thermal Comfort, Mobility, and Housing Demand**. In *Urban Planning* 6 (1), pp. 5–19. DOI: 10.17645/up.v6i1.3481.

Summary

Urban green spaces reduce elevated urban temperature through evaporative cooling and shading and are thus promoted as nature-based solutions to enhance urban climates. However, in growing cities, the supply of urban green space often conflicts with increasing housing demand. This study investigates the interplay of densification and the availability of green space and its impact on human heat stress in summer. For the case of an open-midrise (local climate zone 5) urban redevelopment site in Munich, eight densification scenarios were elaborated with city planners and evaluated by microscale simulations in ENVI-met. The chosen scenarios consider varying building heights, different types of densification, amount of vegetation and parking space regulations. The preservation of existing trees has the greatest impact on the physical equivalent temperature (PET). Construction of underground car parking results in the removal of the tree population. Loss of all the existing trees due to parking space consumption leads to an average daytime PET increase of 5°C compared to the current situation. If the parking space requirement is halved, the increase in PET can be reduced to 1.3°C–1.7°C in all scenarios. The addition of buildings leads to a higher gain in living space than the addition of floors, but night-time thermal comfort is affected by poor ventilation if fresh air circulation is blocked. The protection of mature trees in urban redevelopment strategies will become more relevant in the changing climate. Alternative mobility strategies could help to reduce trade-offs between densification and urban greening.

Author's contribution

The first author S. Erlwein developed the analytical framework, performed the modelling, analysed the data and wrote the manuscript. The scenario set-up was adapted in discussion with urban planners employed at the City of Munich. S. Pauleit supervised the work, provided scholarly advice, reviewed the draft and helped with language editing.

Paper II

Erlwein, S., Zölch, T. and Pauleit, S. (2021): **Regulating the microclimate with urban green in densifying cities: joint assessment on two scales**. In *Building and Environment* 205, 108233, DOI: 10.1016/j.buildenv.2021.108233

Summary

Green spaces fulfil an important role in regulating the urban microclimate, however they are under high pressure in growing cities. As much as densification is a threat towards existing green spaces, it also offers the possibility to redesign residential areas in a climate-responsive way. To do so, urban green infrastructure needs to be incorporated from the outset into the planning process and the urban context and mutual influences between different scales have to be considered. However, information on how to secure ventilation in densifying neighbourhoods while simultaneously enhancing thermal comfort in open spaces at site scale still is limited. Therefore, we compare microclimatological modelling outcomes on district and block scale for different densification and green intervention scenarios in a real planning case. Our results suggest that green infrastructure can compensate for negative effects of building densification on daytime thermal comfort, but not for impacts on cold air volume flow (CAVF). CAVF is mainly affected by densification, especially by increasing building heights. Strategic placement of trees prevents worsening the nocturnal ventilation, while providing effective cooling during daytime. A replacement of mature trees by new trees in densification scenarios led to an increase of the physiological equivalent temperature (PET) by 7.5–7.9 ◦C. Adding green roofs and green facades did not lead to a decrease of heat stress levels, but significantly reduced surface temperature. A coupling of microclimate models operating on different scales and with different spatial resolutions is important to consider mutual influences between ventilation and outdoor thermal comfort.

Author's contribution

Article II was developed by S. Erlwein and T. Zölch. S. Erlwein reviewed the literature, developed the greening scenarios, performed the microclimate modelling, analysed the data, wrote the manuscript with contributions from T. Zölch and handled the review process. T. Zölch coordinated the FITNAH modelling, contributed with discussion of results and helped with answering to reviewer requests. S. Pauleit provided scholarly advice and helped with language editing and draft reviews.

Paper III

Mittermüller, J., Erlwein, S., Bauer, A., Trokai, T., Duschinger, S., & Schönemann, M. (2021): **Context-Specific, User-Centred: Designing Urban Green Infrastructure to Effectively Mitigate Urban Density and Heat Stress in Different Settings.** Urban Planning, 6(4), 40–53. https://doi.org/10.17645/up.v6i4.4393

Summary

Green infrastructure plays a vital role for cities facing the challenges of urbanisation and climate change. It has the potential to mitigate the adverse effects of urban density and the heat island effect, enhancing the ecological and social resilience of cities and their inhabitants. This study identifies contextual, psychological, and social factors which influence people's subjective evaluation of urban green infrastructure (UGI), density, and heat stress. Planning recommendations for effective, context-specific, user-centred design are developed to increase the social and health benefits of UGI in limited space. To do so, a mixed-methods approach that combines social surveys, GIS-analysis, and microclimate modelling was employed. The field studies were undertaken in two contrasting neighbourhoods in Munich, Germany: a densely built and scarcely vegetated inner-city neighbourhood and a declaimed "green and compact" neighbourhood at the outskirts. Both sites are assessed in terms of their supply of green infrastructure, building and population density, and outdoor summer heat loads drawing on geostatistical data and mean radiant temperature modelling. This assessment is compared to the inhabitants' subjective evaluation thereof retrieved from face-to-face questionnaires, and semi-standardised interviews. The results indicate that the existence and the amount of UGI per se are not decisive for people's perception of urban heat, density, and neighbourhood attractiveness. It is rather the perceived accessibility of green spaces, their design, quality, and contextual factors like traffic or the presence of other people that define its value for urban dwellers.

Author's contribution

The first authorship of article III is shared between J. Mittermüller and S. Erlwein. Both first authors conceived the design of the study, analysed the research results, created the figures and wrote the draft of the article. J. Mittermüller, A. Bauer, S. Duschinger conducted the social surveys, T. Trokai created the subjective heat maps and analysed the semi-standardised interviews supervised by S. Erlwein, J. Mittermüller and A. Bauer. S. Erlwein supervised and analysed the microclimate modelling with SOLWEIG. M. Schönemann conducted the geostatistical analysis. A. Bauer and S. Duschinger helped to improve the manuscript draft.

Paper IV

Erlwein, S., Wamsler, C., Meister, J. & Pauleit, S. **Governance of densification and climate change adaptation: How can conflicting demands for housing and greening in cities be reconciled?** Land Use Policy (in re-review)

Summary

Urban green spaces are important for climate change adaptation, in particular to reduce the negative impacts of heat waves on human well-being. However, in growing cities urban green spaces are under pressure due to increasing housing demand and densification. Municipalities face the challenge of addressing both the housing shortage and the need for climate change adaptation on limited space. This study assessed the barriers that hinder successful integration in urban policymaking. More specifically, it analyses structural conditions impeding or promoting climate resilient urban development in growing, densifying areas. Based on interviews with urban and green space planning officers and policy analyses, we investigate current discourses and the interrelations between actors, power, resources and regulations. Our results show that improved cooperation between individual administrative departments, as well as administration and politics is decisive for better integration of green spaces in urban planning, negotiations with investors and sustained citizen involvement. Certain departmental structures and working routines can help to promote such cooperation. We show that it is not the availability of resources alone that is key for integration, as commonly suggested. Instead, transparent communication, the co-development of rules and resolutions with the public, and strategic external resource management are needed for solving conflicting demands for densification and greening in cities. We conclude with recommendations for research, policy and practice.

Author's contribution

S. Erlwein reviewed the literature, conceived the analytical framework and carried out most of the interviews. She analysed the data and wrote the manuscript. J. Meister conducted interviews, contributed to the initial analysis of the interview data and helped refining the manuscript draft. C. Wamsler and S. Pauleit provided scholarly advice on the structure and content of the article and helped to improve the manuscript by reviewing and editing the drafts.

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1. Introduction

1.1. Research background and problem definition

Urban areas are hubs for infrastructure, goods and people. Cities consume two-thirds of the world's energy and are responsible for 70% of the global carbon emissions (UN-Habitat 2020). Therefore, reducing the carbon footprint of urban areas is key for global climate protection and becomes ever more urgent, as the urban population is steadily increasing: Whereas in Europe 74% of all people already live in cities, the percentage of urban settlers will increase globally from 55% in 2018 to 68% in 2050 (UN 2018).

Consequently, urban land cover is projected to triple between 2000 and 2030 (Seto et al. 2012). Expansion of urban areas at low densities, without systematic large scale land-use planning is also referred to as "urban sprawl" (Schneider and Woodcock 2008; Burchfield et al. 2006; Bruegmann 2008). For instance, the amount of new urban land take relative to existing urban areas exceeds urban population growth by a ratio of 1.5 in developed countries (UN-Habitat 2020). For most European regions, the built-up land per capita has increased during the past decades, at the same time the land-use intensity (the amount of people per area of built-up land) has decreased (Li et al. 2022). Generation of traffic, low efficiency of infrastructures, destruction of valuable agricultural land and pressure on natural areas are some of the negative impacts of urban sprawl (Gren et al. 2019; Neuman 2005).

Cities with high density housing and promotion of public transport systems are suggested as a sustainable alternative to urban expansion and urban sprawl (Haaland and Konijnendijk van den Bosch, Cecil 2015; Artmann et al. 2019a). Soil conservation, decreased average trip distances (Krehl et al. 2016) and reduced building energy consumption for heating and cooling owing to low surface-to volume ratios are considered as main benefits (Martilli 2014). Yet, highly densified urban areas are prone to a lack of urban green space (Haaland and Konijnendijk van den Bosch 2015) with negative impacts on urban environmental quality such as increased air temperatures, increased amounts of storm water runoff, low biodiversity and polluted air (Miroshnyk et al. 2022; Pauleit and Golding 2005). Importantly, lack of green space will reduce the city's adaptive capacity to climate change as urban areas are not only a cause of climate change, but also severely hit by global temperature rise (Emmanuel and Steemers 2018; Chapman et al. 2017).

Increased levels of outdoor heat stress are of particular concern (Emmanuel and Steemers 2018). Abundance of vegetation as well as urban layout and geometry belong to the most important parameters governing urban microclimate and outdoor thermal comfort that are affected by compaction (Jamei et al. 2016; Pauleit and Golding 2005). Reduced amounts of green space, increase of impervious surfaces, high anthropogenic heat emissions, altered albedo and geometry are all contributing factors to the Urban Heat Island (UHI) phenomena (Oke 1982). On calm, clear nights, the magnitude of the UHI effect can reach up to 12°C (Oke et al. 2017). Increased nighttime temperature is detrimental for human health, especially when they prevent people from recovering from a heat wave (Mora et al. 2017). Due to climate change, the intensity and frequency of heat waves has increased and will continue to do so (IPCC 2021; Rogers et al. 2022). Thus, both climate change and urban growth are likely to exacerbate existing heat stress (Chapman et al. 2017).

In the past decade, green and blue spaces in cities have been promoted as no- or low regret adaptation measures towards climate change (Depietri and McPhearson 2017; European Commission 2016). Bodies of water and vegetated areas reduce urban heat through evaporative cooling and shading (Bowler et al. 2010). For instance, dense foliated trees reduce the direct solar radiation below their crowns to 1-5% (Konarska et al. 2014) and lower daytime air temperature (T_a) by up to 3°C (Lee et al. 2020). A network of large-scale and small-scale green spaces is most effective in regulating the urban climate and in provision of further cultural and provisioning ecosystems services (Haase et al. 2014; Brzoska and Spāģe 2020).

Because of scarcity of land and high housing prices, pressure on urban green spaces is high (Haaland and Konijnendijk van den Bosch 2015). In Europe, increasing population density has led to significant declines in per capita green space provision (Fuller and Gaston 2009). Consequently, concerns for just spatial distribution of urban green spaces in densifying cities (Wolch et al. 2014; Pauleit et al. 2018) and the impact of densification on ecosystems and green space quality have been raised (Miroshnyk et al. 2022). Urban planners are challenged to balance urban green space preservation with other demands for space, such as housing, infrastructure, industry and leisure facilities (Khoshkar et al. 2018; Dorst et al. 2022).

Several closely interrelated and partly complementing concepts have been developed to support the role of green space in cities (Pauleit et al. 2017). Among them, the concept of urban green infrastructure (UGI) emphasizes the idea that urban green spaces are not an amenity and “nice to have”, but rather an essential part of the city, equal to grey infrastructure elements (Hansen and Pauleit 2014). However, for implementation into practice, planners need detailed information about selection of green infrastructure types, their optimal placement and expected ecosystem services (Matthews et al. 2015).

It has been shown that the simplistic suggestion “the greener the better” does not hold true, whereas the design of green spaces and the characteristics of their urban surroundings play a decisive role for their effectiveness (Chapman et al., 2017). Adding to that, several authors argue that the lower amount of urban green spaces in growing cities might be substituted by improving their quality, e.g. by increasing the substrate layer of green roofs or alteration of species composition (Artmann et al. 2019b; Haaland and Konijnendijk van den Bosch 2015). Thus, knowledge about regulating functions of different green space designs and their interaction with the local surroundings is required.

Microclimate modelling allows to quantify the cooling potential of urban green infrastructure and to compare different building and greening designs. A large number of studies have explored idealised urban geometries of neighbourhoods (Chatzidimitrou and Yannas 2016), layouts of single urban street canyons (e.g. Sanusi et al. 2016; Morakinyo and Lam 2016) and the influence of vegetation amount, building density and building height on outdoor human thermal comfort (Perini et al. 2014, Yahia et al. 2018, Lee et al. 2020). While these studies have shown that simultaneously increasing the building height and the green cover provide the best thermal comfort results, urban green space was rather treated as a quantitative parameter disregarding the impact of densification on the qualities of the existing vegetation. There is a lack of studies that consider the relationships between urban infill and the qualities of the existing green spaces, as well as guidance for planning (Haaland and Konijnendijk van den Bosch 2015; Cortekar et al. 2016).

In addition, there is a lack of studies that consider multiple scales and combine investigations of thermal comfort with analysis of ventilation patterns. Bartesaghi Koc et al. (2018) found in their review of thermal comfort investigations that only 4.2% of all assessed studies (165) considered multiple scales to evaluate the cooling impacts of UGI, whereas 49% of them focused on the micro-climate scale. Densification alters area roughness and urban layout, affecting inflow of cold air and local ventilation. Blocking of wind paths leads to deteriorated thermal comfort (Allegrini et al. 2015; He et al. 2020). Therefore, knowledge of ventilation corridors and local wind conditions is necessary to design climate responsive urban neighbourhoods (He et al. 2020).

Moreover, the local context and residents’ needs for heat and stress relief have to be considered, when designing urban green spaces. The interactions between different aspects of urban form and vegetation and their effects on people’s perception of density and thermal comfort still remain to be explored (Klemm et al. 2015; Knöll et al. 2018).

With a reduced amount of green spaces and loss of private green space associated with densification, public green spaces have to provide a wider range of services to communities (Wellmann et al. 2020; Lin et al. 2015). To exploit the full potential of UGI, requirements of the residents and the local context need to be analysed and understood (Klemm et al. 2017).

The integration of large-scale strategy goals, such as climate change adaptation and UGI integration, into daily working routines, also called mainstreaming, represents a challenge for planners and municipalities (Wamsler et al. 2013). Several studies have therefore explored municipal governance processes to identify barriers for mainstreaming climate change adaptation into urban planning and to develop strategies for overcoming them (Eisenack et al. 2014; Uittenbroek et al. 2013; Wamsler et al. 2020b; Wamsler et al. 2013; Wamsler et al. 2017). These studies highlighted several overarching factors impacting planning processes and outcomes, such as governance structures and involved actors (Moser and Ekstrom 2010; Lehmann et al. 2015), which are interdependent and likely to change over time (Eisenack et al. 2014). Thus, analysis of interdependencies between different policy dimensions and consideration of dynamics in policy constellations are central for identifying and overcoming barriers (Aalbers et al. 2019; Arnouts et al. 2012). However, research addressing structural conditions affecting planning processes and outcomes related to integration of nature based solutions or UGI is largely absent (Dorst et al. 2022; Biesbroek et al. 2013; Eisenack et al. 2014). Moreover, as barriers are often context-specific (Biesbroek et al. 2013; Wamsler 2015), assessments are required that explicitly address the integration of UGI in urban planning processes of densifying cities which are exposed to intensified land use conflicts (Khoshkar et al. 2018; Miroshnyk et al. 2022).

Research for this thesis was undertaken within two research projects, “Green City of the Future” and “Densification in the context of climate change”. The project “Green City of the Future”, founded by the Federal Ministry of Education and Research (BMBF), investigated approaches for dealing with climate change impacts in growing cities based on case studies in Munich. An important aspect of the research project was the cooperation with municipal partners and the perspectives of different stakeholders. The research for this thesis contributed a work package on “Regulating capacity of urban green infrastructure for climate change adaptation”. The project “Densification in the Context of Climate Change”, founded by the Bavarian Ministry of Environment and Consumer Protection, aims to develop a collaborative decision support tool for planners. The research for this thesis contributed to work packages on “Potentials for densification” and “Implementation of densification in climate change”.

1.2. Objectives of the thesis

The overall aim of this thesis is to enhance the understanding of the interplay between densification, the cooling potential of UGI and its impact on human heat stress in order to assist climate-adapted urban planning in growing cities. This requires an understanding of which type of densification has which effects on existing greenery, urban microclimate and ventilation. Next, the potential of UGI to compensate for negative effects of densification will be investigated (Paper I and II). As human thermal comfort is not only influenced by physical parameters, but also by individual perception, user perspectives on UGI and urban design are necessary (Paper III). The collected evidence needs to be translated into municipal planning practice. This calls for an understanding of the conditions under which urban planning processes take place in growing cities and which levers are important to promote UGI integration in these processes (Paper IV). In summary, this thesis addresses the following objectives:

Objective 1: Analyse linkages between densification, UGI and outdoor thermal comfort to identify trade-offs and strategies for minimising them

Objective 2: Quantify the climate regulation and densification compensation potential of UGI on block and neighbourhood scale to deepen the knowledge on UGI cooling potential and its strategic use and placement

Objective 3: Assess user perspectives on UGI and neighbourhood designs in relation to density and heat to identify the impact of urban design and greenery on residents

Objective 4: Explore UGI integration in urban development planning in densifying cities to determine levers for implementation in planning practice

These objectives relate directly to the research questions posed in Papers I-IV reprinted in the Appendix:

Paper I: How is urban green space affected by densification and what are the consequences for the microclimate and human heat stress? How can the trade-offs between densification and greening be effectively minimised?

Paper II: Is strategic use of UGI able to compensate for densification in the building stock and loss of existing greening? How does green infrastructure influence the outdoor thermal comfort on block scale and the ventilation on district scale in a densified neighbourhood?

Paper III: How does the design of open and green spaces influence social perception of density and heat? How does a context-specific and user-centred approach for thermally comfortable places look like?

Paper IV: What are decisive structural conditions for green space planning in densifying municipalities? What are levers to promote green space integration in municipal urban development processes?

1.3. Structure of the thesis

The thesis is structured according to the four research objectives and the analytical framework (Figure 1). The following chapter 2 explores the conceptual background by introducing the research topics and related scientific concepts. Chapter 3 briefly presents the study areas and the employed research methods. Chapter 4 (Sections 4.1 to 4.4) summarises the findings. The synthesised results are discussed and recommendations for urban planning are developed in Chapter 5. Chapter 6 highlights the core findings and outlines further research needs.

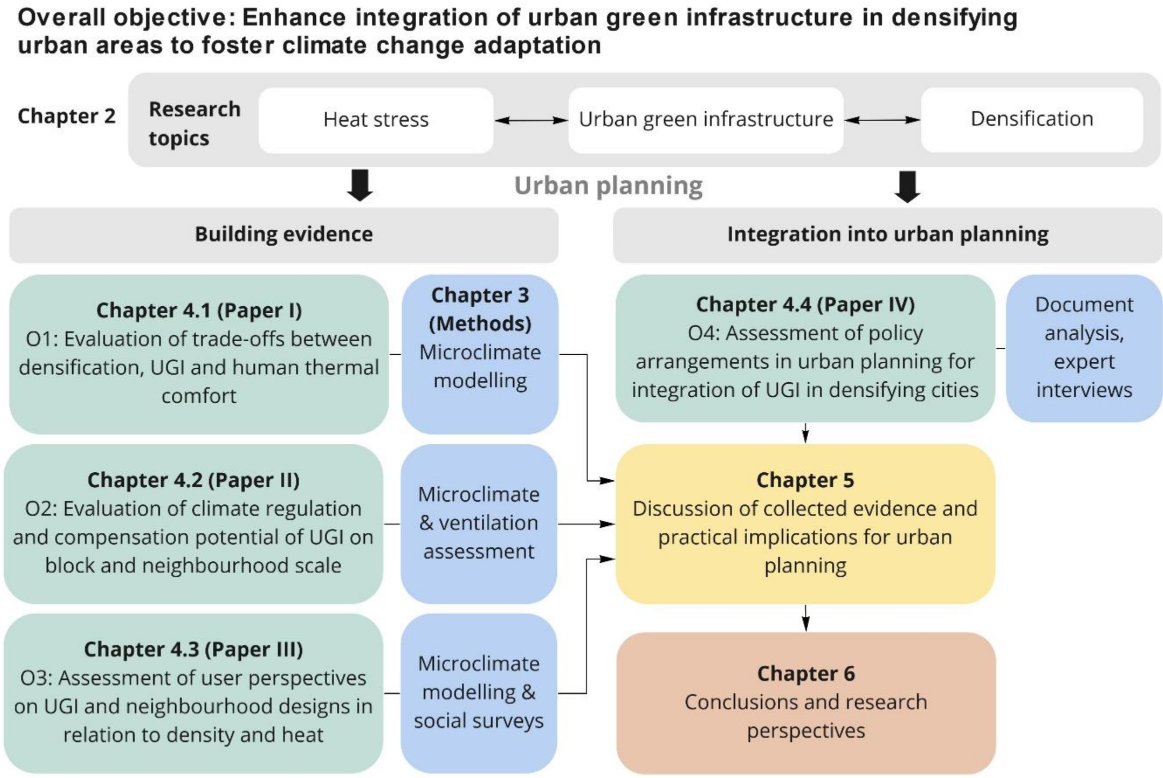

Figure 1: Structural overview of the thesis and the related articles.

2. Background and key concepts

The following chapter outlines the research area and the thematic focus of this thesis. This thesis relates to the fields of urban ecology, climate change adaptation and sustainability transformation. Urban ecology in its broader sense refers to an interdisciplinary research field that seeks to relate ecology as a natural science with urban planning for improvement of living conditions and environmentally friendly urban development (Breuste et al. 2016, p. 22). In that sense urban ecology is also understood as a programme for action and urban design (Breuste et al. 2016, p. 22; Trepl 1994). Climate change adaptation is concerned with moderating harm for population, infrastructure or other elements at risk from consequences of climate change, while also exploring potential benefits (IPCC 2007). Climate change adaptation efforts are increasingly associated with achieving climate resilience – the ability of social-ecological systems to withstand and recover from climate related shocks and impacts (Carter et al. 2015). Sustainability transformation explores how social-ecological systems (such as cities) can change towards sustainability goals (Abson et al. 2017) (such as liveable and healthy neighbourhoods), as they are also stated in the United Nations Sustainable Development Goals (SDGs) (UN 2016) and the New Urban Agenda (UN 2017) for urban areas. Urban and sustainability transformation research seek to identify leverage points for system chance and address urban challenges (Abson et al. 2017; Hölscher and Frantzeskaki 2021). With respect to this thesis, the ecological functions of small scale urban green spaces, such as trees, roof and facade greening and their interrelations with the urban development process of densification are of central interest. The focus is set on adaptation to urban heat stress in light of increasing intensity and frequency of heat waves. It explores how enhanced integration of urban green infrastructure can be achieved for more sustainable planning outcomes and which changes are required in this regard in urban planning. In the following, the three main topics of this thesis, namely urban heat stress, urban densification and urban green infrastructure planning are introduced with respect to current scientific literature. Basic concepts necessary for the understanding of the research approach and results are defined.

2.1. Urban heat stress

2.1.1. Negative effects of heat on human health

Excessive heat has several negative consequences on human health including an increase of mortality. Heat stress occurs when the thermoregulatory system of the human body is unable to compensate for the excess heat (Mora et al. 2017). Direct health risks induced by heat stress range from lack of concentration, exhaustion, dehydration, heat stroke and heat cramps to death (Ward Thompson et al. 2016; Buchin et al. 2016). Indirect effects relate to increased risk of death from pre-existing cardiovascular and respiratory diseases (Smoyer-Tomic et al. 2003; Hallegatte et al. 2011) and degraded air quality as the concentration of pollutants increases (Harlan and Ruddell 2011). Prolonged periods of high temperature are especially detrimental - the extremely hot summer of 2003 is estimated to have caused 70,000 heat-related fatalities in Southern and Western Europe (Robine et al. 2008; EEA 2012). Over the past 70 years, both the number and the duration of heat waves in Europe have increased (Matzarakis et al. 2020; Rogers et al. 2022).

Heat loads are highest when high air temperature (T_a) combines with high solar radiation load and low wind speed (Mühlbacher et al. 2020; Lee and Mayer 2018), but thresholds and definitions for heat days differ depending on geographical context and local climate (Matzarakis et al. 2020). For Germany, hot days are characterised by daytime maximum T_a above 30 °C with clear skies and low wind speed (up to 2 m/s; Mühlbacher et al. 2020). During daytime, the peak of heat stress is reached in the afternoon (Matzarakis et al. 2010). On a tropical night, nightly T_a does not fall below 20 °C (Mühlbacher et al. 2020). High nighttime temperature is particularly hazardous as it negatively affects sleep quality and recovery from daytime heat (Beckmann et al. 2021; Okamoto-Mizuno and Mizuno 2012). As the urban heat island effect leads to higher nighttime T_a compared to rural areas, urban populations are especially affected by heat (Emmanuel and Steemers 2018).

Young children, the elderly, people with cardio-vascular problems and socially-isolated persons belong to the most vulnerable individuals (Buchin et al. 2016; Brown and Walker 2008). It is suggested that people living on their own tend to ignore or miscalculate heat risk and are more likely to lack support in case of emergency (Bao et al. 2015; Depietri et al. 2013). Additionally, vulnerability is not only dependent on personal characteristics, but also on the quality of housing and the built environment (Gabriel and Endlicher 2011). Inhabitants of densely built-up districts with little green spaces or poor housing insulation are at higher risk than low-density dwellers (Gabriel and Endlicher 2011; Depietri et al. 2013). In view of climate change and the increase in heat events, the climate-adapted design of urban residential areas and their open spaces is thus of great importance. Heat stress assessment provides clues as to what adjustments are needed.

2.1.2. Urban microclimate and human thermal comfort

For assessment of the urban climate different spatial scales and different meteorological layers can be distinguished (Oke et al. 2017)(Figure 2). On mesoscale, the climate of a city is primarily influenced by processes in the urban boundary layer that reaches vertically from ground level to the limit where cities do no longer interfere with the atmosphere (Oke et al. 2017). An example for a mesoscale phenomenon is the boundary-layer urban heat island (Deilami et al. 2018; Oke et al. 2017). On neighbourhood (local) scale, the topography and morphology of the urban environment plays a dominant role. The classification of rural and urban sites into local climate zones (LCZ) thus supports the comparison of local scale phenomena (Stewart and Oke 2012). Microclimate phenomena relate to the scale of single streets and building blocks and appear in the urban canopy layer, reaching from ground level to mean building and tree heights (Oke et al. 2017). The micro-scale is the scale at which pedestrians and urban dwellers perceive thermal conditions and thus the prominent spatial scale for studies on human thermal comfort (Lee and Mayer 2018; Lenzholzer et al. 2018)

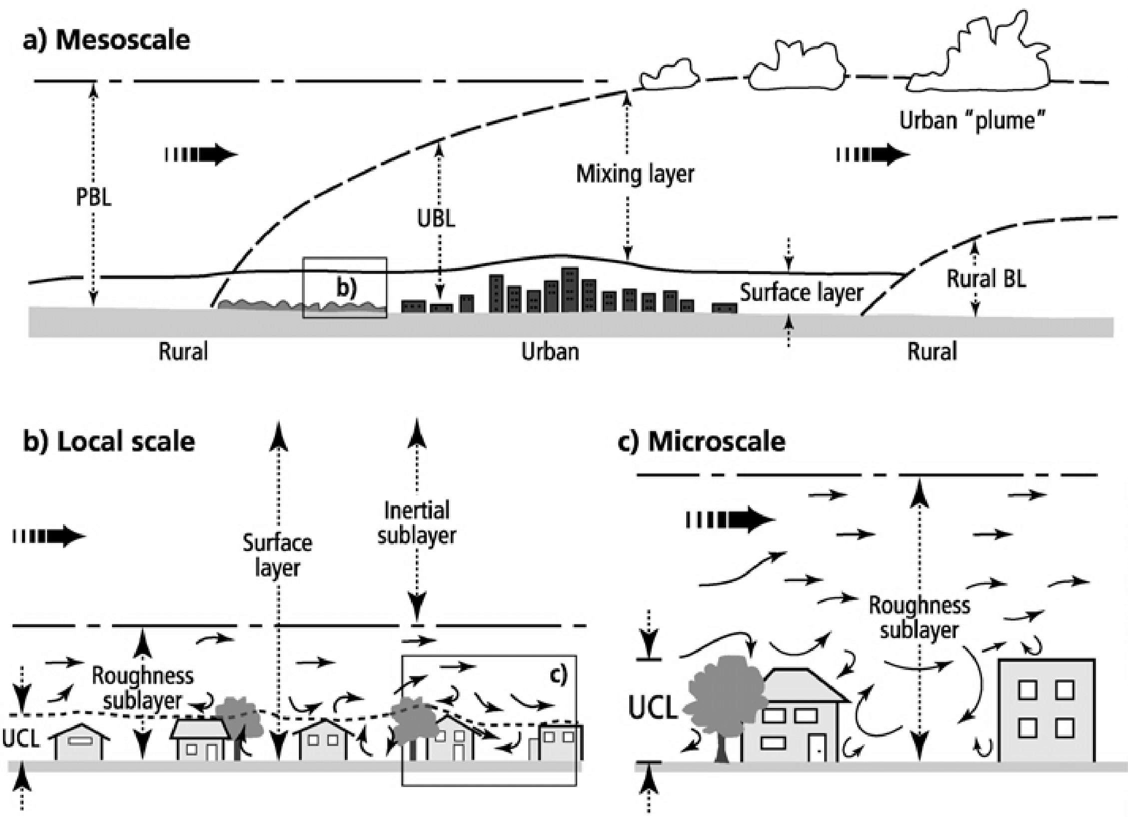

Figure 2: Schematic visualisation of the three spatial scales and their related meteorological layers. UBL stands for Urban Boundary Layer and UCL for Urban Canopy Layer (Oke 2011, p. 121)

Initially applied to indoor environments, human thermal comfort is often described as the "*condition of mind that expresses satisfaction with the thermal environment*" (ASHREA 55, 2013). Human heat stress constitutes dissatisfaction due to extra warmth. To assess human heat stress and human thermal comfort, over 165 indices are used (Staiger et al. 2019). However, a majority of these indices only rely on one meteorological variable, whereas only four indices consider all basic meteorological and physiological parameters governing human heat balance and thermal comfort (Staiger et al. 2019).

The Physiological Equivalent Temperature (PET) belongs to this group of more sophisticated heat budget models of the human body (Blazejczyk et al. 2012; Perini et al. 2018). Unlike the first heat-balance model "predicted mean vote" (PMV), it has been developed for outdoor conditions (Mayer and Höppe 1987) and is widely used in thermal comfort studies (Perini et al. 2018). PET expressed in °C, is defined as the "*air temperature at which, in a typical indoor setting, the heat budget of the human body is balanced with the same core and skin temperature equal to those under the conditions being assessed*" (Höppe 1999). The index considers the six basic parameters T_a, mean radiant temperature (T_{mrt}), relative humidity (Rh), wind speed, insulation of clothing and activity of the person to calculate the human heat balance (Matzarakis et al. 1999). The index is frequently applied to regions with a temperate climate (Hirashima et al. 2018).

The influence of different meteorological variables differs depending on the weather conditions (Höppe 1999). On cloudless summer days with little wind, T_{mrt} is the dominating factor for outdoor human thermal comfort in Central Europe (Holst and Mayer 2011; Lee and Mayer 2018). In absence of the possibility to calculate PET, T_{mrt} can thus be used for an approximation of human thermal comfort on hot and calm summer days.

Thresholds for human heat stress vary in differing climatic contexts due to different thermal sensations of residents (Krüger et al. 2017). Thus, calibrations of the index for local climates are necessary. In a recent calibration for the German cities Kassel and Freiburg, PET values above 35 °C were perceived as hot and PET values above 38 °C as very hot (Hirashima et al. 2018), whereas Holst and Mayer (2011) suggest a PET transition value of 35°C towards warm and 40 °C towards hot based on investigations in Freiburg. As regards T_{mrt}, values above 55.5 °C and 60 °C correspond to strong and severe heat events respectively (Thorsson et al. 2007). For the vulnerable population groups depicted above, even lower T_{mrt} or PET values may correspond to strong or severe heat stress.

2.1.3. Objective thermal condition and subjective thermal perception

Several studies have demonstrated deviations between observed thermal conditions and actual sensations by people (Wang et al. 2017; Franck et al. 2013; Lemonsu et al. 2020). These deviations are related to psychological and behavioural factors: despite experiencing the same environments, thermal sensations of people are likely to differ based on their (cultural) backgrounds and expectations (Djongyang et al. 2010; Nikolopoulou and Steemers 2003; Pearlmutter et al. 2014). Spatial characteristics influence thermal perception: Variable, diverse environments are preferred over monotonous ones even if physical heat stress might be higher (Nikolopoulou and Steemers 2003). People felt more comfortable in a street with small trees and front gardens than in a street with tall trees that provided more shade (Klemm et al. 2015). Degree of naturalness and perceived sense of control (the ability to alter environmental conditions) and duration of experience constitute further important psychological parameters (Nikolopoulou and Steemers 2003).

For holistic assessment of the effect of urban spatial characteristics on human thermal perception, Lenzholzer et al. (2018) proposed a framework considering findings from environmental psychology. The framework differentiates between objective thermal conditions and subjective thermal perception (Figure 3). While objective thermal conditions are expressed in physical and physiological factors, subjective thermal perception is guided by psychological and behavioural aspects. Factors controlling momentary (here and now) and long-term thermal perception (regular experiences) are distinguished. The impact of different urban spatial environments on objective thermal conditions is assessed with quantitative research approaches, whereas qualitative research methods are required to investigate subjective perception of environmental stimuli.

Although several personal factors of thermal perception (e.g. people’s clothing, mood, company) cannot be influenced, the spatial environment can be shaped by design and planning (Frerichs and Küpper 2017). An understanding of the spatial factors influencing the perception of heat provides clues to sustainable neighbourhood design (Lenzholzer et al. 2018; Klemm et al. 2017). However, the majority of analysis either assesses objective conditions or subjective conditions, whereas more analysis combining both perspectives are required (Klemm et al. 2015; Lenzholzer et al. 2018). Moreover, a large amount of research on thermal perception focusses on momentary perception (how a person feels in this moment) rather than long term experience (how a person experiences different spatial typologies) (Lenzholzer et al. 2018). However, as long term perception is changing less quickly then momentary perception, it provides more useful information for climate-resilient urban design (Lenzholzer et al. 2018), necessitating further inquiries in this direction.

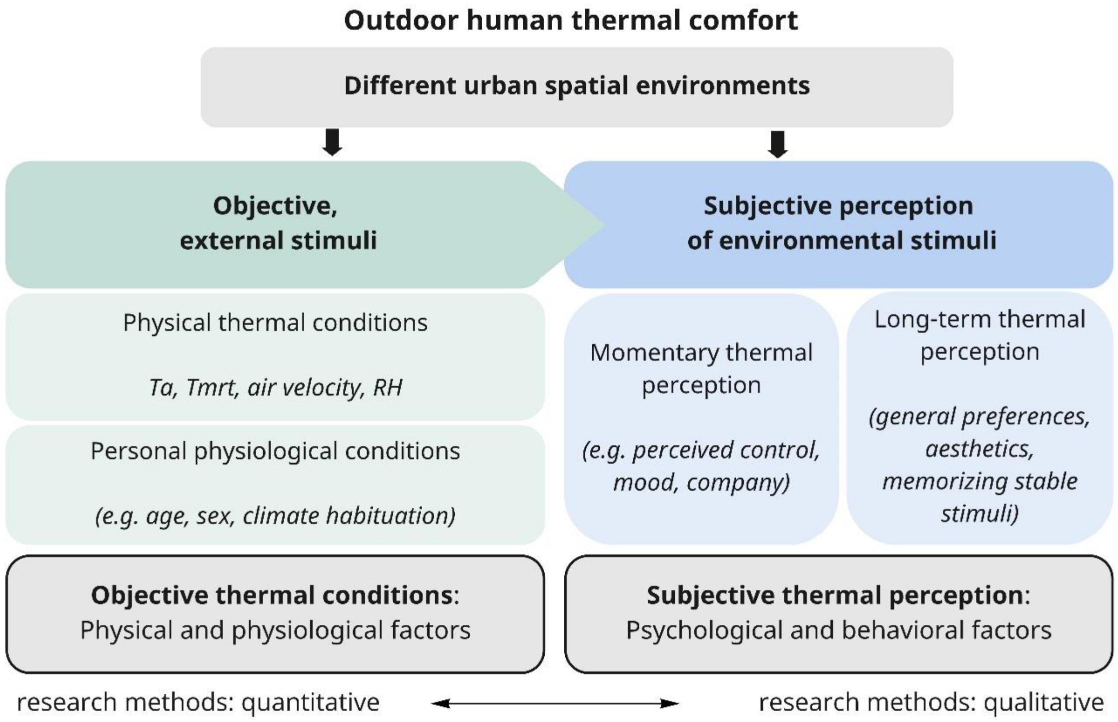

Figure 3: Concept and aspects of outdoor human thermal comfort after Lenzhölzer et al. 2018

2.2. Urban Densification

As outlined in the previous chapter, thermal comfort is influenced by urban morphology. Densification of the building stock alters the proportion of sealed and unsealed land cover types, but also the spatial characteristics of urban neighbourhoods. This sections briefly defines what is understood by densification in the context of this thesis and introduces different types of building stock densification and their impact on the urban microclimate and urban green spaces.

2.2.1. Definition and types of densification

As controversial as the discussion about sustainable urban form is, as diverse are the concepts of what is meant by densification and density. Thus, a compact city with a high density of amenities and people and short distances has been suggested as a sustainable urban form for its potentials in energy savings, transportation and infrastructure efficiency, but also for promoting social integrity and cultural diversity (Gren et al. 2019; Ahlfeldt and Pietrostefani 2017; Artmann et al. 2019b). Deteriorated environmental qualities (e.g. fresh air, green space supply, habitats for species) (Gren et al. 2019; Haaland

and Konijnendijk van den Bosch 2015; Neuman 2005), higher cost of land and housing and increased social inequities (Debrunner et al. 2020) are cited as disadvantages. With respect to densification, this thesis follows the definition of the European Environmental Agency, characterising it as "*land development that takes place within urban areas, making maximum use of the existing infrastructure instead of building on previously undeveloped land" (EEA 2018).* In that sense, densification refers to densification in the building stock and is understood as a countermeasure against urban sprawl.

Densification of housing within the existing building stock corresponds to the infill development policies of various European countries to limit urban sprawl and make efficient use of limited space for living (Eggimann et al. 2021; Artmann et al. 2019b). For instance, Germany has set itself the goal of reducing the amount of new land taken up to less than 30 hectares per day by 2030 (Bundesregierung 2016). However, the country missed its earlier goal for 2020, with a lasting land consumption of 52 hectares per day (UBA 2021). Similarly, remote sensing analyses revealed that land take is still dominant in European cities. In relation to land take, densification accounts for only 9 % of total land consumption (EEA 2018). Reasons for land take are manifold: economic growth, cheap building land prizes in sub-urban areas, increasing prosperity and demands for living space, retreat of trade and employment from the cities to the urban fringe (Siedentop 2018). As an example, per capita living space in Germany has increased from 34.8 m² to 1990 to 47.4 m² in 2020 (Statistisches Bundesamt 2021). Soil sealing is often linked with a redesign of private gardens (e.g. conversion of front gardens into car parks) and an increased number of car parking space (Wellmann et al. 2020; Kabisch and Haase 2013).

The potential and forms of densification of the building stock vary depending on the considered settlement type (BBSR 2014). Three basic forms of this type of densification – (1) addition of storeys, (2) addition of buildings and (3) conversion of previously developed land - can be distinguished. While secondary dwelling units (attached or detached from primary structures) are a common form of densification for low-density housing areas, development of inner court yards is connected with perimeter building blocks. Several studies have explored the densification potential of different settlement types (Eggimann et al. 2021), or different forms of densification (Wegmann and Nemirow 2011; Tichelmann et al. 2016). For Germany, a potential of 1.1 million additional flats or 84.2 million m² additional living space has been estimated if all suitable residential buildings were to be topped with additional floors (Tichelmann et al. 2016). However, ownership structures complicate a fast activation of this potential. Thus, neighbourhoods with post-war free standing multi-storey blocks with good public transport connection have been identified as sustainable densification options (Eggimann et al. 2021): an energetic refurbishment of the buildings significantly reduces energy consumption and thus carbon emissions. At the same time, the public transport infrastructure allows higher people density, avoiding individual motorized traffic (Eggimann et al. 2021).

Ownership structures and access to land constitute decisive factors for control of urban planners over densification (Boulton et al. 2018). On the one hand, the initiative or consent of building or property owners is necessary for modifications of the existing building stock to realize e.g. additional floors or fill gaps between buildings. On the other hand, lack of municipal land resources or regulations can result in uncontrolled urban infill (Wegmann and Nemirow 2011). Typical examples for this type of densification are the building of a second home on the property or the replacement of a single-family home with an apartment building. Without a local land use plan, open space design statutes or tree protection ordinances, this form of gradual densification is hardly controllable by urban planning.

The discussion about what type of densification is most sustainable and which density is appropriate in which place is also complicated by the fact that there is no single understanding of density. In addition to various density parameters such as built density, population density and activity density (buildings, people or activities per amount of space), several spatial density indicators exist, like built-up volume and floor area ratio (Krehl et al. 2016). Different authors prefer other names for similar parameters, interpret parameters differently or consider other parameters relevant. Thus, Ahlfeldt and Pietrostefani (2017) considered the effects of densification based on different understandings of density. They concluded that economic density (number of people living or working in an area) is associated with 70% positive effects, whereas morphological density (density of the built environment) is associated with 56% positive effects, such as cities productivity, efficiency of public services delivery, safety and energy efficiency. Negative effects relate to open space preservation, biodiversity, traffic flow, health and well-being (Ahlfeldt and Pietrostefani 2017). Again, the type of spatial delineation and the parameters chosen have a major impact on the study results. This is complicated by the fact that there is hardly an objective benchmark for appropriate density, since cultural and social values play a decisive role in the perception and acceptance of density (Eggimann et al. 2021; Wicki and Kaufmann 2022). Individuals living in urban neighbourhoods are more likely to accept densification compared to suburban or rural residents (Wicki and Kaufmann 2022). Perceived deterioration of the status quo weighs more negatively than potential benefits of densification, especially public transport accessibility, availability of shopping facilities and housing costs were observed to be decisive (Wicki and Kaufmann 2022). The search for the most sustainable urban form and appropriate density thus represents a controversial and broad field of debate. The spatial and social context and also the distribution of dense and sparse neighbourhoods within a city are important criteria for the evaluation of urban form.

2.2.2. Influence of densification on the urban microclimate

On the microscale, design of buildings and street canyons as well as the relation between green space to buildings represent main microclimate modifiers (Erell 2017). Infill development modifies the built environment by 1) altering aspect ratios of buildings and street canyons, 2) altering building orientation and configuration and 3) change of surface materials (Figure 4).

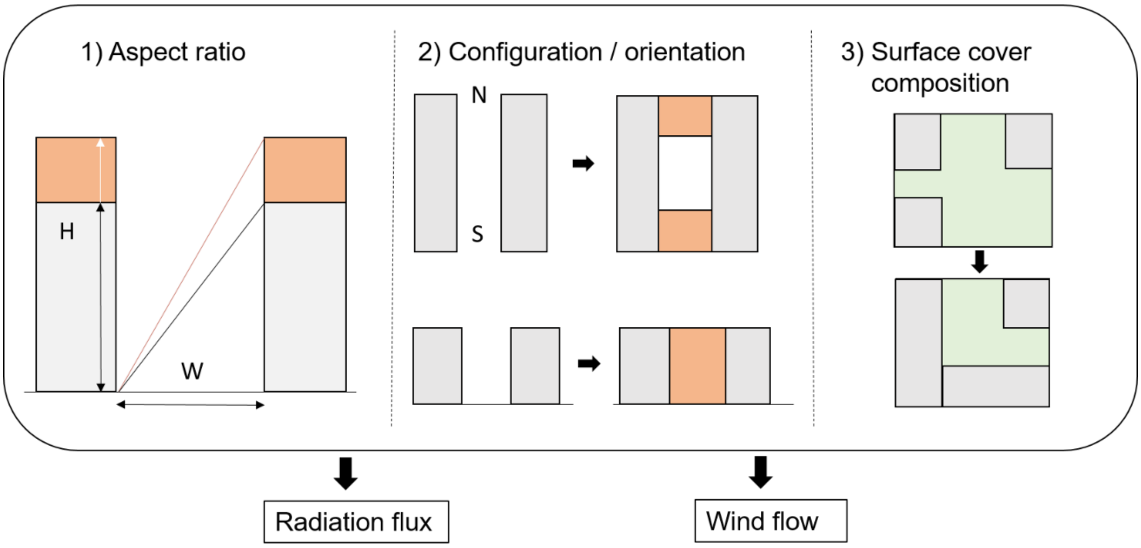

Figure 4: Main urban microclimate influences of densification. Densification of the building stock alters 1) aspect ratio, 2) the configuration and orientation of buildings and 3) the composition of surface cover, affecting radiation flux and wind flow.

Increasing building height affects radiation flux and wind flow. Aspect ratio (ratio of building height to canyon width), street orientation and sky view factor (SVF; visible amount of sky) are main microclimate modifiers for street canyons (Erell 2017). Taller buildings increase the aspect ratio and decrease the ground level sky view factor (SVF). Shallow street canyons with a lower aspect ratio receive a higher amount of direct solar radiation reaching to pedestrian level than streets with higher aspect ratios. Thus, on a hot summer day, narrow canyons with a lower aspect ratio are more favourable than unshaded wide canyons due to the lower amount of solar access and consequently lower T_{mrt} (Ramyar et al. 2019; Chatzidimitriou and Axarli 2017; Shashua-Bar et al. 2006). At the same time, narrow streets or courtyards portray higher nighttime T_a due to a slower dissipation of daytime heat (Loibl et al. 2019; Lobaccaro et al. 2019). Moreover, decreasing street width reduces wind penetration (Ramyar et al. 2019).

Similar to increased building heights, additional buildings or new building configurations affect solar access and wind flow. Lower SVF and higher building densities increase the amount of shaded area during daytime, but reduce nocturnal cooling rates by modifying out-going longwave radiation and turbulent heat exchange (Onomura et al. 2016). In middle Europe, especially the SVF of the southern half of the upper hemisphere (SVF 90-270) is decisive for solar radiation load and human thermal comfort (Holst and Mayer 2011). Trade-offs between more and less shade are apparent between day and nighttime, but also for cold and warms seasons in temperate climates. Introduction of new buildings influences wind flow patterns, affecting street canyon and neighbourhood ventilation. While new building structures perpendicular to the dominant wind direction reduce wind speed (Jamei et al. 2016), tall and thin buildings and those with a stepped height structure potentially induce wind flow (Moonen et al. 2012). Isolated buildings have different flow regimes than arrays of buildings (Gago et al. 2013). The impact of densification on wind flow is highly dependent on urban geometry and main wind direction, requiring context-specific analysis.

Moreover, densification of the building stock is likely to alter composition of surface cover. Urban surfaces absorb solar and infrared radiation and emit heat to the atmosphere, largely influenced by their albedo and emissivity (Gago et al. 2013). Due to evaporative cooling, planted ground cover combines low reflectance due to low albedo with low surface temperature. Artificial materials such as asphalt emit considerably more infrared radiation than lawn or, in the case of white materials, reflect more incoming shortwave radiation (Erell 2017, p. 85). Hence the fraction of vegetated surfaces has an important impact on outdoor urban temperature, especially during nighttime (Konarska et al. 2016a; Chatzidimitriou and Axarli 2017).

Comparing different types of densification, Ward and Grimmond (2017) argue that increasing building height has less of an impact on microclimate than increasing building extent mainly due to the important role of vegetated surfaces. Similarly, Perini and Magliocco (2014) found lower T_a and increased thermal comfort with taller buildings and lower building fraction than vice versa. The most comfortable situation was achieved when building heights as well as green coverage were increased (Perini and Magliocco 2014). Independent of densification type, higher people or activity density is likely to increase the amount of anthropogenic heat release (Chapman et al. 2017). However, there is a lack of studies that analyse the interplay between densification and thermal comfort not only in generic analysis, but in real planning cases where trade-offs between different intended uses of space have to be considered (Cortekar et al. 2016). Moreover, more research on the impact different forms of densification have on district and microscale is required. A lower amount of cold air volume flow on district scale is likely to reduce air flow on microscale, affecting nocturnal cooling. Yet, assessments combining investigation of ventilation on district scale and thermal comfort on block scale to detect mutual influences are largely missing (Bartesaghi Koc et al. 2018).

2.2.3. Effect of densification on urban green space

Densification of the building stock tends to have a negative impact on urban green space (Haaland and Konijnendijk van den Bosch, Cecil 2015; Brunner and Cozens 2013; Pauleit et al. 2005). Additional buildings and larger size of new dwellings increase soil sealing and limit the growing space for urban trees (Brunner and Cozens 2013). Compacted soils and space conflicts with underground pipes and cables pose obstacles to tree planting in compacted areas (Haaland and Konijnendijk van den Bosch 2015). Such green space enhancement remains rare: the EEA reports that the ratio of so-called green recycling – reuse of previously developed land for creating urban green areas – in Europe is less than 0.01 ha created green areas for each ha of land take (EEA 2018). Quantitative open space standards bear the risk of low quality green and are often not achieved (Byrne et al. 2010).

It has been demonstrated that densification of the building stock affects private and public green space differently. Whereas Wellmann et al. (2020) observed an increase of net public green infrastructure in Berlin from 1990 to 2020, private green cover decreased mainly due to gradual soil sealing in low density residential areas. A strong decrease of private green cover without a compensation by larger public green spaces was also reported by Lin et al. (2015). This increases the pressure on remaining green spaces and raises the topic of social justice and fair access to urban green spaces. With growing population density, the same amount of public green space has to provide a wider range of services to communities (Lin et al. 2015). In addition, residents living in dense built environments have a tendency to visit green space further from home, also called compensation traveling (Haaland and Konijnendijk van den Bosch 2015). However, not all residents have the resources to do so, asking for a fair distribution of urban green space (Hoover et al. 2021; Boulton et al. 2018) and a public green space design that meets the requirements of local residents (Lin et al. 2015). For this reason, the perception and needs of residents should be taken into account when planning streets and squares.

Moreover, there seems to be no direct correlation between amount of green space and population growth (Kabisch and Haase 2013; Wellmann et al. 2020). From 1990 to 2006, residential areas in Europe increased regardless of population development, whereas population decline does not necessarily lead to an improved supply with urban green space (Kabisch and Haase 2013). In fact, for Berlin, Wellmann et al. (2020) identified neighbourhoods with shrinking population and a tendency towards soil sealing as well as districts with increase in population numbers and growing green space cover. The authors conclude that not the overall urban form - whether spread or compact - is decisive for sustainability, but rather the distribution of compact and spread places within a city (Wellmann et al. 2020). Therefore, studies are required that assess the impact of densification on UGI on the scale of district and blocks, as these are the scales connected to the perception of urban residents and where urban planning defines the use of spaces and the distribution of green and grey in binding land use plans (Cortekar et al. 2016).

2.3. Urban Green Infrastructure Planning

This chapter provides background on UGI as a planning approach and explores its capacity for urban adaptation to climate change and subjective benefits in relation to density and heat for residents. It further explores the barriers and drivers for UGI implementation in urban planning.

2.3.1. Concept of green infrastructure

In the 1990s, growing concern of uncontrolled urban sprawl gave birth to the concept of green infrastructure (GI) in the USA (Benedict and McMahon 2002). Since then, the concept of GI has been applied to different planning contexts and policy objectives, including storm water management (Hansen et al. 2021). The European Commission (2013) has defined GI as "*a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services".* This definition underpins the connotation that green and blue elements have an essential function, like grey infrastructure and that they should be strategically thought of, planned for and maintained (Hansen et al. 2017a). In an urban context, UGI is employed as an integrative and pro-active planning approach that considers different spatial scales (Demuzere et al. 2014; Pauleit et al. 2017). Four core principles of UGI planning have been highlighted: connectivity, multifunctionality, green-grey integration and social inclusion (Pauleit et al. 2017; Hansen et al. 2017a). Connectivity relates to creation of green space networks that provide wider benefits than single green spaces

(Hansen et al. 2017b). Green-grey integration seeks to combine urban green spaces with other types of urban infrastructure such as sewer systems and transport lines (Hansen et al. 2017b). In dense cities, examples for functional or physical integration of UGI into grey infrastructure are green roofs, green facades or street trees (Artmann et al. 2019a). Multifunctionality is seen as a key towards the implementation of compact green cities as it provides multiple benefits at the same time (Hansen et al. 2019). Social inclusion asks for collaborative and participatory planning processes, including the knowledge and need of different population groups (Hansen et al. 2017b). UGI is recognised as a suitable planning concept to address a variety of urban challenges and policy goals: climate change adaptation, social cohesion, biodiversity conservation and provision of ecosystem services (Davies et al. 2015). The impact of urban green spaces on climate change adaptation and provision of ecosystem services is described in more detail in the next section.

2.3.2. Adapting to density and heat with urban greenery

The microclimate regulating capacity of UGI has been explored in several studies (Norton et al. 2015; Demuzere et al. 2014; Zölch et al. 2016). Urban green provides cooling through shading and evapotranspiration, thus reducing urban heat loads. It fosters rainfall interception and infiltration, mitigating storm water events (Rosenberger et al. 2021). The type of green space (e.g. tree, green roof, green facades) (Zölch et al. 2016; Bowler et al. 2010), its quality (e.g. intensive or extensive roof greening) (Haaland and Konijnendijk van den Bosch 2015), but also its arrangement and spatial distribution (Zölch et al. 2019; Tan et al. 2016; Zhao et al. 2018) are vital for its regulating capacity. On microscale, trees have the highest cooling capacity compared to green roofs and green facades (Gago et al. 2013; Zölch et al. 2016). The cooling effect of trees is mainly attributed to evapotranspiration and reduction of incoming shortwave radiation through shading. For dense, foliated trees the reduction can reach up to 3 °C for daytime T_a, 37 °C for T_{MRT} and 16 °C for PET (Lee et al. 2020). Green roofs are most effective regarding runoff mitigation (Zölch et al. 2017; Rosenberger et al. 2021). Green facades cool ambient temperature through evapotranspiration, yet this cooling effect is limited to the proximity of the facades (Buchin et al. 2016). However, green facades significantly reduce surface temperature of buildings walls with positive effects for indoor temperature and energy demand for cooling (Pérez et al. 2014; Li et al. 2019). Appropriate placement of UGI has to consider possible trade-offs between shading and ventilation and daytime vs nighttime conditions. While dense tree canopies reach a maximum cooling effect in the afternoon by blocking incoming shortwave radiation, they impede the nocturnal cooling of the ground below the canopy as the leaves reduce the outgoing long-wave radiation (Bowler et al. 2010; Rahman et al. 2017). Similarly, tree may attenuate cooling air flow (Bodnaruk et al. 2017; Yahia et al. 2018). Besides the consideration of cooling potentials and the effect on ventilation, optimized green space designs should furthermore consider perceptions and preferences of residents.

Numerous studies have demonstrated positive effects of urban green space on human health and well-being. Urban green spaces have the potential to reduce feelings of stress and anxiety (Reklaitiene et al. 2014; Elsadek et al. 2019b), promote physical activity (Bratman et al. 2019; Cohen et al. 2007) and improve mood, concentration and performance (Elsadek et al. 2019a; Kondo et al. 2018). Elsadek et al. (2019a) observed that views of green facades versus bare walls increased physiological as well as psychological relaxation by inducing feelings of comfort and cheerfulness. Presence of green can enhance social resilience by fostering neighbourhood attachment and strong sense of community (Rall et al. 2017; Kyttä et al. 2013). Thus, urban green space can contribute to density and heat-related stress relief (Kabisch et al. 2021; Kyttä et al. 2013). Knöll et al. (2018) observed that open space typologies such as parks, courtyards and squares constitute the best indicator for perceived urban stress, rather than building density alone. However, not all green spaces are perceived as meaningful and their quality is more important than quantity. Presence of nature, accessibility, resting facilities and perceived safety were identified as important criteria for parks (Kyttä et al. 2013). Carefully designed urban green spaces increase physical and mental health resources or urban dwellers against environmental stressors (Kabisch et al. 2021; Sharifi et al. 2021). Those green spaces should be accessible, available and adaptable (Boulton et al. 2018). However, few studies have established the nexus between green space qualities, human heat perception and climate-responsive urban design (Klemm 2018). Based on microclimate measurements, resident perspectives and feedback from planners, Klemm et al. (2017) developed UGI design guidelines for urban climate adaptation, encompassing three different scales (city, park, street). The design guidelines propose important design criteria such as microclimatic variability, but do not specifically address different target groups (such as older people), other forms of green structures such as green facades and green roofs, or the role of green in relation to the perception of density. Therefore, further studies are needed that explore the interrelations between urban form and subjective perception of density and heat to inform urban planning (Knöll et al. 2018; Klemm et al. 2015).

2.3.3. Barriers and drivers for implementation

Despite the importance of green infrastructure, its implementation and inclusion in urban planning processes is subject to difficulties. Gaps exist between planned and actual existing green space (Boulton et al. 2018). Several studies have analysed drivers and barriers for green space provision and identified active recreation, ecosystem services, protection of biodiversity and climate change adaptation as important drivers for green space supply (Boulton et al. 2018; Wihlborg et al. 2019). Based on the analysis of 104 studies, Boulton et al. (2018) identified seven factors shaping provision of urban green space: resources, governance tools, political leadership, governance structure, economics and markets and organisational culture. Focussing on the application of ecosystem services in urban planning, Rall et al. (2015) reported similar factors, but also highlighted the lack of specific planning measures at the local scale and lack of funding for long-term maintenance and monitoring.

In the field of climate change adaptation research, many studies have assessed barriers and opportunities for integration of climate change adaptation policies into urban planning (e.g. Olazabal et al. 2019; Uittenbroek et al. 2013; Lehmann et al. 2015). In view of more than 200 context-specific barriers (Biesbroek et al. 2013), several efforts have been made to identify categories and types of barriers (Adger et al. 2007; Lehmann et al. 2015; Moser and Ekstrom 2010; Uittenbroek et al. 2013; Wamsler et al. 2020b). Common categories of barriers are 1) resources (financial and/or human), 2) informational and cognitive barriers, 3) social and cultural barriers and 4) policy and legislation. In addition, the three levels of individual actors, the system of concern or governance process and the wider (socio-economic) context are often distinguished (Biesbroek et al. 2013; Lehmann et al. 2015; Moser and Ekstrom 2010). The first level refers to single actors, such as the mayor of a city, whereas municipalities may be the system of concern. Financial crisis or national legislation are examples for the level of the wider socio-economic context. These classifications help to better understand the types of barriers and compare multiple cases. The consideration of hierarchical levels and categories of barriers aims at a more systemic thinking in dealing with barriers, but also in the search for success strategies.

Several success factors for policy implementation have been identified in literature. One of these factors is a common understanding and broad acceptance of policy goals by internal and external stakeholders (van Gossum et al. 2011). Acceptance can be fostered by stakeholder inclusion (Lange et al. 2020) and transparency of rules as well as recurrent public dialogue (Cosens 2013; Olazabal et al. 2019). Policy credibility in turn is supported by coherent rules and procedures, dedicated and supportive actors, history of norms and public opinion and past performance (Averchenkova and Bassi 2016; Khoshkar 2020; Eisenack et al. 2014). Moreover, inter-departmental and multiscale co-ordination, assigned responsibilities and assessment of planning decision impacts are suggested to foster green space integration in planning processes (Rall et al. 2015). Education and engagement of citizens (Rall et al. 2015; Wihlborg et al. 2019), as well as support for planners to develop communication capacities that promote trust and inclusiveness are recommended (Wamsler et al. 2020b). These success factors indicate that various elements are interdependent and must interact for the successful implementation of green infrastructure (Dorst et al. 2021; Loorbach et al. 2020). Therefore, more systemic assessments are needed that consider the interactions between different planning dimensions and analyse structural conditions linked to transformation of planning processes and planning outcomes (Biesbroek et al. 2013; Dorst et al. 2022; Eisenack et al. 2014). Since structural conditions are not only a result of past developments and system manifestations (Dorst et al. 2022), but also shape future planning outcomes, research needs to identify interventions that address the planning context and do not only focus on overcoming single barriers (Biesbroek et al. 2013; Dorst et al. 2022).

2.4. Interim conclusions

The preceding chapter presented the theoretical foundation for the three main topics of this dissertation: urban heat stress, densification and urban green infrastructure planning. In this way, this thesis is connected to the research fields of climate change adaptation, urban ecology and sustainability transformation. The anthropogenic climate change intensifies urban heat loads. Excessive heat during day and nighttime constitutes a severe threat for human health, especially for vulnerable population groups and urban residents. Outdoor human thermal comfort represents a concept for assessing human thermal well-being and is influenced by objective conditions and subjective perceptions. Human thermal comfort investigations are mostly conducted at the microscale. It is the scale that is primarily influenced by urban design and at which urban residents perceive thermal conditions. Thermal perception can differ from observed thermal conditions due to psychological and behavioural factors. Near-natural and diverse environments are preferred over monotonous ones. Thus, urban design and urban planning can help to increase thermal comfort in outdoor spaces. Densification of housing within the building stock as a measure to limit urban sprawl affects urban morphology and thereby also the urban microclimate and the availability and quality of urban green space. Settlement type, access to land and ownership structures are decisive factors for the densification potential by urban planning. Basic forms of densification of the building stock constitute additional storeys, additional buildings or conversion of developed sites. Alteration of the aspect ratio of buildings and street canyons, the building orientation and the surface cover composition affect radiation flux and wind flow. Urban greenery reduces urban heat loads through shading and evapotranspiration, but also offers potential to reduce feelings of crowding in dense urban areas and can improve perceived thermal well-being. The cooling effectiveness and social benefits depend on the type of green space, its quality, arrangement and spatial distribution. Urban green infrastructure as planning concept acknowledges the benefits of urban green space and strives for an uptake in urban development processes. This concept and its planning principles are a key component for developing climate-resilient neighbourhoods in densifying urban areas. However, implementation in urban planning faces several difficulties that require system-based assessments for developing policy recommendations.

Several knowledge gaps regarding strategic use of UGI and its implementation in urban planning procedures remain: Thus, there is a lack of studies that consider the relationship between urban infill and the qualities of existing green spaces. Moreover, studies that consider both local and microscale for joint investigation of thermal comfort and ventilation are largely missing. The relationships between objective conditions and subjective perceptions of heat with different types of urban form, density and greening needs further inquiry to inform urban planners. Finally, there is a lack of strategic guidance for developing UGI in densifying cities in face of land use conflicts and climate change.

3. Material and methods

3.1. Overall research approach

The overall research approach of this thesis draws on a combination of microclimatological modelling, assessment of social perspectives and policy approaches to address the complexity of urban planning (Figure 5). Urban planning processes require the consideration of multiple criteria and the balancing of competing demands on space. To advocate for green space preservation and integration into growing cities, evidenced based information on ecosystem services of UGI is necessary, especially in view of high housing demand and economic interests. At the same time, urban planning needs to consider the perspectives and needs of local residents, especially since densification constitutes a sensitive topic and subjective perception might differ from objective evaluation. Finally, structural conditions - such as planning procedures and involved actors - decide if this knowledge is implemented into urban planning practice or whether it is not taken into account.

To build evidence on the interrelations between densification, outdoor thermal comfort and UGI as stated in objectives 1-3, microclimate modelling was combined with scenario development (studies I and II) and social surveys (study III). To analyse the trade-offs between densification, UGI and thermal comfort, the first study conceived densification scenarios for a residential development with row buildings and assessed their impact on thermal comfort by microclimate modelling on block scale. In study II these scenarios were further developed to investigate the potential of UGI to compensate for negative consequences of densification on thermal comfort and ventilation. For this purpose, the urban climate assessments also considered the neighbourhood scale. This scale was central to study III, where objective conditions were compared to subjective perceptions of density and heat to defer context-specific and user-centred design guidelines for urban green infrastructure. For exploring the integration of UGI into urban planning processes in densifying cities (objective 4), study IV drew on the analytical concept of the policy arrangement approach (PAA) (Arts and van Tatenhove 2004) to analyse the respective structural conditions in four case studies using expert interviews and document analysis. The following sections introduce the study areas and the applied research methods. For further details, the reader is referred to the related publications.

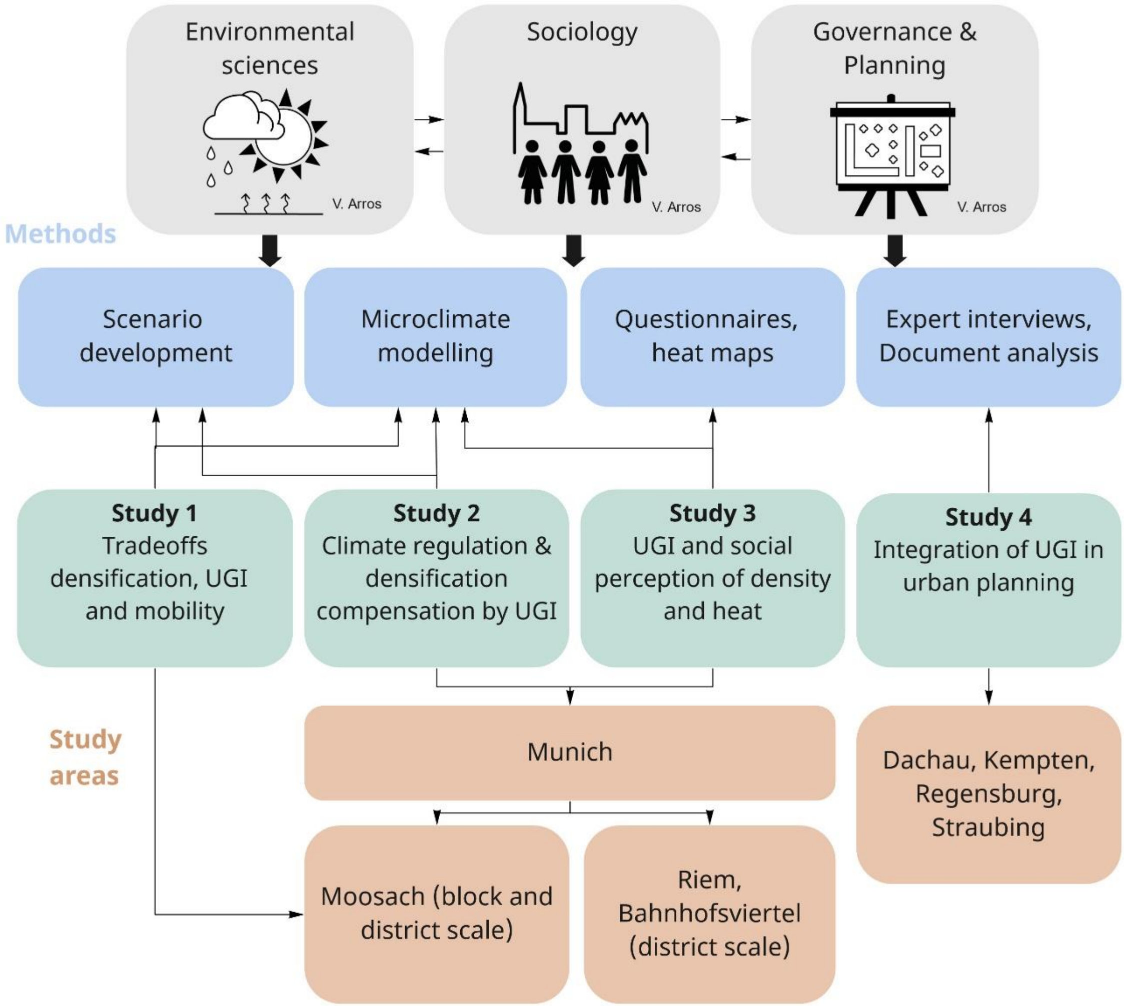

Figure 5: Overview of the applied research approach displaying the mixed methods drawing from a combination of environmental sciences, sociology and governance, the study objectives and the respective study areas.

3.2. Study area description and selection

This section provides an overview of the study areas, which are all located in Germany. Germany was of particular interest for this study, since the country faces the challenges of dealing with climate change (Bundesregierung 2020) and the need to reduce land consumption (Bundesregierung 2016). While Germany has adopted a strategy for climate change adaptation (Bundesregierung 2008), with regular monitoring reports and action plans (Bundesregierung 2020), dual inner development was proposed as a guiding principle to utilise land reserves and further develop urban green space, later established in the Master Plan Urban Nature (Bundesregierung 2019). In this thesis, the spatial scale varied from block to neighbourhood to city scale depending on the underlying research questions (Figure 6). To analyse human thermal comfort and ventilation as well as to compare objective condition and subjective perception, three different neighbourhoods in Munich constituted the places for block and district scale investigations. The analysis of UGI integration into urban planning processes and their underlying structural conditions required a city scale scope. For this purpose, the Bavarian municipalities Dachau, Kempten, Regensburg and Straubing were selected as different representatives for growing municipalities. Short descriptions of the study areas and reasons for their selection are provided in the following sections.

3.2.1. Munich

As Munich, located in the south of Germany (elevation 519 m a.s.l.), is one of Germany's fastest growing and most densely populated cities (LHM 2018a), it is a suitable test site to investigate urban planning conflicts and potentials related to densification. Housing demand in Munich is high: according to an estimate, there is an annual requirement for the building of 8,500 flats per year (LHM 2011). Densification of the stock is one of Munich's central urban development strategies. At the same time, the city has adopted several programmes for green space enhancement and climate change adaptation (LHM 2016, 2018b). Three Munich neighbourhoods representing case studies in the research project "Green City of the Future" were selected for this research: Moosach, Messestadt Riem and Bahnhofsviertel.

Moosach

In Moosach, a city district located in the north-west of Munich, an urban planning competition for a regeneration area provided the possibility to inform this procedural step by microclimatic investigations. The case shows several characteristics that can also be found in other German cities: Thus, the regeneration area is characterised by linear free standing multi-storey blocks from the 1940s and 1950s, a frequent settlement type in Germany (ZSK 2017). The housing development is in need of regeneration to address social challenges, improve energy efficiency of the building stock and improve handling of stationary traffic. Short connections to the public transport system and uniform ownership structures result in a high densification potential (LHM 2018a). Munich's urban climate map depicts the bioclimatic situation of the investigation area as less favourable (LHM 2014). Therefore, in this area, considerations of changes in the ventilation situation were particularly relevant. According to the LCZ approach, the case area represents an open midrise development (Stewart and Oke 2012). The microclimate modelling assessments concentrated on a representative part of this designated area to analyse different densification scenarios and assess the regulatory potential of UGI (Figure 6).

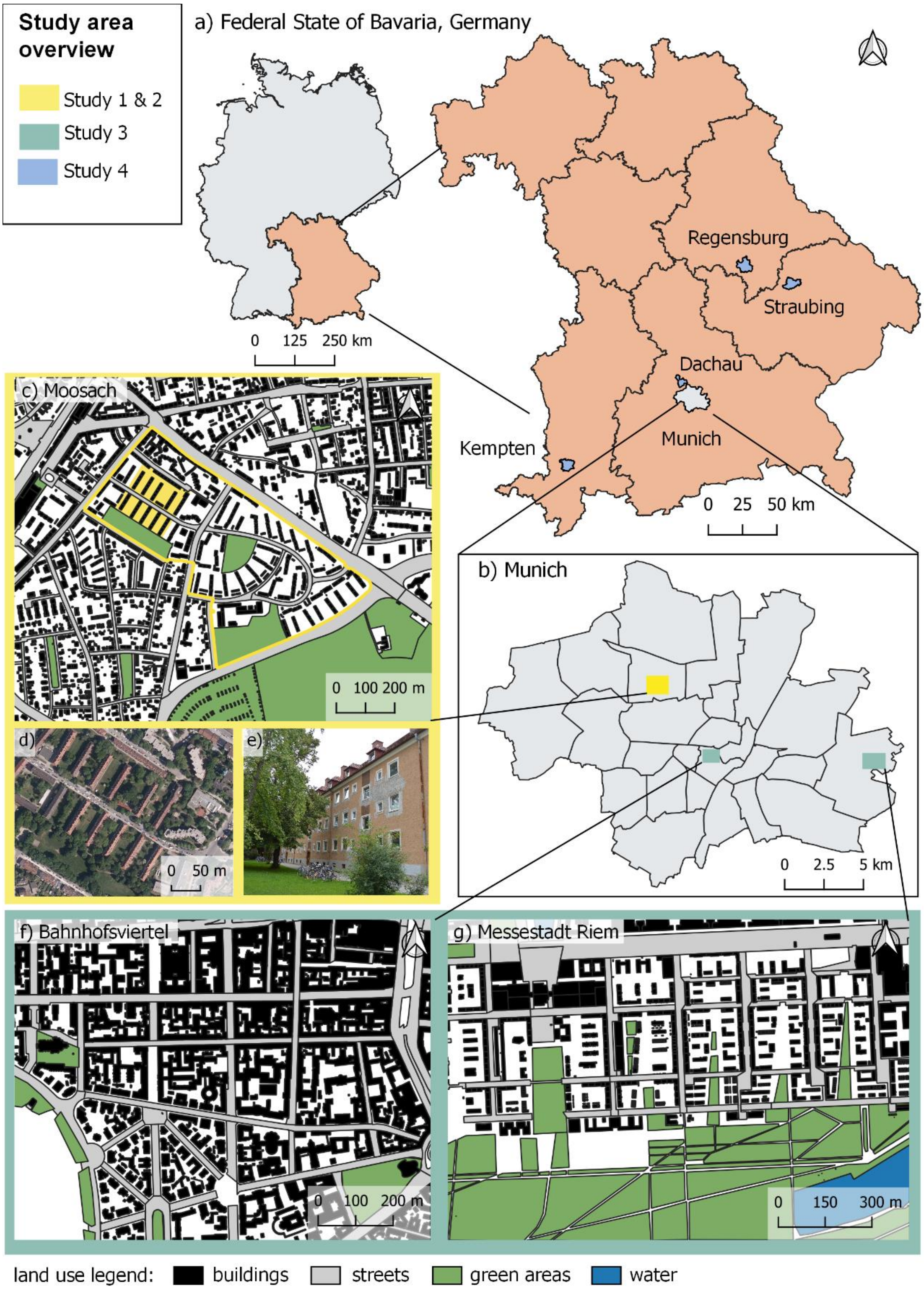

Figure 6: Overview of the study sites and their geographical location: a) Location of the Federal State of Bavaria in Germany and studied municipalities in Bavaria. b) Overview of the investigated study sites in Munich. c) Moosach neighbourhood with urban planning competition area and ENVI-met modelling site. d) Aerial image of the ENVI-met modelling site. e) Impression from the Moosach redevelopment area and overviews of Bahnhofsviertel (f) and Messestadt Riem (g). The map frame colours indicate the affiliation to the respective study.

Bahnhofviertel & Messestadt Riem

Bahnhofsviertel and Messestadt Riem represent two contrasting neighbourhoods in Munich and were therefore interesting for the comparison of objective conditions and subjective perception, as different urban characteristics could be investigated. The Bahnhofsviertel, located directly south of the Munich central station is densely built and sparsely vegetated. It is a transportation hub and home to many small international shops, services, hotels, offices and several university and medical facilities. Messestadt Riem, at the eastern outskirts of Munich, has a medium density and an ample green infrastructure supply. The neighbourhood originally has been designed as a model sustainable residential area with reduced traffic loads, consideration of fresh air corridors and a large park. Both neighbourhoods are under pressure to change due to climate change and densification and have thus been selected as case studies in the project “Green City of the Future”.

3.2.2. Dachau, Kempten, Regensburg, Straubing

Dachau, Kempten, Regensburg and Straubing represent four growing Bavarian municipalities where densification has gained increasing importance over the past years. The cities were selected as case studies for analysis on the current state of integration of UGI into urban planning and the factors underlying it. The selection was preceded by an online survey asking for the significance of densification and climate change adaptation for the respective urban planning departments and their willingness to participate in interviews. All four municipalities have experienced considerable population growth in the past and look forward to further growth (LfStat 2020). The cities differ in their number of inhabitants (Dachau: 47,721, Straubing: 47,791, Kempten: 68,975, Regensburg: 153,094;(LfStat 2021), their spatial location and their progress in the field of climate resilient urban development.

3.3. Development of planning scenarios

For the microclimatic investigations in Moosach, different urban development scenarios were conceived. The development scenarios should, on the one hand, represent a spectrum of densification options and, on the other hand, be practically relevant and interesting for planners. For this reason, all local plans related to residential development in Munich that have come into force in recent years (1 January 2014 – 28 March 2021) were analysed to derive current practice in statutory planning regarding building regulations and green space. Additionally, several workshops were held with city planners from

Munich who had been involved in the redevelopment of the Moosach area to develop plausible scenarios.

The urban planning scenarios were developed in two phases: Phase I focussed on the effects of densification on green space supply and on the microclimate (densification scenarios). The nine densification scenarios differed in terms of 1) type of densification, 2) building height and 3) number of underground car parks. Densification can be achieved by adding one or two floors to the existing building and/or by inserting additional buildings. Adding one or two floors would increase building height from current 12 m to 15 m or 18 m, respectively. It would lead to an increase from current 376 flats in the ENVI-met study area to 427 flats (+14 %) and 512 flats (+36 %) respectively (Table 1). Inserting four floor high buildings as shown in figure 7 would add 176 flats (+47 %) to the study area. Combining the two types of densification would increase the number of flats by 76 %. The number of underground car parks was identified as an essential factor as the construction of underground car parks causes the removal of existing trees from the designated areas. Their number is influenced by the amount of new housing units and parking space policies. As a consequence, the amount of trees in the study varied between 100 %, 65-55 % and 0 %.

Table 1: Overview of the basic parameters of the densification scenarios (ENVI-met study area). Naming of the scenarios: O = densification type additional floors, C = additional buildings; 15/18 = 15/18 m height, a/b/c= one/four/eight underground car parks.

Scenario	Built surface	Floor area ratio	Building height	Number of trees	Number of flats*	Underground parking
Status Quo	24.1 %	0.8	13 m**	158	376	1
O15a	24.1 %	1.3	15 m	158	427	1
O15b	24.1 %	1.3	15 m	102	427	4
O15c	24.1 %	1.3	15 m	0	427	8
C15b	31.1 %	1.7	15 m	84	552	4
C15c	31.1 %	1.7	15 m	0	552	8
O18b	24.1 %	1.6	18 m	102	512	4
O18c	24.1 %	1.6	18 m	0	512	8
C18c	31.1 %	2.5	18 m	0	663	8

Notes: * = Calculation of flats: Current status 46,5 m² per flat, after redevelopment 67,5 m² per flat; ** = Saddle roof

In phase II (study II), focus was set on the capacity of UGI to mitigate negative effects of densification on outdoor thermal comfort and ventilation (greening scenarios). Two levels of green intervention strategies – realistic and optimistic – were analysed for two densification scenarios. The densification scenario with open rows and two additional storeys

(O18) and the scenario with one additional storey and additional buildings (C15) and four underground car parks (b) were selected for comparison as the number of new flats is comparable (Table 1). The realistic green intervention level depicted Munich's current green space regulations and greening practice: 75 % tree replacement of removed trees and implementation of green roofs with 20 cm substrate thickness. The optimistic level represented a more progressive alternative with 100 % tree replacement, a green roof substrate depth of 40 cm, green facades on south-east to west facing walls and additional space for trees along the main avenue. Additionally, for the replaced trees, two different tree ages were distinguished to assess their respective cooling performance: one with small newly planted trees (0-5 years) and one with more mature trees (40-50 years after plantation) (Figure 7). For further details on the scenario development and parameter specifications, see Paper I and II (Erlwein and Pauleit 2021; Erlwein et al. 2021).

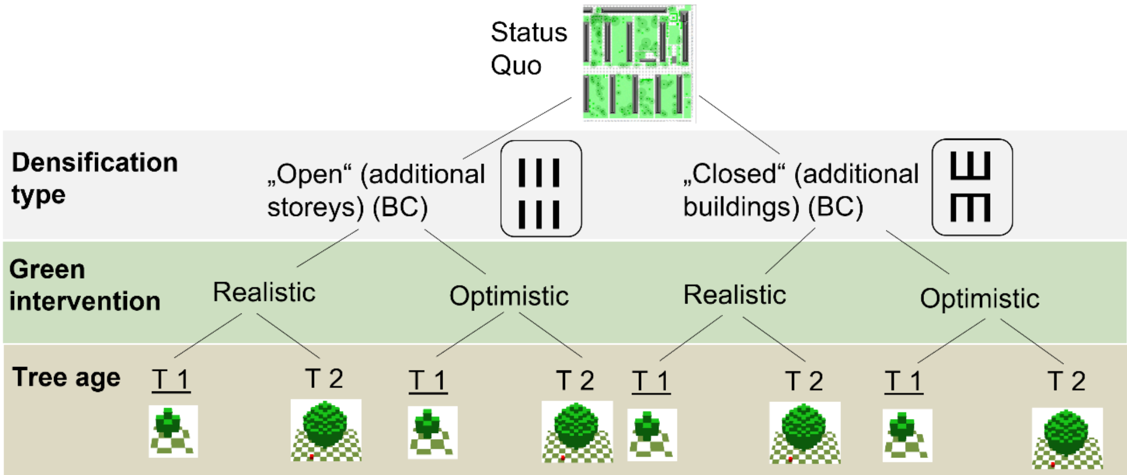

Figure 7: Schematic visualisation of the different greening scenarios. T1 = trees 0-5 years after plantation, T2 = trees 40-50 years after plantation.

3.4. Modelling approaches

For assessment of the microclimate and different planning interventions, numerical modelling was employed since it allows cost and time efficient comparison of different planning and design scenarios. Whereas models are not able to fully represent the complexity of urban environments, they provide means to experiment with and compare specific parameters in quasi-controlled conditions (Oke et al. 2017). If validated and tested, they represent an important urban planning tool. The microclimate assessment was performed with different simulation models, depending on objective and scope of the analysis. This section shortly introduces the simulation models and presents the boundary conditions of the simulations, the approach to analysis of results and the simulation validation.

3.4.1. Selection of modelling days

While the number and intensity of heatwaves is likely to increase due to climate change (Ward Thompson et al. 2016), heat has several negative consequences for human health (see chapter 2.2.2), making it a particular concern for climate-sensitive urban planning. According to the German Meteorological Service (DWD), a typical hot day is characterised by daytime T_a exceeding 30 °C and nightly T_a not falling below 20 °C, clear skies and low wind speed (< 2 m/s) (Mühlbacher et al. 2020). To characterise the microclimatic conditions and urban heat stress in the study area during a typical hot day, we analysed the meteorological data from the two available official weather stations in Munich. Both provided data input for the simulations, depending on their proximity to the study areas: the weather station of the DWD Munich, located 2.6 km south-east from the redevelopment area in Moosach and the station of the Meteorological Institute Munich, located in the city centre in distance of 1.7 km to Bahnhofsviertel and 8.7 km to Messestadt. For the ENVI-met simulations in Moosach, 5 July 2015 was chosen, whereas it was 25 July 2019 for Bahnhofsviertel and Messestadt Riem to cover the same month and year as the social surveys. A statistical analysis of the most common wind direction for each hour in summer (years 1985-2018) was performed to replace measured with statistical wind directions and to stabilize the ENVI-met model runs.

3.4.2. Selection of models and model setup

Three different numerical models were employed for the microclimatic investigations to allow for the analysis of different scales and scopes: ENVI-met, FITNAH and SOLWEIG (Table 2). Whereas ENVI-met represents a sophisticated model for biometeorological investigations on block scale, the model architecture of the SOLWEIG model enables calculations of outdoor thermal comfort at district scale in significantly reduced computation times. The FITNAH model was designed for simulation of wind fields at district and large scales and therefore selected for the ventilation analysis within the project "Green City of the Future" by the project partners. All models belong to the group of computational fluid dynamic models (CFD) and require topographical and meteorological input data in varying detail.

The ENVI-met model was designed for investigation of plant-surface-atmosphere interactions at the microscale and is able to calculate physical parameters like T_a, T_{mrt} and wind flow as well as several thermal comfort indices such as PET, UTCI and PMV (Bruse and Fleer 1998; Simon 2016). It represents one of the most widely used simulation tools for micrometeorological investigations (Tsoka et al. 2018).The three dimensional model considers detailed representation of vegetation and building structures, physiological vegetation processes and operates with a typical resolution of 0.5-10 m in space and up to 2 s in time. Its model performance has been validated in several studies in different climatic contexts with satisfying results (e.g. Jänicke et al. 2015; Lee and Mayer 2016; Morakinyo et al. 2018; Acero and Arrizabalaga 2018). Detailed description of the basic assumptions and physical equations of the model can be found in literature (Bruse and Fleer 1998; Simon 2016). Important improvements for version 4 included parallel computing on several CPU cores (improving computation times), full forcing options of several meteorological parameters and implementation of green roof and green facade modules.

For the block scale analysis in Moosach, ENVI-met version 4.4.3 and 4.4.5 was used with full forcing mode. Land cover, building heights and dimensions were derived from raster data provided by the Bavarian State Office for Survey and Geoinformation. Trees were configured based on recent tree inspection data provided by the City of Munich and on- the-spot visits for missing trees. For sake of simplification, trees were grouped into five tree categories after crown shape and tree height (see paper I, Erlwein and Pauleit 2021). Simulations were launched at 6 am and ran for 48 (survey 1) and 36 hours (survey 2) to overcome initial transient conditions and exclude these (24 hours in the first study and 12 hours in the second study based on further model development and testing) from the analysis. PET results were analysed for daytime and nighttime at a pedestrian level of 1.4 m, which is approximating the human-biometeorological reference height (Mayer and Höppe 1987).

FITNAH 3D (Flow over Irregular Terrain with Natural and Anthropogenic Heat sources) was developed for simulation of wind fields and cold air flow in different landscape settings (Gerhards et al. 2013). The three dimensional, non-hydrostatic model is a well-established tool for urban climate and wind field simulation studies and covers city to district scales (resolution from 50 m to 5 m) (Geo-Net 2021). It was thus selected for the district scale analysis in Moosach. For comparison with the block scale results, the FITNAH 3D simulations used the same meteorological parameters and the same urban planning scenarios as the ENVI-met simulations. A digital surface model (DSM) and building models provided the necessary spatial input for the model set-up; vegetation coverage and characteristics were derived from aerial images. Two parameters were analysed with the FITNAH model: cold air volume flow (CAVF) and PET for comparison with the block scale results. The CAVF density (in m^3/m) describes the amount of cold air that flows with a certain speed though a certain volume of air (VDI 2008a). The CAVF density is decisive for nocturnal thermal comfort as it represents the local ventilation and cooling potential of built-up areas. Since no threshold values for evaluating the CAVF exist, CAVF results were classified following the procedure of the guideline VDI 3787 sheet 1 (VDI 2008b). The FITNAH 3D modelling was conducted by Geo-Net in collaboration with the City of Munich. Maps of the modelling results were provided for interpretation of the results and comparison of the models.

The SOLWEIG (solar and longwave environmental irradiance geometry) model calculates solar fluxes and shadow patterns in complex urban environments (Lindberg et al. 2008). It is part of the Urban Multi-scale Environmental Predictor (UMEP) tool, which was designed as a Plug-In for the free geoinformation software Q-GIS (Lindberg et al. 2018). 2018). Functions and basics of the model are described in Lindberg et al. (2008) and Lindberg and Grimmond (2011). The model has been evaluated and successfully applied in different geographical settings for T_{mrt} estimations (Lindberg and Grimmond 2011; Thom et al. 2016; Lau et al. 2015). Comparative studies have shown that SOLWEIG predicted T_{mrt} more precisely than ENVI-met (Chen et al. 2014; Jänicke et al. 2015). Compared to ENVI-met, SOLWEIG only requires a limited number of inputs and has a relatively low computational time, which allows to consider larger study areas. However, the model does not offer a detailed representation of vegetation, buildings or ground materials or calculation of another thermal comfort index than T_{mrt}. Nevertheless, on a cloudless, summer day, such as the one selected for the investigation, T_{mrt} is the dominating factor for outdoor thermal comfort (Lee and Mayer 2018). Moreover, a land cover and a vegetation scheme can be employed in SOLWEIG to specify certain related model configurations, such as the leaf area index for trees. Due to the low data requirements, the study area size and the research focus on thermal comfort evaluation on hot days, SOLWEIG was selected as the simulation model for the assessments in Riem and Bahnhofsviertel.

Table 2: Selected model configurations for ENVI-met, FITNAH 3D and SOLWEIG used in the urban climate assessments.

	ENVI-met	**FITNAH 3D**	**SOLWEIG**
Version	4.4.3, 4.4.5	v2020	v2019a
Parameters	T_a, T_{mrt}, PET	Cold air volume flow	T_{mrt}
Resolution	2 x 2 m	5 x 5 m	2 x 2 m
Study area	Moosach (block scale)	Moosach (neighbourhood scale)	Bahnhofsviertel, Riem
Area size	180 x 190 m	3250 x 3100 m	1225 x 880 m, 2160 x 1100 m
Simulation days	04 - 05 July 2015	04 - 05 July 2015	25 July 2019

3.4.3. Validation

Evaluation of the model performance is a necessary step for gaining confidence in numerical modelling results (Bennett et al. 2013). To validate the ENVI-met model results and select the best model configuration, a measuring campaign was conducted from 27 July to 28 July 2020 in the redevelopment area Moosach. The self-built weather station was equipped with HOBO and ecomatik sensors (10 s sampling and 5 min logging interval). The coefficient of determination [R^2] and root mean square error [RMSE] were calculated for T_a, Rh and surface temperature to compare measured and modelled data in the frame of several sensitivity tests. Sensitivity tests included modification of soil temperature and soil humidity in the model setup and alteration of the model dimensions. The validation results revealed an overestimation of nocturnal T_a by 0.6 - 2.5 °C by ENVI-met (Figure 8). The best model fit was yielded both with enlarged model dimensions and modified soil temperature. With regard to computation times, the model settings with modified soil temperature were chosen for the scenario simulation runs. The validation results for this setting (R^2 0.99 for Ta, 0.96 for RH) are within the range of other ENVI-met validation studies (Müller et al. 2014; Morakinyo et al. 2018; Zhao et al. 2018). For a more detailed description of the validation procedure and results see Paper II, p. 6.

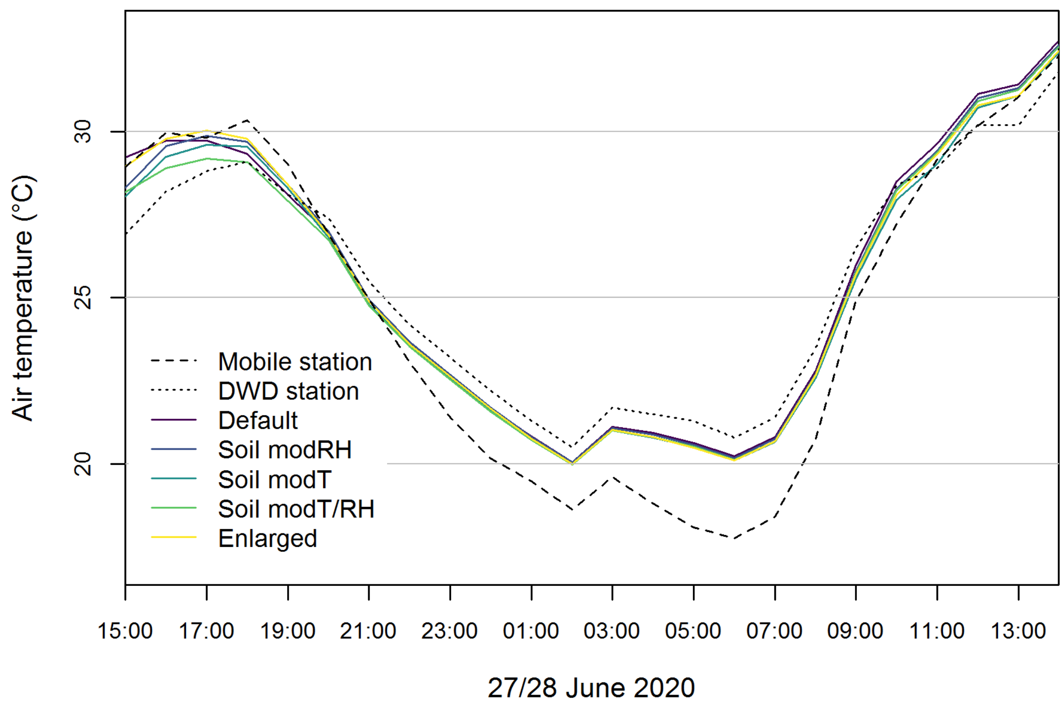

Figure 8: Comparison of modelled and measured T_a over 24 h. Sensitivity tests included alteration of the given soil conditions (soil mod) or the model input area (enlarged). Default refers to the ENVI-met default soil condition settings.

3.5. Assessment of subjective and objective thermal comfort and density

To analyse the relationship between objective assessment and subjective perception of green spaces, thermal comfort and density, a mixed method approach was employed. The approach combined quantitative analysis (microclimate modelling and geostatistical analysis) with questionnaires and semi-standardised interviews. The geostatistical analysis was based on vector and raster data to assess several urban density parameters (e.g. floor area ratio, building coverage, population density) and urban vegetation parameters (e.g. public green spaces). The objective thermal comfort was investigated using the SOLWEIG model (for more information see section 3.4.2).

Face-to-face questionnaires were conducted in both neighbourhoods with pedestrians on warm (>25 °C T_a), sunny days in July 2019 to assess thermal comfort perceptions. Participants were asked to describe their neighbourhood based on polarity profiles, e.g. green vs. grey, unsafe vs. safe. Volunteers were recruited for in-depth interviews. The interviews followed a semi-standardised interview guide to identify attractive and unattractive areas in the neighbourhood. Additionally, interviewees were asked to mark thermally pleasant and unpleasant places on a map. These mental maps were used to create heat maps displaying the subjective heat perception, which were then compared with the objective heat assessment. In contrast to questionnaires and parallel mobile measurements, which aim to determine the present sensation, this approach was directed towards the long-term and holistic thermal perception. The approach for the social surveys was developed and executed by J. Mittermüller, A. Bauer and S. Duschinger, fellow scientists in the “Green City for the Future” project. For more details on the methodological approach see Paper III (Mittermüller et al. 2021).

3.6. Analysis of UGI integration into urban development

In order to analyse the integration of UGI into urban development in densifying cities and assess underlying structural conditions, a case study approach (Yin 2014) was employed. Data collection involved policy document and semi-standardised interviews in four Bavarian municipalities. As the policy arrangement approach (PAA) (Arts et al. 2006) is capable to analyse interrelations between several dimension relevant for policy making, it served as the base for the analytical framework.

3.6.1. Analytical framework policy analysis

Rooted in environmental policy (Arts and van Tatenhove 2004), the PAA constitutes an established approach to analyse environmental policy changes (Mattijssen et al. 2017; Contesse et al. 2018). Four dimensions and their interrelations play a central role (Arts et al. 2006): actor, rules of the game, power and resources and discourses. Actors form coalitions to strengthen their influence and modify the rules of the game that encompass all formal and informal regulations and procedures shaping the power-relationships between actors. Power and resources describe the distribution of resources among actors and their ability to mobilise them (van Gossum et al. 2011). Discourse relates to the narratives, personal world views, but also common understandings of actors and organisations (Arts et al. 2006). Discourses influence the distribution of resources and power, the establishment of rules and the behaviour of actors (van Gossum et al. 2011). All four analytical dimensions are tightly interwoven, with changes in one dimension likely to affect other dimensions as well (Arts et al. 2006). The PAA is flexible in scope and able to capture development changes (Arts and van Tatenhove 2004). Such, the PAA is a powerful framework to gain a better understanding of complex policy arrangements and policy approaches. To adapt the PAA to the study focus, relevant criteria from literature related to barriers and challenges for climate adaptation mainstreaming and governance processes were defined for the policy dimensions to enrich and detail their description for analysis (Figure 9).

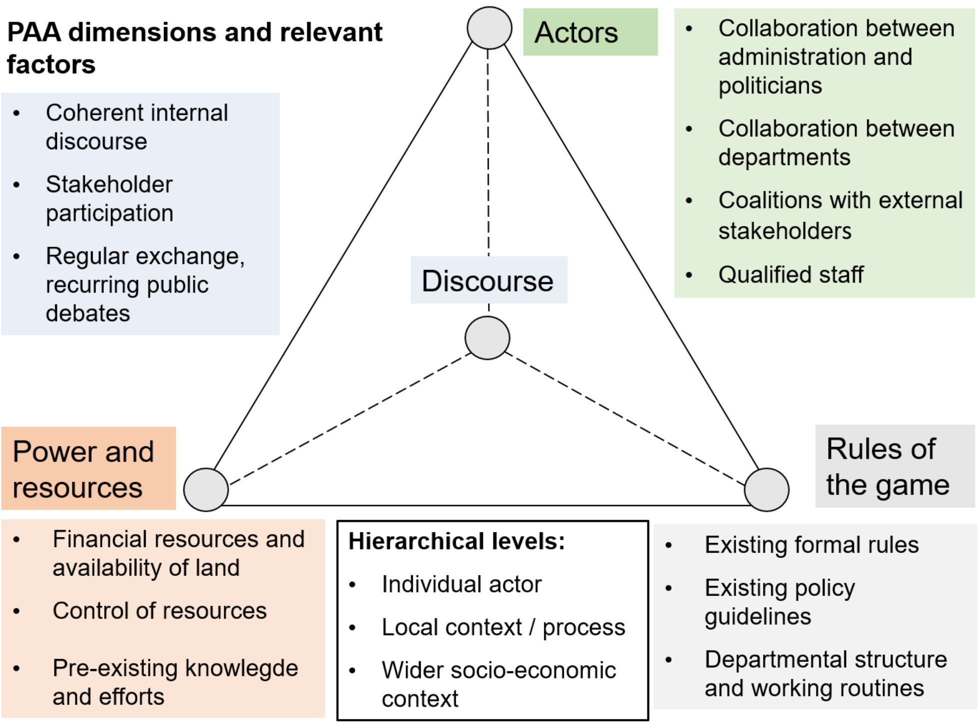

Figure 9: The four dimensions of the policy arrangement approach with defined specifications.

3.6.2. Data collection

Policy documents, reports and regulations related to the topics of climate change adaptation, urban development or urban green space were collected from the municipal websites of the four case study cities Dachau, Kempten, Regensburg and Straubing (see Chapter 3.2.2). The materials provided context for the interviews and information on prevalent discourses and the amount and detail of requirements. In order to be able to assess the importance for the city, the interviewees were asked to identify the most important documents relevant to their work. The named documents were included in the analysis if they were not already part of the collection, resulting in a total of 17 documents.

For insights into municipal planning procedures and into non-published strategies for dealing with densification and urban greening, nine semi-standardised interviews were conducted with leading personnel from the city and green planning departments. These departments were selected as they are responsible for urban and green space planning, implementation of policy guidelines and are familiar with the challenges associated in planning processes. In Regensburg, a political actor was interviewed in addition since environmental concerns and urban greenery are directly related to his office, a constellation that did not exist for the other cities. Respondents were initially recruited via an online survey and contacted via email if they signalled interest for an in-depth interview. The interviews lasted between 30 and 70 minutes and were conducted remotely between June 2020 and June 2021 (for further details see Study IV). The interviews covered municipal approaches for densification and climate change adaptation as well as green space enhancement and preservation, roles and resources of actors involved in densification processes, conflicts and best-practice solutions.

3.6.3. Data analysis

All interviews were recorded, transcribed and analysed using qualitative data analysis software. Development of coding categories was based on the analytical framework and followed an inductive approach (Brymann 2008). At first, information on the four PAA dimensions was collected from documents and interview transcripts, such as types of involved actors, but also reported challenges, benefits and changes over time. From this collection, sub-categories were developed to further distinguish and detail the coding categories. To discover key issues and themes as well as within case study interdependencies between the different policy dimensions (Creswell and Poth 2018), case studies reports were written for each city. Finally, cross case study themes were identified and related to the theoretical framework.

4. Synthesis of Results

The following chapter summarises the main findings of the original research articles I to IV. Sections 1 and 2 report the results of the microclimate assessments on block and district scale and the climate adaptation potential of urban green infrastructure. Section 3 compares the objective assessment and the subjective perception of heat and density by residents. Section 4 describes the findings from the analysis of the municipal policy arrangements regarding UGI and urban planning.

4.1. Trade-offs between urban green space, thermal comfort and densification

The comparison of nine densification scenarios for an urban redevelopment site showed that preservation of the existing vegetation represents the most important factor for diurnal human thermal comfort. On a hot summer day, nearly 100 % of the study area show PET values of strong heat stress, the PET mean value for the existing scenario over the hottest hours (10 am – 4 pm) equals 44.3°C. However, all treeless scenarios were considerably hotter (+ 4.9 – 5.4 °C PET) than scenarios with a remaining proportion of trees regardless of the densification type and building height (Figure 10). This increase in PET raises the perceived heat stress from severe to extreme. The more trees are removed, the higher the median PET because of the reduced shading and evaporative cooling potential. Early consideration of existing vegetation plays an important role for tree conservation as the microclimatic simulations for different densification type's show. Where construction of underground car parks was limited to 50 % of the total area of open spaces and yards with fewer or smaller trees were selected for that purpose, the PET increase through densification could be limited to +1.3 °C for the considered daytime period with the highest heat load (10 am to 4 pm).

Building heights had only a marginal impact on daytime PET, whereas the closure of building rows has two opposing effects: On the one hand, additional shade is created by the new buildings, on the other hand, wind speed is reduced in the enclosed yards leading to heat accumulation in unshaded areas.

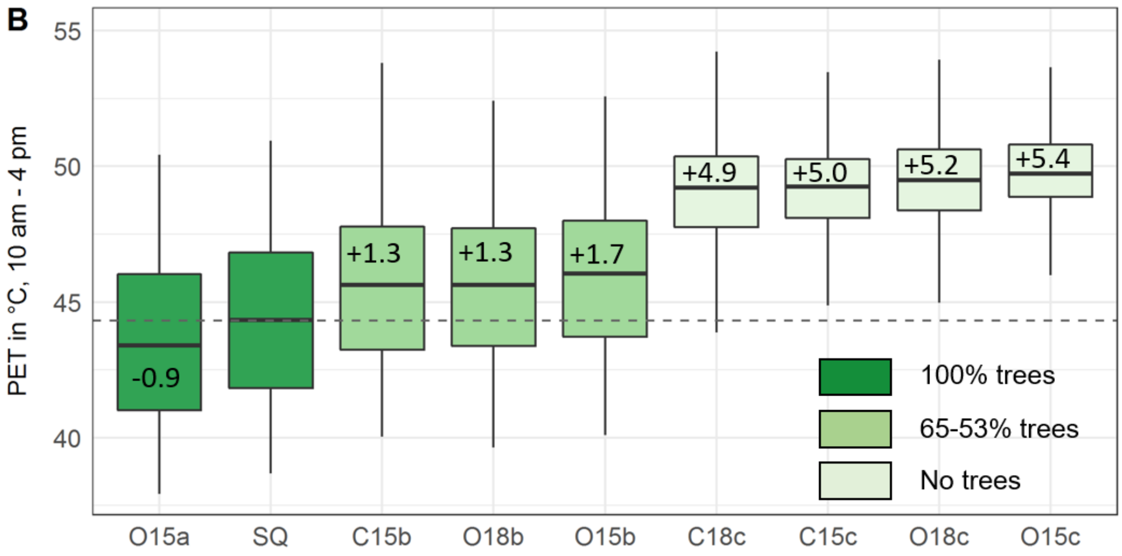

Figure 10: Boxplots of the PET values for all densification scenarios on 5 July 2015 for the daytime period with the highest heat loads (10 am - 4 pm). The colours refer to the number of trees in the respective scenario. The dashed line marks the median PET value of base case (= SQ) (44.3 °C); the numbers in the boxes indicate the respective deviation from the base case median. O = open configuration, C = closed configuration, 15 = 15 m building height, 18 = 18 m building height. a/b/c = one/four/eight underground car parks.

Most of the densification scenarios have higher PET values during daytime and lower values during nighttime. Tree canopies trap radiant heat at night, whereas open spaces with high sky view factors cool down faster during nighttime. This underlines the important of strategic tree placement that shades the hottest places during the day, but allows for penetration of cool winds and heat dissipation during the night.

4.2. Regulating the microclimate with urban green in densifying cities

The analysis of different greening scenarios for the two densification types "additional buildings" and "additional storeys" indicates that strategic planning and planting of urban green can compensate for detrimental effects of densification on the local microclimate in terms of daytime thermal comfort. However, the best results for human thermal comfort are only achieved with mature trees. Mature trees (50 years) reduce heat loads below the conditions in the original setting for both densification types (Figure 11). Newly planted trees (5 years old) improve daytime thermal comfort only slightly compared to scenarios with no tree replacement (-0.1 to -2.1 °C PET), where heat loads are generally higher than in the original setting.

Green roofs and green facades did not reduce PET values on the relevant reference height for the human body (1.4 m height) for the modelled heat day. In the proximity of the greened building facades, a small T_a reduction of 0.4 °C was observed. However, surface temperatures of walls and roofs are lowered by 22 °C by green roofs (substrate thickness 40 cm) and by 16 °C by green facades, thus decreasing heat loads of buildings which affect indoor thermal comfort and cooling demand.

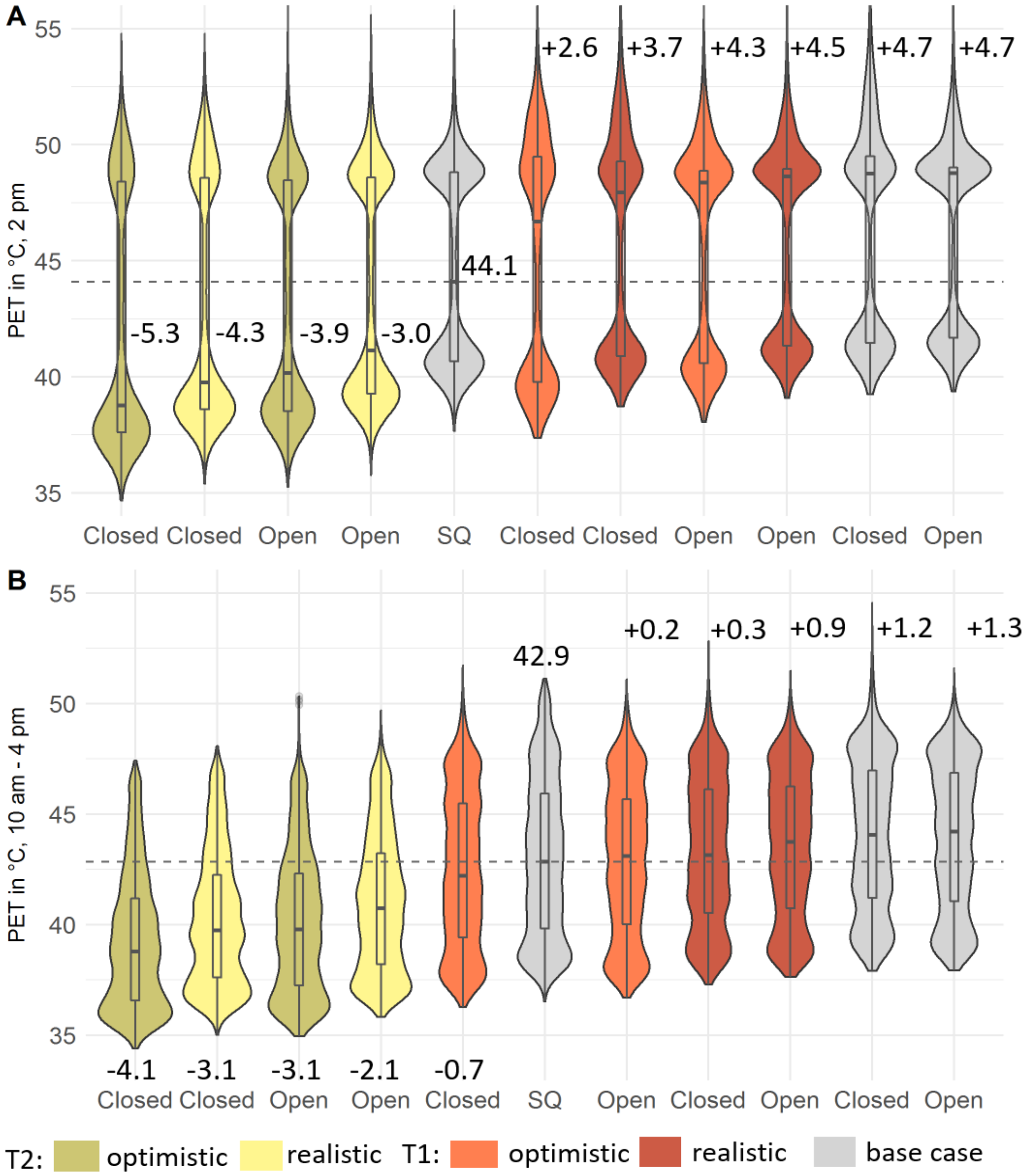

Figure 11: ENVI-met modelling results for all greening scenarios for 5 July 2015, depicted as violin charts with inserted boxplots. The dashed line marks the median of the status quo (SQ), the colours refer to green planning scenarios and the tree age. The shape's width reflects the value's frequency. T 1 = newly planted trees, T 2 = mature trees. A: 2 pm, B: 10 am to 4 pm.

The comparison of daytime thermal comfort on block scale (ENVI-met) and district scale (FITNAH) reveals the same general pattern of cooler and hotter places. The cooling effect of trees (10 to 12 °C) is in the same order of magnitude for both models, yet the absolute PET values differ, due to the different modelling approaches on which the tools are based. In general, the differences between the district scale scenarios in FITNAH are smaller than between the ENVI-met block scale scenarios, mostly owing to the bigger area covered and the diversity of built-up as well as green spaces and roads within the larger area. In addition, the ENVI-met model is able to depict cooling and warming effects at a higher resolution than the FITNAH model (5 x 5 m to 2 x 2 m), thus covering single effects that are not depicted in the FITNAH model.

UGI does not compensate for negative effects of building densification on CAVF. The insertion of new buildings leads to high reductions of ground-level wind speed and ventilation, as well as reductions of the CAVF up to 25 % (Figure 12).

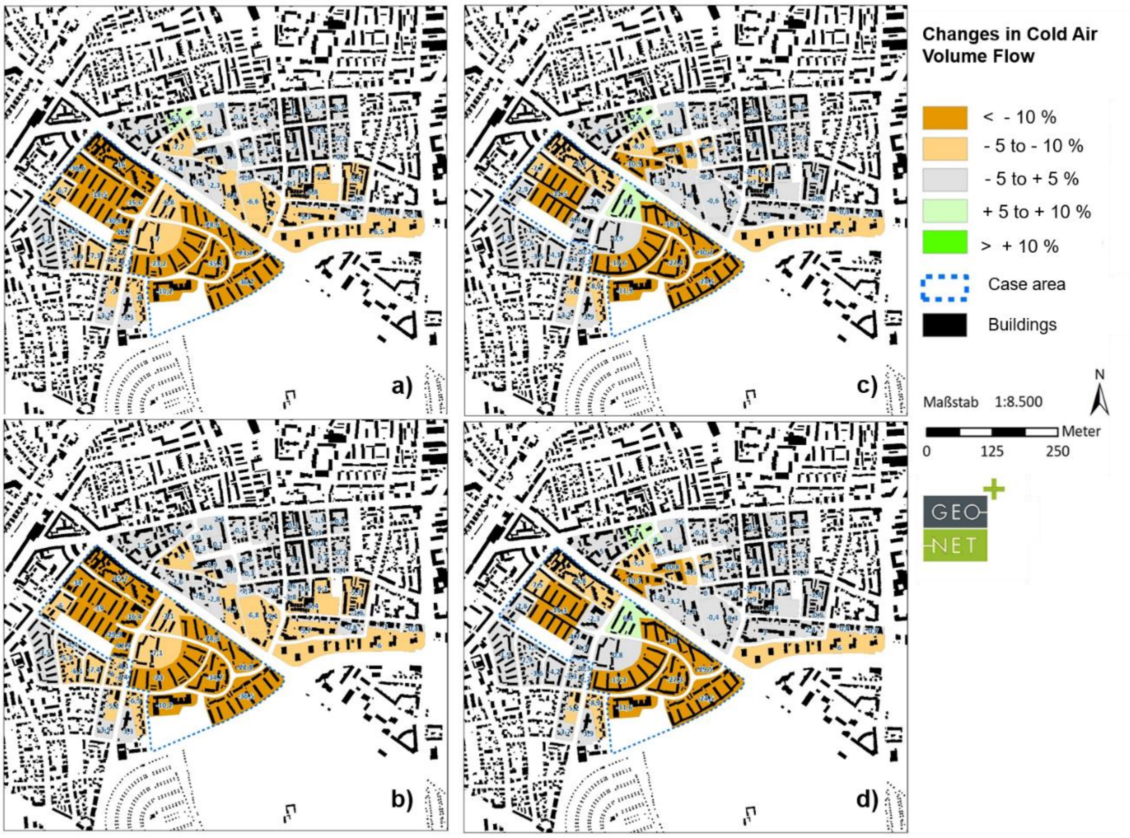

Figure 12. FITNAH differences in CAVF compared to the status quo for the densification scenario „additional storeys", realistic (a) and optimistic greening (b) and scenario "additional buildings", realistic (c) and optimistic greening (d).

By increasing the building height of existing buildings up to 18 m, the impacts on the CAVF are considerably higher. The CAVF is reduced up to 37 % compared to the status quo, with detrimental impact on nocturnal cooling. Values of more than 10 % reduction are considered as serious effects caused through densification (VDI 2008b). Tree plantings constitute potential flow obstacles, especially with low wind speed. When important ventilation corridors were kept open, CAVF did not further decline by increasing the number of trees in the densification scenarios.

To achieve both planning goals, daytime cooling and avoidance of nocturnal heat trapping, trees should be planted in thermal hot spots and arranged in clusters that do not block nocturnal CAVF. The assessment of the ventilation situation provides important information on strategic tree placement and favourable building orientations. Considering wind flow is a prerequisite to create comfortable and climate-responsively designed neighbourhoods.

4.3. Context-specific and user-centred design of urban green infrastructure

The comparison of GIS analysis and microclimate modelling with social surveys including mental mapping and interviews indicates that urban vegetation does not only reduce urban heat loads as modelled, but also lessens feelings of crowding and increases subjective thermal comfort. Not just the quantity and amount of UGI, but the perceived accessibility of green spaces, their design, quality, and contextual elements define the value of UGI for urban residents.

The comparison of microclimate modelling results and perceived thermal comfort maps shows a high agreement in representing the most comfortable and uncomfortable places in the two study areas: the highest objective heat loads of open spaces and unshaded streets are mirrored in the locations of perceived thermal discomfort (Figure 13). Heat stress is highest where high density and lack of vegetation are combined with other heat exacerbating factors, like exhaust fumes. Feelings of heat stress and crowding mutually enforce each other. Most comfortably rated places coincide very well with the existing tree stock and modelled locations of lower heat stress. However, contrary to the simulation, both parks in the neighbourhoods which represent cool islands do not appear to play a critical role in individual heat stress adaptation. They are recognised as cool places by the residents, but are commonly not used as their design does not match users' needs. In Bahnhofsviertel, the park design was described as dark and uninviting, drug and alcohol use were associated with the area. In Riem, the small forest south of the housing estate was perceived as hardly accessible and rather made for animals than for people. To tap the full potential of parks or tree-covered squares for individual heat stress adaptation, thus not only their cooling potential, but also their accessibility and attractiveness is decisive.

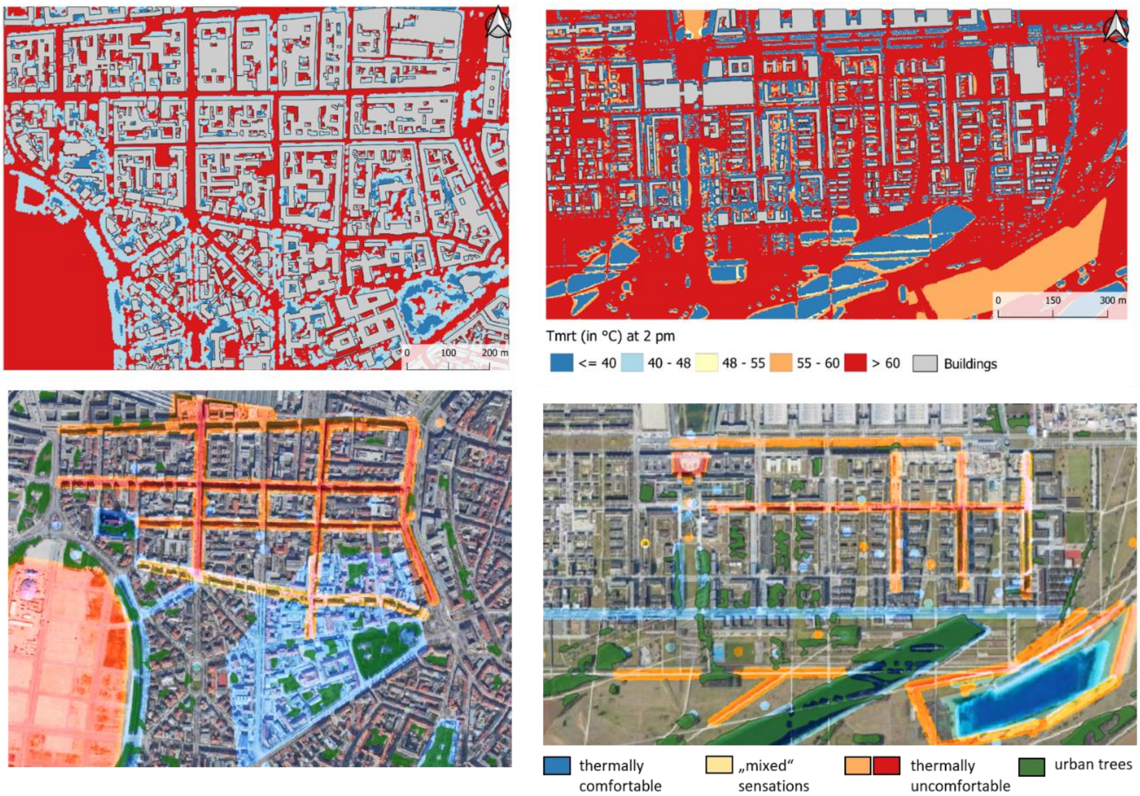

Figure 13: Comparison of modelled T_{mrt} model results for 25 July 2019 and perceived thermal comfort maps of Bahnhofsviertel (left) and Messestadt (right). The colour legend for the microclimate modelling maps (top) relates to the subjective heat categories from the mental mapping (bottom). T_{mrt} thresholds were derived from Thorsson et al (2014).

People density, car traffic and vegetation are decisive factors for the attractivity of street scapes and public spaces. Thus, respondents attributed a low quality of stay to public areas of both neighbourhoods: In the rather dense Bahnhofsviertel, this is related to heavy car traffic and feelings of crowding in its narrow streets. In contrast, the wide streets in Messestadt Riem are perceived as empty and uninteresting due to a low frequency of people activities. More vegetation was claimed in both neighbourhoods to reduce feelings of crowding and heat stress in Bahnhofsviertel and foster feelings of enclosure and stimulate visual variation in Messestadt Riem.

The observations lead to several context-specific and user-centred design recommendations for urban green space (Figure 14): In environments with high building density, traffic reduction, walkability and shaded walkways are priority measures to improve neighbourhood attractivity. If streets are too small for tree plantings, visual green elements at eye level (e.g., green facades, shrubs, or planters) help to reduce heat stress and feelings of crowding, since positive psychological benefits were achieved by urban greenery. In low density settings, green elements can reduce feelings of exposure and create more intimate small-scale public places. Residents of dense and highly stimulating environments prefer more peace and quiet in public parks than residents of lower density neighbourhoods. Younger people and people with different cultural background are more tolerant towards sensory overload than elderly people, which require shaded benches to rest. A lower availability of private (green) space increases the demand for public (green) space, which should be taken into account in the planning of public parks and urban green spaces in densified neighbourhoods. Effective, context-specific, user-centred design of green spaces can increase their social and health benefits.

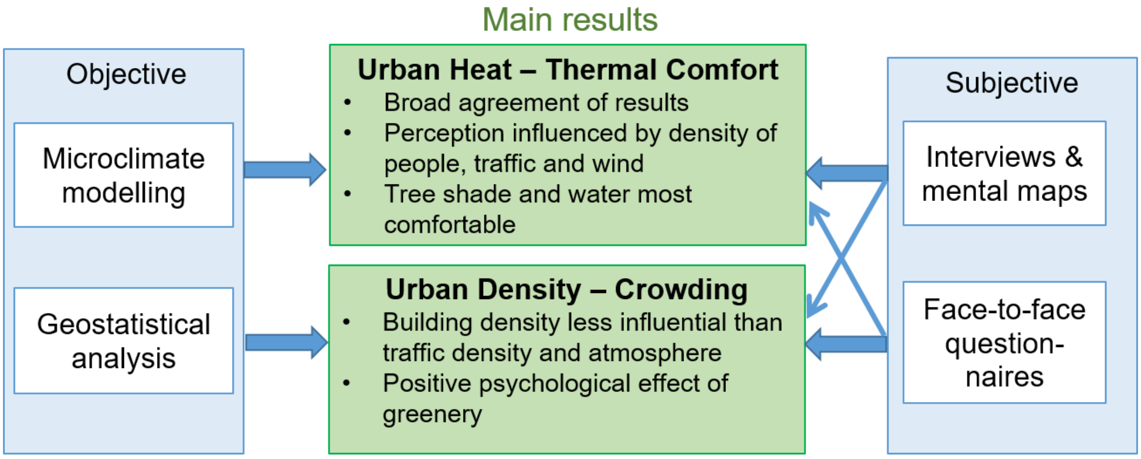

Figure 14: Interaction graph and summary of main results of the mixed-methods study in two Munich neighbourhoods.

4.4. Integration of urban green infrastructure in urban planning

In order to explore UGI integration in urban planning in densifying cities, study IV analysed the extent to which consideration of urban green space is influenced by the local context, constellation of actors, their employment of resources, formal and informal rules and prevalent narratives in four growing Bavarian municipalities. Other than commonly suggested, availability of resources alone are not key for consideration of green space in urban planning, but rather cooperation of actors, public participation in setting of norms and planning decisions, transparent communication and smart use of external resources, such as municipal support networks or research projects. Certain departmental structures and working routines can help to promote the cooperation of actors.

Governance capacity for integration of green space in urban planning was higher for the cities Dachau and Regensburg than Kempten and Straubing and related to a set of factors. As the largest city of the four, Regensburg has employed at specialist that is concerned with climate resilience and climate change adaptation. Moreover, the discourse in the city is in favour of green space conservation: guiding principles and development concepts have been drawn up with public participation, political actors and administration recognise the high demand for housing and the great interest of investors as a means of demanding concessions from them. Similar to Regensburg, Dachau has developed principles for building land development and adopted provisions from Munich. Urban and green planners belong to the same department and an early exchange between the planners at the beginning of an urban development process is an established working routine in the city. Whereas Kempten is a regional leader for climate change mitigation, there were no political majorities for regulations to strengthen inner-city green spaces, such as tree protection statutes. This holds also true for Straubing, where collaboration between municipal and political actors in implementation and monitoring of rules was lacking. Policy concepts from other cities were not deemed fitting to the size and context of the municipality.

Scarcity of land and lack of financial resources often lead to a dependence of municipalities on investors to realise urban planning. However, the municipality's ability to exert influence is also determined by the unity between the administration and political actors. Common understanding and collaboration between these actors are necessary to design, implement and monitor rules and regulations. Due to the lack of cooperation no regulations for the strengthening of green areas were introduced in Straubing and Kempten until the summer of 2021.

Increased importance of climate change adaptation and increased awareness for urban green spaces during the Corona pandemic were part of public discourses in all of the four cities. Specific discourses are influenced by the local context and actors' world views. They can hinder or foster implementation of regulations or collaboration with other departments. The case studies provide examples where public discourses were changed through government change and recurring dialogues with citizens. Thus, the self-image of Regensburg's medieval city centre which is dominated by buildings ("stone") was widened to entail "stone and green", allowing to introduce UGI for heat adaptation.

Internal department structures and affiliations can foster or hinder intersectoral working. Routines for an early integration of e.g. urban green planners in local land use plan processes are eased by similar department affiliations and regular communication between the departments. The employment of external resources helps to overcome limited municipal resources and constitutes an important leverage point to foster climate resilient urban development. Here, a range of different strategies were observed: participation in research projects (Straubing, Dachau, Kempten), additional criteria and request of assessments in the call for competitions for urban development projects (Regensburg, Dachau), membership and exchange in municipal support networks (Kempten, Dachau, Regensburg) and adoption of ideas from pioneer cities (Dachau).

A change of the analysed set-ups can be stimulated by any of the four dimensions (actors, power, rules or discourses) and on any of the three hierarchical levels. Replacement of single actors, new political majorities, restructuring of department affiliations or creation of new positions stimulated change on individual actors and systems level. The availability of new funding programmes and travel restrictions due to the Corona Pandemic as well as debates stimulated by the Fridays for Future movement are examples how the broader social-cultural context can influence the uptake of UGI. Thus, after a change of political majorities and raised awareness for the necessity of climate change adaptation, Kempten has established a sustainability advisory board and is in the process of drawing up a strategy for climate change adaptation with federal funding. In addition, a new national funding programme supports the employment of climate adaptation managers (Center Climate Adaptation 2021). Amendments of the German Building Code, such as the introduction of new land use categories have a direct impact on local land use planning. Finally, pre-existing knowledge and efforts help to support change and implement new strategies more quickly. Thus, in Regensburg, the climate resilience manager was able to draw on preparatory work such as a climate protection strategy and a climate function map to develop strategies for climate change adaptation. Table 3 summarises observed risk and success factors grouped according to the four policy dimensions and examples for change of the policy arrangement.

Table 3: Overview of success and risk factors for integration of UGI in urban development processes specified for the four PAA dimensions and examples for change based on study IV

Dimension	*Success*	*Risk*	*Change example*
Discourse	i) Belief in mandate to shape the future ii) Development of shared vision with stakeholder participation iii) Coherent internal discourse, common understanding of policy goals iv) Regular exchange with all stakeholders, recurring public debates v) Crisis as window of opportunities to stimulate public debate	i) Lack of public support for municipal goals ii) Shifting of responsibility to other hierarchical levels	Raised awareness for urban green space due to travel restrictions in the Corona pandemic
Power and Resources	i) Combination of political will and qualified staff ii) Actors control of resources iii) Employment of external resources (expertise, funding) iv) Exchange with other municipalities v) Pre-existing knowledge and efforts	i) Dependency on investors for urban development ii) Path-dependency for resource aggregation	Employment of climate resilience manager
Rules	i) Existing policy guideline for urban green space development ii) Existing formal rules or regulation for green space integration and conservation iii) Intersectoral working culture and working routines	i) Lack of public support for implementation ii) Lack of political support for monitoring iii) Lacking or late integration of green planners in urban development projects	Changes in the Federal Building Code
Actors and coalitions	i) Collaboration between administration and politicians ii) Collaboration between urban and green planning departments iii) Participation in exchange networks, collaboration with external stakeholders (NGOs, scientists)	i) Lack of trust, no common understanding ii) Lack of interest iii) Sectoral thinking in the administration	Change of political majorities

4.5. Summary of key findings

The key findings from the four studies concerning the four objectives are summarised in Figure 15.

Trade-offs between densification, UGI and thermal comfort (Objective 1)

- Conservation of mature trees has the largest impact on daytime outdoor thermal comfort and is influenced by the parking space key
- Ventilation and nocturnal cooling is impeded by additional buildings, but also by increased building heights
- Alternative mobility solutions are required to solve the conflict between greening and mobility and to achieve dense and green neighbourhoods

Climate regulation and densification compensation by UGI (Objective 2)

- UGI can compensate for negative effects of building densification on daytime thermal comfort, but not on ventilation
- A combined consideration of thermal comfort and ventilation is required to optimise UGI use (e.g. placement of trees outside of cold air corridors)
- Loss of mature trees can only be compensated after 40-50 years

Subjective perception of density and heat (Objective 3)

- Vegetation has psychologicial benefits for adaptation to density and heat: in high density settings UGI reduces feelings of crowding, in low-density neighbourhoods it fosters feelings of enclosure
- To play a role for individual heat adaptation, urban green spaces need to be perceived as accessible and attractive

UGI integration in urban planning (Objective 4)

- Rather than lack of resources alone, several interrelated factors shape UGI integration into urban development
- Cooperation of municipal actors, public participation in establishment of norms and decisions and strategic use of external resources are decisive factors
- Strategies: develop internal working routines and define responsibilities, communicate goals repeatedly, engage in pilot projects and exchange networks

Figure 15: Summary of key findings of the four research studies with respect to the four objectives of this thesis.

5. Discussion

The overall aim of this thesis was to investigate the interrelations between densification and urban green space in order to identify possible courses of action for climate-adapted urban planning in growing cities. To do so, studies I-III collected empirical evidence on the impacts of green and densification on the urban microclimate and the perception of heat and density by residents. Study IV analysed structural conditions promoting or impeding integration of UGI in city development processes. This chapter discusses the key findings of all four studies and reflects on the chosen methodological approach before implications for urban planning are provided.

5.1. Requirements on green space design in densifying cities

This chapter relates to the research objectives from chapter 1.2. The following aspects are discussed: 1) challenges and impacts related to densification, 2) compensation and regulation potential of UGI and 3) planning urban green infrastructure in the context of densification.

5.1.1. Challenges and impacts of densification in a changing climate

The first objective of this thesis was to assess the trade-offs between densification, UGI and human thermal comfort. In study 1 (results Chapter 4.1), conservation of existing vegetation, especially mature trees, has been identified as more important than increase of building mass or building height with respect to the impact on the microclimate. The cooling effect of vegetation was mainly related to shading by larger tree canopies. The importance of the sky view factor and thus the amount of solar radiation a specific site receives has also been highlighted in literature (Ramyar et al. 2019; Erell 2017; Yahia et al. 2018). In the considered neighbourhood, the fraction of shaded area during the hottest hours did not increase considerably with increased building height due to the North-South building orientation. Additional buildings increased the shaded area, but also attenuated the wind flow through the neighbourhood. This is in line with several authors that prefer increasing building heights instead of constructing additional buildings due to the important role of vegetated surfaces for climate regulation (Perini and Magliocco 2014; Chatzidimitriou and Yannas 2016; Ward and Grimmond 2017). Indeed, densification with additional storeys concentrates more housing units on less space and consumes less ground area. However, in real planning cases, both types of densification have an impact on existing green spaces as the construction of apartments is accompanied by the construction of parking spaces. Thus, increasing building heights is also associated with a loss of green space or, in the case of underground garages, by a loss of possible large tree locations, an issue which rarely has been addressed so far in research. Moreover, depending on the prevalent wind direction increased building heights can also affect ventilation and impede nocturnal cooling (study II), highlighting the necessity for context-specific assessments. Finally, the question which green areas and which green qualities are lost and where densification takes place was shown to be more crucial than the absolute amount of green space. Unlike many other microclimatic studies (e.g. Perini and Magliocco 2014; Yahia et al. 2018; Lee et al. 2020), study 1 and 2 explicitly demonstrate the importance of preserving healthy and mature trees.

For climate-resilient densification, the consideration of fresh air corridors also plays a decisive role (Allegrini et al. 2015; Mühlbacher et al. 2020). The findings of study 2 underline the necessity for assessments of local ventilation. Study 2 showed that densification weakens the nocturnal cooling in the respective site, but also has the potential to deteriorate the ventilation of neighbouring areas. As highlighted by Onomura et al. (2016), efficient nocturnal cooling requires open lawns through which cold air can enter residential neighbourhoods. Dense building structures as well as closely spaced trees impede nocturnal heat dissipation (Chatzidimitriou and Yannas 2016). For this reason, in the greening scenarios of the Moosach neighbourhood newly planted trees were distributed strategically so that open patches of grass remained. This is supported by Yahia et al. (2018), who also recommend to remove branches up to a height of 2 m to improve ventilation and cooling.

As regards subjective perception of density, study 3 has shown that building density was less influential on perception of density than traffic or people density. Similarly, Cheng (2010) suggest that social density (interaction between people) is more relevant than spatial density (e.g. height and spacing of buildings). Negative associations have been reported for presence of cars and traffic noise (Axelsson et al. 2014), whereas perceived naturalness of the environment and the presence of green space have been identified as important factors mitigating perceived density (Rapoport 1975; Cheng 2010). In study 3, especially motorised and stationary traffic exacerbated perceived density and heat, whereas presence of vegetation was observed to reduce feelings of crowding and heat stress. This connects to findings of study 1, where car parking space demands influenced the amount of large tree locations and measured thermal comfort. Promoting other modes of transport is therefore an important task, where urban planning can contribute through the reduction of required car parking space, promoting bike and car sharing and establishment of safe pedestrian routes.

5.1.2. Compensation and regulation potential of urban green infrastructure

The second objective of this thesis was to analyse the capacity of UGI for climate regulation and compensation of densification at block and neighbourhood scale. Paper II has demonstrated that trees have the highest cooling potential for human outdoor thermal comfort due to their effective shading of buildings and open spaces. The importance and efficiency of trees has been highlighted by other studies (Erell 2017; Zölch et al. 2016; Lee et al. 2016). The results in paper II have furthermore demonstrated that it is not necessarily the quantity of green spaces, but their quality which is decisive for outdoor human thermal comfort. The difference between newly planted young trees and mature trees was up to 8°C (PET) for the whole study area on the modelled hot summer day. At the beginning, newly planted trees actually represent a deterioration for thermal comfort in summer, since they still provide little shade and potentially slow down ventilation due to their low growth height as demonstrated in the study. The considerable higher cooling capacity of mature trees stresses the necessity to conserve these trees as much as possible.

Tree age is one of many factors that define the cooling capacity of trees. The cooling capacity of trees is furthermore dependent on tree species, growing conditions, geographical location, season (Jamei et al. 2016; Rahman et al. 2019; Rahman et al. 2015), tree placement and individual tree parameters (Rahman et al. 2020). Because the focus of the analysis was on comparing densification scenarios, no distinction was made between individual tree species. Frequently used tree species in Munich served as templates for the modelled trees, but these were not varied between the scenarios. Furthermore, healthy trees were assumed for the modelling. However, recurrent heat summers can cause damage to the trees, affecting evaporative cooling amount by drought stress (Rahman et al. 2015). For the considered summer heat day with weak wind speed, shading by tree crowns plays a greater role than evaporative cooling (Konarska et al. 2016a). For the long-term conservation of trees, however, good growing conditions such as sufficient root space and adequate water and nutrient supply are crucial, especially in view of climate change. This also requires the use of climate-adapted tree species (Sjöman et al. 2012; Sjöman et al. 2018).

In addition to the quality of trees, also their location plays a decisive role (Zölch et al. 2019). Where possible, densification measures should be selected so that large trees can be preserved. Study 1 showed that the increase of heat stress was limited to +1.3 to 1.7 °C (PET) over the time period of 10 am to 4 pm, when construction of underground car parking and removal of existing trees was restricted to those courtyards with less and younger trees. In study 2, compensation of the negative densification effect on the microclimate was achieved with 75 % tree replacement, since the replaced trees were strategically located for heat stress reduction. This involved placement in groups for minimal blocking of ventilation and nocturnal cooling as well as identification of thermal hot spots. In doing so, paper 2 has highlighted the importance of looking at both ventilation and thermal comfort and considering neighbourhood and microscale, which has rarely been done so far (Bartesaghi Koc et al. 2018). The deterioration of ventilation was not compensated by UGI, but the wind flow was not affected by additional trees as essential cold air paths were considered and not blocked. Given the importance of tree locations for provisioning of ecosystem services and for their long-term health, integration of UGI is required at early planning stages where conflicts between individual uses and planning objectives can be addressed in time. At the same time, care must be taken to ensure that defined tree locations are not subsequently used for construction of sewer lines, further underground infrastructure limiting tree root space and fire department access routes.

In line with literature, cooling by green roofs and green facades was limited to the proximity of roof and walls (Hoelscher et al. 2016; Zölch et al. 2016; Pérez et al. 2014). The modelled cooling effect for roof and facade surfaces of 14 °C was in the same order of magnitude as measured by Hoelscher et al. (2016). Shading of facades and insulation by substrate layers result into reported potentials for energy savings (around 30 % during the cooling season) and local noise absorption by green facades (Coma et al. 2017; Besir and Cuce 2018). Green roofs are the most efficient UGI for retention of storm water events (Zölch 2016). Rosenberger et al. (2021) demonstrated that local rain water management including green roofs, rain gardens (landscaped depressions with vegetation designed for infiltration, filtering and storage of rainwater) and permeable pavement significantly improves the local water balance. These interventions reduced surface run-off for rainfall events with return periods of 2 and 10 years in the Moosach neighbourhood to 3 % and 6 %, compared to 40 % and 45 % in the case of densification without these nature-based solutions (Rosenberger et al. 2021). Green roofs with substrate thickness of 20 cm were able to store 100 % of the storm water for all modelled rainstorm events. Thus, green roofs and green facades are no substitute for large trees for heat stress reductions, but should be an essential part of UGI planning due to the other ecosystem services they provide. Furthermore, they are an option when space on ground is limited, such as in narrow streets. Study 2 underlined that strategic employment of UGI can not only compensate for negative effects of densification on heat stress, but also has potential to enhance the climate resilience of urban neighbourhoods. Contrary to more frequent generic studies (e.g. Perini and Magliocco 2014; Morakinyo and Lam 2016) , these assessments have been made for a real planning case on basis of assumptions that were considered as being realistic by local planners.

Study 3 has shown that urban green spaces and elements are also beneficial for the perceived thermal comfort, linking to the third objective of the thesis. This objective was related to the assessment of user perspectives on UGI and neighbourhood designs in relation to density and heat. As depicted in chapter 2.3.2, several studies support the idea that urban green reduces feelings of crowding and increases perceived thermal well-being (Kabisch et al. 2021; Knöll et al. 2018). The research in study 3 shows that it is critical to take into account the local context and residential demands when designing green spaces and neighbourhoods. The results suggest that people and traffic density are more decisive than building density for perception of heat stress and crowding. In line with this, Knöll et al. (2018) report that building heights are less decisive for perceived urban stress compared to socio-contextual factors. Overall, the amount of densification is less decisive, than the influence it has on the overall fabric of the neighbourhood and on the use of public spaces.

Study 3 highlights the importance to collect local knowledge and values connected with public urban space in addition to climate analysis and assessment of density parameters when developing neighbourhoods. This is in line with literature emphasising that especially vulnerable population groups with limited mobility, such as elderly people and small children require green space close to home (Enssle and Kabisch 2020; Frerichs and Küpper 2017; Wüstemann et al. 2017). Also in line with literature, noise and lack of privacy have been identified as disruptive factors for the recreational effect of green spaces (Axelsson et al. 2014). In study 3 this was both related to moving as well as stationary traffic, a fact that is seldom highlighted. In comparing two neighbourhoods of contrasting density, study 3 allowed to identify different functions of urban green space in different urban settings. Whereas it has been observed that greened courtyards encourage neighbourhood gathering and community appropriation (Jennings and Bamkole 2019; van Herzele and Vries 2012), the findings of study 3 suggest that UGI can stimulate feelings of enclosure in low density settings. In high density settings, space on ground for planting trees is limited. There, planters and green facades provide visual stimuli that enhance heat stress relief beyond observed cooling driven by psychological mechanisms. Elsadek et al. (2019a) showed that viewing green facades increased physiological relaxation and induced feelings of comfort and cheerfulness. As has been shown in study 2, the quality of green and its distribution are more important than its quantity also in relation to social and health benefits. A single large park is no substitute for a network of smaller green spaces or green elements close to home. Ha et al. (2022) observed that psychological distress was lower in landscapes with dispersed distribution of urban green space compared to a single concentrated green area. This underscores the importance of including green space in the planning of new neighbourhoods to create green spaces close to home.

5.1.3. Planning urban green infrastructure

The fourth objective of this thesis was to analyse the possibilities for UGI integration in urban planning processes of densifying cities. Studies I-III demonstrate how UGI can be integrated in existing and redeveloped urban neighbourhoods. The studies demonstrated the climate regulation potential, but also psychological and social benefits of strategic UGI implementation in urban development. Despite the recognised benefits of UGI, various obstacles often prevent sufficient consideration and integration into urban planning. Study IV highlighted that several interrelated factors are decisive for UGI integration that relate to different policy dimensions as suggested by the policy arrangement approach. These were availability and strategic use of resources, rules and regulations, collaboration between internal and external stakeholders and the role of the prevailing discourse. Important aspects regarding these interdependencies are discussed below.

Resources are one of the most frequently identified challenges for uptake of climate change adaptation (Olazabal et al. 2019; Uittenbroek et al. 2013; Eisenack et al. 2014; Wamsler et al. 2013), but also for integration of urban green space in urban planning (Rall et al. 2015; Boulton et al. 2018). Although lack of resources can constitute an obstacle, study IV emphasises that the provision of resources alone does not guarantee better integration or successful implementation. If the initiative of an urban green planner is not supported by higher administrative levels and politics, it is not going to pass. Instead, successful implementation of regulations requires the approval by higher administrative levels and politics, as well as qualified and experienced staff (Khoshkar 2020; Holsen 2020; Wamsler et al. 2020b). Similarly, the local discourse determines whether rules are adopted and their consistent implementation is politically supported. Communication with different types of stakeholders is therefore vital. This underpins that not only financial and personal resources (in terms of number of staff) are required, but also means to pursue policies - such actor collaboration, communicative skills and availability of land.

Monitoring of rules and elaboration of guiding principles for UGI integration were identified as important means for dealing with land-use conflicts and setting of policy agendas in study IV. Limited availability of land and property rights have been reported as important barriers for green space enhancement (Khoshkar et al. 2018; Boulton et al. 2018). In their study about structural conditions affecting NBS mainstreaming in Germany, Dorst et al. (2022) name competition over urban space as key obstacle. High prices for land and lacking municipal resources lead to investors playing an increasing role in urban development (Elsmore 2020). However, in study IV, two of the four municipalities had adopted rules that set requirements for investors (e.g. number of subsidised housing units, required green spaces per inhabitant shifting), providing more opportunities for the municipalities to pursue their interests. Modification of planning procedures and regulations (regulatory mainstreaming) corresponds to one of six strategic mainstreaming activities identified by Wamsler et al. (2014). In the case studies, guidelines that can be referred to simplified communication processes and supported planners in the implementation of policies. Thus, clear guidelines and transparent communication have been identified as key elements for integrative negotiations between investors and municipalities in literature (Holsen 2020). Importantly, consistent implementation of regulations and provision of resources to monitor them is vital (Holsen 2020). Consistent implementation does not only require staff resources, but also political support for the administration (Khoskar 2020 (Wamsler et al. 2016)). Involving the population and the relevant stakeholders in drawing up the rule are an important prerequisite for this.

Furthermore, availability of knowledge and awareness of actors play a central role (Khoshkar 2020; Olazabal et al. 2019). Khoshkar (2020) describes basic knowledge of involved persons on potential ecosystem services of urban greenery as a critical prerequisite to foster sustainable transformation. Similarly, knowledge as well as data and awareness challenges were identified as important barriers by Dorst et al. (2022). In line with this, respondents in study IV indicated a lack of specific information on performance of UGI to use as arguments in negotiations. Interviewees strategically sought for external resources to fill this gap. Sources of knowledge and information were municipal exchange platforms, but also participation in research projects. Participation in research projects provided an opportunity to develop new planning strategies, test incentives or to have expert opinions prepared (such as a city climate analysis) for which the expertise or human resources would not be available. Similarly, Wamsler et al. (2020b) reported that strategic collaboration with external stakeholders was one of five strategies municipal staff pursued in order to overcome constraints in environmental and climate policy integration. Thus, assessment as performed in studies I-III provide an evidence-based rationale essential for integrating UGI in urban development planning. These kinds of information are not only valuable for exchange with other municipal departments and in negotiations with investors, but also for convincing citizens.

Citizen involvement in the establishment of concepts and norms represents a commonly suggested success factor in literature on environmental mainstreaming (Cosens 2013; Olazabal et al. 2019) or a barrier if it is absent (Wamsler et al. 2013; Dorst et al. 2022). In study IV, citizen participation was not only seen as mandatory task, but also valued by the respondents due to potential benefits for the planning procedure, such as knowledge on local peculiarities that help to avoid planning errors. Similarly, literature suggests that public participation might also be used to achieve strategic goals (Wamsler et al. 2020b). In the case studies, the development of guiding principles served as a basis for subsequent planning. Moreover, the elaboration of guiding principles also initiated debates on sustainability and urban development issues. This offered the opportunity to shape discourses and re-invent the self-image of the city (as has happened in the city of Regensburg). However, public participation can lead to undesirable outcomes for nature-based solutions and climate change adaptation if it is connected to specific projects (Wamsler et al. 2020a). Thus, personal concerns might outweigh public benefits, such as the availability of parking space at the expense of green space. With regard to densification projects, it has been observed that the fear of deterioration of the status quo outweighs any potential improvement (Wicki and Kaufmann 2022). Therefore it is not only sufficient to highlight benefits of the intended development, but also openly address possible negative impacts and seek means for mitigation (Whittemore and BenDor 2019). In order to do so, proficient communication skills of planners and time to engage in participatory processes are required. Structural conditions, such as a lack of organisational flexibility and a focus on practical and political dimensions of transformation tend to amplify this problem (Wamsler et al. 2020a).

Early integration of urban green space in urban planning processes and involvement of all related departments is a prerequisite for successful integration of climate adaptation concerns in densification projects. However, in study IV, integration of other departments was depending on interests of the urban planners to do so. Literature highlights the central role actors play in urban transformation and planning processes (Hölscher and Frantzeskaki 2021): Their perceptions, preferences, experiences, knowledge and leadership qualities decide about planning outcomes and possibilities for collaboration (Lehmann et al. 2015). Yet, institutional conditions, such as hierarchies and routines affect the environmental performance of urban development by fostering or impeding collaborations between actors (Yin et al. 2016). Establishment of internal working routines that promote interdepartmental exchange, such as „planner rounds“ at the beginning of a project and defined responsibilities throughout the project could help to foster collaboration and consolidate it beyond the personal interests of individual actors (Wamsler et al. 2017; Göpfert et al. 2019; Wamsler 2015). Analysis and transparent display of "integration" windows in relevant urban development planning processes could be a first step towards facilitating interdepartmental integration.

In summary, availability of resources as such is no guarantee for better integration of UGI in urban planning. Instead, more systematic changes are needed that address the interrelations between policy dimensions in planning processes and their structural conditions. On institutional level, integrative planning procedures and routines are required to overcome fragmented governance in the field of urban densification planning. Institutional structures can support actors in developing integrative planning approaches - such as similar department affiliations for urban and green planning, definition of responsibilities for planning, implementation and monitoring and modification of internal working routines to standardise early integration of UGI concerns. Processes for the development of guiding principles secure political support and stimulate exchange with civil society. Supportive discourses are important for the implementation of rules and planning projects. Participation in research projects, exchange in municipal exchange networks or other topic specific platforms are examples for strategic use of external resources for gathering additional funding, expertise or human resources. Information on the climate-regulating services of urban greenery in the project-specific context and the views of residents create an awareness of their importance and provide an evidence-based argumentation basis for negotiations and trade-offs. Knowledge is thus a decisive resource fostering the development of climate-resilient neighbourhoods in densifying cities.

The methodological approach of the dissertation was to examine the integration of green infrastructure into urban planning from multiple perspectives, linking issues such as ventilation and thermal comfort, objective and subjective perception. However, not all topics that are relevant for in climate-adapted urban development could be considered within the scope of the thesis. Thus, water management plays a key role for developing climate resilient neighbourhoods. On the one hand, neighbourhoods must be adapted to heavy rainfall events. On the other hand, urban green spaces need sufficient water supply to maintain their climate regulation services in the long term. Sustainable storm water measures such as green roofs, raingardens and unsealing of areas considerably reduce the risk of flooding, but also help to store and retain rain water (Rosenberger et al. 2021). Therefore, strategies for rainwater management need to be considered in urban planning. Furthermore, urban planning also needs to address the question how urban green spaces are distributed within the city. This relates to the UGI planning principle of connectivity and the goal to create a network of green spaces at the one hand and to questions of social justice at the other hand. If densification tends to lead to the disappearance of private green space in particular (Wellmann et al. 2020), distribution of and access to public green space becomes even more relevant. In addition, enhancing green space is likely to increase property values and housing costs, potentially inducing gentrification and social segregation (Wüstemann et al. 2017; Wolch et al. 2014). A network of green spaces and a design of urban greenery that is adapted to the needs of residents is therefore all the more important. Moreover this thesis has focussed on densification in its physical form and the increment in building density. However, a reduction in urban land consumption can also be accomplished by increasing people density. Two examples for this are moving of 'empty nesters' (single senior citizens living in family houses) or reducing per capita living space (Stieß et al. 2019). Urban planning alone cannot bring about change in this respect, as reducing living space requires broad transformation of culturally established norms (Eggimann et al. 2021). Nevertheless, forms of housing can be promoted that aim for a lower land consumption per capita (such as cooperative housing projects) and the debate can be initiated on how to make forms of housing more flexible.

5.2. Reflection of the methodological approach

To identify possible courses for action for climate-adapted urban planning in growing cities making use of UGI, a mixed-method approach that combined perspectives of different research fields was applied. All research was conducted in close cooperation with partners in planning practice. This chapter reflects on the chosen methodological approach by considering the single methods applied in the studies before addressing the overall approach.

For the objective assessments of human thermal comfort, numerical modelling was the main method of investigation. Numerical modelling offers the possibility to early assess different planning designs and to compare disadvantages and benefits for the local microclimate. The choice of a suitable model depends on the spatial scale, the desired level of detail and the focus of the study - therefore, three different models with different strengths and weaknesses were used in the research design (see chapter 3.4). Of these, ENVI-met represents a sophisticated microclimate model for detailed thermal comfort analysis on block scale, whereas FITNAH was designed to analyse ventilation flow over larger areas. SOLWEIG has computational advantages over ENVI-met in simulating T_{mrt} and is therefore suitable for modelling larger areas (Chen et al. 2014; Liu et al. 2020). Since the models are based on different assumptions, the results are not directly comparable, although similar patterns are evident as shown in Paper II. Thus, models are required that are able to combine different spatial scales through nesting, such as the

PALM-4U model, that was further developed within the MOSAIK project 2016-2019 (Gross et al. 2020). However, at the beginning of the microclimate studies for this thesis, the PALM-4U model was still under development and was therefore not considered. In addition, the current modelling resolution of the PALM-4U model for microscale investigations is a grid size of 10 m (Winkler et al. 2020), allowing less detailed representation of urban topology.

The ENVI-met modelling results have been validated with the data from a measurement campaign in the Moosach study area. The duration of the measurement campaign was limited by availability of human resources, unstable weather conditions and the measuring station availability. However, a 24 hour period with weather conditions representative for a typical summer heat day could be recorded. Besides the overestimation of nighttime temperatures (see Chapter 3.4.3), the ENVI-met model validation revealed that soil humidity and soil temperature represent two sensitive parameters for modelling accuracy. Available instruments covered surface temperature, but not soil humidity or deeper soil layers. Such on-site measurements of the named parameters are recommended. Larger study areas such as the neighbourhoods „Bahnhofsviertel“ and „Messestadt Riem“ with varying urban characteristics would require a network of measurement loggers or a repeated rotation of a mobile weather station to reflect the differences (Gubler et al. 2021). The resources for such a measuring campaign were not available in this project. However, as the SOLWEIG model has been frequently validated in various regions (Liu et al. 2020; Gál and Kántor 2020; Jin et al. 2022), it can be assumed that the modelling results are plausible and reliable within the scope of the usual uncertainties.

Although the anthropogenic heat flux (the energy released to the atmosphere as a result of human activity) constitutes an important source of heat (Chapman et al. 2017; Oke 2011), it was not considered in the microclimate analysis. This is in line with other microclimate or atmospheric studies and stems from the fact that methods for assessment of anthropogenic heat flux are elaborate (Oke et al. 2017, p. 164). For a detailed representation of anthropogenic heat flux, spatially explicit demographic data, which is often not available due to data privacy reasons, but also data on activity patterns of people in the investigated neighbourhood and insulation efficiency of buildings are required.

Due to the focus of the thesis on climate change adaptation, the microclimate simulations were conducted for summerly hot weather conditions. However, urban planning requires that urban spaces and neighbourhoods need to be designed for the whole year. In a next step, the proposed microclimate adaptations could be scrutinised for different seasons.

Due to the detrimental impacts of heat stress on human health and in view of the increasing number of hot days with ongoing climate change, optimising for heat stress situations has a high planning priority. Healthy vegetation that is not under heat stress was assumed for the microclimate modelling. However, the evapotranspirative cooling effect of vegetation declines with insufficient water supply (Rahman et al. 2017). Moreover, successive hot spells have a particularly detrimental effect on tree health (Moser-Reischl et al. 2019). Therefore, consideration of sufficient water supply is an important issue in urban planning. However, much of the cooling effect of trees on low-wind and high-radiation heat days is due to shading (Konarska et al. 2016b).

Different methodological approaches exist to compare objective thermal conditions as measured or modelled and subjective thermal perception (Lenzholzer et al. 2018). The employed methods differ depending on whether long-term or momentary thermal comfort is being investigated. Whereas thermal walks with measurements capture momentary perception (Katzschner 2006), the combination of questionnaires, subjective heat maps and microclimate modelling applied in study 3 aimed at depicting long-term perception, which has been rarely addressed so far (Lenzholzer et al. 2018). As climate change and urban heat stress were in focus of this dissertation, both investigations were conducted for a typical summer heat day. The subjective heat maps allowed for a spatial comparison between modelled and perceived thermal comfort, however several challenges need to be considered during interpretation: Whereas the modelled map provides area-wide coverage of the heat stress distribution, the subjective heat map only has information for the locations for which details were provided by respondents. Furthermore, the amount of data for certain locations is not equally distributed, since not every respondent provided data on the same locations. In addition, the ability of respondents to orient themselves in space plays a role. Therefore, in addition to the distribution of adhesive dots on the map to mark sensitive locations, in-depth questioning was important to also understand the reasons why some places were perceived as pleasant or unpleasant and how a dot marking in the map was to be understood.

The assessment of structural conditions of UGI integration in municipal urban planning was based on document analysis and interviews of urban and green planners. These stakeholders were selected as they coordinate urban planning processes or are responsible for urban green space management. The analysis focussed on the municipal level, since urban land use planning makes binding regulations on land use and the municipal level controls urban development processes. However, higher administrative levels influence municipal agendas through specifying targets, funding programs or amendments to the German Building Code. Moreover, the county level is involved in planning processes in smaller municipalities. Thus, the study should be extended to interviewing further administrative levels and cities of different sizes. On municipal level, the inclusion of further stakeholder groups (investors, civil society, planning offices) would further complete the governance analysis. The document analysis and study of strategic planning documents such as framework plans provided further information in this regard as these documents are usually based on participation processes and thus also depict the discourse formation.

Most of the investigations for this thesis focussed on Munich or Bavaria, respectively. Despite this regional selection of study areas, transferable findings were obtained: Thus, the selected development type of a row development represents one of the most common German settlement forms in cities (ZSK 2017). The conflicts between housing needs and green space conservation are problems that are significant in growing cities across Europe. The conflict shown between parking space needs and green infrastructure emphasises that sustainable mobility is a key factor in developing dense, green and liveable neighbourhoods. Possibilities for the strategic use of green infrastructure for climate-adapted urban development were highlighted. Similarly, in study IV, four Bavarian municipalities were selected as case studies to represent examples for growing cities that have to deal with the conflict between densification and green space development. Although the study has shown that the specific context of the municipality plays a decisive role and that structural conditions for integrating UGI in urban planning alter from case to case, the study led to transferable insights: Such, the study did not focus on individual obstacles for specific cases, but rather on the underlying mechanisms guiding integration of UGI in urban planning. Therefore, the observed interlinkages between different policy dimensions and drivers for change help to gain insights beyond the individual cases and are thus relevant for the German and European planning context.

Key to the overall methodological approach was the combination of different aspects: Such, scenarios for the microclimate simulations where designed based on considerations of planning practice. This allowed to assess the trade-offs between individual mobility demand and tree planting spots, but also to analyse the impact of a modified parking space key on outdoor thermal comfort. The approach combined different scales, allowing to disclose impacts of densification on air flow at neighbourhood scale in addition to thermal comfort assessment at block scale with implications for optimised designs. Whereas the local scale is the reference scale for urban dwellers and for binding-land use plans, planning procedures and outcomes are influenced by structural conditions at city scale, which have been addressed in study IV. The quality of stay and well-being in places is not only determined by objectively measurable parameters, but also depends on subjective perception of urban form and urban spaces by residents. Information on these factors is thus important for urban design and was considered in study 3. Perspectives from planners were integrated through collaboration in scenario developments for the microclimate modelling and semi-standardised interviews in the four case studies.

The consideration of these different aspects was made possible above all by participation in the transdisciplinary research project "Green City of the Future" and close collaboration with partner from planning practice. Research in real planning cases and science-municipality-partnerships offers opportunities and risks (see also (Withycombe Keeler et al. 2019): On the one hand, changes in the timelines of urban development processes are common, whereas funding periods are fixed. Thus, shifts in the timeline are likely to cause problems for planned investigations. Further hindrances include the different expectations at the beginning of the project by scientists and practice partners and a lacking common understanding of the important key issues. On the other hand, this approach offers the possibility for a direct transfer of research findings into practice and a transfer of research needs from planning practice to science. Thus, collaboration with city planners for the research in study 1 and 2 raised attention to implementation barriers for tree locations, such as fire department access roads and below-ground infrastructure. For a successful cooperation, regular exchange is necessary. Research results need to be "translated" into meaningful facts for planning practice. Then what Klemm (2018) describes in analogy to van Kerkhoff (2005) as integrating within science (different disciplines) and integrating beyond science (scientific and practical knowledge) is achieved.

5.3. Implications for urban planning

This chapter summarises the implications for urban planning that can be drawn from the four conducted studies. To illustrate the magnitude of the effects of UGI and densification, quantitative data from the microclimate investigations complement the recommendations. However, the effects of densification on the microclimate strongly depend on case-specific parameters such as the main wind direction and the buildings exposure, which is why case-specific assessments are required.

To balance the demands for housing, inner development and green space conservation, the following recommendations can be given:

- For the free-standing multi-storey housing type, densification with additional storeys is preferable over construction of additional buildings. Though the latter results in more flats, it comes at the cost of increased sealed surfaces, additional tree removal and therefore higher heat loads in summer. Moreover, blocking ventilation flow with buildings increases the heat burden in those enclosed yards during nighttime (up to 5 °C in PET) and daytime (up to 10 °C in PET), if the added buildings do not provide additional shade.

- Ventilation and cold air flow are vital parameters for outdoor thermal comfort and should be considered in densification planning. Whereas new building constructions can block air exchange close to the ground, increasing building heights can contribute to a reduced wind flow as well. Thus, increasing building heights perpendicular to the main wind direction should be avoided. In the case study, there was a 37 % reduction in CAVF due to increased building heights and a 25 % reduction due to added buildings, whereas a reduction of 10 % already represents a serious effect. Therefore assessment and consideration of air flows at district scale is highly recommended for densification planning in the context of climate change.
- To achieve dense and green neighbourhoods, alternative mobility concepts that promote public transport are required. Abolition or reduction of parking space requirements for motorised individual traffic are imperative for maintaining UGI in densifying cities, especially for inner city locations that are well connected to the public transport. Parking spaces for cars generate a considerable demand for space, which leads to sealing above ground or, in the case of underground garages, to areas that are unsuitable for the long-term growth and vitality of large trees. Instead, alternative mobility strategies such as bike sharing and car sharing should be promoted. Reducing the amount of car traffic also increases the walkability in the neighbourhood and reduces stress levels of urban dwellers.

For informed climate-resilient urban planning, it is important to distinguish between different types of green infrastructure:

- Mature trees are the most efficient green infrastructure type for improving outdoor thermal comfort. If trees are removed during building construction and area redevelopment, trees that are planted as replacements take 40 – 60 years to achieve the same cooling effect as mature trees. Thus, conservation of mature trees should be made a priority. If cutting down of trees cannot be avoided, care should be taken that replacement plantings have adequate root space and sufficient water and nutrient supply (Moser-Reischl et al. 2019). Quality is more decisive than quantity - more important than a complete replacement of all felled trees is the conservation of mature trees and provision of good growing conditions.

- The cooling effect of green roofs and green facades on outdoor thermal comfort is limited to the vicinity of the greened surfaces (2 m distance). Yet surface temperatures of buildings are considerably reduced (up to 22°C). Thus, green roofs and green facades should not be considered as a substitute for trees or for green space on ground, but as an addition due to the other ecosystem services they provide, such as storm water retention and reduction of cooling energy demand (Coma et al. 2017).

Not only the amount and quality, but also the strategic placement of green infrastructure is decisive in order to advance the cooling and regulating potential of UGI:

- To optimise human thermal comfort during daytime and nighttime, trees are ideally arranged in clusters that shade thermal hotspots, but allow for ventilation and nocturnal cooling at the same time (Figure 16). Distances between tree groups avoid heat trapping under tree canopies and facilitate wind flow, while also increasing the diversity of thermal sensations in an area. Thus, residents can decide whether they seek shade or sun, which will also differ depending on the seasons. Moreover, tree plantings and increased size of buildings in fresh air corridors should be avoided. Therefore it is recommended to combine observations on block scale as well as district scale to analyse impacts of densification and optimize planning drafts.

- Multifunctionality is one of the key advantages of UGI over technical or grey solutions. By cleverly placing greenery, multiple benefits can be achieved, for example, stress relief from density and heat and climate adaptation for heavy fall events and hot spells. Thus, green roofs in combination with rain gardens constitute an effective measure for sustainable storm water management and ensure that rainwater is retained, stored and evaporated (Rosenberger 2021). Moreover, stored rainwater helps to improve the water supply of greenery in periods with limited rain fall.

- The highest cooling effect of green facades is achieved for south and west-facing expositions. In narrow streets, where tree planting is not possible and would potentially block ventilation, facade greening increases perceived thermal comfort and reduces feelings of crowding compared to bare facades.

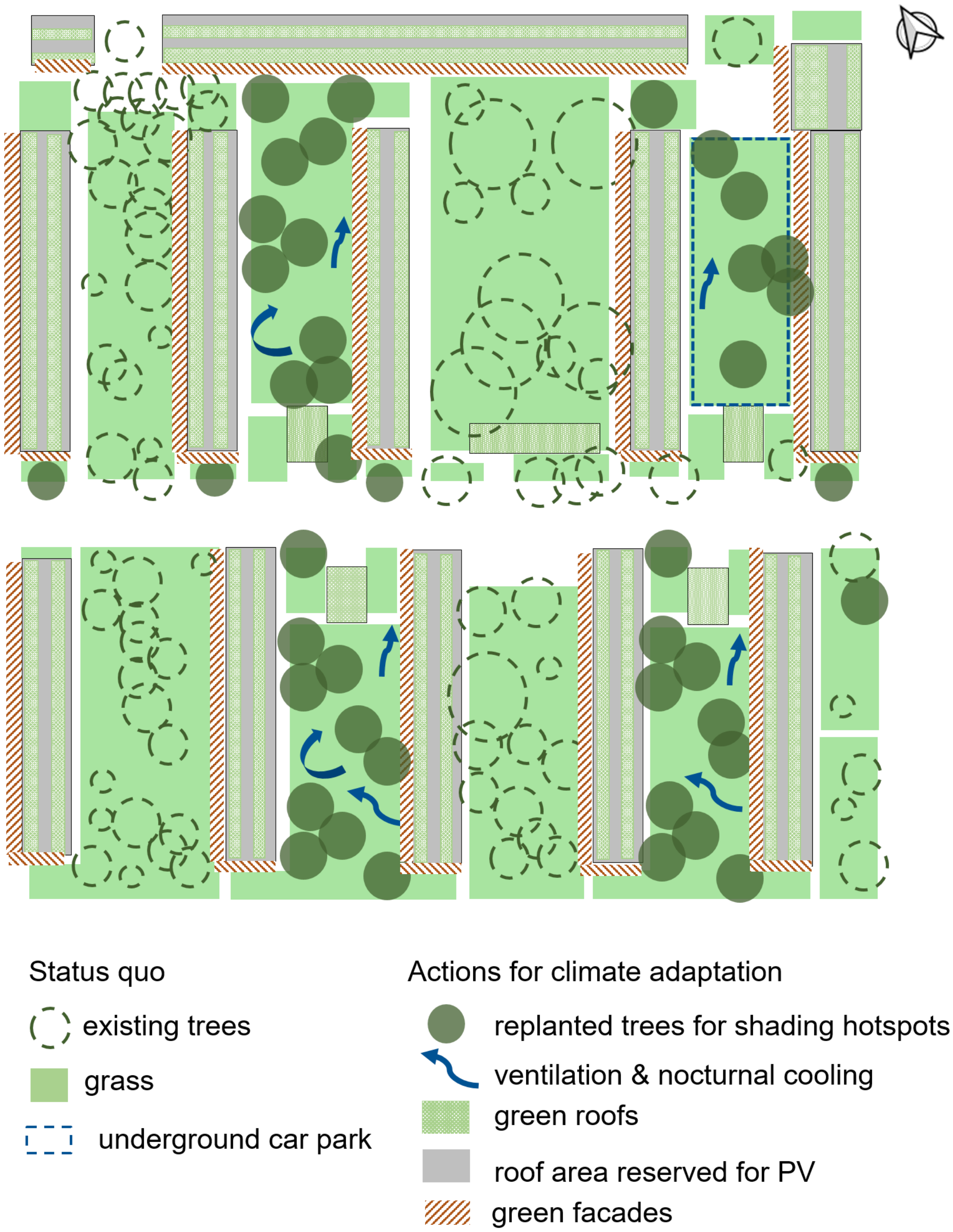

Figure 16: Sketch of climate adaptation potentials for the Moosach study area considering thermal comfort and ventilation. The existing trees are indicated by dashed circles, the replanted trees represent trees after 40-60 years after planting. Green roofs are used on 50% of the roof area so that the other half can be used for photovoltaics (PV). Roofs of auxiliary buildings are fully greened. Green facades are applied to the south and southwest of the buildings for maximum cooling effect.

On a broader scale, the following recommendations for urban green space design that includes user perspectives can be given:

- To be a resource for density and heat adaptation, green spaces must be useful and attractive from the perspective of residents. For people with limited mobility, shaded benches and access to green space close to home are important. Park designs can be perceived as unsafe, dark and obscure or as boring and monotonous. As a result, they are avoided by residents even if they constitute cool islands during heat days. It is therefore important to include the perspectives of locals in the planning process.

- In dense neighbourhoods, walkable and accessible green roofs that provide views into the distance represent a recovery from feelings of crowding and urban stress. Planters and green facades provide visual stimuli that enhance heat stress relief beyond observed cooling driven by psychological mechanisms.

To promote integration of green planning for climate adaptation into urban planning, the following recommendation can be made:

- To minimise the impact of densification on the existing greenery and the microclimate, it is necessary to take into account at an early stage of the planning process the existing trees and the ventilation situation of the planning area. Tree locations and options for roof and facade greening should be considered early as well, as this has an impact on the statics of buildings and planning of underground infrastructure. Adjustments in later planning phases are likely to be costly, time-consuming and planning-intensive.

- Therefore, it is important to involve relevant departments such as the green planning, the environmental and the civil engineering department at an early stage of the urban planning process. For this, it is advisable to analyse the planning routines and determine where an exchange would be possible and to communicate this openly to other departments. Establishment of working routines aimed at exchange help to simplify cooperation and not make it dependent on the interests of individual actors.

- Consistency throughout the planning process is important. Thus, specified tree locations should be adhered to in a binding manner and not be dismissed by e.g. fire brigade access routes. The setting of rules also includes controlling whether they are adhered to. For consistent implementation, provision of resources for monitoring is therefore important (Rall et al. 2018).

- City council resolutions and framework plans help to consolidate goals for UGI implementation and create a framework for action for politics and city administration. This also strengthens the interests of green infrastructure in negotiations with investors and triggers exchanges with the public, which is necessary for promoting support and common understanding.

- External resources can be employed strategically to compensate for lack of municipal means. The case studies have indicated some possible options for doing so, including participation in research projects and funding programs, membership and exchange in municipal support networks and adoption of ideas from pioneer cities.

Finally, in light of the provided evidence, densification should be perceived not only as a threat, but also as a possibility for enhancing urban green space and promoting climate change adaptation. To take advantage of this opportunity, green space enhancement and climate change adaptation have to play an important role in the planning process have to be consistently considered as outlined above.

6. Conclusion

6.1. Contributions of the study

Densification and climate change adaptation represent key challenges for cities (Chapman et al. 2017). Under this premise, the overall aim of this thesis was to enhance the understanding of the interplay between densification, the cooling potential of UGI and its impact on human heat stress in order to assist climate-adapted urban planning in growing cities. To do so, this thesis quantified the influence of densification on outdoor thermal comfort, ventilation and existing green space and the compensation possibilities through UGI. In order to determine the impact of urban design and greenery on urban residents, modelled heat load was compared with subjective perception of heat and density. Policy dimensions related to urban planning were analysed to identify levers for UGI integration in urban developments of growing cities.

The thesis contributes to an enhanced understanding on UGI cooling potential and its strategic use and management in residential areas. Eight densification scenarios were elaborated together with city planners and evaluated by microclimate modelling. The study adressed the rarely considered interplay between car parking space demand and conservation of existing trees in densifying neighbourhoods. On a hot summer day, loss of mature trees due to parking space demand has the largest impact on human thermal comfort. Halving parking space demand is an effective means of reducing impacts on thermal comfort. Densification with additional buildings creates more living space than additional floors, but potentially blocks nocturnal fresh air circulation. By analysing both nighttime and daytime situation and by considering both thermal comfort at the block scale and ventilation at the neighbourhood scale, this thesis improves the understanding of conflicts and synergies for strategic use of UGI. UGI can offset the detrimental impacts of densification on outdoor thermal comfort, but not on CAVF. Local ventilation and outdoor thermal comfort is least affected when buildings are not elevated perpendicular to the predominant wind direction and trees are planted in groups shading thermal hotspots. On a hot summer day, the difference in cooling performance of older trees (40-50 years old) versus newly planted trees is up to 8 °C in PET at 2 pm and 3 °C during daytime (10 am to 4 pm).

The comparison between objective assessments and subjective perceptions of density and heat, conducted in a joint effort with colleagues in the research project “Green City of the Future", emphasises the importance of urban green spaces to foster human thermal comfort and well-being. The presence of greenery contributes to reducing both heat stress and feelings of crowding. The effect exceeds in part the measured observations. However, outcomes of the applied social research methods, including subjective heat maps, questionnaires and semi-standardised interviews, show that it is not the existence and the amount of UGI per se that is decisive. Rather contextual factors such as the perceived accessibility and the presence of other people or motorised traffic determine whether a green space is used and perceived as attractive. The findings therefore emphasise that green spaces have a different impact depending on the spatial context and that urban landscape design should take into account the needs of different citizen groups, such as resting facilities for less mobile residents.

This thesis increased the knowledge on conditions necessary to foster green space integration in urban planning in growing cities. In a case study approach, the four policy dimensions of actors, rules, resources and discourse were analysed through expert interviews and document analysis. The policy arrangement approach (Arts et al. 2004) showed to be a suitable tool for revealing relationships and influence mechanisms in policy making in urban planning. The analysis highlighted that financial and human resources are important factors, but they alone do not guarantee successful integration of UGI in urban planning processes. Instead, cooperation between administration and politics is necessary to adopt concepts and rules and to enable their consistent and consequent implementation. Consistent implementation is facilitated if the rules are clearly communicated and based on a decision or framework plan that has been developed with public participation. This research has shown that funding programmes, community exchange networks, research projects and templates from pioneering cities can be used strategically to overcome a shortage of resources.

6.2. Outlook and future research

This thesis linked several topics related to climate-responsive planning that have rarely been considered together before: the four studies addressed climate change adaptation measures in the context of densification, analysed thermal comfort and ventilation and considered different spatial scales. In doing so, this thesis identified potential trade-offs (such as the conflict between car parking space demand and mature tree conservation) and developed strategies to deal with these difficulties. Given the importance of more holistic assessments, tools should be developed that facilitate a combined analysis of different scales and aspects of thermal comfort and ventilation. As addressed in the discussion (chapter 5.2), most of the established urban climate models are either primarily designed for simulating urban ventilation or for investigating outdoor thermal comfort and cooling potential of vegetation. Thus, the comparison of different spatial scales had to be conducted with two different models with two different parametrisations. A coupling of existing microclimate models by nesting or the development of integrated models is needed to further improve consistency of results. The model PALM 4U (Gross et al. 2020) is taking first steps in this direction, but it would need a resolution that also allows microscale observations for looking at the cooling effect of urban greenery in greater detail (e.g. 2 m instead of 10 m resolution). In addition, an integrated analysis option of heavy rain events would be desirable in order to map all climate-relevant aspects in one tool.

Moreover, the applied microclimate modelling has focused on terraced housing as the most common urban housing type with high densification potential. Nevertheless, the effects of densification and regulation possibilities with green infrastructure should be investigated for other settlement types as well. For example, a change in Germany's building legislation on spacing regulations has made it possible to build much more densely, which will affect areas with detached houses in particular. This type of development is common in smaller cities and towns that are located in the fringe of metropolitan areas and also face high housing demand, resulting in high pressure on urban green space.

While regulating services of UGI are slowly gaining greater attention in urban land use planning, the question arises how social values and benefits for human well-being can be better communicated in planning, so that the multitude of ecosystem services of urban green spaces gain greater weight in decision-making processes. Rall (2018) illustrated the potential of public participation geographic information systems (PPGIS) to visualise forms of engagement with nature and inform urban planning. Other approaches aim to quantify health benefits of urban green space with human health indicators, such as antidepressant describing rates, rates of health-related complaints (Salmond et al. 2016; Tzoulas et al. 2007), resulting in quantified, but not context-specific information. Thus future research should make further efforts in this direction.

Exchange networks on regional and national scale have proven to be a valuable resource for the studied municipalities. Whereas research has been done on transnational municipal networks and their role for climate change adaptation (e.g. (Bulkeley et al. 2003; Fünfgeld 2015; Haupt and Coppola 2019; Kern and Bulkeley 2009), analysis of the role of regional and national networks with respect to green space conservation and enhancement in urban development planning is largely lacking. Such an analysis can provide guidelines for practical implementation at the national level, especially since national and regional levels are more relevant for medium-sized and smaller municipalities than international examples. It would be of great interest to investigate to what extent municipal exchange networks contribute to shaping discourse and, thus, not only offer best practice examples for individual regulations, such as examples of regulations, but also initiate debates about the direction of regulations. This would be especially relevant since shaping the direction of rules has been identified as an important leverage point in sustainable transformation research (Abson et al. 2017).

Moreover, it is likely that interlinkages and importance of the studied dimensions are different in other countries with different climatic conditions and different planning cultures. In this regard, analysis of UGI integration in densifying cities should be extended to other regions and the global south in particular. Research on ecosystem services of UGI is mostly focussed on Europe, the US and Asia, whereas studies on UGI in Africa are rare and concentrated on a few cities and regions (Lindley et al. 2018; Pauleit et al. 2021; Du Toit et al. 2018). In face of the rapid rise of urban populations and urban areas in African states and their vulnerability towards climate change, more efforts to assess the potential of UGI for climate change adaptation and possibilities of implementation for these regions are required.

Finally, the diversity of challenges associated with climate change and the range of concerns that need to be addressed for sustainable planning call for increased transdisciplinary research and closer collaboration between science and practice (Wamsler et al. 2014; Wamsler et al. 2020b; Khoshkar 2020; Wolfram et al. 2019). Partnerships and research in case studies that represent real planning cases provide municipalities the opportunity to gain context-specific information from local assessments (e.g. on social evaluation and adaptation needs) and to experiment with new planning procedures or tools (such as new collaborations with internal departments, new criteria in competition procedures or new forms of engagement with civil society actors and initiatives). Hence, collaboration with external partners has the potential to question established ways of working and thus contribute to sustainable transformation, if a set of criteria are met (Wolfram et al. 2019). For applied research, there is an opportunity to contribute to solving real world problems, to promote interdisciplinary research and to directly transfer research findings into practice (Withycombe Keeler et al. 2019). Therefore, future research on UGI planning and climate change adaptation should aim at inter and transdisciplinary approaches.

Bibliography

Aalbers, C.B.E.M.; Kamphorst, D. A.; Langers, F. (2019): Fourteen local governance initiatives in greenspace in urban areas in the Netherlands. Discourses, success and failure factors, and the perspectives of local authorities. In *Urban Forestry & Urban Greening* 42, pp. 82–99. DOI: 10.1016/j.ufug.2019.04.019.

Abson, D. J.; Fischer, J.; Leventon, J.; Newig, J.; Schomerus, T.; Vilsmaier, U. et al. (2017): Leverage points for sustainability transformation. In *Ambio* 46 (1), pp. 30–39. DOI: 10.1007/s13280-016-0800-y.

Acero, J. A.; Arrizabalaga, J. (2018): Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions. In *Theor Appl Climatol* 131 (1-2), pp. 455–469. DOI: 10.1007/s00704-016-1971-y.

Adger, W. N.; Agrawala, S.; Mirza, M.M.Q.; Conde, C.; O'Brien, K.; Pulhin, J. et al. (2007): Assessment of adaptation practices, options, constraints and capacity. In : Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. International Panel on Climate Change. Cambridge, UK, pp. 717–743.

Ahlfeldt, G. M.; Pietrostefani, E. (2017): Demystifying Compact Urban Growth: Evidence From 300 Studies From Across the World. Coalition for Urban Transitions. London and Washington, DC. Available online at: http://newclimateeconomy.net/content/citiesworking-papers.

Allegrini, J.; Dorer, V.; Carmeliet, J. (2015): Influence of morphologies on the microclimate in urban neighbourhoods. In *Journal of Wind Engineering and Industrial Aerodynamics* 144, pp. 108–117. DOI: 10.1016/j.jweia.2015.03.024.

Arnouts, R.; van der Zouwen, M.; Arts, B. (2012): Analysing governance modes and shifts — Governance arrangements in Dutch nature policy. In *Forest Policy and Economics* 16, pp. 43–50. DOI: 10.1016/j.forpol.2011.04.001.

Artmann, M.; Kohler, M.; Meinel, G.; Gan, J.; Ioja, I.-C. (2019a): How smart growth and green infrastructure can mutually support each other — A conceptual framework for compact and green cities. In *Ecological Indicators* 96, pp. 10–22. DOI: 10.1016/j.ecolind.2017.07.001.

Artmann, M.; Inostroza, L.; Fan, P. (2019b): Urban sprawl, compact urban development and green cities. How much do we know, how much do we agree? In *Ecological Indicators* 96, pp. 3–9. DOI: 10.1016/j.ecolind.2018.10.059.

Arts, B.; van Tatenhove, J. (2004): Policy and power: A conceptual framework between the ‘old’ and ‘new’ policy idioms. In *Policy Sci* 37 (3-4), pp. 339–356. DOI: 10.1007/s11077-005-0156-9.

Arts, B.; Leroy, P.; van Tatenhove, J. (2006): Political Modernisation and Policy Arrangements: A Framework for Understanding Environmental Policy Change. In *Public Organiz Rev* 6 (2), pp. 93–106. DOI: 10.1007/s11115-006-0001-4.

Averchenkova, A.; Bassi, S. (2016): Beyond the targets: assessing the political credibility of pledges for the Paris Agreement. Centre for Climate Change Economics and Policy and Grantham Research Institute on Climate Change and the Environment. London. Available online at: http://eprints.lse.ac.uk/65670/.

Axelsson, Ö.; Nilsson, M. E.; Hellström, B.; Lundén, P. (2014): A field experiment on the impact of sounds from a jet-and-basin fountain on soundscape quality in an urban park. In *Landscape and Urban Planning* 123, pp. 49–60. DOI: 10.1016/j.landurbplan.2013.12.005.

Bao, J.; Li, X.; Yu, C. (2015): The Construction and Validation of the Heat Vulnerability Index, a Review. In *International journal of environmental research and public health* 12 (7), pp. 7220–7234. DOI: 10.3390/ijerph120707220.

Bartesaghi Koc, C.; Osmond, P.; Peters, A. (2018): Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. In *Solar Energy* 166, pp. 486–508. DOI: 10.1016/j.solener.2018.03.008.

Bavarian State Agency for Statistics and Data Processing (LfStat) (2020): Regionalisierte Bevölkerungsvorausberechnung für Bayern bis 2039. Beiträge zur Statistik Bayerns. Fürth (553). Available online at: https://www.statistik.bayern.de/mam/statistik/gebiet_bevoelkerung/demographischer_wandel/a1820b_202000.pdf.

Bavarian State Agency for Statistics and Data Processing (LfStat) (2021): Einwohnerzahlen der Gemeinden, Kreise und Regierungsbezirke. Fürth. Available online at: https://www.statistik.bayern.de/statistik/gebiet_bevoelkerung/bevoelkerungsstand/index.html#link_2, checked on 11/10/2021.

Beckmann, S. K.; Hiete, M.; Beck, C. (2021): Threshold temperatures for subjective heat stress in urban apartments—Analysing nocturnal bedroom temperatures during a heat wave in Germany. In *Climate Risk Management* 32, p. 100286. DOI: 10.1016/j.crm.2021.100286.

Benedict, M.; McMahon, E. (2002): Green Infrastructure: Smart Conservation for the 21st Century. In *Renewable Resources Journal* 20 (3), pp. 12–17.

Bennett, N. D.; Croke, B. F.W.; Guariso, G.; Guillaume, J. H.A.; Hamilton, S. H.; Jakeman, A. J. et al. (2013): Characterising performance of environmental models. In *Environmental Modelling & Software* 40, pp. 1–20. DOI: 10.1016/j.envsoft.2012.09.011.

Besir, A. B.; Cuce, E. (2018): Green roofs and facades: A comprehensive review. In *Renewable and Sustainable Energy Reviews* 82, pp. 915–939. DOI: 10.1016/j.rser.2017.09.106.

Biesbroek, G. R.; Klostermann, J. E. M.; Termeer, C. J. A. M.; Kabat, P. (2013): On the nature of barriers to climate change adaptation. In *Reg Environ Change* 13 (5), pp. 1119–1129. DOI: 10.1007/s10113-013-0421-y.

Blazejczyk, K.; Epstein, Y.; Jendritzky, G.; Staiger, H.; Tinz, B. (2012): Comparison of UTCI to selected thermal indices. In *International Journal of Biometeorology* 56 (3), pp. 515–535. DOI: 10.1007/s00484-011-0453-2.

Bodnaruk, E. W.; Kroll, C. N.; Yang, Y.; Hirabayashi, S.; Nowak, D. J.; Endreny, T. A. (2017): Where to plant urban trees? A spatially explicit methodology to explore ecosystem service tradeoffs. In *Landscape and Urban Planning* 157, pp. 457–467. DOI: 10.1016/j.landurbplan.2016.08.016.

Boulton, C.; Dedekorkut-Howes, A.; Byrne, J. (2018): Factors shaping urban greenspace provision: A systematic review of the literature. In *Landscape and Urban Planning* 178, pp. 82–101. DOI: 10.1016/j.landurbplan.2018.05.029.

Bowler, D. E.; Buyung-Ali, L.; Knight, T. M.; Pullin, A. S. (2010): Urban greening to cool towns and cities: A systematic review of the empirical evidence. In *Landscape and Urban Planning* 97 (3), pp. 147–155. DOI: 10.1016/j.landurbplan.2010.05.006.

Bratman, G. N.; Anderson, C. B.; Berman, M. G.; Cochran, B.; Vries, S. de; Flanders, J. et al. (2019): Nature and mental health: An ecosystem service perspective. In *Science advances* 5 (7), eaax0903. DOI: 10.1126/sciadv.aax0903.

Breuste, J.; Pauleit, S.; Haase, D.; Sauerwein, M.; Lay, M. (2016): Stadtökosysteme. Funktion, Management und Entwicklung. 1. Aufl. 2016. Berlin, Heidelberg: Springer Berlin Heidelberg. Available online at: http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1518331.

Brown, S.; Walker, G. (2008): Understanding heat wave vulnerability in nursing and residential homes. In *Building Research & Information* 36 (4), pp. 363–372. DOI: 10.1080/09613210802076427.

Bruegmann, R. (2008): Sprawl. A Compact History. Chicago: University of Chicago Press. Available online at: http://gbv.eblib.com/patron/FullRecord.aspx?p=408469.

Brunner, J.; Cozens, P. (2013): 'Where Have All the Trees Gone?' Urban Consolidation and the Demise of Urban Vegetation: A Case Study from Western Australia. In *Planning Practice & Research* 28 (2), pp. 231–255. DOI: 10.1080/02697459.2012.733525.

Bruse, M.; Fleer, H. (1998): Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. In *Environmental Modelling & Software* 13 (3-4), pp. 373–384. DOI: 10.1016/S1364-8152(98)00042-5.

Brymann, A. (2008): Social research methods. 3rd edition. New York: Oxford University Press.

Brzoska, P.; Spāģe, A. (2020): From City- to Site-Dimension: Assessing the Urban Ecosystem Services of Different Types of Green Infrastructure. In *Land* 9 (5), p. 150. DOI: 10.3390/land9050150.

Buchin, O.; Hoelscher, M.-T.; Meier, F.; Nehls, T.; Ziegler, F. (2016): Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. In *Energy and Buildings* 114, pp. 27–37. DOI: 10.1016/j.enbuild.2015.06.038.

Bulkeley, H.; DAVIES, A.; EVANS, B. O.B.; GIBBS, D.; KERN, K.; THEOBALD, K. (2003): Environmental Governance and Transnational Municipal Networks in Europe. In *Journal of Environmental Policy & Planning* 5 (3), pp. 235–254. DOI: 10.1080/1523908032000154179.

Bundesinstitut für Bau-, Stadt- und Raumforschung (Ed.) (2014): Städtebauliche Nachverdichtung im Klimawandel. Ein ExWoSt Fachgutachten. Bundesinstitut für Bau-, Stadt- und Raumforschung. Bonn (ExWoSt Informationen, 46/1).

Bundesregierung (2008): Deutsche Anpassungsstrategie an den Klimawandel. Available online at: https://www.bmuv.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/das_gesamt_bf.pdf.

Bundesregierung (2016): Deutsche Nachhaltigkeitsstrategie. Available online at: https://www.bundesregierung.de/breg-de/themen/nachhaltigkeitspolitik/die-deutsche-nachhaltigkeitsstrategie-318846, checked on 2/15/2022.

Bundesregierung (2019): Masterplan Stadtnatur. Maßnahmenprogramm der Bundesregierung für eine lebendige Stadt. Available online at: https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Naturschutz/masterplan_stadtnatur_bf.pdf.

Bundesregierung (2020): Zweiter Fortschrittsbericht zur Deutschen Anpassungsstrategie an den Klimawandel. Available online at: https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimawandel_das_2_fortschrittsbericht_bf.pdf.

Burchfield, M.; Overman, H. G.; Puga, D.; Turner, M. A. (2006): Causes of Sprawl: A Portrait from Space. In *The Quarterly Journal of Economics* 121 (2), pp. 587–633. DOI: 10.1162/qjec.2006.121.2.587.

Byrne, J.; Sipe, N.; Searle, G. (2010): Green around the gills? The challenge of density for urban greenspace planning in SEQ. In *Australian Planner* 47 (3), pp. 162–177. DOI: 10.1080/07293682.2010.508204.

Carter, J. G.; Cavan, G.; Connelly, A.; Guy, S.; Handley, J.; Kazmierczak, A. (2015): Climate change and the city: Building capacity for urban adaptation. In *Progress in Planning* 95, pp. 1–66. DOI: 10.1016/j.progress.2013.08.001.

Center Climate Adaptation (2021): BMU öffnet Förderfenster für kommunale Klimaanpassungsmaßnahmen am 1. Dezember 2021. Available online at: https://zentrum-klimaanpassung.de/bmu-oeffnet-foerderfenster-kommunale-klimaanpassungsmassnahmen-1-dezember-2021, updated on 4/11/2021.

Chapman, S.; Watson, J. E. M.; Salazar, A.; Thatcher, M.; McAlpine, C. A. (2017): The impact of urbanization and climate change on urban temperatures: a systematic review. In *Landscape Ecol* 32 (10), pp. 1921–1935. DOI: 10.1007/s10980-017-0561-4.

Chatzidimitriou, A.; Yannas, S. (2016): Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer. In *Sustainable Cities and Society* 26, pp. 27–47. DOI: 10.1016/j.scs.2016.05.004.

Chatzidimitriou, A.; Axarli, K. (2017): Street Canyon Geometry Effects on Microclimate and Comfort; A Case Study in Thessaloniki. In *Procedia Environmental Sciences* 38, pp. 643–650. DOI: 10.1016/j.proenv.2017.03.144.

Cheng, V. (2010): Understanding density and high density. In Edward Ng (Ed.): Designing high-density cities for social and environmental sustainability. For Social and Environmental Sustainability. London, Sterling, Va.: Earthscan, pp. 3–18.

Chen, Y.-C.; Lin, T.-P.; Matzarakis, A. (2014): Comparison of mean radiant temperature from field experiment and modelling: a case study in Freiburg, Germany. In *Theor Appl Climatol* 118 (3), pp. 535–551. DOI: 10.1007/s00704-013-1081-z.

Cohen, D. A.; McKenzie, T. L.; Sehgal, A.; Williamson, S.; Golinelli, D.; Lurie, N. (2007): Contribution of public parks to physical activity. In *American journal of public health* 97 (3), pp. 509–514. DOI: 10.2105/AJPH.2005.072447.

Coma, J.; Pérez, G.; Gracia, A. de; Burés, S.; Urrestarazu, M.; Cabeza, L. F. (2017): Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades. In *Building and Environment* 111, pp. 228–237. DOI: 10.1016/j.buildenv.2016.11.014.

Contesse, M.; van Vliet, B. J.M.; Lenhart, J. (2018): Is urban agriculture urban green space? A comparison of policy arrangements for urban green space and urban agriculture in Santiago de Chile. In *Land Use Policy* 71, pp. 566–577. DOI: 10.1016/j.landusepol.2017.11.006.

Cortekar, J.; Bender, S.; Brune, M.; Groth, M. (2016): Why climate change adaptation in cities needs customised and flexible climate services. In *Climate Services* 4, pp. 42–51. DOI: 10.1016/j.cliser.2016.11.002.

Cosens, B. A. (2013): Legitimacy, Adaptation, and Resilience in Ecosystem Management. In *E&S* 18 (1). DOI: 10.5751/ES-05093-180103.

Creswell, J. W.; Poth, N. C. (2018): Qualitative Inquiry and Research Design. Choosing among five approaches. 4th edition. Los Angeles, London, New Dehli, Singapore, Washington DC, Melbourne: Sage publications.

Davies, C.; Hansen, R.; Rall, E.; Pauleit, S.; Raffaele Lafortezza ; Yole De Bellis et al. (2015): Green Infrastructure Planning and Implementation - The status of European green space planning and implementation based on an analysis of selected European city-regions (GREEN SURGE Deliverable, 5.1).

Debrunner, G.; Hengstermann, A.; Gerber, J.-D. (2020): The business of densification: distribution of power, wealth and inequality in Swiss policy making. In *Town Planning Review* 91 (3), pp. 259–281. DOI: 10.3828/tpr.2020.15.

Deilami, K.; Kamruzzaman, M.; Liu, Y. (2018): Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. In *International Journal of Applied Earth Observation and Geoinformation* 67, pp. 30–42. DOI: 10.1016/j.jag.2017.12.009.

Demuzere, M.; Orru, K.; Heidrich, O.; Olazabal, E.; Geneletti, D.; Orru, H. et al. (2014): Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. In *Journal of environmental management* 146, pp. 107–115. DOI: 10.1016/j.jenvman.2014.07.025.

Depietri, Y.; Welle, T.; Renaud, F. G. (2013): Social vulnerability assessment of the Cologne urban area (Germany) to heat waves: links to ecosystem services. In *International Journal of Disaster Risk Reduction* 6, pp. 98–117. DOI: 10.1016/j.ijdrr.2013.10.001.

Depietri, Y.; McPhearson, T. (2017): Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In Nadja Kabisch, Horst Korn, Jutta Stadler, Aletta Bonn (Eds.): Nature-Based Solutions to Climate Change Adaptation in Urban Areas, vol. 24. Cham: Springer International Publishing, pp. 91–109.

Djongyang, N.; Tchinda, R.; Njomo, D. (2010): Thermal comfort: A review paper. In *Renewable and Sustainable Energy Reviews* 14 (9), pp. 2626–2640. DOI: 10.1016/j.rser.2010.07.040.

Dorst, H.; van der Jagt, A.; Runhaar, H.; Raven, R. (2021): Structural conditions for the wider uptake of urban nature-based solutions – A conceptual framework. In *Cities* 116, p. 103283. DOI: 10.1016/j.cities.2021.103283.

Dorst, H.; van der Jagt, A.; Toxopeus, H.; Tozer, L.; Raven, R.; Runhaar, H. (2022): What's behind the barriers? Uncovering structural conditions working against urban nature-based solutions. In *Landscape and Urban Planning* 220, p. 104335. DOI: 10.1016/j.landurbplan.2021.104335.

Du Toit, M. J.; Cilliers, S. S.; Dallimer, M.; Goddard, M.; Guenat, S.; Cornelius, S. F. (2018): Urban green infrastructure and ecosystem services in sub-Saharan Africa. In *Landscape and Urban Planning* 180, pp. 249–261. DOI: 10.1016/j.landurbplan.2018.06.001.

Eggimann, S.; Wagner, M.; Ho, Y. N.; Züger, M.; Schneider, U.; Orehounig, K. (2021): Geospatial simulation of urban neighbourhood densification potentials. In *Sustainable Cities and Society* 72, p. 103068. DOI: 10.1016/j.scs.2021.103068.

Eisenack, K.; Moser, S. C.; Hoffmann, E.; Klein, R. J. T.; Oberlack, C.; Pechan, A. et al. (2014): Explaining and overcoming barriers to climate change adaptation. In *Nature Clim Change* 4 (10), pp. 867–872. DOI: 10.1038/NCLIMATE2350.

Elsadek, M.; Liu, B.; Lian, Z. (2019a): Green façades: Their contribution to stress recovery and well-being in high-density cities. In *Urban Forestry & Urban Greening* 46, p. 126446. DOI: 10.1016/j.ufug.2019.126446.

Elsadek, M.; Liu, B.; Lian, Z.; Xie, J. (2019b): The influence of urban roadside trees and their physical environment on stress relief measures: A field experiment in Shanghai. In *Urban Forestry & Urban Greening* 42, pp. 51–60. DOI: 10.1016/j.ufug.2019.05.007.

Elsmore, S. (2020): Strategies of responsibilization: development contributions and the political role of property developers. In *Urban Geography* 41 (3), pp. 389–408. DOI: 10.1080/02723638.2019.1677989.

Emmanuel, R.; Steemers, K. (2018): Connecting the realms of urban form, density and microclimate. In *Building Research & Information* 46 (8), pp. 804–808. DOI: 10.1080/09613218.2018.1507078.

Enssle, F.; Kabisch, N. (2020): Urban green spaces for the social interaction, health and well-being of older people— An integrated view of urban ecosystem services and socio-environmental justice. In *Environmental Science & Policy* 109, pp. 36–44. DOI: 10.1016/j.envsci.2020.04.008.

Erell, E. (2017): Urban Greening and Microclimate Modification. In Puay Yok Tan, Chi Yung Jim (Eds.): Greening Cities. Singapore: Springer Singapore, pp. 73–94.

Erlwein, S.; Zölch, T.; Pauleit, S. (2021): Regulating the microclimate with urban green in densifiying cities: Joint assessment on two scales. In *Building and Environment* 205, p. 108233. DOI: 10.1016/j.buildenv.2021.108233.

Erlwein, S.; Pauleit, S. (2021): Trade-Offs between Urban Green Space and Densification: Balancing Outdoor Thermal Comfort, Mobility, and Housing Demand. In *Urban Planning* 6 (1), pp. 5–19. DOI: 10.17645/up.v6i1.3481.

European Commission (2013): Green Infrastrucutre (GI) - Enhancing Europe's Natural Capital. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Commitee of the Regions. Brussels (COM, 0249). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0249.

European Commission (2016): Assessing Adaptation Knowledge in Europe: Ecosystem-Based Adaptation. Final Report.

European Environmental Agency (EEA) (2012): Urban adaptation to climate change in Europe. Challenges and opportunities for cities together with supportive national and European policies. Copenhagen (EEA report, 2). Available online at: https://www.eea.europa.eu/publications/urban-adaptation-to-climate-change.

European Environmental Agency (EEA) (2018): Land recycling and densification. Available online at: https://www.eea.europa.eu/data-and-maps/indicators/land-recycling-and-densification/assessment-1.

Franck, U.; Krüger, M.; Schwarz, N.; Grossmann, K.; Röder, S.; Schlink, U. (2013): Heat stress in urban areas: Indoor and outdoor temperatures in different urban structure types and subjectively reported well-being during a heat wave in the city of Leipzig. In *metz* 22 (2), pp. 167–177. DOI: 10.1127/0941-2948/2013/0384.

Frerichs, S.; Küpper, C. (2017): Umwelt- und Aufenthaltsqualität in kompakt-urbanen und nutzungsgemischten Stadtstrukturen Analysen, Fallbeispiele, Handlungsansätze unter Nutzung und Weiterentwicklung des Bauplanungs- und Umweltrechts. Umweltbundesamt.

Fuller, R. A.; Gaston, K. J. (2009): The scaling of green space coverage in European cities. In *Biology letters* 5 (3), pp. 352–355. DOI: 10.1098/rsbl.2009.0010.

Fünfgeld, H. (2015): Facilitating local climate change adaptation through transnational municipal networks. In *Current Opinion in Environmental Sustainability* 12, pp. 67–73. DOI: 10.1016/j.cosust.2014.10.011.

Gabriel, K. M. A.; Endlicher, W. R. (2011): Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. In *Environmental pollution (Barking, Essex : 1987)* 159 (8-9), pp. 2044–2050. DOI: 10.1016/j.envpol.2011.01.016.

Gago, E. J.; Roldan, J.; Pacheco-Torres, R.; Ordóñez, J. (2013): The city and urban heat islands: A review of strategies to mitigate adverse effects. In *Renewable and Sustainable Energy Reviews* 25, pp. 749–758. DOI: 10.1016/j.rser.2013.05.057.

Gál, C. V.; Kántor, N. (2020): Modeling mean radiant temperature in outdoor spaces, A comparative numerical simulation and validation study. In *Urban Climate* 32, p. 100571. DOI: 10.1016/j.uclim.2019.100571.

Geo-Net (2021): Windfeldsimulation mit dem Strömungsmodell FITNAH-3D. Available online at: https://geo-net.de/de/wind/fitnah-3d.html; https://www.berlin.de/umweltatlas/_assets/literatur/fitnah_modellanwendung.pdf, checked on 1/19/2021.

Gerhards, I.; Philippi, S.; Scheck, N.; Singer-Posern, S.; Voll, M. (2013): Modellgestützte Klimaanalysen und -bewertungen für die Regionalplanung, Grundlagen für einen Leitfaden, herausgegeben vom Projekt KLAMIS – Klimaanpassung in Mittel- und Südhessen. Available online at: https://landesplanung.hessen.de/sites/landesplanung.hessen.de/files/content-downloads/KlimaMORO_klamis_Leitfaden_Klimamodellierung.pdf.

Göpfert, C.; Wamsler, C.; Lang, W. (2019): A framework for the joint institutionalization of climate change mitigation and adaptation in city administrations. In *Mitigation and adaptation strategies for global change* 24 (1), pp. 1–21. DOI: 10.1007/s11027-018-9789-9.

Gren, Å.; Colding, J.; Berghauser-Pont, M.; Marcus, L. (2019): How smart is smart growth? Examining the environmental validation behind city compaction. In *Ambio* 48 (6), pp. 580–589. DOI: 10.1007/s13280-018-1087-y.

Gross, G.; Raasch, S.; Maronga, B. (2020): MOSAIK - Modellbasierte Stadtplanung und Anwendung im Klimawandel. Abschlussbericht. Hannover. Available online at: http://www.uc2-program.org/MOSAIK%20Verbundbericht%20[UC]2%20Phase%201.pdf.

Gubler, M.; Christen, A.; Remund, J.; Brönnimann, S. (2021): Evaluation and application of a low-cost measurement network to study intra-urban temperature differences during summer 2018 in Bern, Switzerland. In *Urban Climate* 37, p. 100817. DOI: 10.1016/j.uclim.2021.100817.

Haaland, C.; Konijnendijk van den Bosch (2015): Challenges and strategies for urban green-space planning in cities undergoing densification: A review. In *Urban Forestry & Urban Greening* 14 (4), pp. 760–771.

Haaland, C.; Konijnendijk van den Bosch, Cecil (2015): Challenges and strategies for urban green-space planning in cities undergoing densification: A review. In *Urban Forestry & Urban Greening* 14 (4), pp. 760–771. DOI: 10.1016/j.ufug.2015.07.009.

Haase, D.; Larondelle, N.; Andersson, E.; Artmann, M.; Borgström, S.; Breuste, J. et al. (2014): A quantitative review of urban ecosystem service assessments: concepts, models, and implementation. In *Ambio* 43 (4), pp. 413–433. DOI: 10.1007/s13280-014-0504-0.

Ha, J.; Kim, H. J.; With, K. A. (2022): Urban green space alone is not enough: A landscape analysis linking the spatial distribution of urban green space to mental health in the city of Chicago. In *Landscape and Urban Planning* 218, p. 104309. DOI: 10.1016/j.landurbplan.2021.104309.

Hallegatte, S.; Henriet, F.; Corfee-Morlot, J. (2011): The economics of climate change impacts and policy benefits at city scale: a conceptual framework. In *Climatic Change* 104 (1), pp. 51–87. DOI: 10.1007/s10584-010-9976-5.

Hansen, R.; Pauleit, S. (2014): From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. In *Ambio* 43 (4), pp. 516–529.

Hansen, R.; Rolf, W.; Pauleit, S.; Born, D.; Bartz, R.; Kowarik, I. et al. (2017a): Urbane grüne Infrastruktur: Grundlage für attraktive und zukunftsfähige Städte. Hinweise für die kommunale Praxis. F+E-Vorhaben „Grüne Infrastruktur im urbanen Raum: Grundlagen, Planung und Umsetzung in der integrierten Stadtentwicklung". Edited by Bundesamt für Naturschutz (BfN). Bonn.

Hansen, R.; Olafsson, A. S.; van der Jagt, A. P.N.; Rall, E.; Pauleit, S. (2019): Planning multifunctional green infrastructure for compact cities: What is the state of practice? In *Ecological Indicators* 96, pp. 99–110. DOI: 10.1016/j.ecolind.2017.09.042.

Hansen, R.; van Lierop, M.; Rolf, W.; Gantar, D.; Šuklje Erjavec, I.; Rall, E. L.; Pauleit, S. (2021): Using green infrastructure to stimulate discourse with and for planning practice: experiences with fuzzy concepts from a pan-European, a national and a local perspective. In *Socio Ecol Pract Res*. DOI: 10.1007/s42532-021-00087-2.

Hansen, Rieke; Rall, Emily; Rolf, Werner; Pauleit, Stephan (Eds.) (2017b): Urban Green Infrastructure Planning: A Guide for Practitioners. Deliverable 5.3. GREEN SURGE report. Available online at: https://ign.ku.dk/english/green-surge/rapporter/D5_3_Urban_GIP_-_A_guide_for_practitioners.pdf.

Harlan, S. L.; Ruddell, D. M. (2011): Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. In *Current Opinion in Environmental Sustainability* 3 (3), pp. 126–134. DOI: 10.1016/j.cosust.2011.01.001.

Haupt, W.; Coppola, A. (2019): Climate governance in transnational municipal networks: advancing a potential agenda for analysis and typology. In *International Journal of Urban Sustainable Development* 11 (2), pp. 123–140. DOI: 10.1080/19463138.2019.1583235.

He, B.-J.; Ding, L.; Prasad, D. (2020): Urban ventilation and its potential for local warming mitigation: A field experiment in an open low-rise gridiron precinct. In *Sustainable Cities and Society* 55, p. 102028. DOI: 10.1016/j.scs.2020.102028.

Hirashima, S. Q. d. S.; Katzschner, A.; Ferreira, D. G.; Assis, E. S. d.; Katzschner, L. (2018): Thermal comfort comparison and evaluation in different climates. In *Urban Climate* 23, pp. 219–230. DOI: 10.1016/j.uclim.2016.08.007.

Hoelscher, M.-T.; Nehls, T.; Jänicke, B.; Wessolek, G. (2016): Quantifying cooling effects of facade greening: Shading, transpiration and insulation. In *Energy and Buildings* 114, pp. 283–290. DOI: 10.1016/j.enbuild.2015.06.047.

Hölscher, K.; Frantzeskaki, N. (2021): Perspectives on urban transformation research: transformations in, of, and by cities. In *Urban Transform* 3 (1). DOI: 10.1186/s42854-021-00019-z.

Holsen, T. (2020): Negotiations Between Developers and Planning Authorities in Urban Development Projects. In *disP - The Planning Review* 56 (3), pp. 34–46. DOI: 10.1080/02513625.2020.1851904.

Holst, J.; Mayer, H. (2011): Impacts of street design parameters on human-biometeorological variables. In *metz* 20 (5), pp. 541–552. DOI: 10.1127/0941-2948/2011/0254.

Hoover, F.-A.; Meerow, S.; Grabowski, Z. J.; McPhearson, T. (2021): Environmental justice implications of siting criteria in urban green infrastructure planning. In *Journal of Environmental Policy & Planning* 23 (5), pp. 665–682. DOI: 10.1080/1523908X.2021.1945916.

Höppe, P. (1999): The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. In *International Journal of Biometeorology* 43 (2), pp. 71–75. DOI: 10.1007/s004840050118.

Intergovernmental Panel on Climate Change (IPCC) (2007): Climate change 2007. AR4 synthesis report: Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge.

Intergovernmental Panel on Climate Change (IPCC) (2021): Climate Change 2021. The Physical Science Basis. Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Jamei, E.; Rajagopalan, P.; Seyedmahmoudian, M.; Jamei, Y. (2016): Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. In *Renewable and Sustainable Energy Reviews* 54, pp. 1002–1017. DOI: 10.1016/j.rser.2015.10.104.

Jänicke, B.; Meier, F.; Hoelscher, M.-T.; Scherer, D. (2015): Evaluating the Effects of Façade Greening on Human Bioclimate in a Complex Urban Environment. In *Advances in Meteorology* 2015, pp. 1–15. DOI: 10.1155/2015/747259.

Jennings, V.; Bamkole, O. (2019): The Relationship between Social Cohesion and Urban Green Space: An Avenue for Health Promotion. In *International journal of environmental research and public health* 16 (3). DOI: 10.3390/ijerph16030452.

Jin, L.; Schubert, S.; Fenner, D.; Salim, M. H.; Schneider, C. (2022): Estimation of mean radiant temperature in cities using an urban parameterization and building energy model within a mesoscale atmospheric model. In *metz* 31 (1), pp. 31–52. DOI: 10.1127/metz/2021/1091.

Kabisch, N.; Haase, D. (2013): Green spaces of European cities revisited for 1990–2006. In *Landscape and Urban Planning* 110, pp. 113–122. DOI: 10.1016/j.landurbplan.2012.10.017.

Kabisch, N.; Kraemer, R.; Masztalerz, O.; Hemmerling, J.; Püffel, C.; Haase, D. (2021): Impact of summer heat on urban park visitation, perceived health and ecosystem service appreciation. In *Urban Forestry & Urban Greening* 60, p. 127058. DOI: 10.1016/j.ufug.2021.127058.

Katzschner, L. (2006): Behaviour of people in open spaces in dependence of thermal comfort conditions. Geneva, Switzerland. Available online at: http://web5.arch.cuhk.edu.hk/server1/staff1/edward/www/plea2018/plea/2006/Vol1/PLEA2006_PAPER714.pdf.

KERN, K.; Bulkeley, H. (2009): Cities, Europeanization and Multi-level Governance: Governing Climate Change through Transnational Municipal Networks. In *JCMS: Journal of Common Market Studies* 47 (2), pp. 309–332. DOI: 10.1111/j.1468-5965.2009.00806.x.

Khoshkar, S.; Balfors, B.; Wärnbäck, A. (2018): Planning for green qualities in the densification of suburban Stockholm – opportunities and challenges. In *Journal of Environmental Planning and Management* 61 (14), pp. 2613–2635. DOI: 10.1080/09640568.2017.1406342.

Khoshkar, S. (2020): From vision to action- advancing green qualities in local planning practice. Doctoral thesis. Royal Institute of Technology, Stockholm.

Klemm, W.; Heusinkveld, B. G.; Lenzholzer, S.; Jacobs, M. H.; van Hove, B. (2015): Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands. In *Building and Environment* 83, pp. 120–128. DOI: 10.1016/j.buildenv.2014.05.013.

Klemm, W.; Lenzholzer, S.; van den Brink, A. (2017): Developing green infrastructure design guidelines for urban climate adaptation. In *Journal of Landscape Architecture* 12 (3), pp. 60–71. DOI: 10.1080/18626033.2017.1425320.

Klemm, W. (2018): Clever and cool. Generating design guidelines for climate-responsive urban green infrastructure. Doctoral thesis. Wageningen University & Research, Wageningen. Landscape Architecture.

Knöll, M.; Neuheuser, K.; Cleff, T.; Rudolph-Cleff, A. (2018): A tool to predict perceived urban stress in open public spaces. In *Environment and Planning B: Urban Analytics and City Science* 45 (4), pp. 797–813. DOI: 10.1177/0265813516686971.

Konarska, J.; Lindberg, F.; Larsson, A.; Thorsson, S.; Holmer, B. (2014): Transmissivity of solar radiation through crowns of single urban trees—application for outdoor thermal comfort modelling. In *Theor Appl Climatol* 117 (3-4), pp. 363–376. DOI: 10.1007/s00704-013-1000-3.

Konarska, J.; Holmer, B.; Lindberg, F.; Thorsson, S. (2016a): Influence of vegetation and building geometry on the spatial variations of air temperature and cooling rates in a high-latitude city. In *Int. J. Climatol.* 36 (5), pp. 2379–2395. DOI: 10.1002/joc.4502.

Konarska, J.; Uddling, J.; Holmer, B.; Lutz, M.; Lindberg, F.; Pleijel, H.; Thorsson, S. (2016b): Transpiration of urban trees and its cooling effect in a high latitude city. In *International Journal of Biometeorology* 60 (1), pp. 159–172. DOI: 10.1007/s00484-015-1014-x.

Kondo, M. C.; Fluehr, J. M.; McKeon, T.; Branas, C. C. (2018): Urban green space and its impact on human health. In *International journal of environmental research and public health* 15 (445). DOI: 10.3390/ijerph15030445.

Krehl, A.; Siedentop, S.; Taubenböck, H.; Wurm, M. (2016): A Comprehensive View on Urban Spatial Structure: Urban Density Patterns of German City Regions. In *IJGI* 5 (6), p. 76. DOI: 10.3390/ijgi5060076.

Krüger, E. L.; Rossi, F.; Drach, P. (2017): Calibration of the physiological equivalent temperature index for three different climatic regions. In *International Journal of Biometeorology* 61 (7), pp. 1323–1336. DOI: 10.1007/s00484-017-1310-8.

Kyttä, M.; Broberg, A.; Tzoulas, T.; Snabb, K. (2013): Towards contextually sensitive urban densification: Location-based softGIS knowledge revealing perceived residential environmental quality. In *Landscape and Urban Planning* 113, pp. 30–46. DOI: 10.1016/j.landurbplan.2013.01.008.

Landeshauptstadt München (LHM) (2011): Langfristige Siedlungsentwicklung. Kongressinformation. München. Available online at: https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Stadtplanung-und-Bauordnung/Projekte/Langfristige-Siedlungsentwicklung/Projekt/Verdichtung.html.

Landeshauptstadt München (LHM) (2014): Stadtklimaanalyse Landeshauptstadt München. Hannover. Available online at: https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Gesundheit-und-Umwelt/Stadtklima/Stadtklimaanalyse.html.

Landeshauptstadt München (LHM) (2016): Konzept zur Anpassung an die Folgen des Klimawandels in der Landeshauptstadt München. With assistance of Veronika Wirth, Michael Schneider, Johannes Rupp. Edited by Referat für Gesundheit und Umwelt. München, Augsburg, Berlin. Available online at: https://www.muenchen.de/rathaus/dam/jcr:8eb68d50-5c21-4948-92ae-62fa129ab566/bericht_klwa_10_2016.pdf.

Landeshauptstadt München (LHM) (2018a): Langfristige Siedlungsentwicklung – Zweiter Statusbericht. Sitzungsvorlagen Nr. 14-20 / V 12595. Available online at: https://www.ris-muenchen.de/RII/RII/DOK/SITZUNGSVORLAGE/5137164.pdf.

Landeshauptstadt München (LHM) (2018b): Prüfauftrag "Mehr Begrünung in München". Mehr Gebäudebegrünung in München umsetzen. Sitzungsvorlage Nr. 14-20/V 12406. Available online at: https://www.ris-muenchen.de/RII/RII/DOK/SITZUNGSVORLAGE/5164391.pdf.

Lange, A.; Ebert, S.; Vetter, A. (2020): Adaptation Requires Participation: Criteria and Factors for Successful Stakeholder Interactions in Local Climate Change Adaptation. In Walter Leal Filho, Johannes Luetz, Desalegn Ayal (Eds.): Handbook of Climate Change Management. Cham: Springer International Publishing, pp. 1–30.

Lau, K. K.-L.; Lindberg, F.; Rayner, D.; Thorsson, S. (2015): The effect of urban geometry on mean radiant temperature under future climate change: a study of three European cities. In *International Journal of Biometeorology* 59 (7), pp. 799–814. DOI: 10.1007/s00484-014-0898-1.

Lee, H.; Mayer, H.; Chen, L. (2016): Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany. In *Landscape and Urban Planning* 148, pp. 37–50. DOI: 10.1016/j.landurbplan.2015.12.004.

Lee, H.; Mayer, H. (2016): Validation of the mean radiant temperature simulated by the RayMan software in urban environments. In *International Journal of Biometeorology* 60 (11), pp. 1775–1785. DOI: 10.1007/s00484-016-1166-3.

Lee, H.; Mayer, H. (2018): Maximum extent of human heat stress reduction on building areas due to urban greening. In *Urban Forestry & Urban Greening* 32, pp. 154–167.

Lee, H.; Mayer, H.; Kuttler, W. (2020): Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions. In *Urban Forestry & Urban Greening* 48, p. 126558. DOI: 10.1016/j.ufug.2019.126558.

Lehmann, P.; Brenck, M.; Gebhardt, O.; Schaller, S.; Süßbauer, E. (2015): Barriers and opportunities for urban adaptation planning: analytical framework and evidence from cities in Latin America and Germany. In *Mitig Adapt Strateg Glob Change* 20 (1), pp. 75–97. DOI: 10.1007/s11027-013-9480-0.

Lemonsu, A.; Amossé, A.; Chouillou, D.; Gaudio, N.; Haouès-Jouve, S.; Hidalgo, J. et al. (2020): Comparison of microclimate measurements and perceptions as part of a global evaluation of environmental quality at neighbourhood scale. In *International Journal of Biometeorology* 64 (2), pp. 265–276. DOI: 10.1007/s00484-019-01686-1.

Lenzholzer, S.; Klemm, W.; Vasilikou, C. (2018): Qualitative methods to explore thermo-spatial perception in outdoor urban spaces. In *Urban Climate* 23, pp. 231–249. DOI: 10.1016/j.uclim.2016.10.003.

Li, J.; Zheng, B.; Shen, W.; Xiang, Y.; Chen, X.; Qi, Z. (2019): Cooling and Energy-Saving Performance of Different Green Wall Design: A Simulation Study of a Block. In *Energies* 12 (15), p. 2912. DOI: 10.3390/en12152912.

Li, M.; Verburg, P. H.; van Vliet, J. (2022): Global trends and local variations in land take per person. In *Landscape and Urban Planning* 218, p. 104308. DOI: 10.1016/j.landurbplan.2021.104308.

Lin, B.; Meyers, J.; Barnett, G. (2015): Understanding the potential loss and inequities of green space distribution with urban densification. In *Urban Forestry & Urban Greening* 14 (4), pp. 952–958. DOI: 10.1016/j.ufug.2015.09.003.

Lindberg, F.; Holmer, B.; Thorsson, S. (2008): SOLWEIG 1.0--modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. In *International Journal of Biometeorology* 52 (7), pp. 697–713. DOI: 10.1007/s00484-008-0162-7.

Lindberg, F.; Grimmond, C.S.B. (2011): The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation. In *Theor Appl Climatol* 105 (3-4), pp. 311–323. DOI: 10.1007/s00704-010-0382-8.

Lindberg, F.; Grimmond, C.S.B.; Gabey, A.; Huang, B.; Kent, C. W.; Sun, T. et al. (2018): Urban Multi-scale Environmental Predictor (UMEP): An integrated tool for city-based climate services. In *Environmental Modelling & Software* 99, pp. 70–87. DOI: 10.1016/j.envsoft.2017.09.020.

Lindley, S.; Pauleit, S.; Yeshitela, K.; Cilliers, S.; Shackleton, C. (2018): Rethinking urban green infrastructure and ecosystem services from the perspective of sub-Saharan African cities. In *Landscape and Urban Planning* 180, pp. 328–338. DOI: 10.1016/j.landurbplan.2018.08.016.

Liu, D.; Hu, S.; Liu, J. (2020): Contrasting the performance capabilities of urban radiation field between three microclimate simulation tools. In *Building and Environment* 175, p. 106789. DOI: 10.1016/j.buildenv.2020.106789.

Lobaccaro, G.; Acero, J. A.; Martinez, G. S.; Padro, A.; Laburu, T.; Fernandez, G. (2019): Effects of Orientations, Aspect Ratios, Pavement Materials and Vegetation Elements on Thermal Stress inside Typical Urban Canyons. In *International journal of environmental research and public health* 16 (19). DOI: 10.3390/ijerph16193574.

Loibl, W.; Etminan, G.; Österreicher, D.; Ratheiser, M.; Stollnberger, R.; Tschannett, S. et al. (2019): Urban Densification and Urban Climate Change – Assessing Interaction through Densification Scenarios and Climate Simulations. In Manfred Schrenk, Vasily V. Popovich, Peter Zeile, Pietro Elisei, Clemens Beyer, Judith Ryser (Eds.): IS THIS THE REAL WORLD? Perfect Smart Cities vs. Real Emotional Cities. Proceedings of the 24th International Conference on Urban Planning, Regional Development and Information Society. Schwechat: CORP - Competence Center of Urban and Regional Planning.

Loorbach, D.; Wittmayer, J.; Avelino, F.; Wirth, T. von; Frantzeskaki, N. (2020): Transformative innovation and translocal diffusion. In *Environmental Innovation and Societal Transitions* 35, pp. 251–260. DOI: 10.1016/j.eist.2020.01.009.

Martilli, A. (2014): An idealized study of city structure, urban climate, energy consumption, and air quality. In *Urban Climate* 10, pp. 430–446. DOI: 10.1016/j.uclim.2014.03.003.

Matthews, T.; Lo, A. Y.; Byrne, J. A. (2015): Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. In *Landscape and Urban Planning* 138, pp. 155–163. DOI: 10.1016/j.landurbplan.2015.02.010.

Mattijssen, T.J.M.; van der Jagt, A.P.N.; Buijs, A. E.; Elands, B.H.M.; Erlwein, S.; Lafortezza, R. (2017): The long-term prospects of citizens managing urban green space: From place making to place-keeping? In *Urban Forestry & Urban Greening* 26, pp. 78–84. DOI: 10.1016/j.ufug.2017.05.015.

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

Matzarakis, A.; Rutz, F.; Mayer, H. (2010): Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. In *International Journal of Biometeorology* 54 (2), pp. 131–139. DOI: 10.1007/s00484-009-0261-0.

Matzarakis, A.; Laschewski, G.; Muthers, S. (2020): The Heat Health Warning System in Germany—Application and Warnings for 2005 to 2019. In *Atmosphere* 11 (2), p. 170. DOI: 10.3390/atmos11020170.

Mayer, H.; Höppe, P. (1987): Thermal comfort of man in different urban environments. In *Theor Appl Climatol* 38 (1), pp. 43–49. DOI: 10.1007/BF00866252.

Miroshnyk, N. V.; Likhanov, A. F.; Grabovska, T. O.; Teslenko, I. K.; Roubík, H. (2022): Green infrastructure and relationship with urbanization – Importance and necessity of integrated governance. In *Land Use Policy* 114, p. 105941. DOI: 10.1016/j.landusepol.2021.105941.

Moonen, P.; Defraeye, T.; Dorer, V.; Blocken, B.; Carmeliet, J. (2012): Urban Physics: Effect of the micro-climate on comfort, health and energy demand. In *Frontiers of Architectural Research* 1 (3), pp. 197–228. DOI: 10.1016/j.foar.2012.05.002.

Mora, C.; Counsell, C. W. W.; Bielecki, C. R.; Louis, L. V. (2017): Twenty-Seven Ways a Heat Wave Can Kill You: Deadly Heat in the Era of Climate Change. In *Circulation. Cardiovascular quality and outcomes* 10 (11). DOI: 10.1161/CIRCOUTCOMES.117.004233.

Morakinyo, T. E.; Lam, Y. F. (2016): Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. In *Building and Environment* 103, pp. 262–275. DOI: 10.1016/j.buildenv.2016.04.025.

Morakinyo, T. E.; Lau, K. K.-L.; Ren, C.; Ng, E. (2018): Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving. In *Building and Environment* 137, pp. 157–170. DOI: 10.1016/j.buildenv.2018.04.012.

Moser-Reischl, A.; Rahman, M. A.; Pauleit, S.; Pretzsch, H.; Rötzer, T. (2019): Growth patterns and effects of urban micro-climate on two physiologically contrasting urban tree species. In *Landscape and Urban Planning* 183, pp. 88–99. DOI: 10.1016/j.landurbplan.2018.11.004.

Moser, S. C.; Ekstrom, J. A. (2010): A framework to diagnose barriers to climate change adaptation. In *Proceedings of the National Academy of Sciences of the United States of America* 107 (51), pp. 22026–22031. DOI: 10.1073/pnas.1007887107.

Mühlbacher, G.; Koßmann, M.; Sedlmaier, K.; Winderlich, K. (2020): Stadtklimatische Untersuchungen der sommerlichen Temperaturverhältnisse und des Tagesgangs des Regionalwindes ("Alpines Pumpen") in München. Offenbach: Deutscher Wetterdienst (Berichte des Deutschen Wetterdienstes, 252). Available online at: https://refubium.fu-berlin.de/bitstream/handle/fub188/27970/252_pdf.pdf?sequence=1&isAllowed=y.

Müller, N.; Kuttler, W.; Barlag, A.-B. (2014): Counteracting urban climate change: adaptation measures and their effect on thermal comfort. In *Theor Appl Climatol* 115 (1-2), pp. 243–257. DOI: 10.1007/s00704-013-0890-4.

Neuman, M. (2005): The Compact City Fallacy. In *Journal of Planning Education and Research* 25 (1), pp. 11–26. DOI: 10.1177/0739456X04270466.

Nikolopoulou, M.; Steemers, K. (2003): Thermal comfort and psychological adaptation as a guide for designing urban spaces. In *Energy and Buildings* 35, pp. 95–101. DOI: 10.1016/S0140-6701(03)92082-0.

Norton, B. A.; Coutts, A. M.; Livesley, S. J.; Harris, R. J.; Hunter, A. M.; Williams, N. S.G. (2015): Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. In *Landscape and Urban Planning* 134, pp. 127–138. DOI: 10.1016/j.landurbplan.2014.10.018.

Okamoto-Mizuno, K.; Mizuno, K. (2012): Effects of thermal environment on sleep and circadian rhythm. In *Journal of physiological anthropology* 31, p. 14. DOI: 10.1186/1880-6805-31-14.

Oke, T. R. (1982): The energetic basis of the urban heat island. In *Q.J Royal Met. Soc.* 108 (455), pp. 1–24. DOI: 10.1002/qj.49710845502.

Oke, T. R. (2011): Urban heat islands. In I. Douglas, D. Goode, M. Houck, R. Wang (Eds.): The Routledge Handbook of Urban Ecology. London, pp. 120–131.

Oke, T. R.; Mills, G.; Christen, A.; Voogt, J. A. (2017): Urban climates. Cambridge: Cambridge University Press.

Olazabal, M.; Galarraga, I.; Ford, J.; Sainz De Murieta, E.; Lesnikowski, A. (2019): Are local climate adaptation policies credible? A conceptual and operational assessment framework. In *International Journal of Urban Sustainable Development* 11 (3), pp. 277–296. DOI: 10.1080/19463138.2019.1583234.

Onomura, S.; Holmer, B.; Lindberg, F.; Thorsson, S. (2016): Intra-urban nocturnal cooling rates: development and evaluation of the NOCRA model. In *Met. Apps* 23 (3), pp. 339–352. DOI: 10.1002/met.1558.

Pauleit, S.; Ennos, R.; Golding, Y. (2005): Modeling the environmental impacts of urban land use and land cover change—a study in Merseyside, UK. In *Landscape and Urban Planning* 71 (2-4), pp. 295–310. DOI: 10.1016/j.landurbplan.2004.03.009.

Pauleit, S.; Golding, Y. (2005): The spatial impact of urban compaction: A fine-scale investigation based on Merseyside. In *Town Planning Review* 76 (2), pp. 143–166. DOI: 10.3828/tpr.76.2.3.

Pauleit, S.; Zölch, T.; Hansen, R.; Randrup, T. B.; van den Bosch, C. K. (2017): Nature-Based Solutions and Climate Change- Four Shades of Green. In Nadja Kabisch, Horst Korn, Jutta Stadler, Aletta Bonn (Eds.): Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Cham: Springer International Publishing, pp. 29–49.

Pauleit, S.; Hansen, R.; Lindschulte, K.; Rolf, W.; Bartz, R.; Becker, C. W.; Kowarik, I. (2018): Alles wird grün? Die Chancen von grüner Infrastruktur im Rahmen der Nachverdichtung. In Ilke Marschall (Ed.): Landschaftsplanung im Prozess und Dialog. Beiträge zur gemeinsamen Fachtagung von BfN, BBN und FH Erfurt vom 27.03.-29.03.2017 in Erfurt. Bonn: BfN (BfN-Skripten, 498), pp. 140–153.

Pauleit, S.; Vasquéz, A.; Maruthaveeran, S.; Liu, L.; Cilliers, S. S. (2021): Urban Green Infrastructure in the Global South. In Charlie M. Shackleton, Sarel S. Cilliers, Elandrie Davoren, Marié J. Du Toit (Eds.): Urban Ecology in the Global South. Cham: Springer International Publishing (Cities and Nature), pp. 107–143.

Pearlmutter, D.; Jiao, D.; Garb, Y. (2014): The relationship between bioclimatic thermal stress and subjective thermal sensation in pedestrian spaces. In *International Journal of Biometeorology* 58 (10), pp. 2111–2127. DOI: 10.1007/s00484-014-0812-x.

Pérez, G.; Coma, J.; Martorell, I.; Cabeza, L. F. (2014): Vertical Greenery Systems (VGS) for energy saving in buildings: A review. In *Renewable and Sustainable Energy Reviews* 39, pp. 139–165. DOI: 10.1016/j.rser.2014.07.055.

Perini, K.; Magliocco, A. (2014): Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. In *Urban Forestry & Urban Greening* 13 (3), pp. 495–506. DOI: 10.1016/j.ufug.2014.03.003.

Perini, K.; Chokhachian, A.; Auer, T. (2018): Green Streets to Enhance Outdoor Comfort. In : Nature Based Strategies for Urban and Building Sustainability: Elsevier, pp. 119–129.

Rahman, M. A.; Armson, D.; Ennos, A. R. (2015): A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. In *Urban Ecosyst* 18 (2), pp. 371–389. DOI: 10.1007/s11252-014-0407-7.

Rahman, M. A.; Moser, A.; Rötzer, T.; Pauleit, S. (2017): Within canopy temperature differences and cooling ability of Tilia cordata trees grown in urban conditions. In *Building and Environment* 114, pp. 118–128. DOI: 10.1016/j.buildenv.2016.12.013.

Rahman, M. A.; Moser-Reischl, A.; Rötzer, T.; Pauleit, S. (2019): Comparing the transpirational and shading effects of two contrasting urban tree species. In *Urban Ecosyst* 22 (4), pp. 683–697. DOI: 10.1007/s11252-019-00853-x.

Rahman, M. A.; Stratopoulos, L. M.F.; Moser-Reischl, A.; Zölch, T.; Häberle, K.-H.; Rötzer, T. et al. (2020): Traits of trees for cooling urban heat islands: A meta-analysis. In *Building and Environment* 170, p. 106606. DOI: 10.1016/j.buildenv.2019.106606.

Rall, E.; Bieling, C.; Zytynska, S.; Haase, D. (2017): Exploring city-wide patterns of cultural ecosystem service perceptions and use. In *Ecological Indicators* 77, pp. 80–95. DOI: 10.1016/j.ecolind.2017.02.001.

Rall, E. L.; Kabisch, N.; Hansen, R. (2015): A comparative exploration of uptake and potential application of ecosystem services in urban planning. In *Ecosystem Services* 16, pp. 230–242. DOI: 10.1016/j.ecoser.2015.10.005.

Rall, E. L. (2018): Forms of Engagement: Public Participation Geographic Information Systems as a Tool for Cultural Ecosystem Service Assessment and Urban Green Infrastructure Planning. Doctoral thesis. Technische Universität München (TUM), Freising. Chair for Strategic Landscape Management and Planning.

Ramyar, R.; Ramyar, A.; Kialashaki, Y.; Bryant, M.; Ramyar, H. (2019): Exploring reconfiguration scenarios of high-density urban neighborhoods on urban temperature–The case of Tehran (Iran). In *Urban Forestry & Urban Greening* 44, p. 126398. DOI: 10.1016/j.ufug.2019.126398.

Rapoport, A. (1975): Toward a Redefinition of Density. In *Environment and Behavior* 7 (2), pp. 133–158. DOI: 10.1177/001391657500700202.

Reklaitiene, R.; Grazuleviciene, R.; Dedele, A.; Virviciute, D.; Vensloviene, J.; Tamosiunas, A. et al. (2014): The relationship of green space, depressive symptoms and perceived general health in urban population. In *Scandinavian journal of public health* 42 (7), pp. 669–676. DOI: 10.1177/1403494814544494.

Robine, J.-M.; Cheung, S. L. K.; Le Roy, S.; van Oyen, H.; Griffiths, C.; Michel, J.-P.; Herrmann, F. R. (2008): Death toll exceeded 70,000 in Europe during the summer of 2003. In *Comptes rendus biologies* 331 (2), pp. 171–178. DOI: 10.1016/j.crvi.2007.12.001.

Rogers, C.D.W.; Kornhuber, K.; Perkins-Kirkapatrick, S. E.; Loikith, P. C.; Singh, D. (2022): Sixfold Increase in Historical Northern Hemisphere Concurrent Large Heatwaves Driven by Warming and Changing Atmospheric Circulations. In *Journal of Climate* 35 (3), pp. 1063–1078. DOI: 10.1175/JCLI-D-21-0200.1.

Rosenberger, L.; Leandro, J.; Pauleit, S.; Erlwein, S. (2021): Sustainable stormwater management under the impact of climate change and urban densification. In *Journal of Hydrology* 596, p. 126137. DOI: 10.1016/j.jhydrol.2021.126137.

Salmond, J. A.; Tadaki, M.; Vardoulakis, S.; Arbuthnott, K.; Coutts, A.; Demuzere, M. et al. (2016): Health and climate related ecosystem services provided by street trees in the urban environment. In *Environmental health : a global access science source* 15 Suppl 1, p. 36. DOI: 10.1186/s12940-016-0103-6.

Sanusi, R.; Johnstone, D.; May, P.; Livesley, S. J. (2016): Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer. In *Journal of environmental quality* 45 (1), pp. 167–174. DOI: 10.2134/jeq2015.01.0039.

Schneider, A.; Woodcock, C. E. (2008): Compact, Dispersed, Fragmented, Extensive? A Comparison of Urban Growth in Twenty-five Global Cities using Remotely Sensed Data, Pattern Metrics and Census Information. In *Urban Studies* 45 (3), pp. 659–692. DOI: 10.1177/0042098007087340.

Seto, K. C.; Güneralp, B.; Hutyra, L. R. (2012): Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. In *Proceedings of the National Academy of Sciences of the United States of America* 109 (40), pp. 16083–16088. DOI: 10.1073/pnas.1211658109.

Sharifi, F.; Nygaard, A.; Stone, W. M. (2021): Heterogeneity in the subjective well-being impact of access to urban green space. In *Sustainable Cities and Society* 74, p. 103244. DOI: 10.1016/j.scs.2021.103244.

Shashua-Bar, L.; Hoffman, M. E.; Tzamir, Y. (2006): Integrated thermal effects of generic built forms and vegetation on the UCL microclimate. In *Building and Environment* 41 (3), pp. 343–354. DOI: 10.1016/j.buildenv.2005.01.032.

Siedentop, S. (2018): Ursachen der Flächeninanspruchnahme in Deutschland – eine Zwischenbilanz. In Martin Behnisch, Odette Kretschmer, Gotthard Meinel (Eds.): Flächeninanspruchnahme in Deutschland. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 45–55.

Simon, H. (2016): Modeling urban microclimate. Development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met. Dissertation. Johannes Gutenberg-University, Mainz. Available online at: https://openscience.ub.uni-mainz.de/handle/20.500.12030/4044.

Sjöman, H.; Gunarsson, A.; Pauleit, S. (2012): Selection approach of urban trees for inner-city environments: learning from nature. In *Arboriculture&Urban Forestry* 38 (5), pp. 194–204.

Sjöman, H.; Hirons, A. D.; Bassuk, N. L. (2018): Improving confidence in tree species selection for challenging urban sites: a role for leaf turgor loss. In *Urban Ecosyst* 21 (6), pp. 1171–1188. DOI: 10.1007/s11252-018-0791-5.

Smoyer-Tomic, K. E.; Kuhn, R.; Hudson, A. (2003): Heat Wave Hazards: An Overview of Heat Wave Impacts in Canada. In *Natural Hazards* 28 (2/3), pp. 465–486. DOI: 10.1023/A:1022946528157.

Staiger, H.; Laschewski, G.; Matzarakis, A. (2019): Selection of Appropriate Thermal Indices for Applications in Human Biometeorological Studies. In *Atmosphere* 10 (18) (1). DOI: 10.3390/atmos10010018.

Statistisches Bundesamt (2021): Bautätigkeit und Wohnungen. Bestand an Wohnungen (Fachserie 5, Reihe 3). Available online at: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Wohnen/Publikationen/Downloads-Wohnen/bestand-wohnungen-2050300207004.html.

Stewart, I. D.; Oke, T. R. (2012): Local Climate Zones for Urban Temperature Studies. In *Bull. Amer. Meteor. Soc.* 93 (12), pp. 1879–1900. DOI: 10.1175/BAMS-D-11-00019.1.

Stieß, I.; Umbach-Daniel, A.; Fischer, C. (2019): Smart small living? Social innovations for saving energy in senior citizens’ households by reducing living space. In *Energy Policy* 133, p. 110906. DOI: 10.1016/j.enpol.2019.110906.

Tan, Z.; Lau, K. K.-L.; Ng, E. (2016): Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. In *Energy and Buildings* 114, pp. 265–274. DOI: 10.1016/j.enbuild.2015.06.031.

Thom, J. K.; Coutts, A. M.; Broadbent, A. M.; Tapper, N. J. (2016): The influence of increasing tree cover on mean radiant temperature across a mixed development suburb in Adelaide, Australia. In *Urban Forestry & Urban Greening* 20, pp. 233–242. DOI: 10.1016/j.ufug.2016.08.016.

Thorsson, S.; Lindberg, F.; Eliasson, I.; Holmer, B. (2007): Different methods for estimating the mean radiant temperature in an outdoor urban setting. In *Int. J. Climatol.* 27 (14), pp. 1983–1993. DOI: 10.1002/joc.1537.

Tichelmann, K.; Groß, K.; Günther, M. (2016): Wohnraumpotentiale durch Aufstockungen. Deutschlandstudie 2015. Darmstadt. Available online at: https://www.baustoffindustrie.de/fileadmin/user_upload/bbs/Dateien/Downloadarchiv/Bauwirtschaft/Aufstockung_Langfassung.pdf.

Trepl, L. (1994): Geschichte der Ökologie, vom 17. Jahrhundert bis zur Gegenwart: Beltz Athenäum.

Tsoka, S.; Tsikaloudaki, A.; Theodosiou, T. (2018): Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–A review. In *Sustainable Cities and Society* 43, pp. 55–76. DOI: 10.1016/j.scs.2018.08.009.

Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kaźmierczak, A.; Niemela, J.; James, P. (2007): Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. In *Landscape and Urban Planning* 81 (3), pp. 167–178. DOI: 10.1016/j.landurbplan.2007.02.001.

Uittenbroek, C. J.; Janssen-Jansen, L. B.; Runhaar, H. A. C. (2013): Mainstreaming climate adaptation into urban planning: overcoming barriers, seizing opportunities and evaluating the results in two Dutch case studies. In *Reg Environ Change* 13 (2), pp. 399–411. DOI: 10.1007/s10113-012-0348-8.

Umweltbundesamt (UBA) (2021): Siedlungs-und Verkehrsfläche. Available online at: https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/siedlungs-verkehrsflaeche#anhaltender-flachenverbrauch-fur-siedlungs-und-verkehrszwecke-, checked on 2/3/2022.

UN-Habitat (2020): The value of sustainable urbanization. World Cities Report 2020. Nairobi, Kenya.

United Nations (UN) (2016): The Sustainable Development Goals Report. New York. Available online at: https://unstats.un.org/sdgs/report/2016/the%20sustainable%20development%20goals%20report%202016.pdf.

United Nations (UN) (2017): New Urban Agenda. Available online at: https://unhabitat.org/sites/default/files/2019/05/nua-english.pdf.

United Nations (UN) (2018): World Urbanisation Prospects: The 2018 Revision. Key Facts. Department of Economic and Social Affairs, Population Division.

van Gossum, P.; Arts, B.; Wulf, R. de; Verheyen, K. (2011): An institutional evaluation of sustainable forest management in Flanders. In *Land Use Policy* 28 (1), pp. 110–123. DOI: 10.1016/j.landusepol.2010.05.005.

van Herzele, A.; Vries, S. de (2012): Linking green space to health: a comparative study of two urban neighbourhoods in Ghent, Belgium. In *Popul Environ* 34 (2), pp. 171–193. DOI: 10.1007/s11111-011-0153-1.

Verein deutscher Ingenieure (VDI) (2008a): Environmental meteorology: Local cold air. Guideline 3787, sheet 5. Available online at: https://www.vdi.de/richtlinien/details/vdi-3787-blatt-5-umweltmeteorologie-lokale-kaltluft-1.

Verein deutscher Ingenieure (VDI) (2008b): Environmental meteorology: Methods and presentation of investigations relevant for planning urban climate. Guideline 3787, sheet 1. Available online at: https://www.vdi.de/richtlinien/details/vdi-3785-blatt-1-umweltmeteorologie-methodik-und-ergebnisdarstellung-von-untersuchungen-zum-planungsrelevanten-stadtklima.

Wamsler, C.; Brink, E.; Rivera, C. (2013): Planning for climate change in urban areas: from theory to practice. In *Journal of Cleaner Production* 50, pp. 68–81. DOI: 10.1016/j.jclepro.2012.12.008.

Wamsler, C.; Luederitz, C.; Brink, E. (2014): Local levers for change: Mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. In *Global Environmental Change* 29, pp. 189–201. DOI: 10.1016/j.gloenvcha.2014.09.008.

Wamsler, C. (2015): Mainstreaming ecosystem-based adaptation: transformation toward sustainability in urban governance and planning. In *E&S* 20 (2). DOI: 10.5751/ES-07489-200230.

Wamsler, C.; Niven, L.; Beery, T. H.; Bramryd, T.; Ekelund, N.; Jönsson, K. I. et al. (2016): Operationalizing ecosystem-based adaptation: harnessing ecosystem services to buffer communities against climate change. In *E&S* 21 (1). DOI: 10.5751/ES-08266-210131.

Wamsler, C.; Pauleit, S.; Zölch, T.; Schetke, S.; Mascarenhas, A. (2017): Mainstreaming Nature-Based Solutions for Climate Change Adaptation in Urban Governance and Planning. In Nadja Kabisch, Horst Korn, Jutta Stadler, Aletta Bonn (Eds.): Nature-Based Solutions to Climate Change Adaptation in Urban Areas, vol. 23. Cham: Springer International Publishing, pp. 257–273.

Wamsler, C.; Alkan-Olsson, J.; Björn, H.; Falck, H.; Hanson, H.; Oskarsson, T. et al. (2020a): Beyond participation: when citizen engagement leads to undesirable outcomes for nature-based solutions and climate change adaptation. In *Climatic Change* 158 (2), pp. 235–254. DOI: 10.1007/s10584-019-02557-9.

Wamsler, C.; Wickenberg, B.; Hanson, H.; Alkan Olsson, J.; Stålhammar, S.; Björn, H. et al. (2020b): Environmental and climate policy integration: Targeted strategies for overcoming barriers to nature-based solutions and climate change adaptation. In *Journal of Cleaner Production* 247, p. 119154. DOI: 10.1016/j.jclepro.2019.119154.

Wang, Y.; Groot, R. de; Bakker, F.; Wörtche, H.; Leemans, R. (2017): Thermal comfort in urban green spaces: a survey on a Dutch university campus. In *International Journal of Biometeorology* 61 (1), pp. 87–101. DOI: 10.1007/s00484-016-1193-0.

Ward Thompson, C.; Lauf, S.; Kleinschmit, B.; Endlicher, W. (2016): Heat waves and urban heat islands in Europe: A review of relevant drivers. In *The Science of the total environment* 569-570, pp. 527–539. DOI: 10.1016/j.scitotenv.2016.06.119.

Ward, H. C.; Grimmond, C.S.B. (2017): Assessing the impact of changes in surface cover, human behaviour and climate on energy partitioning across Greater London. In *Landscape and Urban Planning* 165, pp. 142–161. DOI: 10.1016/j.landurbplan.2017.04.001.

Wegmann, J.; Nemirow, A. (2011): Secondary units and urban infill: A literature review. University of California, Institute of Urban and Regional Development. Berkeley (Working Paper, No. 2011-02).

Wellmann, T.; Schug, F.; Haase, D.; Pflugmacher, D.; van der Linden, S. (2020): Green growth? On the relation between population density, land use and vegetation cover fractions in a city using a 30-years Landsat time series. In *Landscape and Urban Planning* 202, p. 103857. DOI: 10.1016/j.landurbplan.2020.103857.

Whittemore, A. H.; BenDor, T. K. (2019): Exploring the Acceptability of Densification: How Positive Framing and Source Credibility Can Change Attitudes. In *Urban Affairs Review* 55 (5), pp. 1339–1369. DOI: 10.1177/1078087418754725.

Wicki, M.; Kaufmann, D. (2022): Accepting and resisting densification: The importance of project-related factors and the contextualizing role of neighbourhoods. In *Landscape and Urban Planning* 220, p. 104350. DOI: 10.1016/j.landurbplan.2021.104350.

Wihlborg, M.; Sörensen, J.; Alkan Olsson, J. (2019): Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities. In *Journal of environmental management* 233, pp. 706–718. DOI: 10.1016/j.jenvman.2018.12.018.

Winkler, M.; Steuri, B.; Stalder, S.; Antretter, F. (2020): Evaluating the Practicability of the new Urban Climate Model PALM-4U using a Living-Lab Approach. In *E3S Web Conf.* 172, p. 11010. DOI: 10.1051/e3sconf/202017211010.

Withycombe Keeler, L.; Beaudoin, F.; Wiek, A.; John, B.; Lerner, A. M.; Beecroft, R. et al. (2019): Building actor-centric transformative capacity through city-university partnerships. In *Ambio* 48 (5), pp. 529–538. DOI: 10.1007/s13280-018-1117-9.

Wolch, J. R.; Byrne, J.; Newell, J. P. (2014): Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. In *Landscape and Urban Planning* 125, pp. 234–244. DOI: 10.1016/j.landurbplan.2014.01.017.

Wolfram, M.; Borgström, S.; Farrelly, M. (2019): Urban transformative capacity: From concept to practice. In *Ambio* 48 (5), pp. 437–448. DOI: 10.1007/s13280-019-01169-y.

Wüstemann, H.; Kalisch, D.; Kolbe, J. (2017): Access to urban green space and environmental inequalities in Germany. In *Landscape and Urban Planning* 164, pp. 124–131. DOI: 10.1016/j.landurbplan.2017.04.002.

Yahia, M. W.; Johansson, E.; Thorsson, S.; Lindberg, F.; Rasmussen, M. I. (2018): Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania. In *International Journal of Biometeorology* 62 (3), pp. 373–385. DOI: 10.1007/s00484-017-1380-7.

Yin, Y.; Olsson, A. R.; Hakansson, M. (2016): The role of local governance and environmental policy integration in Swedish and Chinese eco-city development. In *Journal of Cleaner Production* 134, pp. 78–86. DOI: 10.1016/j.jclepro.2015.10.087.

Zentrum für Stadtnatur und Klimaanpassung (ZSK) (2017): Teilprojekt 1: Klimaschutz und grüne Infrastruktur in der Stadt: Abschlussbericht. Munich. Available online at: https://www.zsk.tum.de/fileadmin/w00bqp/www/PDFs/Berichte/ZSK_TP1_Schlussbericht_20170731_mitUnterschriften_aktJan18.pdf.

Zhao, Q.; Sailor, D. J.; Wentz, E. A. (2018): Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. In *Urban Forestry & Urban Greening* 32, pp. 81–91. DOI: 10.1016/j.ufug.2018.03.022.

Zölch, T.; Maderspacher, J.; Wamsler, C.; Pauleit, S. (2016): Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. In *Urban Forestry & Urban Greening* 20, pp. 305–316. DOI: 10.1016/j.ufug.2016.09.011.

Zölch, T.; Henze, L.; Keilholz, P.; Pauleit, S. (2017): Regulating urban surface runoff through nature-based solutions - An assessment at the micro-scale. In *Environmental research* 157, pp. 135–144. DOI: 10.1016/j.envres.2017.05.023.

Zölch, T.; Rahman, M. A.; Pfleiderer, E.; Wagner, G.; Pauleit, S. (2019): Designing public squares with green infrastructure to optimize human thermal comfort. In *Building and Environment* 149, pp. 640–654. DOI: 10.1016/j.buildenv.2018.12.051.

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Appendix: Published articles and manuscripts

Article I

Erlwein, S. and Pauleit, S. (2021). Trade-Offs between Urban Green Space and Densification: Balancing Outdoor Thermal Comfort, Mobility, and Housing Demand. *Urban Planning*, *6*(1), 5–19. DOI: 10.17645/up.v6i1.3481.

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Article

Trade-Offs between Urban Green Space and Densification: Balancing Outdoor Thermal Comfort, Mobility, and Housing Demand

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Abstract

Urban green spaces reduce elevated urban temperature through evaporative cooling and shading and are thus promoted as nature-based solutions to enhance urban climates. However, in growing cities, the supply of urban green space often conflicts with increasing housing demand. This study investigates the interplay of densification and the availability of green space and its impact on human heat stress in summer. For the case of an open-midrise (local climate zone 5) urban redevelopment site in Munich, eight densification scenarios were elaborated with city planners and evaluated by microscale simulations in ENVI-met. The chosen scenarios consider varying building heights, different types of densification, amount of vegetation and parking space regulations. The preservation of existing trees has the greatest impact on the physical equivalent temperature (PET). Construction of underground car parking results in the removal of the tree population. Loss of all the existing trees due to parking space consumption leads to an average daytime PET increase of 5°C compared to the current situation. If the parking space requirement is halved, the increase in PET can be reduced to 1.3°C–1.7°C in all scenarios. The addition of buildings leads to a higher gain in living space than the addition of floors, but night-time thermal comfort is affected by poor ventilation if fresh air circulation is blocked. The protection of mature trees in urban redevelopment strategies will become more relevant in the changing climate. Alternative mobility strategies could help to reduce trade-offs between densification and urban greening.

Keywords

densification; ENVI-met simulations; green infrastructure; outdoor thermal comfort

Issue

This article is part of the issue “Urban Planning and Green Infrastructure” edited by Paul Osmond (University of New South Wales, Australia) and Sara Wilkinson (University of Technology Sydney, Australia).

1. Introduction

In the past decade, green and blue spaces in cities have been promoted as no or low regret adaptation measures to climate change (European Commission, 2016). Bodies of water and vegetated areas regulate air temperature (T_a) and radiative heat load and thus improve outdoor human thermal comfort through evaporative cooling and shading (Bowler, Buyung-Ali, Knight, & Pullin, 2010). Among these, trees are the most effective in reducing incoming shortwave radiation (Erell, 2017; Zölch, Maderspacher, Wamsler, & Pauleit, 2016). Dense, foliated tree crowns reduce the transmissivity of direct solar radiation to 1%–5% (Konarska, Lindberg, Larsson, Thorsson, & Holmer, 2014), reducing daytime T_a by up to 3°C, the mean radiant temperature by up to 37°C and the physical equivalent temperature (PET) directly beneath the tree crown by up to 16°C (Lee, Mayer, & Kuttler, 2020). However, ongoing urbanisation and population growth lead to high pressure on open spaces in cities. Therefore, urban areas undergoing densification by the addition of buildings or the increase in the size of existing buildings often exhibit a lack of urban green space (Haaland & van den Bosch, 2015).

Reduced amounts of green space, an increase of impervious surfaces, altered albedo and geometry are all contributing factors to the Urban Heat Island phenomena (Oke, 1982). Such infill development is likely to further increase urban heat load, exacerbating existing outdoor heat stress (Emmanuel & Steemers, 2018).

Confronted with the need to meet the housing demand on one hand and the challenge to adapt cities to climate change on the other, city planners require information about the effects of densification on urban microclimate, green space availability and its ecosystem services. The factors that influence urban climate and urban heat have been studied from the city level (e.g., Akbari & Kolokotsa, 2016; Deilami, Kamruzzaman, & Liu, 2018) to the neighbourhood scale (Pacifici, Marins, Catto, Rama, & Lamour, 2017) and single urban facets (e.g., Jamei & Rajagopalan, 2018; Lee et al., 2020). While climate adaptation planning needs to adopt a multiscale perspective to address the Urban Heat Island as well as local thermal hotspots (Demuzere et al., 2014), the microclimatic level is the reference scale for outdoor human thermal comfort investigations (Hirashima, Katzschner, Ferreira, Assis, & Katzschner, 2018; Mayer & Höppe, 1987). The urban layout and geometry, as well as abundance of vegetation, are some of the most important parameters governing urban microclimate and outdoor thermal comfort (Erell, Pearlmutter, & Williamson, 2011; Jamei, Rajagopalan, Seyedmahmoudian, & Jamei, 2016). Altered aspect ratios and sky view factors affect the short- and long-wave radiation as well as the wind speed (Erell et al., 2011). For instance, higher aspect ratios due to taller buildings are likely to lead to lower daytime and higher night-time air temperature (Jamei et al., 2016). Wide E–W oriented streets are more prone to thermal discomfort than narrow and N–S oriented street canyons due to longer times of solar exposure (Ali-Toudert & Mayer, 2006); thus vegetation plays an important role, especially for E–W oriented streets (Sanusi, Johnstone, May, & Livesley, 2016).

Differing from these studies that concentrate on single urban street canyons, other investigations have compared city quarters with different amounts of vegetation, built area coverages and building heights (Yahia, Johansson, Thorsson, Lindberg, & Rasmussen, 2018) or have altered these characteristics for a specific setting to study their micrometeorological impacts (Perini & Magliocco, 2014). Yahia et al. (2018) found the strongest relationship (R^2 0.97) to be between sky view factor and PET at 2 pm, and shading to be more important than ventilation. Simultaneously increasing the building height and the green coverage provided the best thermal comfort for pedestrians (Lee et al., 2020; Perini & Magliocco, 2014). In this regard, increasing building height is preferred over increasing built area coverage (Emmanuel & Steemers, 2018); however, in these studies green coverage was rather treated as a quantitative parameter with disregard of the impact of densification on the qualities of the existing vegetation. Investigating nature-based solutions in a densely built-up area, Zölch et al. (2016) emphasised that the qualities of urban greening and the placement of street trees have a decisive influence on outdoor thermal comfort. The effects of densification on existing vegetation were not investigated. In their review of challenges and strategies for densifying cities, Haaland and van den Bosch (2015) noted that there is a lack of studies that consider the interplay of urban infill and the qualities of the existing green space, as well as the planning advice to deal with both.

In reference to the microscale, the aim of this study is therefore to answer the following research questions: i) How is urban green space (especially urban trees) affected by densification and what are the consequences for human heat stress? ii) How can the trade-offs between densification and greening be effectively minimised? Based on an actual planning case in the city of Munich (Germany), we compare different development scenarios to quantify the effects of densification on the existing green space and human heat stress. In a first step, we derive key parameters for the development of realistic densification scenarios by planning in exchange with city planners. Second, we create densification scenarios that portray different planning options for the open midrise redevelopment area. Finally, micrometeorological simulations (ENVI-met model) are carried out to compare the densification alternatives with the current situation and to discuss the implications for urban planning.

2. Study Area

Munich, located in the south of Germany (48°8′N, 11°24′E, elevation 519 m a.s.l.), is one of the fastest-growing cities in Germany and is expected to reach 1.85 million inhabitants by 2035 (Landeshauptstadt München, 2011). With an annual average T_a of 9.7°C and an average precipitation of 944 mm (reference period 1981–2010; German Meteorological Service, 2018), Munich's climate corresponds to the Cfb category of the Köppen-Geiger classification. The characteristics of the city's climate include warm summers, an absence of dry seasons and highest precipitation rates during the summertime (Mühlbacher, Koßmann, Sedlmaier, & Winderlich, 2020).

While housing demand in Munich is high (according to an estimate, there is an annual requirement for the building of 8,500 flats per year; Landeshauptstadt München, 2011), the potential for the development of new residential areas outside the city and through the conversion of disused land has become scarce. One of the city's strategies for dealing with this scarcity is "qualified densification" in the stock (Landeshauptstadt München, 2011). This is especially the case with housing estates from the 1950s to the 1980s, which account for a quarter of all residential areas in Munich and offer great potential for gaining new residential space. The urban redevelopment area in Munich's city district, Moosach, is characterised by free-standing multistorey blocks from the 1950s. Free-standing multistorey blocks have a high potential for densification due to the presence of generous green spaces and, often, uniform ownership structures, that simplify planning and communication processes. Furthermore these multistorey blocks represent one of the most common building types in Munich (Pauleit & Duhme, 2000) and, more generally, in German cities (Zentrum für Stadtnatur und Klimaanpassung, 2017). The study area comprises 10-row buildings with pitched roofs of 14 m in height (four floors including the attic floor; Figure 1). There are large green spaces between the building rows—some with a high tree cover, some rather open—that result in a vegetation cover of 50%. Thus, the area can be characterised as local climate zone 5 (open midrise). Local climate zones represent universal climate-based classifications of urban and rural sites that share similar characteristics regarding surface cover, building structure, materials and human activity (Stewart & Oke, 2012).

A particular challenge for developing green and dense city quarters in Munich lies in providing sufficient car parking space. According to Bavarian planning regulations, one parking space has to be provided for each residential unit (Art. 47 BayBO). Based on a resolution by the City Council of Munich, this ratio can be reduced when access to public transport and local amenities is sufficient or in the case of subsidised residential construction. To do so, a profound mobility concept has to be provided, in which required criteria and alternative mobility solutions have to be stated. Reductions below a 0.8 ratio require extensive compensation measures, while 0.3 represents the maximum reduction ratio (Landeshauptstadt München, 2020).

3. Methodology

3.1. Development of Densification Scenarios

To gain insights in current planning policy into Munich and to derive realistic densification scenarios, we investigated all the local plans that have come into force in recent years (1 January 2014–28 March 2019). Local plans are legally binding planning instruments that concretise the possible use of a certain area and provide guidelines for possible structural development. Since inner-city development and residential areas were particularly of interest for this study, we excluded all the local plans relating to outdoor, special and industrial areas from further analysis (25 out of 60 plans). The remaining 35 plans were categorised regarding their location, type of development, permissible floor space and floor area, building height, planned residential units and plan layouts. Of further interest were the regulations dealing with parking space and green space provision.

Figure 1. Spatial assignment of investigation area. Location of the city district Moosach within Munich (a); map of the study site's wider neighbourhood (b); aerial image of the study site (c); row buildings and the middle street in the study site (d). Source: Sabrina Erlwein (with basic geographical data provided by the Bavarian State Office for Survey and Geoinformation 2018).

Although most of the areas were well connected to transport nodes and thus qualified for a parking space reduction, the ratio of parking spaces per residential unit was reduced from 1 to 0.6 only in three out of 35 local plans. Moreover, in 91.5% of the plans analysed, the required parking spaces had to be provided by underground car parks. The areas designated for underground parking usually extended over the entire green space between the buildings. Therefore, parking space provision was identified as one key parameter affecting green space provision.

Additionally, four workshops were held with city planners involved in the redevelopment of the study area (24 June, 25 July, 10 October, 16 December 2019). The participants included personnel from the Department of Urban Planning and Building Regulations (overall project management and green planning) and the Department of Health and Environment (climate change mitigation and adaptation). While the first two meetings focussed on planning challenges and goals for the development area and identification of key parameters for densification, the last two were used to discuss and refine the developed densification scenarios.

The scenarios are distinct by i) type of densification, ii) building height and iii) number of underground car parks (Figure 2). The category 'type of densification' distinguishes between the addition of floors, in which the buildings' free-standing form is retained (O = open blocks), and the addition of buildings, whereby the existing buildings are closed alongside the road (C = closed rows). The building height varies between one and two additional floors (in total 15/18 m). Furthermore, we varied the number of underground car parks (a = 1, b = 4, c = 8) to reflect the different parking space policies. For instance, the additional housing units gained by adding one floor (Table 1) could be supplied by the existing underground car park (a), if the parking space key was reduced to 0.3. If the current regulation was applied or if the ratio was even increased, four (b) or more (c) underground car parks would be necessary. The construction of underground car parks causes the removal of existing trees from the designated areas. In case b (four

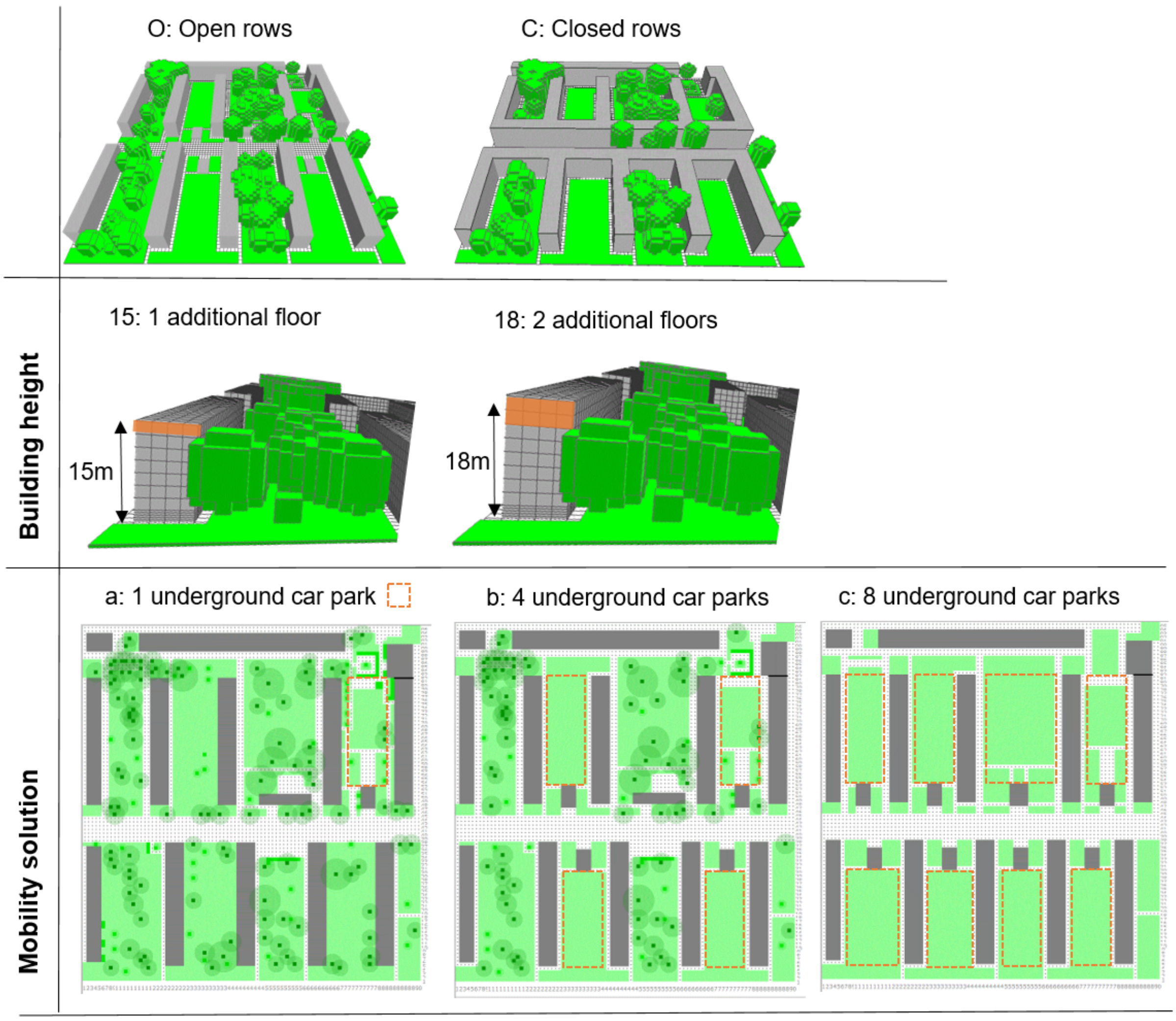

Figure 2. Scheme for all densification scenarios with basic categories of densification type, building height and mobility solution; locations of underground car parks are marked with dashed lines. Source: Sabrina Erlwein.

Table 1. Overview of the basic parameters of the densification scenarios.

Scenario	Built surface	Floor area ratio	Building height	Number of trees	Number of flats*	Underground parking
Status Quo	24.1%	0.8	13 m**	158	376	1
O15a	24.1%	1.3	15 m	158	427	1
O15b	24.1%	1.3	15 m	102	427	4
O15c	24.1%	1.3	15 m	0	427	8
C15b	31.1%	1.7	15 m	84	552	4
C15c	31.1%	1.7	15 m	0	552	8
O18b	24.1%	1.6	18 m	102	512	4
O18c	24.1%	1.6	18 m	0	512	8
C18c	31.1%	2.5	18 m	0	663	8

Notes: * = Calculation of flats: Current status 46,5 m^2 per flat, after redevelopment 67,5 m^2 per flat; ** = Saddle roof

underground car parks), the underground car parks were preferably assigned to lawns with a few trees to preserve as many trees as possible.

Further modification of supply of greenery included the removal of all the trees that were closer than 4 m to the buildings since they would not survive the construction works. The name of the scenario indicates the parameters used (e.g., O15b = open rows, 15 m height and four underground car parks). Since the chosen scenarios reflect planning scenarios, not all twelve conceivable combinations were simulated but only those that could occur in reality. For instance, in the case of the most extreme densification (C18), parking demand triggered by new flats would be too high to be covered by just four underground car parks, thus only scenario C18c was simulated. To calculate the number of new apartments for each scenario, we used actual data from the housing association. After the renovation, the living space per residential unit would increase from the current 46.5 to 67.5 m^2.

3.2. Urban Micrometeorological Simulation Model ENVI-Met

All simulations in this study were performed with the three dimensional microscale model ENVI-met (Bruse & Fleer, 1998; Simon, 2016), version 4.4.3. ENVI-met is one of the most widely used simulation tools, being successfully applied in various contexts and geographical zones for micrometeorological investigations (Tsoka, Tsikaloudaki, & Theodosiou, 2018). ENVI-met considers complex interactions of building structures, atmosphere, soil and vegetation processes (Simon et al., 2018), with a typical resolution of 0.5–10 m in space and up to 2 s in time. Numerous studies have assessed the model's accuracy and have testified it to be well suited to outdoor comfort investigations, especially during daytime (Acero & Arrizabalaga, 2018; Lee, Mayer, & Chen, 2016). The ENVI-met application BIOMET allows the calculation of several thermal comfort indices, such as Universal Thermal Comfort Index and PET. The PET was chosen for this study as it is adapted for outdoor settings (Mayer & Höppe, 1987), constitutes one of the recommended thermal comfort indices for human bio-meteorological investigations (Staiger, Laschewski, & Matzarakis, 2019), and is frequently used and thus further developed (Hirashima et al., 2018). In a recent calibration for the German cities Kassel and Freiburg, PET values above 35°C were perceived as hot and PET values above 38°C as very hot (Hirashima et al., 2018), while Holst and Mayer (2010) suggest a PET transition value of 35°C toward warm and 40°C toward hot based on investigations in Freiburg. Recently, Zölch, Rahman, Pfleiderer, Wagner, and Pauleit (2019) evaluated the model performance of ENVI-met for Munich and found an underestimation of T_a during the evening hours of 1.0–1.5 K. However, the overall model performance was found to be satisfactory (R^2 of 0.94). Therefore ENVI-met is regarded as a suitable micrometeorological investigation tool for this study.

3.3. Model Configuration and Meteorological Input Data

The required meteorological data for the ENVI-met simulation were extracted from the weather station of the German Meteorological Service, City-Station ID 3379, located approximately 2.8 km from the study area. The weather data for the past 10 years were analysed to select two running days (4 and 5 of July 2015) that representes typical hot days. Hot days are characterised by daytime maximum T_a above 30°C and a nightly T_a not below 20°C, with clear skies and low wind speed (up to 2 m/s; Mühlbacher et al., 2020). This focus was chosen as the number and intensity of hot days is likely to increase due to climate change (Mühlbacher et al., 2020). Heat stress negatively affects human health leading to a lack of concentration, exhaustion, dehydration, heat stroke, hyperthermia and eventually death (Ward Thompson, Lauf, Kleinschmit, & Endlicher, 2016). ENVI-met version 4.4.3 allows full forcing of wind speed and wind direction. However, if the wind direction changes too fast, the simulation is aborted. Thus, the most common wind direction for each hour during summertime was statistically identified based on the German Meteorological Service weather station data (1985–2018) and used as model input.

A figure presenting all the meteorological input variables can be found in S1 of the Supplementary File.

The chosen horizontal and vertical resolution of 2×2 m represents a compromise between sufficient geometric detail and sufficient computational speed (Zölch et al., 2016). For higher accuracy of surface interactions, the lowest vertical cell was further divided into five subboxes. The grid was rotated 32° from the north to rectify the building structure. The building heights and dimensions were derived from the GIS-Data provided by the City of Munich. The pavement and building materials were identified by visits to the site (for configuration details see Table 2).

Recent tree inspection data (including tree species, tree height and crown dimensions) from the municipal company were available for most of the study area. The data were supplemented by on-the-spot visits to include missing trees and to identify unclear tree locations. Out of 158 trees, 27 different tree species were identified in the study area and were sorted into five different categories for the sake of simplification. As the main cooling effect of trees is attributed to shading (Erell et al., 2011), the focus was set on tree characteristics that influence the reduction of radiation load, namely tree height, canopy shape and foliage density (Rahman, Stratopoulos et al., 2020). Based on the inspection data and on definitions of the City of Munich from local plans, we defined three different tree heights (small = 6 m, medium = 15 m, large = 22 m), into which the existing trees were classified. The crown height to diameter ratio was calculated for each tree to sort it into either spherical or cylindrical crown form. However, all the small trees were grouped into one category since differences among their crown shapes were small. ENVI-met uses the leaf area density (LAD) to define the foliage density. The LAD values of predefined species in ENVI-met's tree manager Albero range from 0.4 (populus alba) to 2.0 (e.g., acer platanoides). For new tree configurations, Albero offers LAD 0.3 m^2/m^3 and LAD 1.1 m^2/m^3 as standard values. Since foliage density also varies within species due to the growing season and the tree's age (Rahman, Stratopoulos et al., 2020), which complicates representation by categories and tree parametrisation not being the aim of this study, the medium LAD of 1.1 m^2/m^3 was chosen for all tree categories. The final five tree categories including their parameters are presented in Table 3.

Simulations were launched at 6 am for a total model time of 48 hours (Table 2). We excluded the first 24 hours from the analysis to overcome initial transient conditions. Simulation outcomes were analysed for the hottest (2 pm) and coolest hour (4 am), to detect possible trade-offs between daytime and night-time at a pedestrian level of 1.4 m height (approximating to the human-biometeorological reference height; Mayer & Höppe, 1987). In addition, we computed and mapped the averages from 10 am to 4 pm to better depict the design parameters' influence on the shadow cast during the day (Holst & Mayer, 2011). Compared to an analysis of just one point in time, this makes it possible to derive more robust design implications (Lee et al., 2016).

Table 2. ENVI-met model setup and meteorological input data.

Start of simulation	4 July 2015, 6 am
Duration of simulations	48 h
Modell grid size/resolution	$90 \times 95 \times 25/2 \times 2$ m
Building materials	Brick (wall), tile (roof)
Wind speed (10 m above ground)	0.7 m-s–2.0 m/s
Wind direction	240°–310°
Max/min T_a	35.4°C/21.7°C
Cloud cover	cloud-free
Lateral boundary conditions	Full forcing
Initial soil temperature	Upper layer (0–0.2 m): 23.85°C, middle layer (−0.5 m): 23.9°C, deep layer (−2 m): 19.9°C
Relative soil humidity	Upper layer: 50%; middle and deep layer: 60%

Table 3. Tree categories used in the ENVI-met simulation (base case).

Category	Size	Height	Diameter	LAD	Count
K1	Small (all forms)	6 m	5 m	1.1	44
K2	Medium, spherical	15 m	11 m	1.1	19
K3	Medium, cylindrical	15 m	9 m	1.1	50
K4	Large, spherical	22 m	17 m	1.1	12
K5	Large, cylindrical	22 m	11 m	1.1	34

4. Results

4.1. Comparison of Day-Time Thermal Comfort for the Current Situation and Densification Scenarios

Simulation results for the current situation reveal overall very hot thermal conditions for pedestrians at 2 pm (Figure 3). Nearly 100% of the study area experiences extreme heat stress (PET mean value of 46.9°C). The coolest locations were found in the shadows of trees and buildings (PET 41°C–43°C), whereas the thermal hotspots were found in front of the sun-facing façades (SE orientation) and the poorly ventilated areas (PET 55°C–56.6°C). This pattern was mainly attributed to the impact of solar radiation as expressed by the mean radiant temperature. On cloudless summer days, the mean radiant temperature is the dominating factor for outdoor human thermal comfort in Central Europe (Ali-Toudert & Mayer, 2007; Holst & Mayer, 2011; Lee & Mayer, 2018). All densification scenarios except for scenario O15a, were, on average, hotter than the base case. In scenario O15a, the buildings were raised by one storey, but the existing vegetation was completely preserved. There, the full tree canopy combined with the additional shadow cast from the elevated buildings further reduced the short-wave radiation densities and thus improved the thermal comfort compared to the base case. The impact of additional underground car parks becomes visible in the remaining scenarios: The higher the number of removed trees, the greater the penetration of solar radiation and the higher the median PET (Figure 4a). Remarkably, at noon the median difference between 100% trees and 65%–53 % trees is larger than that between the latter and zero trees (PET median difference of 2.0°C–2.1°C compared to 0.5°C–0.6°C). However, while in scenarios with 65%–53% trees, 75 % of all locations were cooler than 50°C (PET), nearly half of the study area in the tree-less scenarios was hotter than 50°C (PET; Figure 3, Figure 4). The variety of cooler and hotter grid cells is higher in scenarios with trees (PET interquartile range of 5.9°C–5.4°C to 3.2°C–1.3°C) but also in scenarios with a more closed building arrangement compared to the default arrangement of free-standing blocks. Building heights have only a marginal impact on noon simulation outcomes.

The closure of the building rows has two opposing effects: On the one hand, the newly introduced buildings shade one side of the street and a portion of the northern

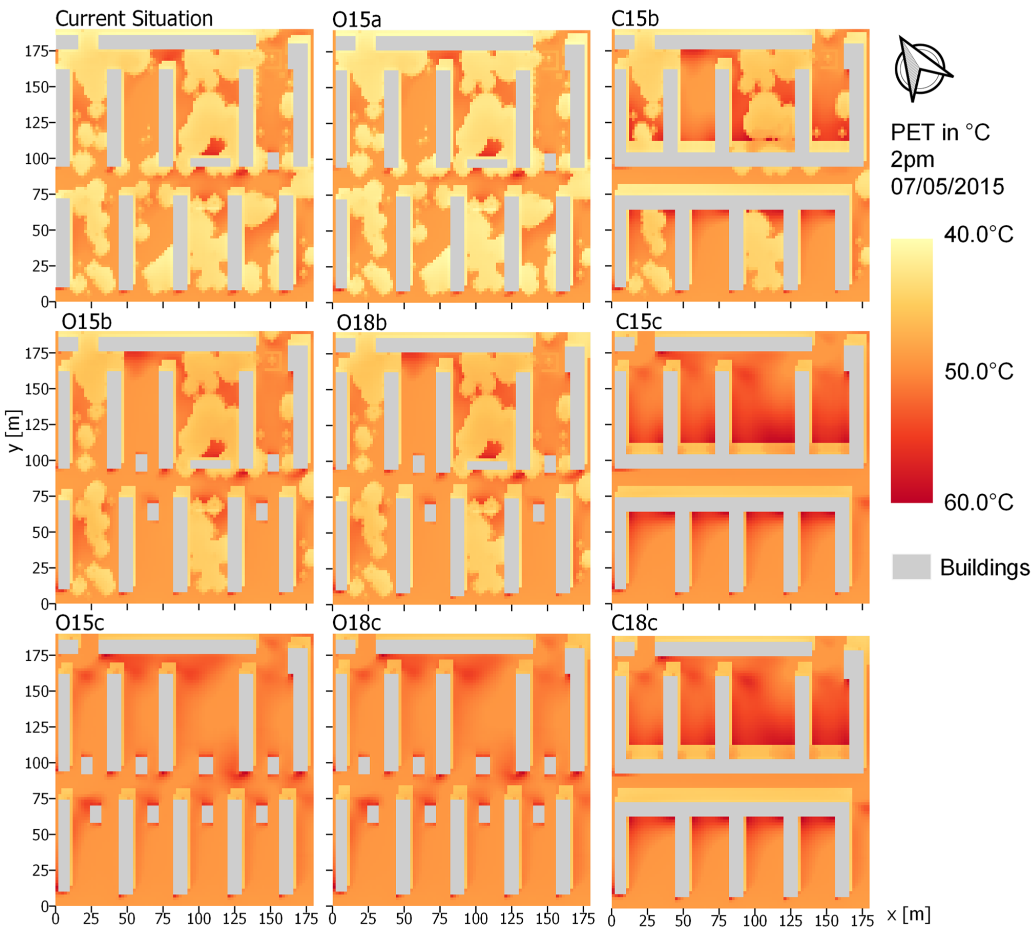

Figure 3. Simulated PET values at 2 pm on 5 July 2015 for the current situation and the eight densification scenarios (1.4 m height). Notes: O = open rows, C = closed rows; 15/18 = 15/18 m building height; a/b/c = 1/4/8 underground car parks. Source: Sabrina Erlwein.

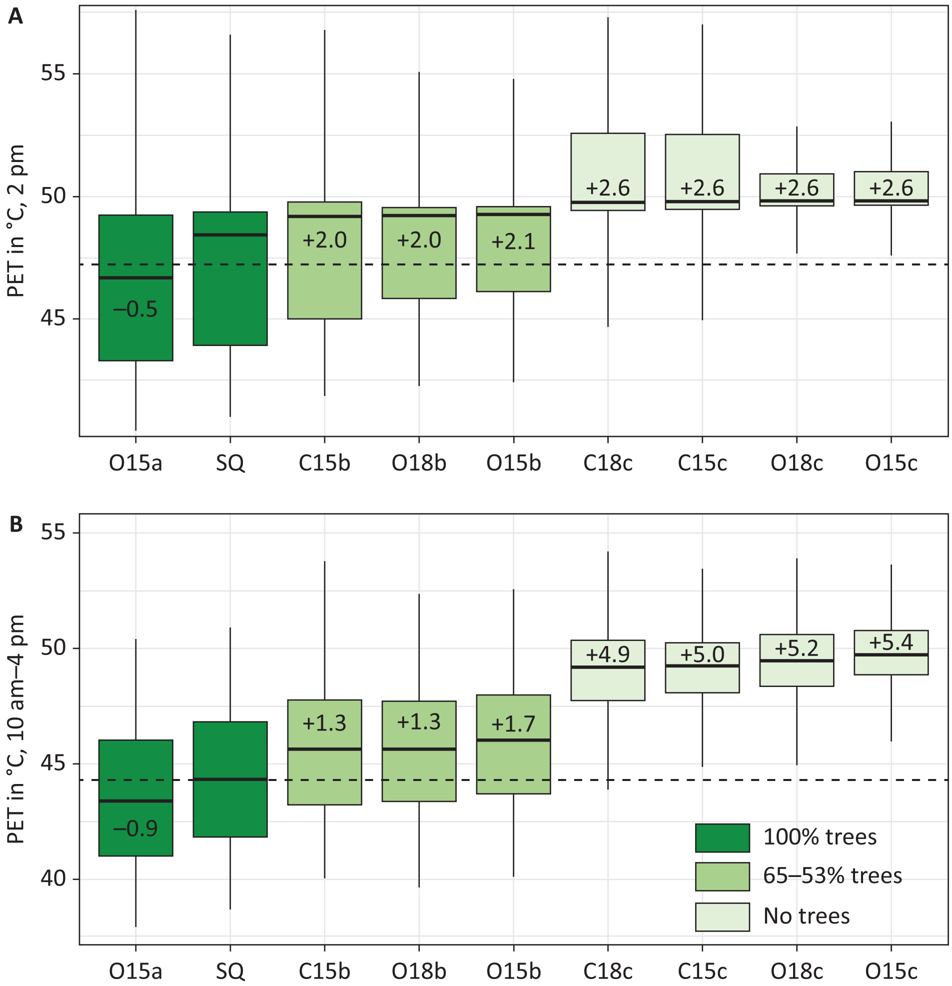

Figure 4. Boxplots of the PET values for all densification scenarios at 2 pm (A) and 10 am–4 pm (B) on 5 July 2015. The colours refer to the number of trees in the respective scenario. The dashed line marks the median value of the current situation; the numbers in the boxes indicate the respective deviation from the base case (= SQ) median. Source: Sabrina Erlwein.

yards. On the other hand, heat accumulates especially in the northern yards, enlarging the total area with PET values above 51°C to nearly 40% (compared to 7% in the current situation and 23%–25% in the open row simulations; see S2 of the Supplementary File). At the same time, wind speed in the enclosed yards is—0.6 m s-1 lower compared to the open row configuration, whereas elevated wind speed in the middle street indicates a channelling effect (Figure 5).

If not only the hottest hour, but the time period from 10 am to 4 pm is considered, the contrast between 100% (category c) and 50% (category b) tree removal becomes more prominent (Figure 4, A). The removal of all existing trees leads to an increase in average PET by 4.9°C–5.4°C compared to the current situation. This increase can be considered as a significant deterioration of thermal comfort under a human-biometeorological perspective. In contrast, average increase in PET is reduced to 1.3°C–1.7°C if only half of the trees are removed. While the largest differences in thermal comfort are again attributed to the presence of trees and their blocking of direct solar radiation, higher building heights result in slightly lower PET temperature averages (0.1°C–0.4°C), both for the open row and closed row configuration. This is because higher buildings cast more shadows and thus reduce the mean radiant temperature. The hottest overall thermal conditions are observed for scenario O15c, without trees, open rows and lower building heights, while scenario O15a (all trees preserved) is the coolest one. For the spatial distribution of PET values, see S4 of the Supplementary File.

4.2. Comparison of Night-Time (4 am) Thermal Comfort for the Current Situation and Densification Scenarios

In contrast to the daytime situation, in the early morning (4 am) green spaces with high tree cover are slightly warmer (+0.9°C for PET) than only grassed areas. Tree canopies reduce the amount of out-going longwave radiation and retain daily heat, while high sky view factors are beneficial for nocturnal cooling. The warmest spots are located in the vicinity of NE oriented building facades, whereas non-disclosed areas are the coolest ones (Figure 6). The PET averages 18.8°C for the base

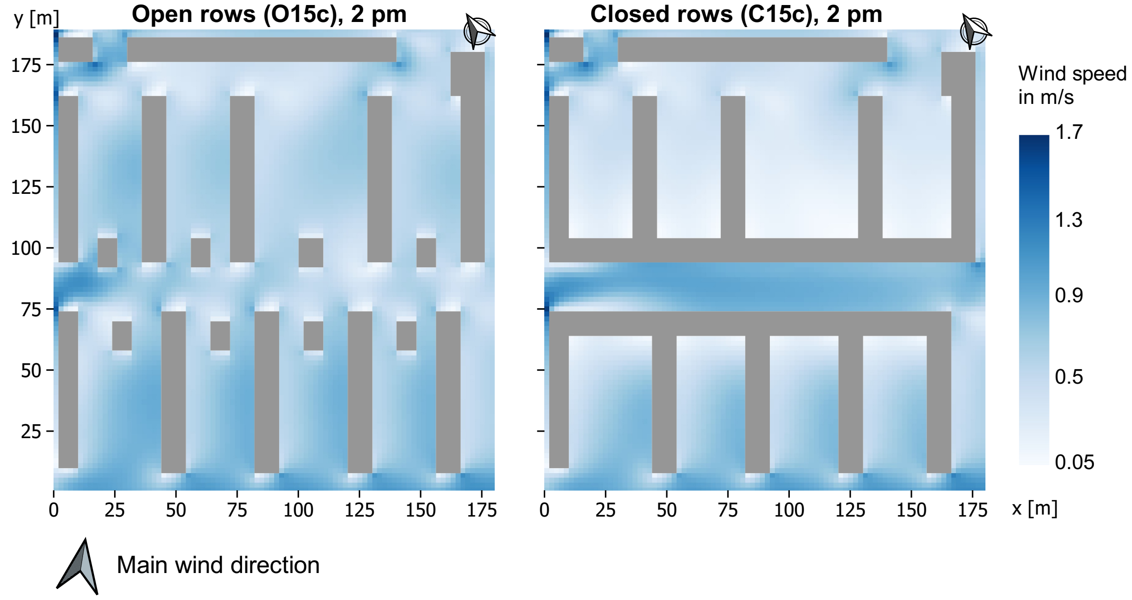

Figure 5. Wind speed at 1.4 m height for two different building configurations without trees on 5 July 2015. Source: Sabrina Erlwein.

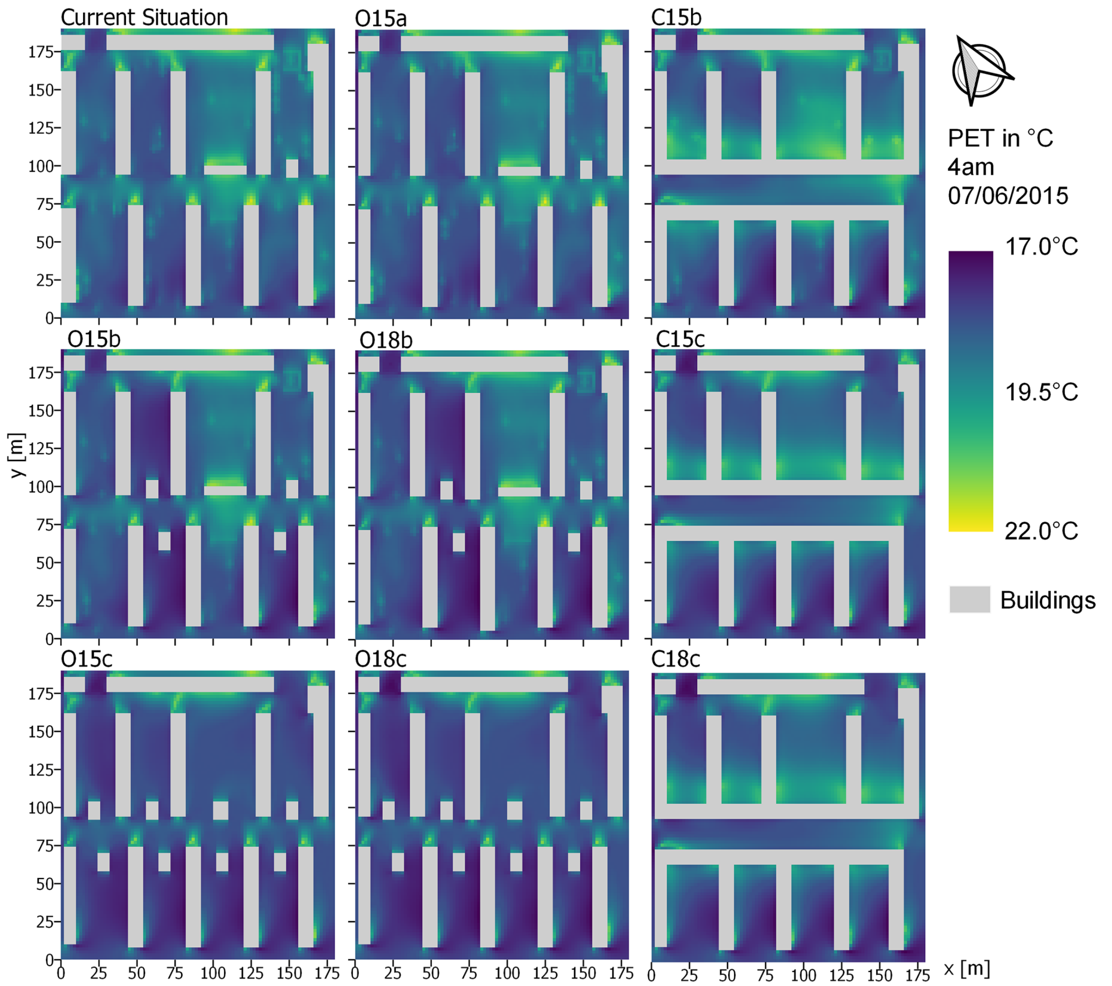

Figure 6. Simulated PET values at 4 am for the current situation and the eight densification scenarios (1.4 m height). Notes: O = open rows; C = closed rows, 15/18 = 15/18 m building height, a/b/c = 1/4/8 underground car parks. Source: Sabrina Erlwein.

case (Figure 7). In the absence of solar radiation, the PET range between the warmest and the coolest spot is just 4.1°C PET (and 0.8°C for T_a). Only scenario C15b (closed rows, trees in every 2nd courtyard) is on average warmer (+0.1°C for PET) than the current situation (Figure 7). However, differences in average PET are small (18.4°C to 18.9°C). Unlike during the day, the number of trees and the sky view factor in the respective set-up are not the most influential factors for thermal comfort. Instead, building arrangements with open rows that permit infiltration of airflow are cooler than the 'closed rows' design scenarios. Similar to the daytime observations, the northern courtyards are more affected by an elevated temperature than the southern ones (18.7°C vs 20.0°C for PET). In the warmest scenario, combining closed rows with longwave radiation retaining tree canopies (C15b), 45% of the area is warmer than 19°C, while it is 12% for the coolest scenario O18c (open rows, no trees; S3 of the Supplementary File). Higher buildings heights are associated with a lower overall PET.

For side-by-side comparison of all the modelling results for daytime and night-time, Figure 8 depicts the average PET deviations of all the densification scenario outcomes from the current situation.

5. Discussion

When comparing eight densification scenarios for an urban redevelopment site, preservation of the existing vegetation was identified as the most important parameter in reducing diurnal outdoor heat stress. All treeless scenarios were significantly hotter regardless of densification type and building height, followed by those scenarios featuring a reduced amount of vegetation. These findings are in line with other studies that identified trees as being the most efficient in heat mitigation due to their shading potential (Chatzidimitriou & Yannas, 2016; Erell, 2017; Lee et al., 2016;). Open spaces with high sky view factors cool down faster during the night-time as heat dissipation is not hindered by obstacles (Erell et al., 2011). Tree canopies trap radiant heat at night, retaining daytime heat (Bowler et al., 2010). Thus, most of the densification scenarios are hotter during daytime and cooler during night-time, due to their reduced number of trees; however, free flows of cooling wind are equally important. The four coolest scenarios at 4 am were those with open row buildings as south-westerly airflow can penetrate into the green spaces between the buildings. With closed rows, these wind flows are blocked (reducing wind speed by 0.6 m/s), this being especially detrimental for the northern courtyards. There, night-time PET (4 am) is up to 2.0°C warmer and daytime PET (2 pm) is as much as 4.8°C–6.8°C warmer.

While a large number of studies have shown how adding green infrastructure can help to mitigate increased summer temperature (Lee et al., 2016; Perini & Magliocco, 2014; Zölch et al., 2016), this study stresses that preservation of fully grown and high quality green infrastructure elements in urban redevelopment sites is equally important. The cooling capacity of trees is not uniform, but depends on tree species, growing conditions (Rahman, Moser, Rötzer, & Pauleit, 2019), geographical location, season (Jamei et al., 2016), placement of trees and individual tree parameters (e.g., tree height, healthiness; Rahman, Stratopoulos et al., 2020). In fact, several authors argue that a lower number of urban green spaces in growing cities might be substituted by improving their quality (Artmann, Inostroza, & Fan, 2019; Haaland, & van den Bosch, 2015). Similarly, a loss of urban green space might be acceptable if the

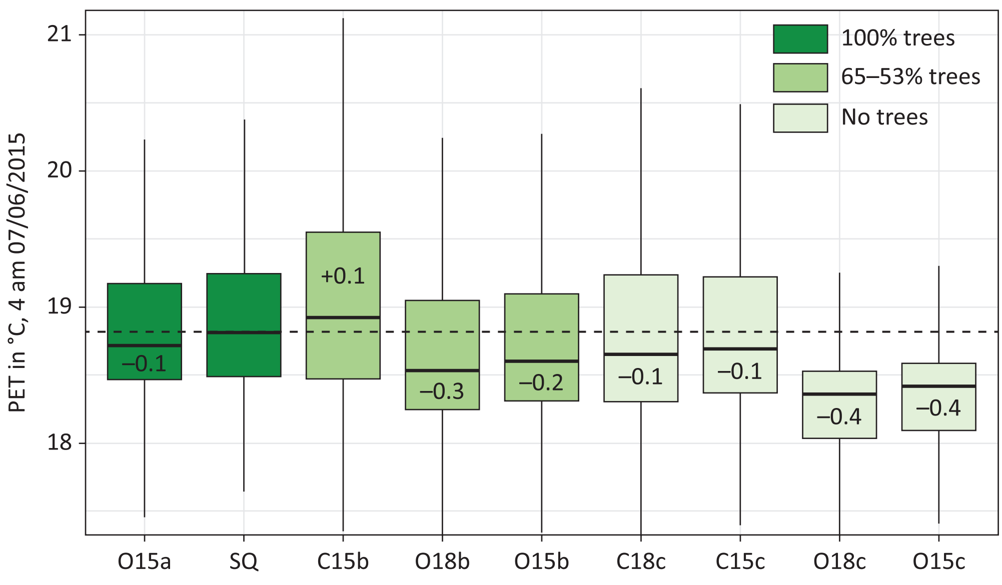

Figure 7. Boxplots of PET values for all the densification scenarios at 4 am on 5 July 2015. Notes: The colours refer to the number of trees in the respective scenario. The dashed line marks the median value of the current situation; the numbers in the boxes indicate the respective deviation from the base case (= SQ) median. Source: Sabrina Erlwein.

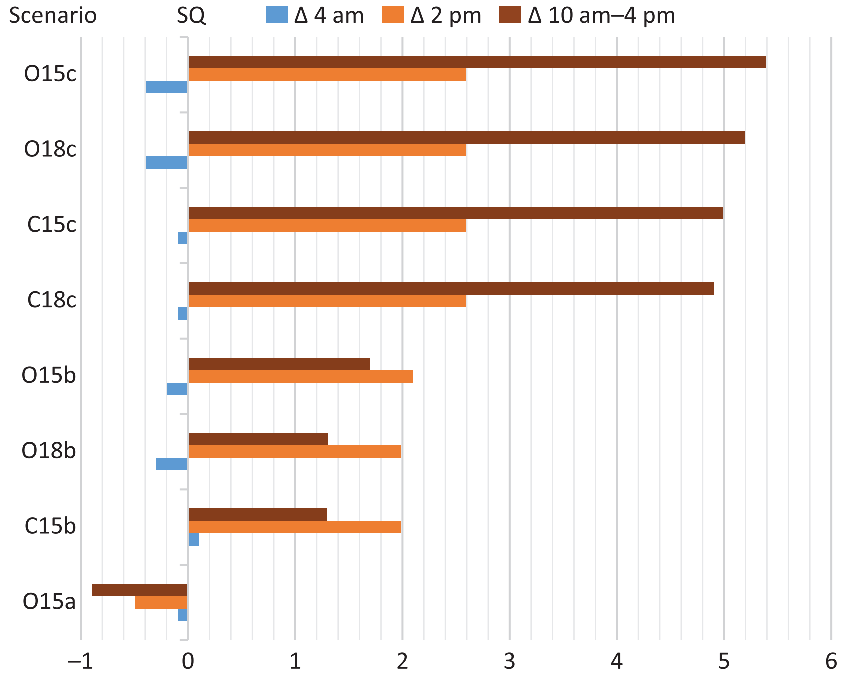

Figure 8. Deviations (in °C) from the average PET of the current situation for daytime (5 July 2015) and 4 am (6 July 2015) for all the densification scenarios. Notes: O = open rows; C = closed rows, 15/18 = 15/18 m building height, a/b/c = 1/4/8 underground car parks. Source: Sabrina Erlwein.

existing qualities are preserved. However, newly planted trees are unlikely to be fully grown trees, but rather small trees with limited crown volumes. Growing conditions for urban trees are often harsh due to limited growth volumes, compacted soils and reduced water availability (Moser, Rötzer, Pauleit, & Pretzsch, 2015). As the replanting of trees is time-consuming and often associated with high costs, the loss of old shade-giving trees cannot be easily compensated in the short or medium term. Where construction of underground car parks was limited to 50% and yards with fewer or smaller trees were selected for that purpose ('b'-scenarios) the PET increases through densification could be limited to +1.3°C for the daytime average (10 am to 4 pm).

5.1. Limitations of the Methodological Approach

The presented study focused on an extreme weather condition of severe summer heat and low wind speed to compare different densification impacts. This focus is due to the fact that climate change is likely to exacerbate already elevated urban heat. As a result, PET values for the chosen heat stress situation were very high; even in the shade of trees, thermal comfort levels remained on an extreme heat stress level. Since a heatwave with no rain preceded the modelling day, the soil humidity was decreased from 75% to 50% according to the available measurement data. Bande et al. (2019) found an overestimation of the mean radiant temperature values in ENVI-met due to the soil properties and report limits in the vertical moisture transfer with the top layer drying out too quickly. Thus, the exceptionally high PET values might have been caused by the limited availability of soil moisture. Nevertheless, the findings of this study are still considered valid, as the main focus of the study was set on comparing the relative differences between the investigated densification scenarios rather than on reporting the absolute PET values. All the simulation runs were performed under the same meteorological and identical full forcing conditions in the ENVI-met model.

The model outcomes are representative for similar building geometries, that are widespread in German cities. However, the impacts of building geometry alterations on the mean radiant temperature and subsequently PET are dependent on axis orientation and main wind directions (Chatzidimitriou & Axarli, 2017; Holst & Mayer, 2011). Due to the row building's NE–SW orientation, only a small part of the area benefitted from the enlarged shadow cast due to the increased building height during the hottest hours of the day. With an E–W orientation, additional shade due to higher building height might have made a more important contribution. For improved transferability of results, more axis orientations and main wind directions would need to be studied.

In light of climate change, we investigated thermal comfort situations for daytime and night-time for a hot summer situation. However, if planners seek to optimise thermal comfort throughout the year, potential trade-offs between different seasons should be considered. For instance, although detrimental in the summertime, wind-blocking by trees in winter might be beneficial especially in colder climates to reduce wind chill effects (Sjöman, Hirons, & Sjöman, 2016). However, from a climate change perspective, the situation of heat waves during hot summertime is of particular concern for climate-sensitive urban planning in Central European cities such as Munich.

5.2. Implications for Urban Planners

This study showed that trees play a pivotal role in heat stress mitigation and that preservation of existing trees is the most efficient and most affordable measure for climate change adaptation. In practice, the provision of new apartments leads to an increased need for parking spaces, resulting in tree removals. To balance housing demand and preservation of urban green space, the following recommendations can be given to urban planners.

First, particularly in the case of inner-city locations that are usually well connected to public transport, parking space ratios should be reduced by the employment of mobility concepts. Car-sharing and bike-sharing stations guarantee individual mobility, whereby strengthening of public transport is not only beneficial for the residents, but also for the entire neighbourhood (Stevenson et al., 2016).

Second, we recommend that architects and planners seek an early consideration of valuable mature vegetation in the built layout. If the construction of underground car parking is necessary, this should preferably be located in those areas with fewer trees. This is also important considering the fact that trees not only improve the local microclimate but also provide multiple ecosystem services such as stormwater retention, biodiversity and increased well-being (Hansen & Pauleit, 2014). In comparison to preservation, the replacement of trees is a time- and cost-consuming process.

Third, for the investigated free-standing multistorey housing type, densification through additional storeys is more beneficial in terms of climate adaptation than the addition of buildings. Although the addition of new buildings creates two to three times more new flats, this comes at the cost of lost unsealed open space and additional tree removals. The heat burden in closed building arrangements is significantly increased for areas with low wind speed, both for daytime and night-time. While shading by trees is an option to reduce daytime human heat stress (Lee et al., 2020; Rahman, Hartmann et al., 2020), tree canopies will exacerbate the nocturnal situation in those yards. Designs that consider nocturnal airflow will improve thermal comfort.

Finally, we recommend perceiving densification not only as a threat but also as a chance for upgrading urban green spaces and for introducing new green elements. To do so, we suggest the strategic planting of trees in thermal hotspots and taking care that good growing conditions are provided (see also Zölch et al., 2019). Green infrastructure elements can be combined with blue infrastructure elements such as rain gardens, to improve stormwater retention and water supply for the existing vegetation under dry conditions. Thus, meeting the increased housing demand can be achieved while green quality is increased.

6. Conclusions

This study investigated the impact of densification on urban green space availability and outdoor thermal comfort for an open midrise development site in Munich. Densification scenarios for a typical housing area of free-standing multistorey blocks in Munich were developed alongside planners and were thus considered to be realistic. We showed that the construction of parking space and the loss of existing trees have the greatest impact on PET outcomes. Replacing large trees is not only costly and time-consuming but is also ineffective in the short to medium term. Maintaining existing and mature vegetation reduces PET increase by 4°C compared to the base case (10 am to 4 pm). Thereby, the cooling effect during daytime outweighs the slight warming due to heat trapping at night. Wind blocking by buildings and trees reduces thermal comfort even in low wind conditions (<2 m/s). Thus, additional buildings should be carefully placed. Discussions with planners revealed that such quantitative information is urgently needed to consider the impacts of densification on human thermal comfort. Thus, this study contributed some important insights into urban planning. In light of climate change, mobility strategies that reduce the need for both above-ground and below-ground parking space are required for climate-sensitive densification of built areas. Future research should investigate thermal comfort during different seasons that have different requirements for light availability and shading. Other settlement types, benefits to stormwater management and the impacts or potentials of changed surfaces and materials, e.g., wood instead of concrete construction, require further investigation. Further studies should also analyse the perception of the quality of outdoor open spaces with regard to thermal comfort, but also the relationship between indoor and outdoor thermal comfort to arrive at a more integrative assessment of densification scenarios.

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Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the author (unedited).

References

Acero, J. A., & Arrizabalaga, J. (2018). Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions. *Theoretical and Applied Climatology*, *131*(1-2), 455–469. https://doi.org/10.1007/s00704-016-1971-y

Akbari, H., & Kolokotsa, D. (2016). Three decades of urban heat islands and mitigation technologies research. *Energy and Buildings*, *133*, 834–842. https://doi.org/10.1016/j.enbuild.2016.09.067

Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, *41*(2), 94–108. https://doi.org/10.1016/j.buildenv.2005.01.013

Ali-Toudert, F., & Mayer, H. (2007). Thermal comfort in an east–west oriented street canyon in Freiburg (Germany) under hot summer conditions. *Theoretical and Applied Climatology*, *87*(1/4), 223–237. https://doi.org/10.1007/s00704-005-0194-4

Artmann, M., Inostroza, L., & Fan, P. (2019). Urban sprawl, compact urban development and green cities. How much do we know, how much do we agree? *Ecological Indicators*, *96*, 3–9. https://doi.org/10.1016/j.ecolind.2018.10.059

Bande, L., Afshari, A., Al Masri, D., Jha, M., Norford, L., Tsoupos, A., . . . Armstrong, P. (2019). Validation of UWG and ENVI-met models in an Abu Dhabi District, based on site measurements. *Sustainability*, *11*(16). https://doi.org/10.3390/su11164378

Bayerische Staatskanzlei. (2020). *Bayerische Bauordnung (BayBO) in der Fassung der Bekanntmachung vom 14. August 2007* [Bavarian building regulation in the version of the announcement of 14th August 2007] (GVBl. S. 588, BayRS 2132-1-B). Munich: Bayerische Staatskanzlei.

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, *97*(3), 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006

Bruse, M., & Fleer, H. (1998). Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software*, *13*(3/4), 373–384. https://doi.org/10.1016/S1364-*8152*(98)00042-5

Chatzidimitriou, A., & Axarli, K. (2017). Street canyon geometry effects on microclimate and comfort; a case study in Thessaloniki. *Procedia Environmental Sciences*, *38*, 643–650. https://doi.org/10.1016/j.proenv.2017.03.144

Chatzidimitriou, A., & Yannas, S. (2016). Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer. *Sustainable Cities and Society*, *26*, 27–47. https://doi.org/10.1016/j.scs.2016.05.004

Deilami, K., Kamruzzaman, M., & Liu, Y. (2018). Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. *International Journal of Applied Earth Observation and Geoinformation*, *67*, 30–42. https://doi.org/10.1016/j.jag.2017.12.009

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., . . . Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, *146*, 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025

Emmanuel, R., & Steemers, K. (2018). Connecting the realms of urban form, density and microclimate. *Building Research & Information*, *46*(8), 804–808. https://doi.org/10.1080/09613218.2018.1507078

Erell, E. (2017). Urban greening and microclimate modification. In P. Y. Tan & C. Y. Jim (Eds.), *Greening cities* (pp. 73–94). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-4113-6_4

Erell, E., Pearlmutter, D., & Williamson, T. (2011). *Urban microclimate: Designing the spaces between buildings*. London: Earthscan.

European Commission. (2016). *Assessing adaptation knowledge in Europe: Ecosystem-based adaptation* (Project No. DESNL16057). Brussels: European Commission. Retrieved from https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/ecosystem_based_adaptation_en.pdf

German Meteorological Service. (2018). Vieljährige Stationsmittelwerte für die Klimareferenzperiode 1981–2010, für aktuellen Standort und Bezugsstandort: Stations-ID 3379 Muenchen-Stadt [Multi-year station mean values for the climate reference period 1981–2010, for current location and reference site: Station ID 3379 Munich city]. *DWD*. Retrieved from https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/multi_annual/mean_81-10

Haaland, C., & van den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening*, *14*(4), 760–771.

Hansen, R., & Pauleit, S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *Ambio*, *43*(4), 516–529.

Hirashima, S. Q. d. S., Katzschner, A., Ferreira, D. G., Assis, E. S. d., & Katzschner, L. (2018). Thermal comfort comparison and evaluation in different climates. *Urban Climate*, *23*, 219–230. https://doi.org/10.1016/j.uclim.2016.08.007

Holst, J., & Mayer, H. (2010). Urban human-biometeorology: Investigations in Freiburg (Germany) on human thermal comfort. *Urban Climate News*, *38*, 5–10.

Holst, J., & Mayer, H. (2011). Impacts of street design parameters on human-biometeorological variables.

Meteorologische Zeitschrift, *20*(5), 541–552. https://doi.org/10.1127/0941-2948/2011/0254

Jamei, E., & Rajagopalan, P. (2018). Effect of street design on pedestrian thermal comfort. *Architectural Science Review*, *28*(455), 1–20. https://doi.org/10.1080/00038628.2018.1537236

Jamei, E., Rajagopalan, P., Seyedmahmoudian, M., & Jamei, Y. (2016). Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renewable and Sustainable Energy Reviews*, *54*, 1002–1017. https://doi.org/10.1016/j.rser.2015.10.104

Konarska, J., Lindberg, F., Larsson, A., Thorsson, S., & Holmer, B. (2014). Transmissivity of solar radiation through crowns of single urban trees: Application for outdoor thermal comfort modelling. *Theoretical and Applied Climatology*, *117*(3/4), 363–376. https://doi.org/10.1007/s00704-013-1000-3

Landeshauptstadt München. (2011). *Langfristige Siedlungsentwicklung: Kongressinformation* [Long term settlement development: Congress information]. Munich: Landeshauptstadt München. Retrieved from https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Stadtplanung-und-Bauordnung/Projekte/Langfristige-Siedlungsentwicklung/Projekt/Verdichtung.html

Landeshauptstadt München. (2020). Mobilitätskonzept [Mobility concept]. *Landeshauptstadt München*. Retrieved from https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Stadtplanung-und-Bauordnung/Lokalbaukommission/Kundeninfo/Mobilitaetskonzept.html

Lee, H., & Mayer, H. (2018). Maximum extent of human heat stress reduction on building areas due to urban greening. *Urban Forestry & Urban Greening*, *32*, 154–167.

Lee, H., Mayer, H., & Chen, L. (2016). Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany. *Landscape and Urban Planning*, *148*, 37–50. https://doi.org/10.1016/j.landurbplan.2015.12.004

Lee, H., Mayer, H., & Kuttler, W. (2020). Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E–W urban street canyons under Central European conditions. *Urban Forestry & Urban Greening*, *48*. https://doi.org/10.1016/j.ufug.2019.126558

Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, *38*(1), 43–49. https://doi.org/10.1007/BF00866252

Moser, A., Rötzer, T., Pauleit, S., & Pretzsch, H. (2015). Structure and ecosystem services of small-leaved lime (Tilia cordata Mill.) and black locust (Robinia pseudoacacia L.) in urban environments. *Urban Forestry & Urban Greening*, *14*(4), 1110–1121. https://doi.org/10.1016/j.ufug.2015.10.005

Mühlbacher, G., Koßmann, M., Sedlmaier, K., & Winderlich, K. (2020). *Stadtklimatische Untersuchungen der sommerlichen Temperaturverhältnisse und des Tagesgangs des Regionalwindes („Alpines Pumpen") in München*. *Berichte des Deutschen Wetterdienstes: Vol. 252* [Urban climatic studies of summer temperature conditions and the diurnal cycle of the regional wind ("Alpine Pumping") in Munich. Reports of the German Weather Service: Vol. 252]. Offenbach: Deutscher Wetterdienst.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*(455), 1–24. https://doi.org/10.1002/qj.49710845502

Pacifici, M., Marins, K. R. d. C., Catto, V. d. M., Rama, F., & Lamour, Q. (2017). Morphological and climate balance: Proposal for a method to analyze neighborhood urban forms by way of densification. *Sustainable Cities and Society*, *35*, 145–156. https://doi.org/10.1016/j.scs.2017.07.023

Pauleit, S., & Duhme, F. (2000). Assessing the environmental performance of land cover types for urban planning. *Landscape and Urban Planning*, *52*(1), 1–20. https://doi.org/10.1016/S0169-*2046*(00)00109-2

Perini, K., & Magliocco, A. (2014). Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. *Urban Forestry & Urban Greening*, *13*(3), 495–506. https://doi.org/10.1016/j.ufug.2014.03.003

Rahman, M. A., Hartmann, C., Moser-Reischl, A., Strachwitz, M. F., von Paeth, H., Pretzsch, H., . . . Rötzer, T. (2020). Tree cooling effects and human thermal comfort under contrasting species and sites. *Agricultural and Forest Meteorology*, *287*. https://doi.org/10.1016/j.agrformet.2020.107947

Rahman, M. A., Moser, A., Rötzer, T., & Pauleit, S. (2019). Comparing the transpirational and shading effects of two contrasting urban tree species. *Urban Ecosystems*, *22*(4), 683–697. https://doi.org/10.1007/s11252-019-00853-x

Rahman, M. A., Stratopoulos, L. M. F., Moser-Reischl, A., Zölch, T., Häberle, K.-H., Rötzer, T., . . . Pauleit, S. (2020). Traits of trees for cooling urban heat islands: A meta-analysis. *Building and Environment*, *170*. https://doi.org/10.1016/j.buildenv.2019.106606

Sanusi, R., Johnstone, D., May, P., & Livesley, S. J. (2016). Street orientation and side of the street greatly influence the microclimatic benefits street trees can provide in summer. *Journal of Environmental Quality*, *45*(1), 167–174. https://doi.org/10.2134/jeq2015.01.0039

Simon, H. (2016). *Modeling urban microclimate: Development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met* (Doctoral dissertation). Johannes Gutenberg-University, Mainz. Retrieved from https://openscience.ub.uni-mainz.de/handle/

20.500.12030/4044

Simon, H., Linden, J., Hoffmann, D., Braun, P., Bruse, M., & Esper, J. (2018). Modeling transpiration and leaf temperature of urban trees: A case study evaluating the microclimate model ENVI-met against measurement data. *Landscape and Urban Planning*, *174*, 33–40. https://doi.org/10.1016/j.landurbplan.2018.03.003

Sjöman, J. D., Hirons, A., & Sjöman, H. (2016). Branch area index of solitary trees: Understanding its significance in regulating ecosystem services. *Journal of Environmental Quality*, *45*(1), 175–187. https://doi.org/10.2134/jeq2015.02.0069

Staiger, H., Laschewski, G., & Matzarakis, A. (2019). Selection of Appropriate thermal indices for applications in human biometeorological studies. *Atmosphere*, *10*. https://doi.org/10.3390/atmos10010018

Stevenson, M., Thompson, J., Sá, T. H. d., Ewing, R., Mohan, D., McClure, R., . . . Woodcock, J. (2016). Land use, transport, and population health: estimating the health benefits of compact cities. *The Lancet*, *388*, 2925–2935. https://doi.org/10.1016/S0140-6736(16)30067-8

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Tsoka, S., Tsikaloudaki, A., & Theodosiou, T. (2018). Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications: A review. *Sustainable Cities and Society*, *43*, 55–76. https://doi.org/10.1016/j.scs.2018.08.009

Yahia, M. W., Johansson, E., Thorsson, S., Lindberg, F., & Rasmussen, M. I. (2018). Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania. *International Journal of Biometeorology*, *62*(3), 373–385. https://doi.org/10.1007/s00484-017-1380-7

Ward Thompson, C., Lauf, S., Kleinschmit, B., & Endlicher, W. (2016). Heat waves and urban heat islands in Europe: A review of relevant drivers. *The Science of the Total Environment*, *569/570*, 527–539. https://doi.org/10.1016/j.scitotenv.2016.06.119

Zentrum für Stadtnatur und Klimaanpassung. (2017). *Teilprojekt 1: Klimaschutz und grüne Infrastruktur in der Stadt: Abschlussbericht* [Subproject 1: Climate protection and green infrastructure in the city: Final report]. Munich: Zentrum für Stadtnatur und Klimaanpassung. Retrieved from https://www.landschaftsentwicklung.wzw.tum.de/fileadmin/w00bds/www/Bilder/Projekte/ZSK/ZSK_TP1_Schlussbericht_20170731_mitUnterschriften_aktJan18.pdf

Zölch, T., Maderspacher, J., Wamsler, C., & Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening*, *20*, 305–316. https://doi.org/10.1016/j.ufug.2016.09.011

Zölch, T., Rahman, M. A., Pfleiderer, E., Wagner, G., & Pauleit, S. (2019). Designing public squares with green infrastructure to optimize human thermal comfort. *Building and Environment*, *149*, 640–654. https://doi.org/10.1016/j.buildenv.2018.12.051

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Article II

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Regulating the microclimate with urban green in densifiying cities: Joint assessment on two scales

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Climate-responsive design

ABSTRACT

Green spaces fulfill an important role in regulating the urban microclimate, however they are under high pressure in growing cities. As much as densification is a threat towards existing green spaces, it also offers the possibility to redesign residential areas in a climate-responsive way. To do so, urban green infrastructure needs to be incorporated from the outset into the planning process and the urban context and mutual influences between different scales have to be considered. However, information on how to secure ventilation in densifying neighbourhoods while simultaneously enhancing thermal comfort in open spaces at site scale still is limited. Therefore, we compare microclimatological modelling outcomes on district and block level for different densification and green intervention scenarios in a real planning case. Our results suggest that green infrastructure can compensate for negative effects of building densification on daytime thermal comfort, but not for impacts on cold air volume flow (CAVF). CAVF is mainly affected by densification, especially by increasing building heights. Strategic placement of trees prevents worsening the nocturnal ventilation, while providing effective cooling during daytime. A replacement of mature trees by new trees in densification scenarios led to an increase of the physiological equivalent temperature (PET) by 7.5–7.9 °C. Adding green roofs and green facades did not lead to a decrease of heat stress levels, but significantly reduced surface temperature. A coupling of microclimate models operating on different scales and with different spatial resolutions is important to consider mutual influences between ventilation and outdoor thermal comfort.

1. Introduction

The increase in urban population and the rising demand for housing per capita lead to a high pressure on existing urban green spaces [1]. Built densification of the urban fabric can happen either as building up of smaller or bigger tracts of open land within the city or by adding buildings into already existing built areas, e.g. housing areas [2]. Moreover, the size of existing buildings can be increased and green areas be paved over to make space for car parks or other uses [3]. However, both large-scale and small-scale green spaces fulfill an important role in regulation of the urban climate and in provision of further cultural and provisioning ecosystem services [4,5]. While densification on a city-wide scale threatens fresh air corridors and amplifies the urban heat island effect [6,7], high levels of soil sealing and loss of existing vegetation on a local scale lead to a deterioration of human thermal comfort and an increase of human heat stress [8]. High heat loads have numerous negative health effects [9]. In the wake of climate change, the intensity and frequency of heat days will increase worldwide [10,11]. On the other hand, densification offers the possibility to redesign residential areas in a climate-responsive way. When developing new housing and when increasing residential density, urban green space must therefore be incorporated from the outset so that it can provide climate-regulating services [12].

Among possible green interventions, trees constitute the most effective option to reduce heat stress at the local scale [13]. The cooling effect of trees is mainly attributed to evapotranspiration and shading and can reach up to 3 °C for daytime Ta and 16 °C for PET [14]. Like trees, green roofs provide regulating ecosystem services for rainfall interception and infiltration [15], evaporative cooling and changes in surface albedo, lowering of building envelope temperatures [16]. Vertical greening has been promoted as another climate adaptation option for dense neighbourhoods where no space for tree planting is left [1]. The highest cooling benefits are achieved for sunexposed westward oriented facades [17] and can reach up to 15.5 °C for surface

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temperature [18] and 2.3 °C for mean radiant temperature [19].

As space in growing cities is a scarce and desired resource, green spaces must compete with other land use demands. Owing to that, a large number of studies have explored the most efficient tree planting strategies in parks [20,21], street canyons, e.g. Ref. [22], street parking lots [23] and idealized urban geometries of neighbourhoods [24]. However, there is no one-size-fits-all solution, as e.g. tree cooling capacity is dependent on several local factors, including prevailing wind conditions, urban set up, growing conditions and water availability. Additionally, more than one function might be intended for the urban green space, so that it must serve different needs [25]. Hence, findings from generic studies have to be transferred to real planning cases [26].

Moreover, focus is often given to one specific setting, e.g. a street block without consideration of its surroundings and the mutual influences that exist between a specific space and its wider urban area. Changes in one place are likely to have an impact on adjacent areas: Thus, the upwind surface coverage has an effect on downwind thermal conditions [27]. Furthermore it has been observed that parks not only influence thermal conditions in the built surrounding, but also vice versa [28]. Cold air paths foster the removal of overheated air masses in inner urban areas and play a pivotal role to avoid or reduce overheating, especially during nighttime [29,30]. Densification alters an areas' roughness or can block existing cold air-paths, thus reducing inflow of cold air and deteriorating outdoor thermal comfort [31,32]. Long-row buildings perpendicular to the wind flow or big trees are prone to weaken local ventilation [33]. Thus knowledge of cold air tracks and local ventilation is necessary to design climate responsive urban neighbourhoods [33,34]. However, Bartesaghi et al. [35] found in their review that until now, only 4.2% of all assessed studies (165) considered multiple scales, while 49% of them focused on the micro-climate scale. Consequently, there is a paucity of information to establish how different modes of densification, such as adding more buildings, or adding more storeys to existing buildings, will affect different climatic goals such as reducing daytime thermal loads in open spaces and securing ventilation for fresh air at night. Therefore, more attention should be given to mutual influences between different scales.

Against this background, our study addresses the following research questions:

- Is the addition of new green able to compensate for increased built densification and loss of existing green?
- How does the introduction of green infrastructure influence the climatic situation both on block scale (focus on outdoor thermal comfort) and on district scale (focus on ventilation)?
- How can the introduction of new green be achieved in a real planning case, that aims to achieve multiple goals?

To answer these questions, we compare microclimatological modelling outcomes on district level and block level for a real planning case. Different densification and green intervention scenarios are assessed using two different simulation models, ENVI-met and FITNAH. For this article, densification is understood as an establishment of new buildings in inner urban areas not built-up previously or the addition or extension of buildings in already existing built areas. The latter is in the focus of this study. For realistic test settings, the chosen scenarios have been developed together with city and green space planners. Due to the detrimental health impacts of excessive heat and the need for cities to adapt to climate change, our focus is set on heat stress in summertime.

2. Study area

The study has been conducted in Munich (48°8′N, 11°24′E, 519 m above sea level), one of the most densely populated and fastest growing cities in Germany [36]. The city's climate is classified as moderately warm with an average air temperature (T_a) of 9.5 °C and an annual mean precipitation of 959 mm (1981–2010) [37]. With warm summers, an absence of dry seasons and highest precipitation rates during the summertime, Munich's climate corresponds to the Cfb category of the Köppen-Geiger classification [30]. Since 1955, a significant increase of T_a by about 0.31 °C per decade has been observed and an urban heat island effect is clearly detectable. Similarly, the number of hot days with maximum air temperatures of more than 30 °C is increasing [30].

Munich has adopted a strategy for adaptation to climate change [38] and defined green space standards to strengthen inner-city green spaces, for instance by requesting greening of flat roofs with an area of more than 100 m^2, green roofs on garages and underground car park accesses and minimum plant qualities for trees [39,40]. Regulations in local plans are regularly revised to support Munich's climate change adaptation goals. The most important cold air production areas as well as corridors within the city boundaries are depicted in Munich's urban climate map [41].

The study area is located in Moosach, a city district in the north-west of Munich. There, a 3.4 ha large area of free-standing multistorey blocks from the 1940s–1960s was declared as a regeneration area (Fig. 1). Renovation needs of the buildings, large green space supply (50% percent of the area is greened), short connections to the public transport system and uniform ownership structures contribute to a high densification potential. A commercial district and the quarter's railway station border the area in the northwest. To the southeast, there is a large green space of an allotment garden area and a large green cemetery. Otherwise, the study area is surrounded by residential areas. According to Munich's urban climate map, the bioclimatic situation of the study area is less favorable, with the allotment garden as the only zone of high climatic relevance [41]. While the climate analysis on district scale considers the larger spatial context, the block scale investigations represent a typical section within the regeneration area. The case area represents an open midrise development according to the local climate zone approach of Stewart and Oke [42].

3. Data and methods

This study combines micrometeorological modelling at the district scale and block scale to investigate human thermal outdoor comfort and cold air flows for a real planning case and its possible future developments. At the district scale, the simulations concentrate on the regeneration area, and at the block scale, they focus on the study area as shown in Fig. 1.

3.1. Greening scenarios

To identify useful scenarios for densification and green infrastructure planning, a bilateral exchange with city planners of the City of Munich took place during the period 24 July 2019 and 2 September 2020. Participants in these meetings involved personnel from the Department of Urban Planning and Building Regulations and the Department of Health and Environment. The planners provided insights in Munich's local plan and green space regulations and feedback on the draft densification scenarios. In a first step, different densification scenarios and their impact on the existing vegetation and the local microclimate were analysed. The results were published in Erlwein et al. [43]. Following from that, the planners selected two densification set-ups for further analysis regarding possible green interventions.

Hence, the analysed scenarios in this study distinguish between two different forms of densification, two levels of green intervention strategies (realistic and optimistic) and in the case of the block scale study of daytime thermal comfort, between newly planted (T 1) and mature trees (T 2). Based on the status quo, we defined six scenarios for the district scale and ten scenarios for the block scale (Fig. 2). In the case of densification with addition of buildings (referred to as "closed" set-up in the forthcoming), buildings are added perpendicular to the existing free-standing multi-storey blocks, resulting in U-shaped building blocks (building height 15 m). To achieve roughly the same number of new flats

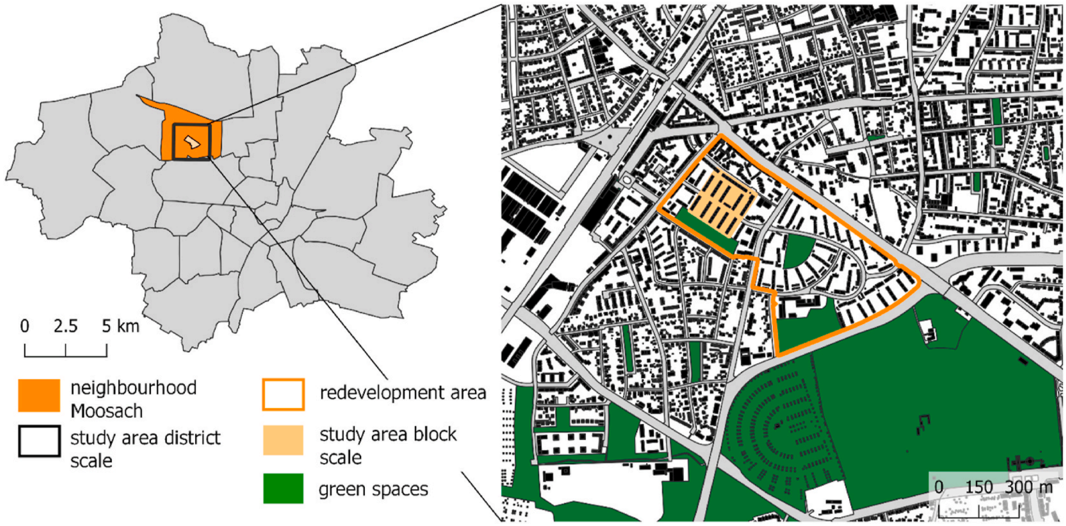

Fig. 1. Location of the redevelopment area within the Moosach district and of the nested study areas for modelling of ventilation and thermal comfort.

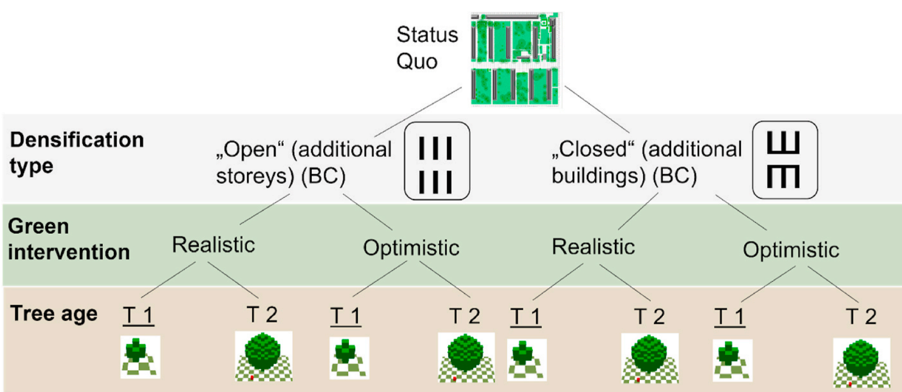

Fig. 2. Systematic representation of the scenarios for the microclimate and ventilation assessment. Starting from the status quo (SQ), two different types of densification are distinguished. From the base case (BC) of each densification type, two levels of green interventions are assessed (realistic and optimistic). Mature trees (T 2) and newly planted trees (T 1) are distinguished on block scale (the underline marks the block scale-only scenarios). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with the densification type "additional storeys" (referred to as "open" in the forthcoming), building heights were increased to 18 m to add two storeys (for further details see Ref. [43]). The "realistic" greening scenario represents the implementation of Munich's current green space regulations, while the "optimistic" greening scenario depicts a more progressive alternative whereby green facades, thicker green roof substrate layers and additional space for trees are considered. The current situation (SQ) serves as the reference for all scenarios.

In the "realistic" scenarios, 75% of all trees must be removed due to construction works for new buildings or underground car parks (Table 1 presents an overview of the greening scenarios). This corresponds to a realistic replacement rate according to the collaborating city planners. To optimise outdoor human thermal comfort, we strategically positioned the replaced trees in thermal hot spots derived from the analysis of the base case scenarios. Trees are grouped rather than equally spread over the yards to improve wind penetration [21] and nocturnal cooling [14] (Fig. 3). This tree placement strategy also accounts for individual thermal preferences as well as for varying conditions in different seasons by creating microclimatic variability [28]. In the optimistic scenario with 100% tree replacement, a new street tree avenue is introduced for the southern sidewalk. Due to limited street widths, this requires a redesign of the streets into one-way streets. Therefore, the additional tree avenue is only considered in the "optimistic" scenarios. Since the substituted trees are planted on underground car parks, a maximum tree height of 15 m and 11 m diameter is assumed (representative for e.g. *Carpinus betulus*) as larger trees are not likely to develop on these locations. This is due to the difficult growing conditions on underground car parks: limited rooting space, altered soil moisture and increased soil temperature impose a significant impact on tree growth [44]. Moreover, insurance companies require that the concrete ceiling of underground garages is tested for water impermeability after 30–45 years, requiring the removal of all overlying soil substrate and trees [45]. Munich's most widespread street tree, *Acer platanoides* [13] (15 m height, 7 m width),

Table 1
Configuration of different green infrastructure elements for realistic and optimistic scenarios. T1 = young trees, T2 = mature trees, LAD = leaf area density, LAI = leaf area index.

	Realistic	Optimistic
Tree replacement	75%	100%
Specifications for replaced trees (both realistic and optimistic)	T 1: small trees = 5 m height, 3 m width, LAD 1.1 m^3/m^2 T 2: street tree = 15 m height, 7 m width, LAD 2.0 m^3/m^2 T2: courtyard tree = 15 m height, 15 m width, LAD 1.1 m^3/m^2	
Green roofs	20 cm substrate layer, Grass LAI (1.5 m^2/m^2)	40 cm substrate layer, Grass LAI (1.5 m^2/m^2)
Green facades	–	S and SW facades 30 cm thickness, LAI 1.85
Unsealing	–	Additional tree alley

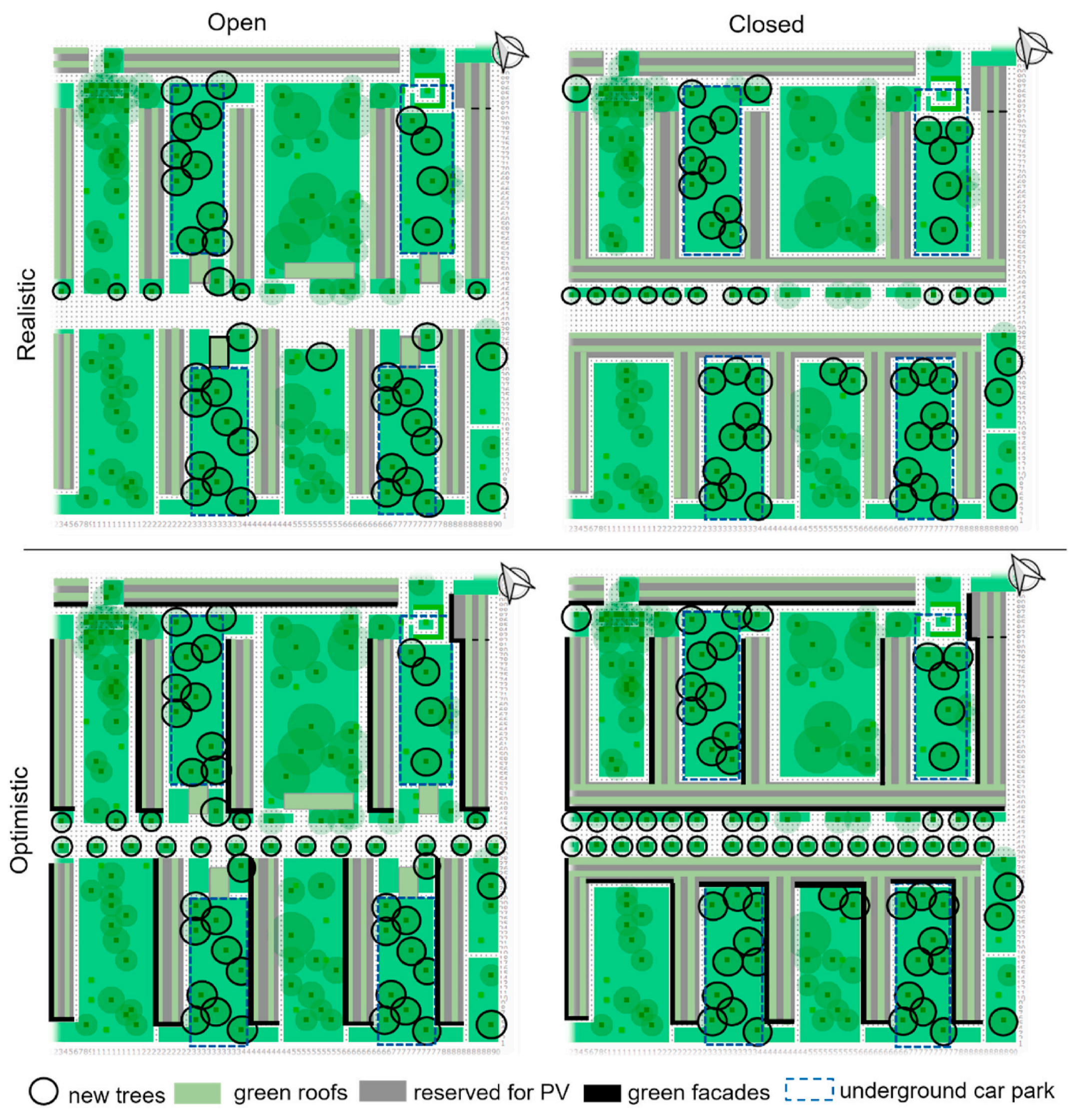

Fig. 3. "Realistic" and "optimistic" green planning scenarios (T 2) for the two different densification types as depicted for the block scale. New trees substitute trees removed during the construction phase (75% realistic, 100% optimistic replacement). 50% of the roof area are greened, 50% reserved for solar panels (PV). Facade greening is applied to S and SW-facing facades in the optimistic scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

served as a model for the tree avenue. In the ENVI-met study on block scale, newly planted (0–5 years after plantation) and mature trees (40–50 years after plantation) are compared to assess how the cooling effect differs shortly after planting and shortly before the renovation of the underground garages. Tree dimensions for certain tree ages are derived from measurements by Moser-Reischl et al. [46]. For more details on tree characterisation, see Table A1 and A2. In the realistic scenarios, 50% of the roof area is covered by green roofs with a substrate depth of 20 cm, while it is 40 cm for the "optimistic" scenarios. A substrate depth of 20 cm corresponds to Munich's greening regulations in recent local plans, while 40 cm represents intensive green roofs that allow for a wider variability of plant species. The remaining 50% of the roof area in each scenario are reserved for solar panels. The green roofs and the reserved areas for the solar panels are equally distributed on each roof.

Although green facades provide several ecosystem services, e.g. evaporative cooling, insect habitat, air filtration, provisions for them are rarely made in Munich's local plans [43]. Thus for the "optimistic" scenarios, all walls facing south-east to west, which receive the most radiation during daytime [47], are greened with *Parthenocissus tricuspidata* (leaf area density (LAD) 1.85, 30 cm thickness) [19] as ground rooted facade greening is funded by the City of Munich. 43% of the building facade are reserved for windows and door openings (Table A3).

3.2. Micrometeorological observations

A field measurement campaign was conducted from 27 July, 2 p.m., to 28 July 2020, 5 p.m., with a self-built weather station equipped with HOBO and Ecomatik sensors. The sensors recorded T_a, relative air humidity, wind speed (at 2 m height), black globe temperature (at 1.4 m height) and surface temperature with a 10-s sampling and 5 min logging interval (Fig. A1 for further information regarding the sensors see Table A4). The weather station was placed on the lawn between the row buildings as a representative non-treed location within the study site and with a sufficient distance to the road and the building facades (Fig. 4). The measured time period was representative for a hot day with maximum T_a exceeding 30 °C, no clouds and wind speed below 2 m per second. Continuous meteorological data are available from the weather station of the German Weather Service (DWD), located 2.6 km from the

Fig. 4. Automatic weather station and placement within the ENVI-met model area in Munich, Moosach.

study area.

3.3. Microclimate modelling

3.3.1. ENVI-met model set-up

ENVI-met is a three-dimensional (3D) non-hydrostatic model built to investigate plant-surface-atmosphere interactions at the microscale [48, 49]. It is based on computational fluid dynamics, and is one of the most widely used simulation tools for micrometeorological investigations [50]. ENVI-met's plant module ALBERO allows a realistic representation of trees, while the application BIOMET calculates several thermal comfort indices such as physiological equivalent temperature (PET). Detailed descriptions of the model can be found in Bruse and Fleer [48] and Simon [49]. For this study, ENVI-met version 4.4.5 and BIOMET version 1.5 were used.

The study area was represented in ENVI-met with a model domain of 90 × 95 x 25 grids with 2 m vertical and horizontal resolution. For higher accuracy of surface interactions, the lowest vertical cell was further divided into five sub-boxes. The grid was rotated 32° from the north to rectify the building structure. Brick was used as wall material and tile as roof material according to the present building characteristics. 158 existing trees were grouped into five categories after crown shape and tree height for sake of simplification [43]; Appendix Table A1).

3.3.2. ENVI-met model validation and adjustment

For the model validation and adjustment, the ENVI-met data for the grid cell of the weather station were compared to the hourly aggregated weather station recordings for 27 and 28 July 2020. Meteorological data from the DWD weather station were used to force the model. The simulation runs started on 27 July 2020, 6 a.m. The coefficient of determination (R^2) and the root mean square error (RMSE) were calculated for T_a, relative humidity and the surface temperature over 24 h. While modelled and measured data fitted reasonably well for T_a and

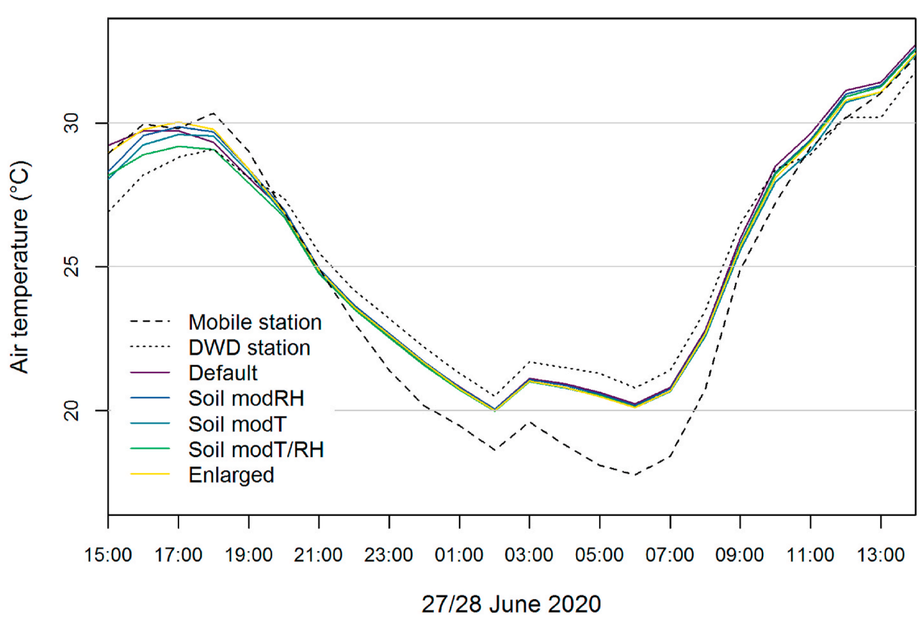

Fig. 5. Comparison of modelled (coloured) and measured (grey and black) T_a over 24 h. Sensitivity tests included alteration of the given soil conditions (soil mod) or the model input area (enlarged). Default refers to the ENVI-met default soil conditions settings.

RH during daytime (see Fig. 5), ENVI-met overestimated nocturnal T_a (10 p.m. - 5 a.m.) by 0.6–2.5 °C. Relative humidity was slightly underestimated during daytime and deviated significantly from 3 a.m. to 8 a.m. (5–10%). In order to decrease the observed deviations, several sensitivity tests were performed, including changed soil properties and an expansion of the model area in upwind direction. The default settings for soil temperature and soil moisture were adjusted to measured values from the DWD station to better represent local conditions. The model grid was duplicated in upwind direction to reduce the influence of the boundary conditions (see Table 2). Though all the modifications improved the model fit, the deviations during nighttime still remained large. Overall, the model output seems to be rather controlled by the weather input data from DWD station, than by the local setting provided in the model area. The best model fits were found for adapted (increased) soil temperatures and the enlarged model area (Table 2). Considering the trade-off between a slightly better match (lowest RMSE for T_a and RH) and a significantly longer modelling time when a larger study area was employed (+50%), the modelling runs for the study were performed using the adapted ground temperatures measured at the DWD station (Soil modT). The validation results for this setting (R^2 0.99 for T_a and 0.96 for RH, see also Fig. A2) are within the range of other validation studies [51–53]. Due to this and the good agreement during daytime, ENVI-met is regarded as a suitable investigation tool for this study.

Weather records from the Munich city centre weather station of the DWD were analysed to identify a typical hot day with maximum T_a above 30 °C and a nocturnal T_a not below 20 °C, with a clear sky and low wind speed (maximum of 2 m/s) [30]. Table 3 provides an overview of the final ENVI-met modelling set-up.

3.3.3. Configuration of the FITNAH 3D model

FITNAH 3D (Flow over Irregular Terrain with Natural and Anthropogenic Heat sources) is a common and well-established model for urban climate modelling studies ranging from city-wide scales to the scales of districts (resolution from 50 m to 5 m) focusing on the identification of cold air flows within urban structures [54]. It is three-dimensional, non-hydrostatic and is, compared to other wind field models, also able to simulate solar radiation, T_a and air humidity for the representation of local air flow patterns [55].

For this study, the simulation was setup for a model area of about 10 km^2 with a 5 × 5 m raster resolution (Table 3). The vertical resolution is non-equidistant starting from 2 m above ground and is increasing with elevation. A digital surface model and a building model for the redevelopment area was used as input data for FITNAH 3D. The existing vegetation was recorded on the basis of recent aerial photos. For FITNAH 3D, the same vegetation characteristics were applied for the green space planning scenarios as in the ENVI-met set-up.

Table 2
Overview of all modifications of the four configuration tests and validation results. Statistical determinants are presented for T_a and RH over 24 h. Soil modT = adjusted soil temperature, soil modRH = adjusted soil moisture, soil modT/RH = combination of both.

		Default Soil	Soil modT	Soil modRH	Soil mod T/RH	Enlarged model
Set-up						
Soil T. (<20 cm, <50 cm, <200 cm depth)		19.85, 19.85, 19.85	20.6, 21.5, 20.8	same as default	20.6, 21.5, 20.8	soil T/RH same as default; new model size: 160 (+70) x 105 (+10) grids
Soil humidity (<20 cm, <50 cm, <200 cm depth)		70%, 75%, 75%	same as default	50%, 60%, 60%	50%, 60%, 60%	
Validation results						
T_a,	R^2 RMSE	0.98/ 1.35 °C	0.99/ 1.24 °C	0.99/ 1.3 °C	0.99/ 1.3 °C	0.99/1.22 °C
RH	R^2 RMSE	0.95/ 4.67%	0.96/ 4.44%	0.96/ 4.35%	0.95/ 4.6%	0.96/4.3%

Table 3
ENVI-met and FITNAH 3D model set up and meteorological input data for the study simulation runs.

	ENVI-met	FITNAH 3D
Start of simulation	07/04/2015 at 7 a.m.	07/04/2015 at 9 p.m.
Duration of simulations	36 h	17 h
Modell grid size/ resolution	90 × 95 x 25/2 × 2 m	3250 m × 3100 m x 3000 m/5 m × 5 m
Building materials	Brick (wall), tile (roof)	Brick
Wind speed (10 m above ground)	0.7–2.0 m/s	
Wind direction	240–310°	
Max/min T_a	35.4 °C/21.7 °C	
Cloud cover	cloud-free	
Lateral boundary conditions	Full forcing	zero-gradient
Initial soil temperature	20.6 °C/21.6 °C/20.5 °C/ 19.85 °C	20 °C
Relative soil humidity	Upper layer: 70%, middle and deep layer: 75%	60%

3.3.4. Analysed parameters in ENVI-met and FITNAH

PET-simulation outputs were analysed at the pedestrian level of 1.4 m height (2.0 m for FITNAH) (approximating to the human biometeorological reference height [56] for the hottest daytime (i.e. 2 p.m.). PET represents one of the most widely used human thermal comfort parameters and is suitable for outdoor environments [57]. We also computed the PET averages for ENVI-met from 10 a.m. to 4 p.m. to take into account the shadow cast during the day. Thus, its impact on human heat stress is better reflected [58]. PET above 35 °C is considered as warm, whereas PET above is considered as hot.

Moreover, we investigated nocturnal T_a (4 a.m.) and cold air volume flow (CAVF, for FITNAH). The cold air flow density represents the amount of cold air that flows with a certain speed through a certain volume of air [59]. When assessing the nocturnal microclimatic situation, the CAVF density (in m3/ms) is decisive for describing the transport of cold air from the surroundings or the larger open spaces into built-up areas and, thus, for the local ventilation and cooling potential of these built-up areas. For the evaluation of the CAVF, no threshold values exist. Therefore, the results are distributed by a z-transformation as proposed by the guideline VDI 3787 sheet 1 [60] and categorized into intensities from low to very high. Moreover, the CAVF figures represent the nocturnal wind field by describing wind directions and intensities.

4. Results

4.1. Daytime thermal comfort on block and district scale

4.1.1. PET at 2 p.m. (ENVI-met)

Since a pronounced heat situation was chosen for the model input, the simulated PET at 2 p.m. for the existing situation (Fig. A3) and for all scenarios display overall hot to very hot conditions (Fig. 6). Areas with a lower heat load are only found in the shadow of buildings and trees. For the densification type "open", the hot spots in the base case are found in front of south facing facades and sunlit spots between dense tree agglomerations (PET up to 56 °C). For the second densification type "closed", further hot spots are located in weakly ventilated areas, such as the corners of the buildings in the courtyards. At 2 p.m., little additional shade is gained by the increased building heights, whereas the added building blocks in the "closed" scenario provide additional shade. (For in-depth analysis regarding the effect of densification see Ref. [43].)

Tree plantings in these hot spots effectively reduce the average PET

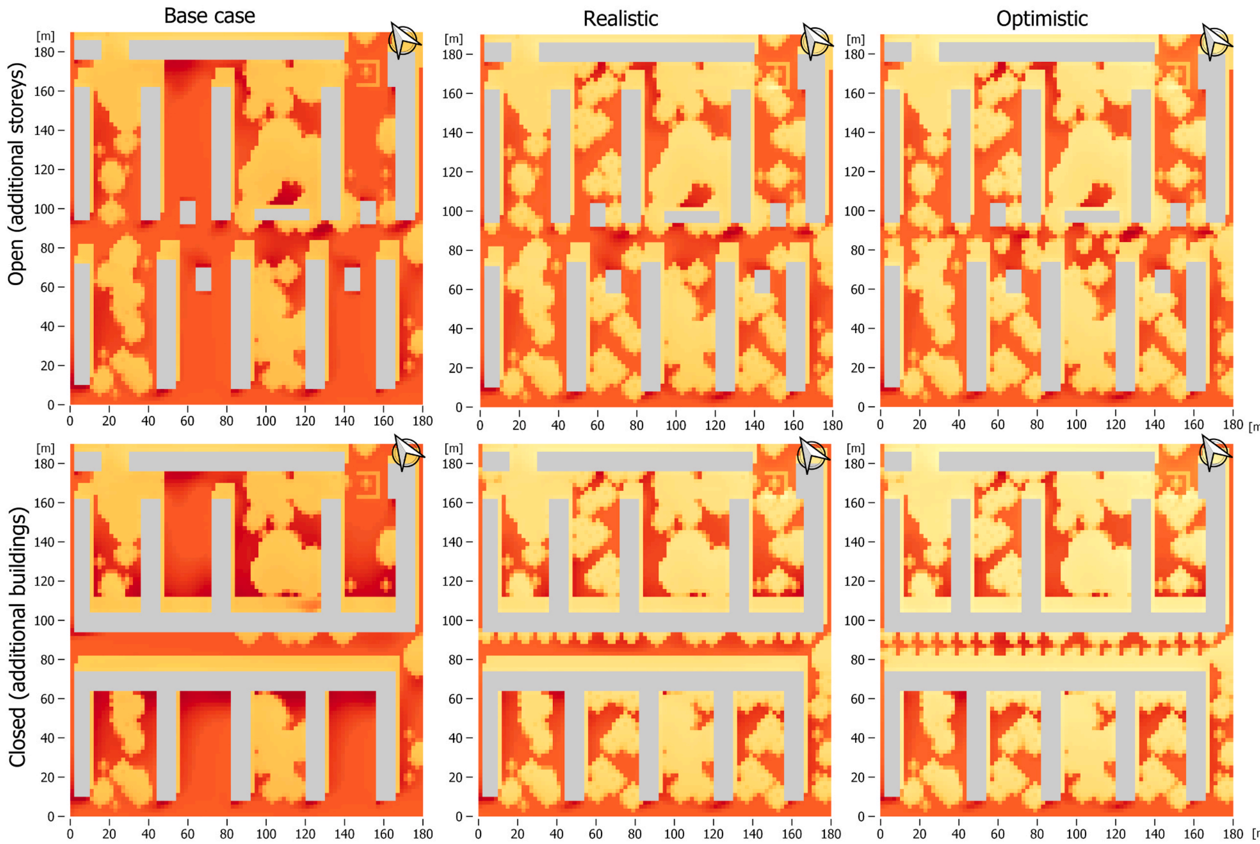

Fig. 6. Simulated PET in ENVI-met for both densification types and greening scenarios ("realistic" and "optimistic") with mature trees (50 years old) for 5 July 2015, 2 p.m.

in the realistic and optimistic scenarios: For the type "open", the average PET of 48.8 °C of the base case scenario is reduced by 7.6 °C (realistic scenario) and 8.6 °C (optimistic scenario) (Table 4). For the type "closed", the respective cooling effect reaches a magnitude of 9.0 °C (realistic) and 10.0 °C (optimistic) compared to the average PET of 48.8 °C. The higher cooling rate in the "optimistic" scenarios is due to the newly introduced street tree planting in the south avenue which provides additional shade (see Fig. 6).

4.1.2. PET at 10 a.m. - 4 p.m. (ENVI-met)

If the period from 10 a.m. to 4 p.m. is considered, the absolute cooling rates are halved (Table 4), but the overall pattern stays the same. For both daytime analysis, a larger heat stress reduction was visible for the type "open". Having larger areas with high PET in the closed row configuration, trees in these locations cause a larger reduction of PET. The lack of shade in both base cases is more prominent at 2 p.m., where the areas between the houses are almost completely exposed to the sun (Fig. 6). The incoming shortwave radiation is not blocked by tree canopies as it is the case in the green adaptation scenarios. Before and after noon, the buildings themselves shade a larger part of the lawns. Thus, the contribution of the tree shade is of lesser importance.

4.1.3. Young tree (T 1) scenarios (ENVI-met)

The analysis presented above refers to fully developed trees. However, after building construction is completed, newly planted trees rather have limited crown diameters and tree heights. Fig. 7 displays the PET results at 2 p.m. for the same scenarios with similar tree positions, but with newly planted trees (5 m height, 3 m crown diameter) (T 1).

The area that is cooled by the trees' shade is greatly reduced. In all scenarios, more than 50% of the area remains above 45 °C. This PET value is associated with extreme heat stress [58]. The cooling compared to the respective base cases ranges from (−0.42 °C to −2.1 °C) (Table 4), which is considerably less than for 50 year old trees. Fig. 8 reveals that the average heat load is higher than the status quo (SQ) for 2 p.m. and as well as the period 10 a.m. to 4 p.m. Only the scenario with full tree replacement for the closed rows can compensate for the daytime warming caused by the densification if the period from 10 a.m. to 4 p.m. is considered.

The displayed values in Fig. 8 show the deviation between the average PET of the status quo and the other scenarios. For the green adaptation scenarios with mature trees (T 2), the area with high heat loads is greatly reduced compared to the scenarios with newly planted trees (T 1) and the densification base cases. From 10 a.m. to 4 p.m., the optimistic scenario of the type "closed" has the highest frequency of 36 °C grid cells and no area is hotter than 47.5 °C. In contrast, 15% of the

Table 4
Comparison of median PET (°C) for the base case and the respective scenarios for 5 July 2015, for 2 p.m. and 10 a.m. to 4 p.m. (ENVI-met). BC = base case, T1 = newly planted trees, T2 = mature trees.

	Open BC	Open real. T2	Open opti. T2	Open real. T1	Open opti. T1	Closed BC	Closed real. T2	Closed opti. T2	Closed real. T1	Closed Opti. T1
2 p.m.	48.8	−7.6	−8.6	−0.1	−0.41	48.8	−9.0	−10.0	−0.81	−2.1
10 a.m.- 4 p.m.	44.2	−3.5	−4.4	−0.5	−1.1	44.1	−4.3	−5.3	−0.9	−1.9

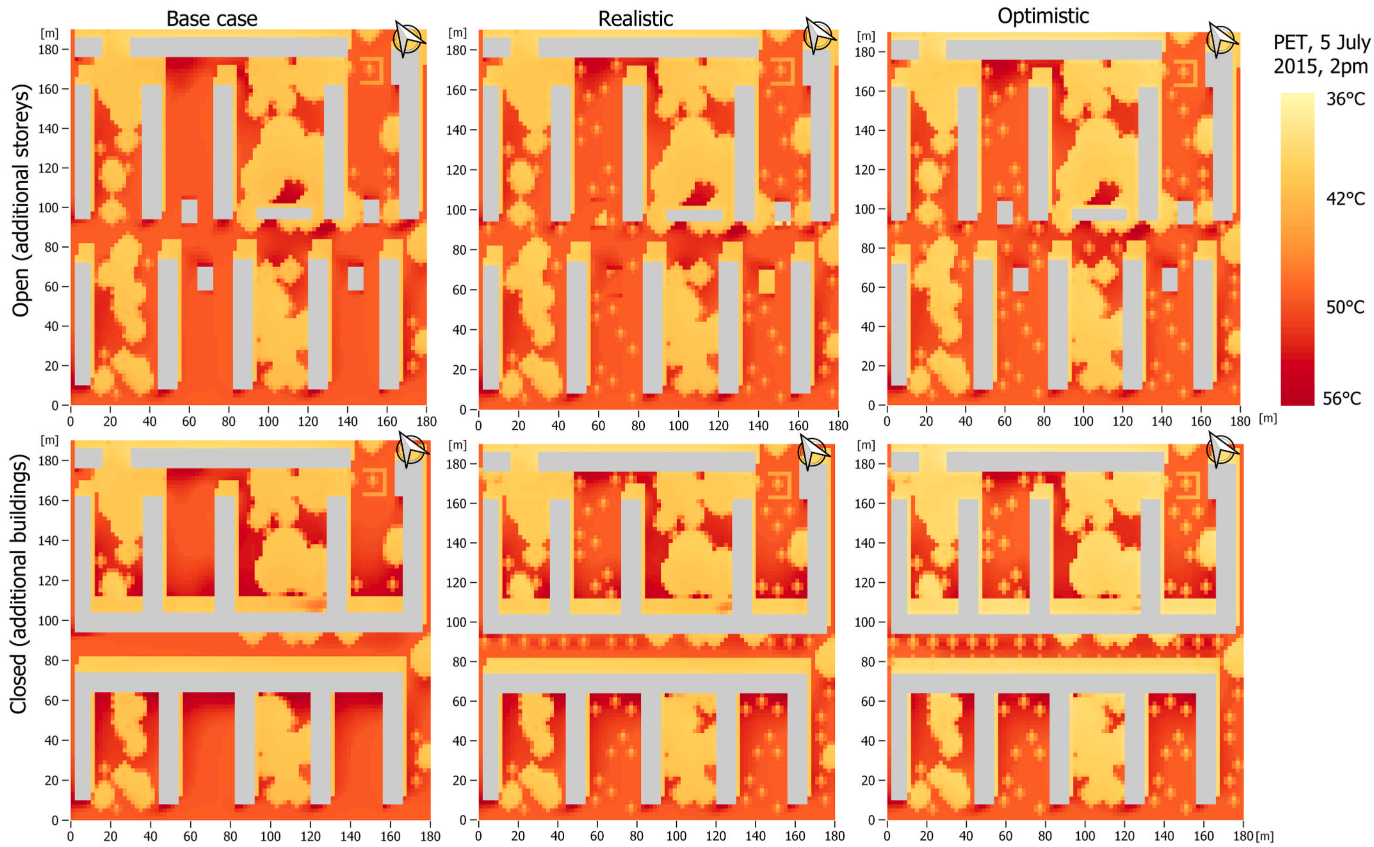

Fig. 7. Simulated PET in ENVI-met for both densification types with newly planted trees (5 years old) for 5 July 2015, 2 p.m.

area in most of the young tree scenarios (except the "closed optimistic" scenario), are hotter than 47.5 °C and almost no areas are below 36 °C. The order of the scenarios from coolest to hottest changes with respect to the considered period. During 10 a.m. to 4 p.m., the "closed optimistic" scenario (T1) is on average slightly cooler (0.7 °C) than the status quo and the difference between the "closed realistic" (T1) and "open optimistic" scenario (T1) has almost disappeared (0.1 °C). At 2 p.m., all scenarios with young trees are hotter than the status quo (by 2.6–4.5 °C PET) and the "closed realistic" scenario (T1) is cooler than the "open optimistic" scenario (T1) (−0.5 °C). In the "optimistic" scenarios, an additional street tree avenue was introduced. Its shading effect is more prominent in the course of 10 a.m. to 4 p.m. than at 2 p.m., causing the described differences.

4.1.4. *Impact of green roofs and green facades*

In the sections above, heat reductions were attributed to the presence of trees although the green adaptation measures also included roof and facade greening. In our results, no cooling effect of green roofs and green facades on PET at 1.4 m height are recognised. Additional test simulations, that only contained either green roofs or green facades and no replaced trees, were performed based on the base case densification scenarios to better distinguish the effects of green roofs and green facades. Their results confirm the lacking cooling effect on PET. Regarding T_a, a reduction of 0.4 °C is observed up to 4 m distance from the west-facing greened facades (Fig. 9). The T_a in front of south-facing facades which receive the highest solar radiation loads at 2 p.m., is up to 1.3 °C cooler when greened. The effect is restricted to the proximity (0–2 m) of the facade. Moreover, the surface temperature of the greened facades and green roofs differs greatly from the non-greened roofs and walls. At 2 p.m., the surface temperature of the green roofs with a 20 cm substrate layer is 19 °C cooler, while it is reduced by 22 °C for a 40 cm substrate thickness compared to the bare roof (50 °C). South-facing facades that heat up to 50 °C at 2 p.m., are 14 °C cooler if greened. While the same effect is achieved by trees that cast their shade on the facade (−16 °C), a combination of tree shade and facade greening achieves an even larger reduction of 21 °C (Fig. 10).

4.1.5. *Comparison of daytime thermal comfort with district scale results*

On district scale, the general pattern of cooler and hotter places is the same as on the block scale. Differences between the scenarios are smaller for the redevelopment area than for the block-scale site. This is mainly due to the larger area covered and the heterogeneity with built-up as well as green areas and streets within the wider area.

Fig. 11 shows the differences (PET) between the "open" base case and "optimistic" scenarios for both the district scale and the block scale. While the cooling effect for trees is in the same order of magnitude for both models (−12 to - 10 °C), it is noticeable that the block scale results of the ENVI-met model suggest a cooling effect (−3 °C) even in those green spaces that were not altered between the base case and the optimistic scenario. Moreover, in the ENVI-met model, PET is slightly higher in some parts of the study area in the "optimistic" scenarios than in the base case setting (+0.5 °C). The FITNAH model does not indicate a heat load reduction in unaltered yards or any warming effects. The observed warming on block scale is associated with reduced wind speed (−0.2 to −0.4 m/s) caused by the additionally planted trees. This effect is cannot be detected on district scale due to the coarser modelling resolution (5 m compared to 2 m).

4.2. *Nocturnal thermal comfort on block and district scale (T_a, ventilation)*

4.2.1. *Ventilation (FITNAH)*

Fig. 12 illustrates the current ventilation situation at district scale by depicting the intensity of the CAVF as well as the wind field in 2 m above

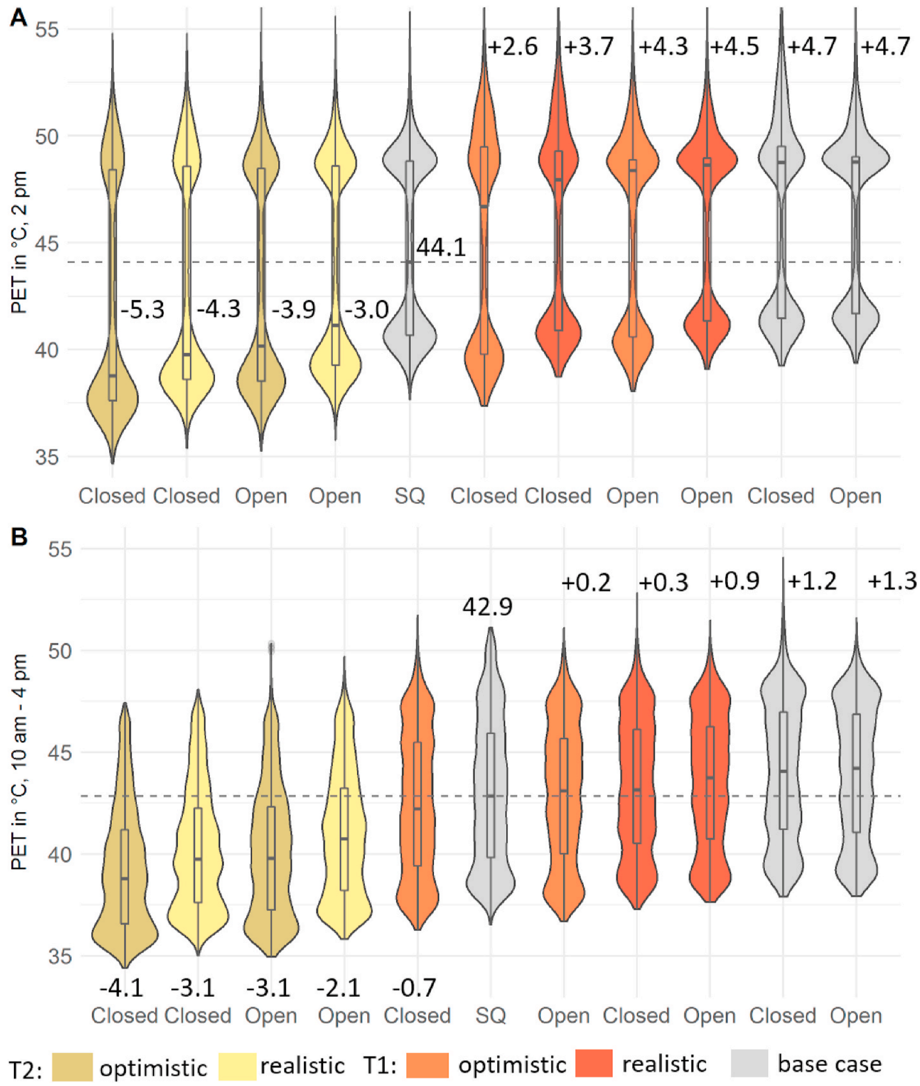

Fig. 8. Violin charts with inserted box plots of all scenarios for PET in °C for 5 July 2015 on block scale (ENVI-met). The dashed line marks the median of the status quo (SQ), the colors refer to green planning scenarios and the tree age. The shape's width reflects the value's frequency. T 1 = newly planted trees, T 2 = mature trees. A: 2pm, B: 10 a.m. to 4 p.m. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ground. With the main wind direction from the west and the large green space of the graveyard in the south, which serves as a cold air production area, the redevelopment area is well ventilated. Especially the residential areas in the south and south-west of the redevelopment area benefit from the cold air flow into the built-up area. Within the studied site, the intensity of the CAVF weakens because of the roughness of the building blocks.

When analysing the nocturnal ventilation for the greening scenarios (Fig. 13), it can be clearly shown that the main decrease results from the type of densification and not the level of greening. The closing of building rows through additional buildings leads to high reductions of ground-level wind speed and ventilation, as well as reductions of the CAVF. By increasing the building height of existing buildings, the impacts on the CAVF are significantly higher and reach up to reductions of 37% compared to the status quo. This can be explained by the final building height of 18 m and the building orientation in mainly north-south direction (except the ENVI-met case area). The raised buildings seem to function as a markedly stronger barrier for the CAVF than the original building height of 15 m. Moreover, the negative effects of densification on ventilation are greater for the previously better ventilated building blocks.

Besides the effects within the redevelopment area, the planned interventions also lead to a decrease in the CAVF in neighbouring areas. Especially adjacent areas to the north-east are affected by reductions of up to 11.5% of CAFV and receive in large parts less cold air than in the status quo. Values of more than 10% reduction are considered as serious effects caused by densification planning (VDI 2008).

4.2.2. Air temperature at 4 a.m

At 4 a.m., T_a differs only slightly between the scenarios on block scale: The average difference between the coolest (closed realistic and closed optimistic, each 20.92 °C) and the hottest scenario (status quo, 21.03 °C) is only 0.11 °C. On district scale, significant differences are discernible regarding building typologies and surface materials: Sealed and enclosed area are hottest (19–21 °C), whereas the graveyard in the south constitutes a cool oasis with T_a of 15.5–17.5 °C. As T_a increases below tree crowns, additional trees lead to a reduced cooling rate. However, the impact is limited to the locations directly underneath the tree crowns. Moreover, warmer air gets trapped in between the buildings. This effect is bigger for the type “closed”. The overestimation of the ENVI-met model results regarding nocturnal T_a as observed in the validation are replicated in the differences between the two model outcomes. The lower values of FITNAH results seem to be thus closer to reality.

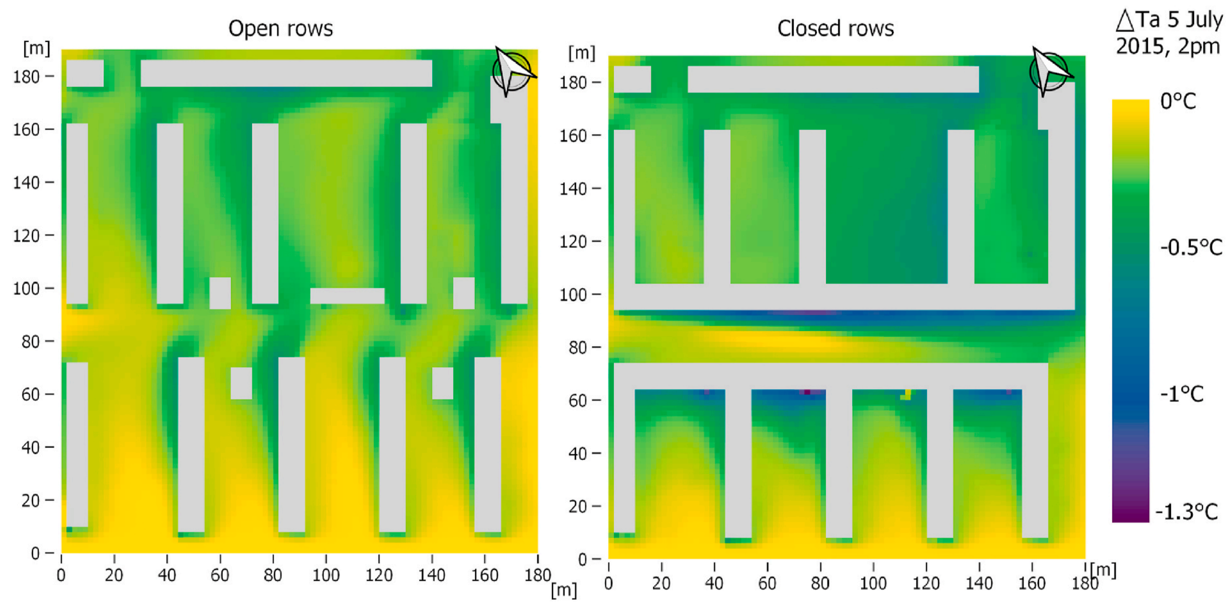

Fig. 9. T_a difference maps (ENVI-met) between base case densificationscenarios and test simulations for facade greening for 5 July 2015, 2 p.m. Facade test simulations considered only green facades, no replaced trees or green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

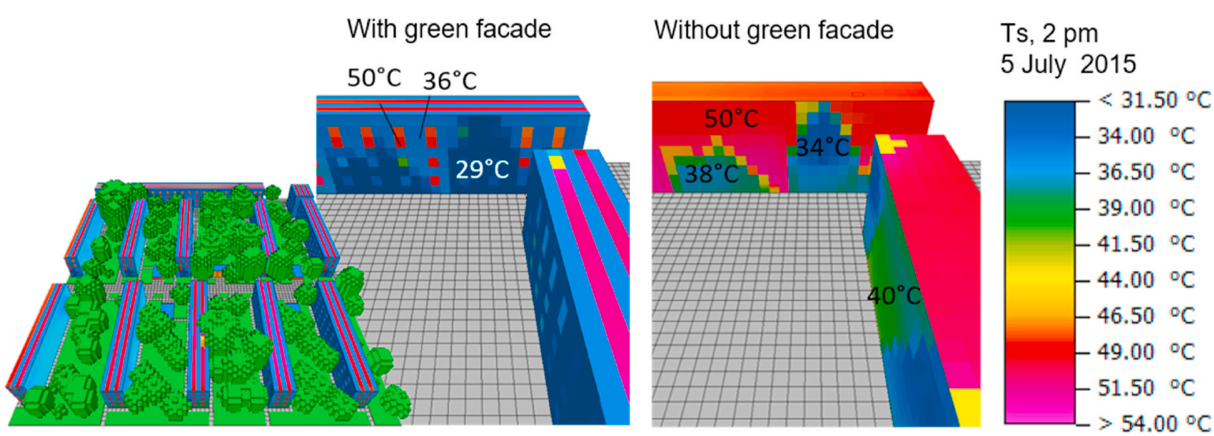

Fig. 10. Surface temperature for green roofs and facades in the case of the open optimistic scenario vs. bare ones in the open base case for 5 July 2015 at 2 p.m. (ENVI-met). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Discussion

5.1. Effects of different greening approaches on block and district scale

Our results show that strategic planning and planting of urban green can compensate for detrimental effects of densification on the local microclimate in terms of daytime thermal comfort.

However, the best results for human thermal comfort are only achieved with mature trees. Newly planted trees (5 years old) improved daytime thermal comfort only slightly compared to scenarios with no tree replacement (−0.1 to −2.1 °C PET), but with one exception, heat loads were higher than in the original setting. Mature trees (50 years) reduced heat loads below the original conditions for both densification types. Making use of strategic tree placement in thermal hot spots, this even can be achieved with 75% of the original amount of trees given that deliberate growing conditions, maintenance and care are provided. Removal of trees during building construction comes at the cost that newly planted trees have lower cooling capacities and underground parking lots do not provide suitable growing conditions for large trees [44]. While trees effectively improve human thermal comfort during daytime, we observed that trees reduce wind velocities and CAVF during the night. The CAVF reduction rates remain at a relatively high level, in particular for the scenarios of the type “open” and within the building blocks in the south of the redevelopment area. This impact of trees was also reported by other studies [53,61], advocating that tree planting positions should be optimized to avoid blocking of existing wind corridors.

When important ventilation corridors were kept open, CAVF did not further decline by increasing the number of trees, and consequently raising the share of tree-shaded area for cooling during daytime. Other studies that found little influence of reduced wind speed on thermal comfort focused on daytime situations only [62]. This highlights the importance to consider both nocturnal and daytime conditions and to take into account thermal indices on block scale as well as district scale ventilation.

On blockscale, the applied scenarios for the densification type “closed” were the coolest during daytime due to the highest amount of shaded areas. On district scale, we observed that the closed rows block ground-level wind speeds. However, the impact on nocturnal T_a was small (0.1 °C). This might be due to the fact that in our case study the

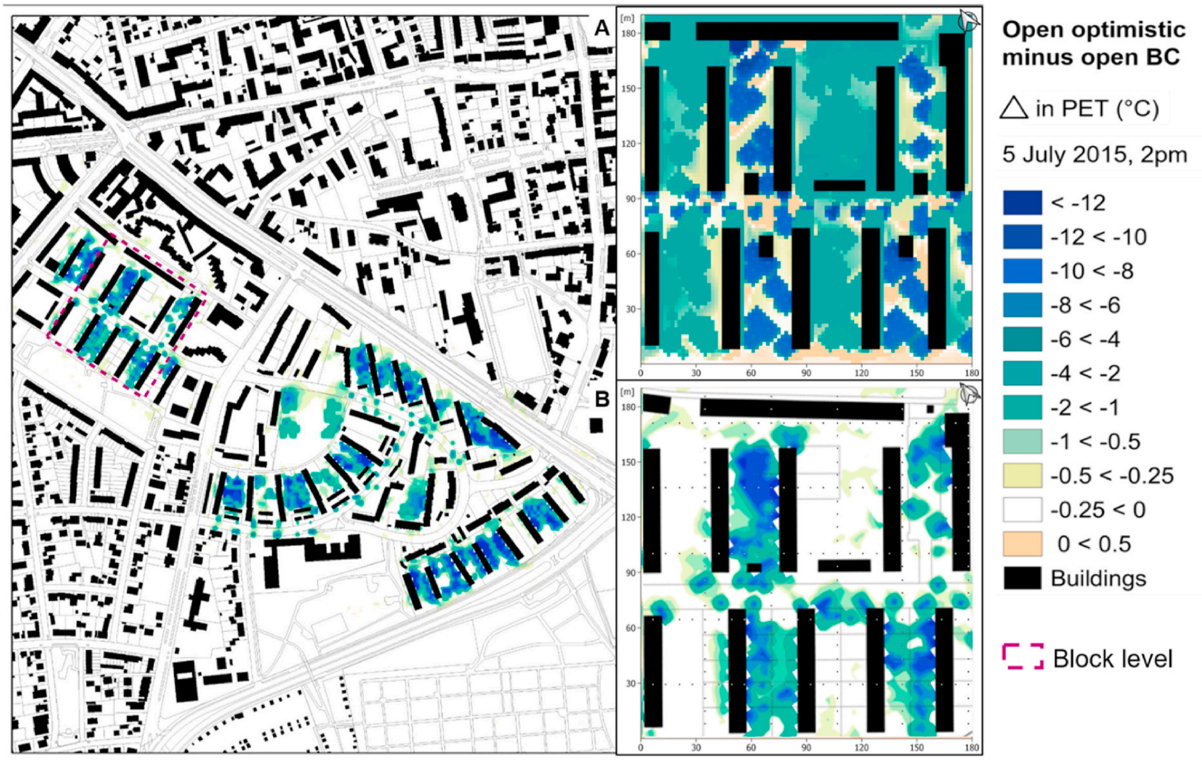

Fig. 11. Differences between the base case (BC) and the optimistic scenario for the densification type "open" on 5 July 2015 at 2 p.m. for the district (FITNAH) and the block scale (ENVI-met) (A). (B) represents a zoom of the FITNAH result map for the block scale area.

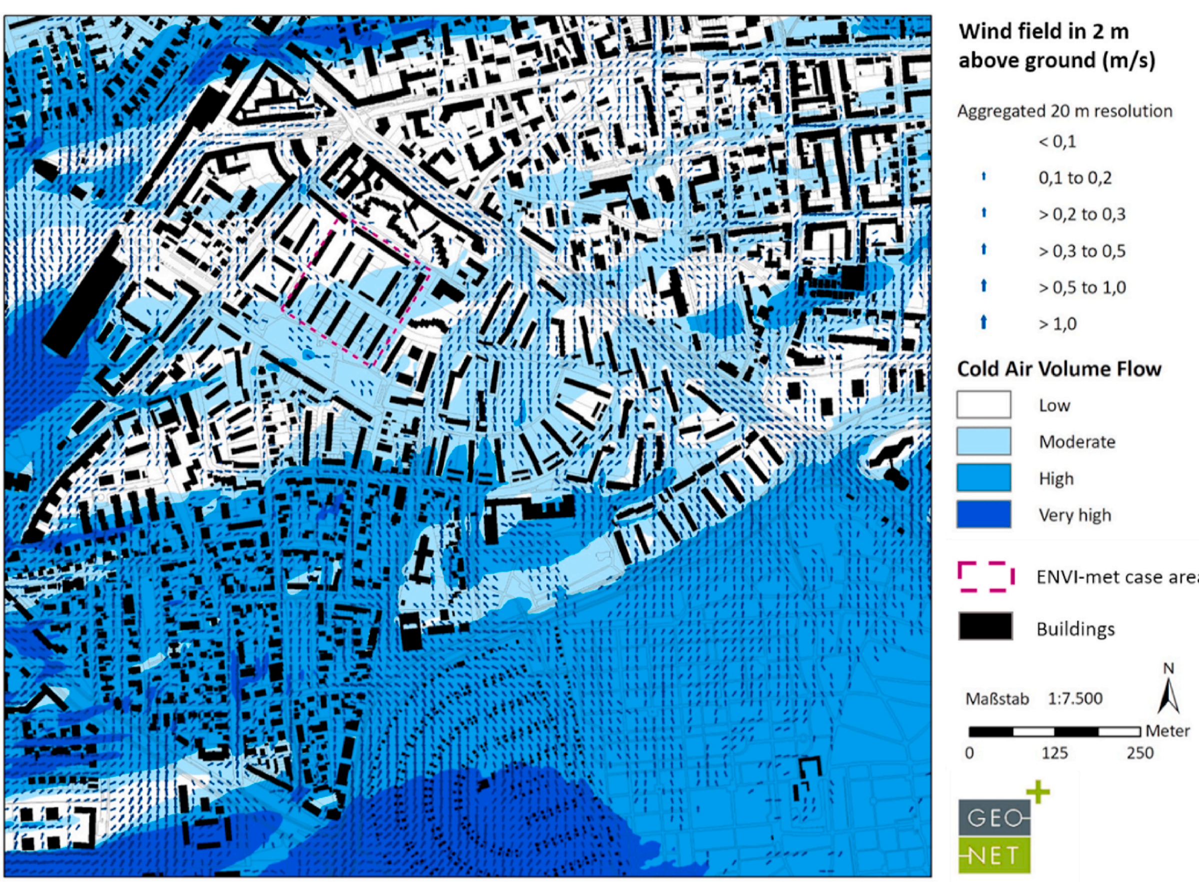

Fig. 12. Ventilation situation of the status quo described by the CAVF at 4 a.m. at district scale (FITNAH).

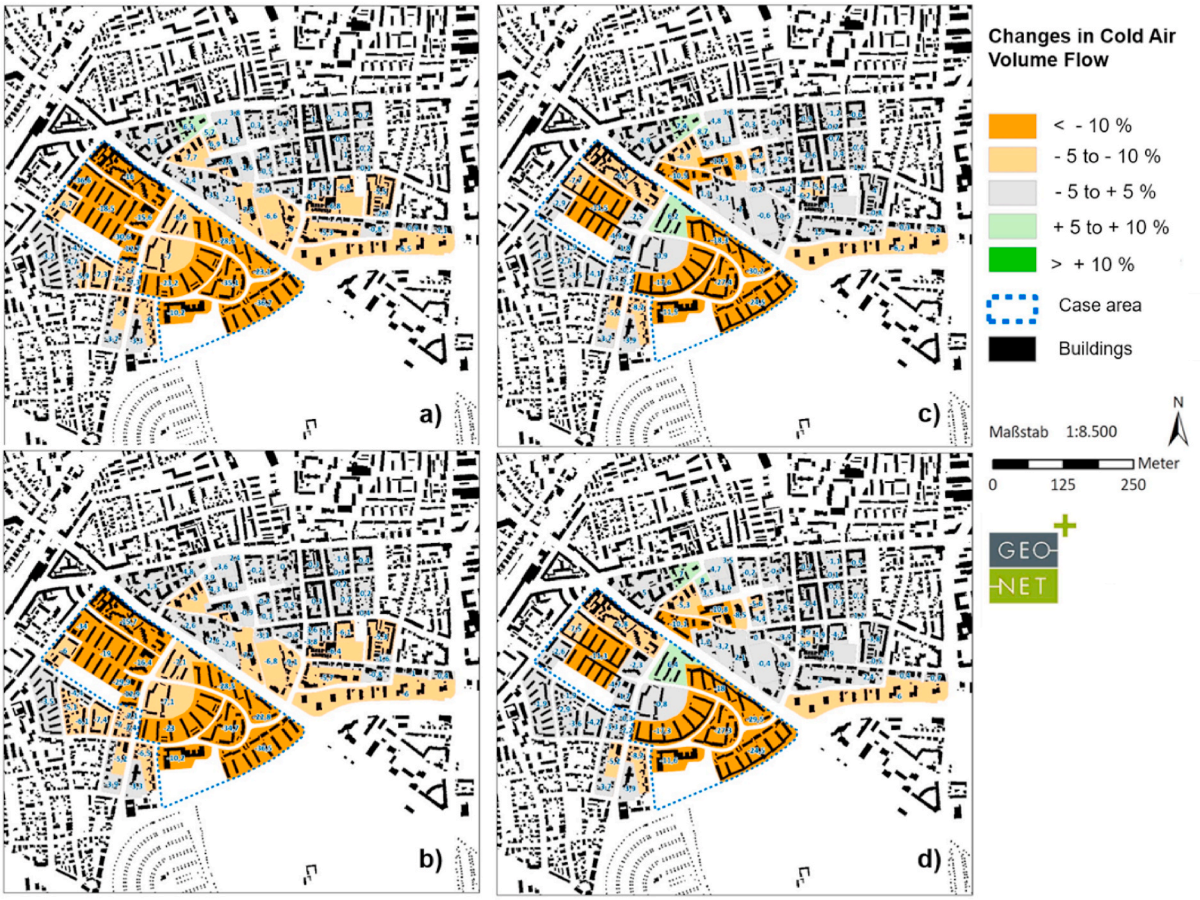

Fig. 13. FITNAH-differences in CAVF compared to the status quo for „additional storeys ", realistic (a) and optimistic greening (b), and „additional buildings", realistic (c) and optimistic greening (d).

amount of unsealed soil remained relatively high (44%). Grassed open spaces, though among the hottest during daytime, are important for nocturnal cooling [63].

Our results suggest that the potential of green roofs and green facades to improve outdoor human thermal comfort are limited and restricted to the proximity of the building facades. However, the facades' and roofs' surface temperatures were reduced by 22 °C by green roofs with 40 cm substrate and by 16 °C by green facades. This is in line with other studies that found only a negligible cooling effect of green roofs on street level for T_a and PET (max. 0.3 °C), while at the same time reporting a significant roof temperature reduction of 26 °C [64]. Though green roofs and green facades are not efficient in cooling the outdoor microclimate, they have been associated with ecosystem services such as habitat provision for wildlife, local noise absorption, energy savings and thermal insulation [65,66]. For our study area in Moosach, Rosenberger et al. [15] found that green roofs are an indispensable measure for adapting to future heavy rainfall events.

5.2. Limitations of the methodological approach

For the presented study, healthy vegetation was assumed. Due to model limitations, we did not consider vegetation that has suffered damage due to prolonged dry periods, which will become more frequent as climate change progresses. For trees, drought stress affects tree growth and stomatal conductivity and, thus, also their cooling capacity. However, the impact varies between different tree species [67]. For grassed open spaces, evapotranspirational cooling is strongly reduced under drought stress conditions [68]. Yet, the shading of trees (during daytime) and openness of the sky (during nighttime) has the largest influence on human thermal comfort. The PET observations are transferable to similiar buildings types. Modelling outcomes for other building orientations or other main wind directions will differ.

In the configuration tests, soil humidity and soil temperature were identified as important variables to improve the ENVI-met model fit and, thus, should be ideally measured in the specific study area. In this study, we referred to the closest available measurements. Nocturnal T_a results of the ENVI-met model were mainly influenced by the measured T_a data from the official weather station and less sensitive towards local conditions. However, the relative differences between the scenarios were similar to those observed in the FITNAH model.

Our observations for the block and district scale were based on two different models, ENVI-met and FITNAH, which are based on different assumptions, controlling the model outcomes. This procedure was chosen in order to achieve more accurate results: While ENVI-met is an established microclimate model, it has weaknesses in the correct representation of air flow. FITNAH represents a sophisticated model for air flow simulations and allows larger scale studies, but has limited options to assess the effects of microscale interventions like green roofs and green facades. Despite these differences, both models were run for the same meteorological conditions and similar scenario settings and showed generally good agreement regarding outputs for human thermal comfort. For future research, a coupling of microclimate models operating on different scales and with different spatial resolutions by nesting the smaller grid into the larger could further improve the consistency between the model results, as it is already under way for the newly developed model PALM-4U [69].

Our study focused on a summer heat stress situation due to its relevance for human health. However, urban planners need to design outdoor spaces that provide thermal comfort throughout the year. For that reason, our planting strategy did not seek to achieve maximum tree cover, but also considered seasonally different (light) requirements as several patches of the study area were designed to remain exposed to the sun.

5.3. Planning recommendations for residential densification areas

Our results indicate that removal of old trees in densification projects should be avoided and else reduced to a minimum as mature trees provide considerably more cooling than newly planted trees. To achieve the same cooling effect as mature trees, newly planted trees must become at least 40–60 years old. Moreover, the placement of trees plays a decisive role for optimizing human thermal comfort throughout the day: to achieve both daytime cooling and to avoid nocturnal heat trapping, trees should be planted in thermal hot spots and arranged in clusters that do not hinder nocturnal cold air flow. Optimized tree locations also provide enough root space and sufficient water and nutrient supply for the trees. As nocturnal ventilation is mainly affected by changes in the building structures, building heights should not be increased perpendicular to the main wind direction in autochthonous weather conditions. During heat situations in summer, the closing of building rows decreases ground-level wind speeds and, thus, air exchange. Hence, we recommend to always investigate the ventilation situation at district scale as a prerequisite for microclimate optimisation by green infrastructure in order to ensure a strategic placement for the implementation of green measures. If only weak CAVFs reach the project area, further tree planting should be avoided to avoid additional flow obstacles and ensure nocturnal cooling. In an open midrise development with limited soil sealing and sufficient green space, nocturnal temperatures are less likely to exceed the critical threshold of 20 °C in the temperate climate zone. In this case, the benefit of additional shading during the day outweighs the potential reduction of the nocturnal CAVF. Green roofs and green facades should be considered as a valuable addition to climate resilient neighbourhood planning, but not as a substitute for trees. Both provide further ecosystem services such as stormwater retention and air purification.

6. Conclusions

This study has demonstrated that the joint assessment of greening interventions at district and block scale is a prerequisite to create comfortable and climate-responsively designed neighbourhoods. By applying two different climate models, ENVI-met and FITNAH, we investigated thermal comfort and ventilation at two different scales to identify conflicts and similarities between these parameters. We have shown that green infrastructure can compensate for negative effects of building densification on daytime thermal comfort, but not on CAVF. In our case, CAVF was significantly reduced (minus 37%) by increasing buildings height, deteriorating nocturnal cooling. As such an increase of building heights perpendicular to the main wind direction should be avoided, especially in weakly ventilated areas. New buildings provide additional shade but negatively affect ground level wind speed and ventilation. Alterations to the building structure will also affect CAVF and outdoor thermal comfort in the adjacent areas. To reduce trade-offs, it is vital to assess both daytime and nocturnal as well as block and district scale conditions for microclimate optimisation. This helps planners when carefully deciding on urban green measures for regulating heat stress during the day while enhancing nocturnal ventilation. While this study presented a first approach to assess greening interventions at district scale and block scale by applying two independent climate models with different strengths and limitations, a coupling of microclimate models by nesting or development of integrated models is recommended to further improve consistency of results for future research. Our results emphasize the importance of existing vegetation, especially mature trees, for adaptation to heat in summer. If new trees are introduced in a residential area, we recommend their strategic placement in thermal hot spots and in clusters that do not obstruct nocturnal ventilation corridors. Finally, modification of the building structure should carefully regard ventilation patterns at district scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Tree categories, their respective characteristics and the amount of each tree category in the status quo and both base case densification scenarios.

Category	Size	Height	Diameter	LAD	Status Quo	Open BC	Closed BC
K1	Small (all forms)	6 m	5 m	1.1	44	24	16
K2	Medium, spherical	15 m	11 m	1.1	18	12	7
K3	Medium, cylindrical	15 m	9 m	1.1	50	31	31
K4	Large, spherical	22 m	17 m	1.1	12	7	7
K5	Large, cylindrical	22 m	11 m	1.1	34	28	23
					158	**102**	**84**

Table A2
Tree types of replaced trees and their quantity in the respective green scenarios for the block scale scenario. LAD = leaf area density.

Tree type	size	LAD	Realistic		optimistic	
			open	closed	open	closed
Street tree (e.g. *Acer platanoides*)	15 m height, 7 m width	2.0	5	11	19	28
Courtyard (e.g. *Carpinus betulus*)	15 m height, 11 m width	1.1	37	42	37	42

Table A3
Amount of each green measure for the different scenarios on block scale.

	Open	Closed
Trees (realistic/optimistic)	42/56	53/70
Green roofs (m^2)	4.640 (50%)	4.458 (50%)
Green facades	43%	43%

Table A4
Specification of the HOBO and Ecomatik sensors used in the measurement campaign in summer 2020 in Munich.

name	parameter	accuracy
S-THB-M002	Air temperature	±0.21 °C
S-THB-M002	Relative humidity	±2.5%
T-Surface sensor Ecomatik	Surface temperature	±0.2 °C
HOBO S-WSB-M003	Wind speed	±1.1 m/s or ± 4%
Black globe Ecomatik	Black globe temperature	±0.2 °C

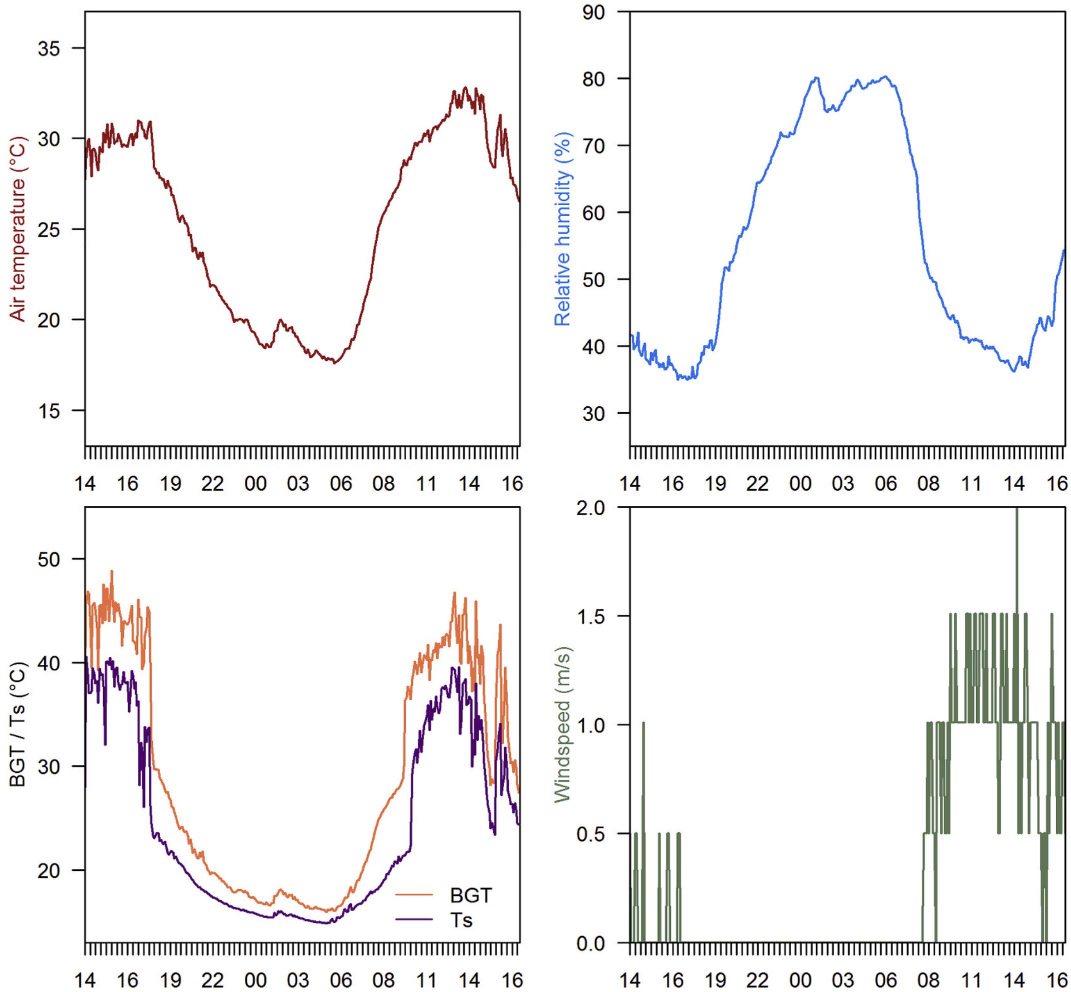

Fig. A1. Meteorological conditions in the study area from 27 July 2 p.m. to 28 July 2020, 4 p.m. as observed by the mobile weather station. BGT = black globe temperature, Ts = surface temperature.

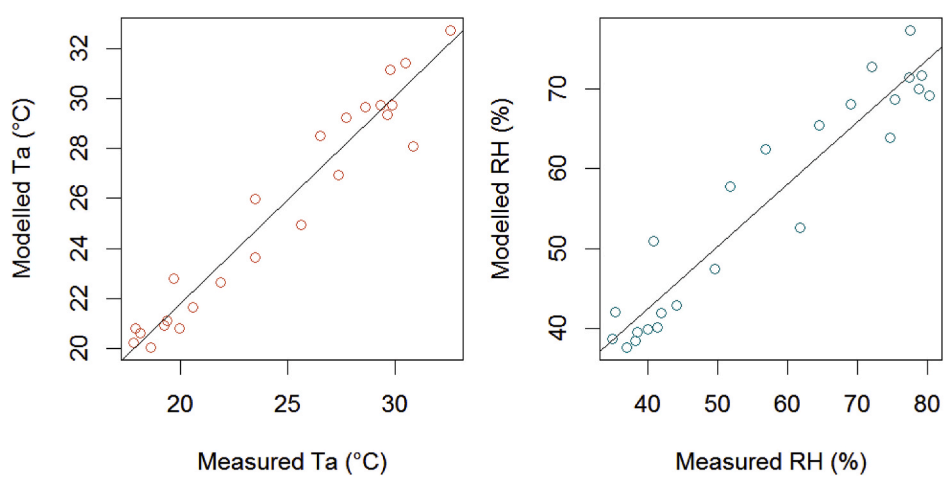

Fig. A2. Comparison of modelled (ENVI-met) and observed hourly air temperature (Ta) and relative humidity (RH) from 27 July 2pm to 28 July 2020 4 p.m.

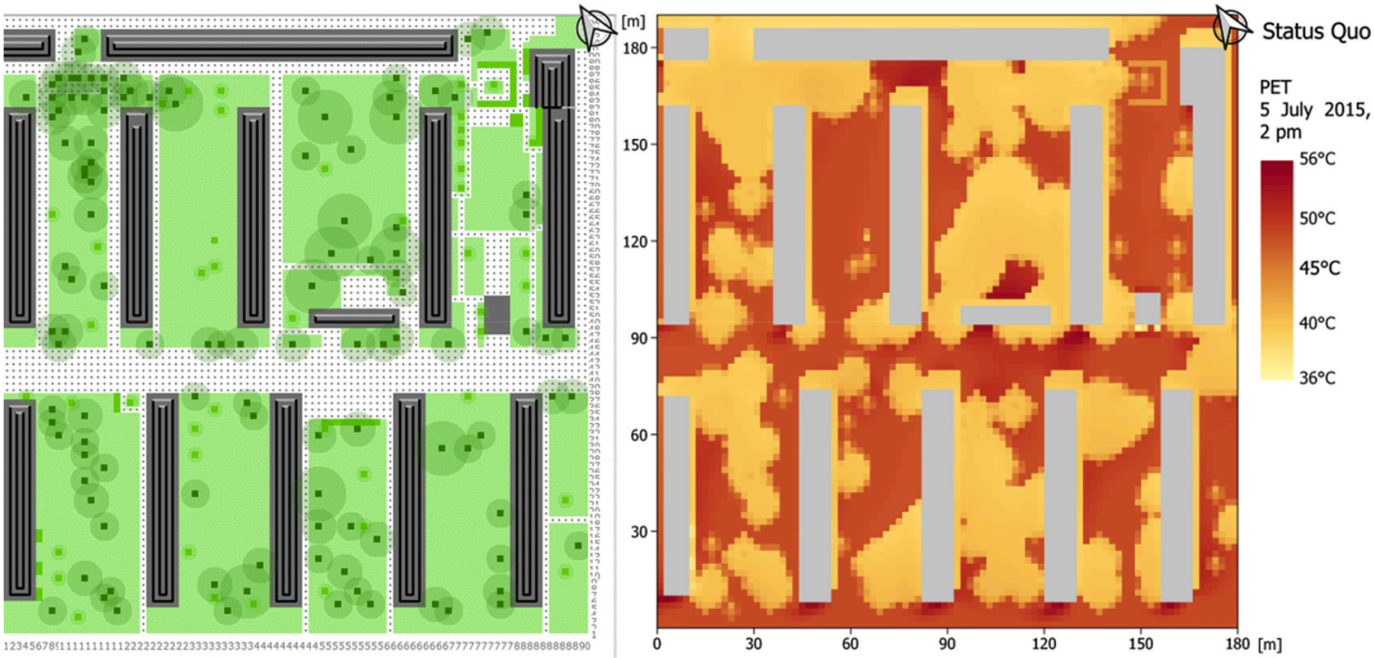

Fig. A3. Model implementation of the status quo and its modelling results for PET for the 5 July 2015 at 2 p.m.

References

[1] Christine Haaland, Cecil Konijnendijk van den Bosch, Challenges and strategies for urban green-space planning in cities undergoing densification: a review, Urban For. Urban Green. 14 (4) (2015) 760–771, https://doi.org/10.1016/j.ufug.2015.07.009.

[2] Gisela Beckmann, Fabian Dosch, Monitoring der Siedlungsflächenentwicklung, in: Martin Behnisch, Odette Kretschmer, Gotthard Meinel (Eds.), Flächeninanspruchnahme in Deutschland, Springer Berlin Heidelberg, Berlin, Heidelberg, 2018, pp. 3–24.

[3] Michael W. Strohbach, Anneke O. Döring, Malte Möck, Maycon Sedrez, Olaf Mumm, Anne-Kathrin Schneider, et al., The "hidden urbanization": trends of impervious surface in low-density housing developments and resulting impacts on the water balance, Front. Environ. Sci 7 (2019), https://doi.org/10.3389/fenvs.2019.00029.

[4] Dagmar Haase, Neele Larondelle, Erik Andersson, Martina Artmann, Sara Borgström, Jürgen Breuste, et al., A quantitative review of urban ecosystem service assessments: concepts, models, and implementation, Ambio 43 (4) (2014) 413–433, https://doi.org/10.1007/s13280-014-0504-0.

[5] Patrycia Brzoska, Aiga Spāģe, From city- to site-dimension: assessing the urban ecosystem services of different types of green infrastructure, Land 9 (5) (2020) 150, https://doi.org/10.3390/land9050150.

[6] T.R. Oke, The energetic basis of the urban heat island, Q.J Royal Met. Soc 108 (455) (1982) 1–24, https://doi.org/10.1002/qj.49710845502.

[7] Sarah Chapman, James E.M. Watson, Alvaro Salazar, Marcus Thatcher, Clive A. McAlpine, The impact of urbanization and climate change on urban temperatures: a systematic review, Landsc. Ecol. 32 (10) (2017) 1921–1935, https://doi.org/10.1007/s10980-017-0561-4.

[8] Rohinton Emmanuel, Koen Steemers, Connecting the realms of urban form, density and microclimate, Build. Res. Inf. 46 (8) (2018) 804–808, https://doi.org/10.1080/09613218.2018.1507078.

[9] Camilo Mora, Chelsie W.W. Counsell, Coral R. Bielecki, Leo V. Louis, Twenty-seven ways a heat wave can kill you: deadly heat in the era of climate change. In *circulation*, Cardiovascular quality and outcomes 10 (11) (2017), https://doi.org/10.1161/CIRCOUTCOMES.117.004233.

[10] A. Revi, D.E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R.B.R. Kiunsi, M. Pelling, et al., Urban areas, in: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M. D Mastrandrea (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovermental Panel on Climate Change (IPCC). Cambridge, United Kingdom and New York, 2014, pp. 535–612.

[11] Catharine Ward Thompson, Steffen Lauf, Birgit Kleinschmit, Wilfried Endlicher, Heat waves and urban heat islands in Europe: a review of relevant drivers, Sci. Total Environ. 569–570 (2016) 527–539, https://doi.org/10.1016/j.scitotenv.2016.06.119.

[12] Martina Artmann, Luis Inostroza, Peilei Fan, Urban sprawl, compact urban development and green cities. How much do we know, how much do we agree? Ecol. Indicat. 96 (2019) 3–9, https://doi.org/10.1016/j.ecolind.2018.10.059.

[13] Teresa Zölch, Johannes Maderspacher, Christine Wamsler, Stephan Pauleit, Using green infrastructure for urban climate-proofing: an evaluation of heat mitigation measures at the micro-scale, Urban For. Urban Green. 20 (2016) 305–316, https://doi.org/10.1016/j.ufug.2016.09.011.

[14] Hyunjung Lee, Helmut Mayer, Wilhelm Kuttler, Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions, Urban For. Urban Green. 48 (2020) 126558, https://doi.org/10.1016/j.ufug.2019.126558.

[15] Lea Rosenberger, Jorge Leandro, Stephan Pauleit, Sabrina Erlwein, Sustainable stormwater management under the impact of climate change and urban densification, J. Hydrol. 596 (2021) 126137, https://doi.org/10.1016/j.jhydrol.2021.126137.

[16] W.C. Li, K.K.A. Yeung, A comprehensive study of green roof performance from environmental perspective, International Journal of Sustainable Built Environment 3 (1) (2014) 127–134, https://doi.org/10.1016/j.ijsbe.2014.05.001.

[17] Gabriel Pérez, Julià Coma, Ingrid Martorell, Luisa F. Cabeza, Vertical Greenery Systems (VGS) for energy saving in buildings: a review, Renew. Sustain. Energy Rev. 39 (2014) 139–165, https://doi.org/10.1016/j.rser.2014.07.055.

[18] Marie-Therese Hoelscher, Thomas Nehls, Britta Jänicke, Gerd Wessolek, Quantifying cooling effects of facade greening: shading, transpiration and insulation, Energy Build. 114 (2016) 283–290, https://doi.org/10.1016/j.enbuild.2015.06.047.

[19] Britta Jänicke, Fred Meier, Marie-Therese Hoelscher, Dieter Scherer, Evaluating the effects of façade greening on human bioclimate in a complex urban environment, Advances in Meteorology 2015 (2015) 1–15, https://doi.org/10.1155/2015/747259.

[20] Sahar Sodoudi, Huiwen Zhang, Xiaoli Chi, Felix Müller, Huidong Li, The influence of spatial configuration of green areas on microclimate and thermal comfort, Urban For. Urban Green. 34 (2018) 85–96, https://doi.org/10.1016/j.ufug.2018.06.002.

[21] Teresa Zölch, Mohammad A. Rahman, Elisabeth Pfleiderer, Georg Wagner, Stephan Pauleit, Designing public squares with green infrastructure to optimize human thermal comfort, Build. Environ. 149 (2019) 640–654, https://doi.org/10.1016/j.buildenv.2018.12.051.

[22] Morakinyo, Tobi Eniolu, Yun Fat Lam, Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort, Build. Environ. 103 (2016) 262–275, https://doi.org/10.1016/j.buildenv.2016.04.025.

[23] Dragan D. Milošević, Ivana V. Bajšanski, Stevan M. Savić, Influence of changing trees locations on thermal comfort on street parking lot and footways, Urban For. Urban Green. 23 (2017) 113–124, https://doi.org/10.1016/j.ufug.2017.03.011.

[24] Angeliki Chatzidimitriou, Simos Yannas, Microclimate design for open spaces: ranking urban design effects on pedestrian thermal comfort in summer, Sustainable Cities and Society 26 (2016) 27–47, https://doi.org/10.1016/j.scs.2016.05.004.

[25] Manuel Wolff, Dagmar Haase, Mediating sustainability and liveability—turning points of green space supply in European cities, Front. Environ. Sci 7 (2019), https://doi.org/10.3389/fenvs.2019.00061.
[26] Jörg Cortekar, Steffen Bender, Miriam Brune, Markus Groth, Why climate change adaptation in cities needs customised and flexible climate services, Climate Services 4 (2016) 42–51, https://doi.org/10.1016/j.cliser.2016.11.002.
[27] Satoru Iizuka, Yingli Xuan, Chika Takatori, Hirosuke Nakaura, Akari Hashizume, Environmental impact assessment of introducing compact city models by downscaling simulations, Sustainable Cities and Society 63 (2020) 102424, https://doi.org/10.1016/j.scs.2020.102424.
[28] Wiebke Klemm, Sanda Lenzholzer, van den Brink, Adri, Developing green infrastructure design guidelines for urban climate adaptation, Journal of Landscape Architecture 12 (3) (2017) 60–71, https://doi.org/10.1080/18626033.2017.1425320.
[29] Günther Gross, Numerical simulation of the nocturnal flow systems in the freiburg area for different topographies, Contrib. Atmos. Phys. 62 (1989) (1989) 57–72.
[30] Gudrun Mühlbacher, Meinolf Koßmann, Katrin Sedlmaier, Kristina Winderlich, Stadtklimatische Untersuchungen der sommerlichen Temperaturverhältnisse und des Tagesgangs des Regionalwindes ("Alpines Pumpen") in München. Offenbach: deutscher Wetterdienst (Berichte des Deutschen Wetterdienstes, 252), Available online at: https://www.dwd.de/DE/leistungen/pbfb_verlag_berichte/pdf_einzelbaende/252_pdf.pdf?__blob=publicationFile&v=4, , 2020.
[31] Jonas Allegrini, Viktor Dorer, Jan Carmeliet, Influence of morphologies on the microclimate in urban neighbourhoods, J. Wind Eng. Ind. Aerod. 144 (2015) 108–117, https://doi.org/10.1016/j.jweia.2015.03.024.
[32] Weiwen Wang, Edward Ng, Chao Yuan, Siegfried Raasch, Large-eddy simulations of ventilation for thermal comfort — a parametric study of generic urban configurations with perpendicular approaching winds, Urban Climate 20 (2017) 202–227, https://doi.org/10.1016/j.uclim.2017.04.007.
[33] Bao-Jie He, Lan Ding, Deo Prasad, Urban ventilation and its potential for local warming mitigation: a field experiment in an open low-rise gridiron precinct, Sustainable Cities and Society 55 (2020) 102028, https://doi.org/10.1016/j.scs.2020.102028.
[34] Evyatar Erell, David Pearlmutter, Terry Williamson, Urban Microclimate. Designing the Spaces between Buildings, Earthscan, London, 2011.
[35] Bartesaghi Koc, Carlos, Paul Osmond, Alan Peters, Evaluating the cooling effects of green infrastructure: a systematic review of methods, indicators and data sources, Sol. Energy 166 (2018) 486–508, https://doi.org/10.1016/j.solener.2018.03.008.
[36] Landeshauptstadt München, Langfristige siedlungsentwicklung – zweiter statusbericht. Sitzungsvorlagen nr. 14-20/V 12595, Available online at: https://www.ris-muenchen.de/RII/RII/DOK/SITZUNGSVORLAGE/5137164.pdf, 2018.
[37] Deutscher Wetterdienst, Vieljährige Stationsmittelwerte für die Klimareferenzperiode 1981-2010, für aktuellen Standort und Bezugsstandort: stations-ID 3379 Muenchen-Stadt, Available online at: https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/multi_annual/mean_81-10/, 2018.
[38] Landeshauptstadt München, Konzept zur Anpassung an die Folgen des Klimawandels in der Landeshauptstadt München, With assistance of Veronika Wirth, Michael Schneider, Johannes Rupp. Edited by Referat für Gesundheit und Umwelt. München, Augsburg, Berlin. Available online at: https://www.muenchen.de/rathaus/dam/jcr:8eb68d50-5c21-4948-92ae-62fa129ab566/bericht_klwa_10_2016.pdf, 2016.
[39] Landeshauptstadt München, Freiflächengestaltungssatzung, 2011st ed. Available online at: https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Stadtplanung-und-Bauordnung/Lokalbaukommission/Kundeninfo/Freiflaechengestaltungssatzung.html, 1996. checked on 2020.
[40] Landeshauptstadt München, Prüfauftrag "mehr begrünung in münchen". Mehr gebäudebegrünung in münchen umsetzen. Sitzungsvorlage nr. 14-20/V 12406, Available online at: https://www.ris-muenchen.de/RII/RII/DOK/SITZUNGSVORLAGE/5164391.pdf, 2018.
[41] Landeshauptstadt München, Stadtklimaanalyse landeshauptstadt münchen. Hannover, Available online at: https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Gesundheit-und-Umwelt/Stadtklima/Stadtklimaanalyse.html, 2014.
[42] I.D. Stewart, T.R. Oke, Local climate zones for urban temperature studies, Bull. Am. Meteorol. Soc. 93 (12) (2012) 1879–1900, https://doi.org/10.1175/BAMS-D-11-00019.1.
[43] Sabrina Erlwein, Stephan Pauleit, Trade-offs between urban green space and densification: balancing outdoor thermal comfort, mobility, and housing demand, Urban Planning 6 (1) (2021) 5–19, https://doi.org/10.17645/up.v6i1.3481.
[44] Jennifer Mullaney, Terry Lucke, Stephen J. Trueman, The effect of permeable pavements with an underlying base layer on the growth and nutrient status of urban trees, Urban For. Urban Green. 14 (1) (2015) 19–29, https://doi.org/10.1016/j.ufug.2014.11.007.
[45] Patricia Schlote, The Suitability of Tree Plantings on Underground Car Parks in Munich. Barriers and Drivers of Tree Plantings on Underground Car Parks in Munich According to Key Actors, Master thesis, Technical University of Munich, 2021.
[46] Astrid Moser-Reischl, Thomas Rötzer, Stephan Pauleit, Hans Pretzsch, Structure and ecosystem services of small-leaved lime (Tilia cordata Mill.) and black locust (Robinia pseudoacacia L.) in urban environments, Urban For. Urban Green. 14 (4) (2015) 1110–1121, https://doi.org/10.1016/j.ufug.2015.10.005.
[47] Hyunjung Lee, Helmut Mayer, Liang Chen, Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany, Landsc. Urban Plann. 148 (2016) 37–50, https://doi.org/10.1016/j.landurbplan.2015.12.004.
[48] Michael Bruse, Heribert Fleer, Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model, Environ. Model. Software 13 (3–4) (1998) 373–384, https://doi.org/10.1016/S1364-8152(98)00042-5.
[49] Helge Simon, Modeling Urban Microclimate. Development, Implementation and Evaluation of New and Improved Calculation Methods for the Urban Microclimate Model ENVI-Met, Dissertation. Johannes Gutenberg-University, 2016. Mainz. Available online at: https://openscience.ub.uni-mainz.de/handle/20.500.12030/4044.
[50] S. Tsoka, A. Tsikaloudaki, T. Theodosiou, Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–A review, Sustainable Cities and Society 43 (2018) 55–76, https://doi.org/10.1016/j.scs.2018.08.009.
[51] Morakinyo, Tobi Eniolu, Kevin Ka-Lun Lau, Chao Ren, Edward Ng, Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving, Build. Environ. 137 (2018) 157–170, https://doi.org/10.1016/j.buildenv.2018.04.012.
[52] Nicole Müller, Wilhelm Kuttler, Andreas-Bent Barlag, Counteracting urban climate change: adaptation measures and their effect on thermal comfort, Theor. Appl. Climatol. 115 (1–2) (2014) 243–257, https://doi.org/10.1007/s00704-013-0890-4.
[53] Qunshan Zhao, David J. Sailor, Elizabeth A. Wentz, Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment, Urban For. Urban Green. 32 (2018) 81–91, https://doi.org/10.1016/j.ufug.2018.03.022.
[54] Geo-Net, Windfeldsimulation mit dem Strömungsmodell FITNAH-3D, Available online at: https://geo-net.de/de/wind/fitnah-3d.html, 2021. checked on 1/19/2021.
[55] Ivo Gerhards, Simone Philippi, Natalie Scheck, Sonja Singer-Posern, Michael Voll, Modellgestützte Klimaanalysen und -bewertungen für die Regionalplanung, Grundlagen für einen Leitfaden, herausgegeben vom Projekt KLAMIS – klimaanpassung in Mittel- und Südhessen, Available online at: https://landesplanung.hessen.de/sites/landesplanung.hessen.de/files/content-downloads/KlimaMORO_klamis_Leitfaden_Klimamodellierung.pdf, 2013.
[56] Helmut Mayer, P. Höppe, Thermal comfort of man in different urban environments, Theor. Appl. Climatol. 38 (1) (1987) 43–49, https://doi.org/10.1007/BF00866252.
[57] Henning Staiger, Gudrun Laschewski, Andreas Matzarakis, Selection of appropriate thermal indices for applications in human biometeorological studies, Atmosphere 10 (18) (2019), https://doi.org/10.3390/atmos10010018 (1).
[58] Jutta Holst, Helmut Mayer, Impacts of street design parameters on human-biometeorological variables, In metz 20 (5) (2011) 541–552, https://doi.org/10.1127/0941-2948/2011/0254.
[59] Verein deutscher Ingenieure, Environmental meteorology: local cold air. Guideline 3787, sheet 5, Available online at: https://www.vdi.de/richtlinien/details/vdi-3787-blatt-5-umweltmeteorologie-lokale-kaltluft-1, 2008.
[60] Verein deutscher Ingenieure, Environmental meteorology: methods and presentation of investigations relevant for planning urban climate. Guideline 3787, sheet 1, Available online at: https://www.vdi.de/richtlinien/details/vdi-3785-blatt-1-umweltmeteorologie-methodik-und-ergebnisdarstellung-von-untersuchungen-zum-planungsrelevanten-stadtklima, 2008.
[61] Senlin Zheng, Lihua Zhao, Qiong Li, Numerical simulation of the impact of different vegetation species on the outdoor thermal environment, Urban For. Urban Green. 18 (2016) 138–150, https://doi.org/10.1016/j.ufug.2016.05.008.
[62] Ruzana Sanusi, Denise Johnstone, Peter May, Stephen J. Livesley, Street orientation and side of the street greatly influence the microclimatic benefits street trees can provide in summer, J. Environ. Qual. 45 (1) (2016) 167–174, https://doi.org/10.2134/jeq2015.01.0039.
[63] Shiho Onomura, Björn Holmer, Fredrik Lindberg, Sofia Thorsson, Intra-urban nocturnal cooling rates: development and evaluation of the NOCRA model, Met. Apps 23 (3) (2016) 339–352, https://doi.org/10.1002/met.1558.
[64] Maria Knaus, Dagmar Haase, Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany, Urban For. Urban Green. 53 (2020) 126738, https://doi.org/10.1016/j.ufug.2020.126738.
[65] A.B. Besir, E. Cuce, Green roofs and facades: a comprehensive review, Renew. Sustain. Energy Rev. 82 (2018) 915–939, https://doi.org/10.1016/j.rser.2017.09.106.
[66] Julià Coma, Gabriel Pérez, Alvaro de Gracia, Silvia Burés, Miguel Urrestarazu, Luisa F. Cabeza, Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades, Build. Environ. 111 (2017) 228–237, https://doi.org/10.1016/j.buildenv.2016.11.014.
[67] Mohammad A. Rahman, D. Armson, A.R. Ennos, A comparison of the growth and cooling effectiveness of five commonly planted urban tree species, Urban Ecosyst. 18 (2) (2015) 371–389, https://doi.org/10.1007/s11252-014-0407-7.
[68] Andrew M. Coutts, Emma C. White, Nigel J. Tapper, Jason Beringer, Stephen J. Livesley, Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments, Theor. Appl. Climatol. 124 (1–2) (2016) 55–68, https://doi.org/10.1007/s00704-015-1409-y.
[69] Günther Gross, Siegfried Raasch, Björn Maronga, Mosaik - modellbasierte Stadtplanung und Anwendung im Klimawandel, Abschlussbericht. Hannover (2020). Available online at: http://www.uc2-program.org/MOSAIK%20Verbundbericht%20[UC]2%20Phase%201.pdf.

Article III

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Article

Context-Specific, User-Centred: Designing Urban Green Infrastructure to Effectively Mitigate Urban Density and Heat Stress

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Abstract
Green infrastructure plays a vital role for cities facing the challenges of urbanisation and climate change. It has the potential to mitigate the adverse effects of urban density and the heat island effect, enhancing the ecological and social resilience of cities and their inhabitants. This study identifies contextual, psychological, and social factors which influence people's subjective evaluation of urban green infrastructure (UGI), density, and heat stress. Planning recommendations for effective, context-specific, user-centred design are developed to increase the social and health benefits of UGI in limited space. To do so, a mixed-methods approach that combines social surveys, GIS-analysis, and microclimate modelling was employed. The field studies were undertaken in two contrasting neighbourhoods in Munich, Germany: a densely built and scarcely vegetated inner-city neighbourhood and a declaimed "green and compact" neighbourhood at the outskirts. Both sites are assessed in terms of their supply of green infrastructure, building and population density, and outdoor summer heat loads drawing on geostatistical data and mean radiant temperature modelling. This assessment is compared to the inhabitants' subjective evaluation thereof retrieved from face-to-face questionnaires, and semi-standardised interviews. The results indicate that the existence and the amount of UGI per se are not decisive for people's perception of urban heat, density, and neighbourhood attractiveness. It is rather the perceived accessibility of green spaces, their design, quality, and contextual factors like traffic or the presence of other people that define its value for urban dwellers.

Keywords
crowding; mental maps; neighbourhood quality; outdoor thermal comfort; psychological evaluation; UGI; urban density; urban stress; urban vegetation

Issue
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1. Introduction

Adapting to climate change while addressing increasing housing demands is among the key challenges for growing cities in the fight against urban sprawl (Wolff & Haase, 2019). Climate change exacerbates the urban heat island effect (Chapman et al., 2017) and increasing densification is reducing unsealed and green urban areas (Haaland & van den Bosch, 2015). However, research has shown that urban green infrastructure (UGI) does not only lower urban heat levels through shading and evapotranspiration (Bartesaghi Koc et al., 2018) but provides further ecosystem services and enhances social resilience (Bowler et al., 2010; Rall et al., 2017). To exploit the full potential of UGI for residents and enhance adaptation capacities, a context-specific and user-centred design focus is necessary (Hansen & Pauleit, 2014; Klemm et al., 2017). Therefore, this article explores people's subjective evaluation of UGI in connection with density and heat stress.

1.1. Perception of Urban Density

Urban density is a complex phenomenon: In the "compact city" model of the European Commission, a high density of people, jobs, and dwellings is promoted to improve the environmental sustainability and liveability of cities (Commission of European Communities, 1990). Reduced commuter traffic, promotion of public transport, higher social interactions, reduced ground space per capita, and reduced emissions are seen as benefits of high-density cities (Jabareen, 2006). However, critics argue that fresh air, green space supply, and habitats for species are rather provided in lower-density cities (Neuman, 2005), and that a higher cost of land can lead to social inequities (Debrunner et al., 2020). In city planning, urban density mainly refers to building density (height, volume, and spacing) and population density (Cheng, 2010). The term "crowding" is used when density levels are evaluated as too high and a person experiences "sensory and social overload" (Rapoport, 1975, p. 134), a loss of control, or behaviour constraints due to density. Feelings of crowding can occur at very different density levels depending on the (social and material) setting, but also on the individuals themselves and their subjective evaluation of the situation. Cultural, emotional, contextual, and other factors influence whether dense settings are perceived as crowded and result in stressful experiences (Frerichs & Küpper, 2017; Rapoport, 1975). While certain characteristics of the built environment such as street width (Husemann, 2005), building coverage ratio or block size (Knöll et al., 2018) have been found to increase the feeling of crowding and urban stress, vegetation seems to have a positive effect on the evaluation of density. In a study by Husemann (2005), streets with trees were evaluated as less dense and less crowded than streets without trees. In a participatory study, Kyttä et al. (2013) observed that positively rated urban places had a significantly higher proportion of vegetation than negative ones and a lower building density. The interactions between different aspects of urban form and vegetation and their effects on people's perception of density and crowding still remain rather unclear (Knöll et al., 2018). In this regard, more empiric research focusing on people's evaluation of "real" complex urban environments has been called for to gain a deeper understanding of the dynamics involved.

1.2. Outdoor Thermal Comfort and Urban Vegetation

As excessive heat negatively affects human health (Lau et al., 2015), heat stress has become an increasing concern for urban planners, especially against the backdrop of climate change and already elevated urban temperatures (Chapman et al., 2017). Several thermal indices have been developed for the investigation of human thermal comfort, such as physiological equivalent temperature and the universal thermal climate index (Staiger et al., 2019). Microclimatological studies have found that UGI and especially trees can significantly improve human thermal comfort. Large, dense trees reduce daytime air temperature by up to 3°C and physiological equivalent temperature directly beneath tree crowns by up to 16°C (Lee et al., 2020).

However, findings from environmental psychology suggest that despite being exposed to the same environmental conditions, thermal sensations of people differ (Nikolopoulou & Steemers, 2003) and that subjective thermal preferences might even contradict physical conditions: Comparing different street designs, Klemm et al. (2015) found that people felt more comfortable in a street with small trees and front gardens than in a street with tall trees, even though the latter showed lower physical heat stress. According to Nikolopoulou and Steemers (2003), the range of psychological factors influencing thermal comfort includes naturalness (degree of artificiality), expectations, former experience, time of exposure, perceived control, and environmental stimulation. Furthermore, the duration of experience influences the thermal perception of a specific site (Klemm et al., 2015). Overall, the psychological impact of urban green spaces on people's perceived thermal comfort remains a relatively unexplored research topic (Klemm et al., 2015).

Thus, this article investigates the interactions between density, heat, and vegetation from a user perspective. By comparing their objective assessment with people's subjective evaluation, we can pinpoint parallels and disparities, exploring factors that influence the perception of the urban environment.

2. Methodology

We employed a mixed-methods approach that combines surveys, GIS-analysis, and microclimate modelling to analyse the evaluation of heat, density, and urban vegetation (Figure 2). The field studies were undertaken in two contrasting neighbourhoods in Munich, Germany.

2.1. Study Areas

The study site is Munich, one of the fastest-growing and densest German cities (Landeshauptstadt München, 2018). Two contrasting neighbourhoods were selected: a densely-built and sparsely vegetated inner-city neighbourhood (Bahnhofsviertel), and a more sparsely built neighbourhood with ample green infrastructure at the outskirts (Messestadt; Figure 1). The Bahnhofsviertel, located directly south of the Munich central station, is not only a transportation hub, but also attracts a diversity of people and businesses. Sporting many small international shops, services, hotels, offices, and several university and medical facilities, the streets are usually bustling with people while at the same time being home to only 5,685 residents. Unlike the Bahnhofsviertel, which has grown and evolved over time, the Messestadt has been planned from scratch as a sustainable residential area on a former airport site at the eastern outskirts of Munich. It was designed in the 1990s with reduced traffic loads, a large landscape park, and is home to 11,895 people from more than 100 nationalities.

2.2. Objective Evaluation

2.2.1. Geostatistical Analysis of Urban Vegetation and Density Parameters

Urban density was analysed based on the data provided by GeodatenService München (2020) from Munich's official city map (*Stadtgrundkarte*) using GIS. The floor area ratio was calculated as the total gross floor area (ground floor area multiplied by the number of floors) of all buildings divided by the block area for each city block. As additional parameters for urban density, building coverage (residential/non-residential), traffic areas, and public green space were analysed. Information on the quality of other surfaces (sealed/non-sealed, green/non-green) was obtained from raster data in the European Settlement Map (2017). To determine tree coverage, data on tree cover from satellite data from the Street Tree Layer (2018) were used. Population density (i.e., number of residents) was determined based on 100 m × 100 m raster data from ZENSUS (2011), as the most current dataset available.

2.2.2. Modelling of Mean Radiant Temperature With SOLWEIG

Outdoor human thermal comfort was assessed with the solar flux model SOLWEIG (Lindberg et al., 2018). SOLWEIG has been applied in various microclimatological studies to determine the mean radiant temperature (T_{mrt}; e.g., Jänicke et al., 2016; Lau et al., 2015). In Central Europe, T_{mrt} is the dominating factor for outdoor human thermal comfort if a cloudless, summer day is considered (Lee & Mayer, 2018). As a representative for a severely hot day, the 25th July 2019 (T_{max} > 30°C, T_{min} > 20°C, wind speed below 2 m/s) was selected for the simulation study. The required meteorological input data was provided by the Meteorological Institute Munich (2018). Its weather station is located in the city centre of Munich (distance to study areas: 8.7 km to Messestadt, and 1.7 km to Bahnhofsviertel). High-resolution digital elevation models, land cover data, and colour-infrared imagery to identify vegetation used for the model setup were provided by the Bavarian State Office for Survey and Geoinformation (2018). As a compromise between accuracy and modelling time, we set the pixel resolution to 2 m. We analysed the simulation outcomes for 2 pm, as this represents the hour with the maximum human heat stress.

2.3. Subjective Evaluation

2.3.1. Questionnaires on Neighbourhood Quality and Public (Green) Spaces

Face-to-face questionnaires were conducted in both neighbourhoods in July 2019 (Bahnhofsviertel: n = 76; Messestadt: n = 68; for detailed sociodemographic information see Table S1 in the Supplementary File). To ensure the representation of a diversity of people, spaces, and atmospheres, the questionnaires were conducted in seven different locations within each neighbourhood (including green spaces, public squares, main and side streets) on all days of the week and at different times of the day. Only warm, sunny days (23–30°C) were selected for the surveys. In the questionnaire, the participants were presented with a polarity profile, which they were asked to use to describe the neighbourhood (see Figure 5 here and Questionnaire S2 in the Supplementary File). The profile was guided by Kyttä et al. (2013) and based on criteria of applicability and comprehensibility (even for non-residents). Moreover, respondents were asked to spontaneously name places in the neighbourhood that they experienced as pleasant or unpleasant on hot days (free mentions). If respondents were residents of the study area, they were also asked if they would like to participate in an in-depth interview.

2.3.2. In-Depth Interviews and Mental Mapping

This way, we were able to recruit a random sample of 28 residents (Bahnhofsviertel: n = 11, Messestadt: n = 17) for semi-standardised interviews with a duration of 40 to 90 minutes (for sociodemographic characterisation see Table S3 in the Supplementary File). Interviews were recorded, transcribed, and analysed using qualitative data analysis software. The interviews expanded on the answers in the short questionnaire and additionally explored the topics of neighbourhood atmosphere, social cohesion, identification, public (green) spaces, and residential quality. In the interviews, participants were also shown an aerial photograph of their residential area and were encouraged to talk about their everyday activities and mark corresponding routes and locations on the map. To capture thermal comfort conditions in the neighbourhoods' public space, participants marked areas or locations according to their thermal comfort qualities with sticky dots on the map: green dots for places that they generally perceived as pleasant on hot days (> 30°C), red dots for unpleasant ones, and yellow dots for "in between" sensations. In contrast to other ther-

Figure 1. Pictures of distinctive sites of the study areas Bahnhofsviertel (B1–B3) and Messestadt (M1–M4), and their location within Munich.

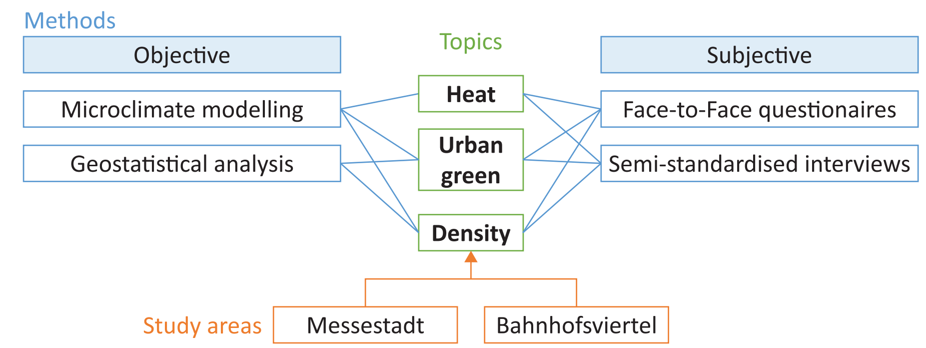

Figure 2. Employed methods and research approach.

mal comfort surveys, which usually focus on right-here-right-now evaluations of current micro-meteorological parameters (like air temperature, sun, humidity, and wind), this mental mapping method allowed us to capture people's long-term memory of holistic thermal perception. All dots were digitised and geocoded using a GIS. Dots referring to larger areas or streets were polygonised. Based on the resulting layers of dots, coloured heat maps were created using Kernel density estimation with a radius of 15 m (Netek et al., 2018).

3. Results

3.1. Density and Vegetation

3.1.1. Objective Assessment of Density and Vegetation

The study area Bahnhofsviertel consists of 35 building blocks which are dominated by four-storey block perimeter construction of mixed ages. Green infrastructure is scarce in the neighbourhood (11%; Figure 3). The study area comprises a small park with many trees (see B3 in Figure 1) and part of an open area (B2) which is empty except for events and rimmed by a tree promenade with benches and playgrounds. Within Bahnhofsviertel itself, though, only the southern streets are lined with trees, and backyards are mainly sealed (94.4%).

Messestadt consists of 48 building blocks featuring mainly three to six-storey apartment buildings (row houses), some perimeter apartment blocks, and some (semi-)detached housing. South of Messestadt is a large park (M3), with a small forest and a swimming lake (M4), connecting the neighbourhood to the surrounding rural zone, only a very small part of which is comprised within the study area. There are several "green links," with playgrounds interlacing the residential area with the park. Although all streets are lined with trees, only tall ones or tree groves appear on the map (Figure 4). Within the residential area, most backyards are green, and buildings on average account for only 43% of the block surface.

With a floor area ratio of 2.7, Bahnhofsviertel is almost twice as densely built-up as Messestadt with a floor area ratio of 1.4. Despite this, the population density in Bahnhofsviertel is rather low, with 66.3 residents per ha. The opposite is true for the residential district Messestadt, whose population density is 117.7 residents per ha.

3.1.2. Subjective Evaluation of Density and Vegetation

As the neighbourhood evaluation shows (polarity profile; Figure 5), the objective assessment of green infrastructure supply and density is well reflected by people's subjective perception. Messestadt is generally perceived as much greener, more relaxed, quiet, and also safer than Bahnhofsviertel, which in turn is rated rather unpleasant, unattractive, and neither bike-, car-, child-, or senior-friendly.

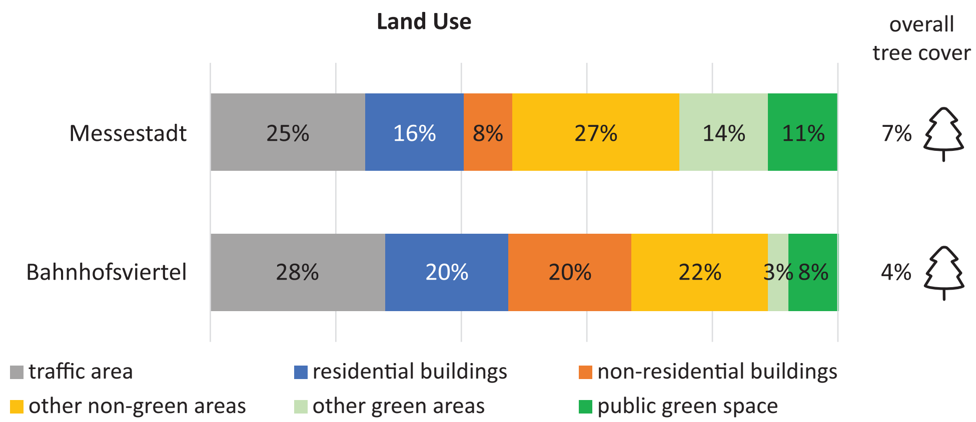

Figure 3. Land use for the study areas of Bahnhofsviertel and Messestadt.

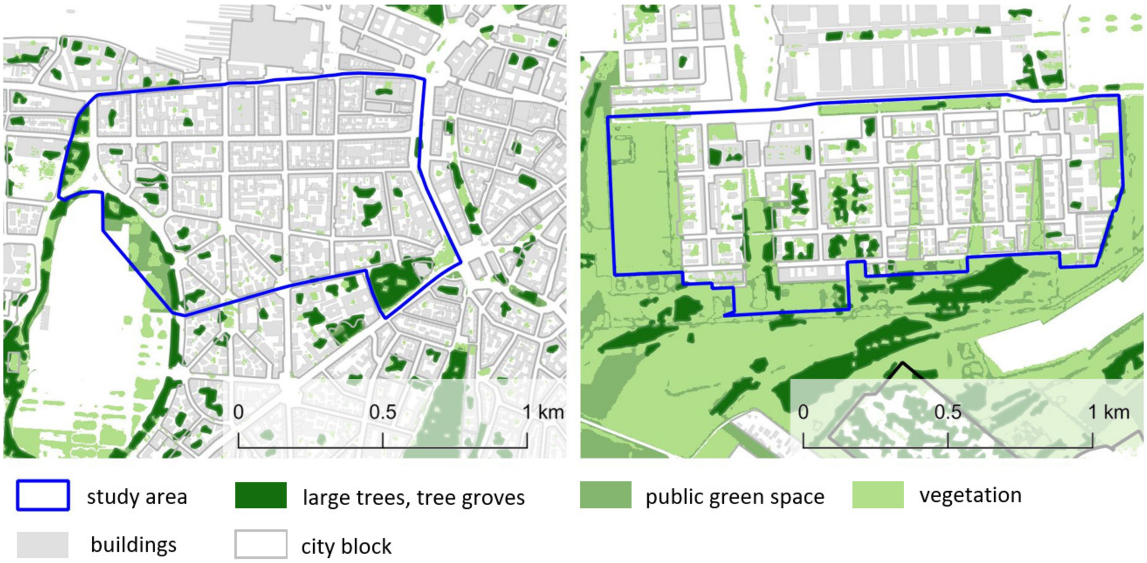

Figure 4. Vegetation within and around the study areas of Bahnhofsviertel (left) and Messestadt (right). Sources: treecover from Street Tree Layer (2018), vegetation from European Settlement Map (2017), city structure from GeodatenService München (2020).

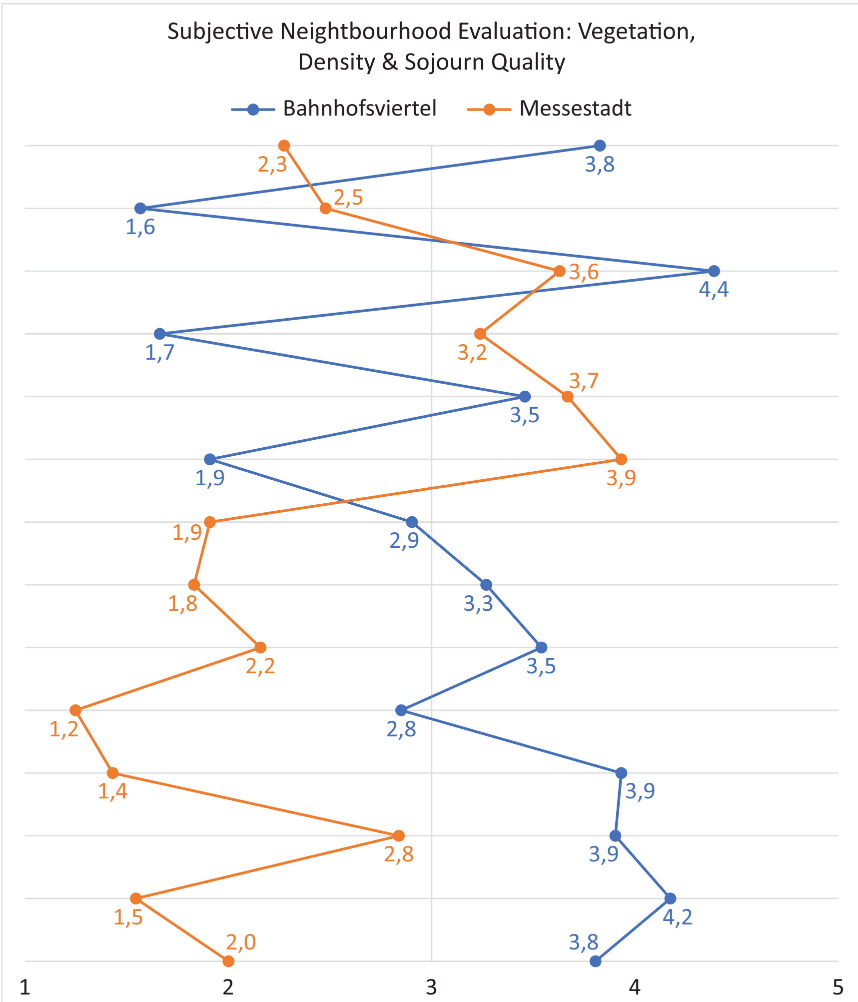

Figure 5. Polarity profile: Subjective evaluation of Bahnhofsviertel (blue) and Messestadt (orange).

Statistical analysis (Table S4 in the Supplementary File) reveals highly significant correlations between the evaluation of greenness and other items of the polarity profile across both neighbourhoods. Respondents who evaluated their neighbourhood as greener tended to also perceive it as less densely built-up and more pleasant. They also rate their neighbourhood more positively on all other items with the strongest correlations for child- and senior-friendliness, and relaxation. We also found differences regarding the evaluation of density, greenness, and quality of stay between social groups. In both Messestadt and Bahnhofsviertel, residents, in comparison to non-residents, gave "better" ratings for all items except emptiness and safety. Non-native speakers perceived the quarters as less densely built-up and more attractive than native speakers. Also, age seems to make a difference: Participants aged 30 or less generally perceived the neighbourhoods as more pleasant, more relaxed, and—marginally significant—not as densely built-up.

The perceptions of density and vegetation were explored in more detail by the in-depth interviews. This quote by a Bahnhofsviertel resident reflects the general impression of most respondents: "It's brutally dense… every square meter is utilised" (Jürgen, 55). There is noise and bustle on the streets, and especially the heavy car traffic and lack of space contribute to feelings of crowding and stress for many respondents: "Of course, that makes it exhausting sometimes because the streets are crowded, people do what they want, there's criss-cross parking in front of the supermarkets and there's no getting through, the sidewalks are full" (Rebecca, 28). However, this density can also be experienced as positive and stimulating: "It's unbelievably narrow, unbelievably dense… everything is quite compact as if you were to press everything together in a ball. Of course, that's also what makes it so appealing, there's an incredible amount of life in it" (Theodor, 51). Street greenery of any kind seems to be the remedy of choice for Bahnhofsviertel residents: "Here [in the southern part of the neighbourhood] it is much greener… when I look out of the window, I could just as well be in the countryside. So that's an enormous relaxation for me….I also think that other people feel less stressed" (Jürgen). The positive psychological effect of vegetation in reducing feelings of crowding and stress is experienced and voiced by almost all respondents: "I think greened streets would definitely help me [to cope]—at least visually" (Micha, 32). One resident, however, voiced objections to planting trees in one of the main streets in the neighbourhood to preserve its historical axis. The large open space Theresienwiese (B2) is an important counterpoint to, and a pleasant relief from, the crowded streets: "When I go grocery shopping, I stop there and sit down. I get to talk to nice people there, but I also find it pleasant in that it's such a wide area. It's soothing to the eye, no advertising" (Rainer, 60). The space's dimensions significantly contribute to its high quality of stay and its function as a social meeting point: "One of my favourite spots is on the steps at the edge of the Theresienwiese, because you simply have this expanse….You take a bottle of wine with you and share it with your friends and look into the distance'' (Micha).

In stark contrast to Bahnhofsviertel, in Messestadt there seems to be almost too much space. While the residents appreciate the low building density of their neighbourhood as a pleasant luxury, the street space (M2) is predominantly perceived as large, monotonous, and characterised by a lack of vegetation: "They have extremely wide sidewalks… there is simply far too much paved area" (Martin, 65). Another resident describes, "in fact, that's very brutal if you look along the streets. There are these concrete walls everywhere that separate the front gardens [from the street]. And if they are not greened, then it is simply brutal" (Anke, 47). A woman who has lived in the neighbourhood for many years admits that she sometimes still gets lost because the streets and the "white sterile building blocks" look so similar. Also, Willy-Brandt-Platz (M1), a large open square at the entrance to Messestadt is perceived by almost all respondents as far too big: "That's the main problem. The square is much, much too big for its function. It has no function" (Thomson, 45). Most would prefer greening the square with planters, arbours, or climbing plants that "would kind of make the space not seem so infinite" (Gertrud, 66). Interestingly, in Messestadt feelings of crowding are only experienced in the park, more precisely at the swimming lake (M4), which is "a people magnet." Most interviewees feel very much attached to "their lake," which, to them, is the biggest asset of the neighbourhood. It serves important social functions, especially for teenagers: "Apart from the lake, there's really no such thing as a real place for me to stay away from home" (Leopold, 14). The remaining "empty" space of the 210-ha park, however, is heavily underused: "On the meadows, there is hardly anyone….I think one prefers sitting down at a lake to somewhere where there is nothing" (Darian, 48). One teenager even suspects that "you are not allowed to go into the meadows" (Leopold). The "generous" supply of (semi-)private green space (e.g., backyards and gardens) further decreases residents' need to use the public park.

In summary, the street space in Bahnhofsviertel is perceived as narrow and crowded, while in Messestadt streets and sidewalks are very wide and at the same time experienced as rather empty. Public spaces in both neighbourhoods seem to have a rather low quality of stay, though for contrasting reasons. In Bahnhofsviertel, this is mainly due to heavy car traffic, feelings of crowding, or lack of safety; in Messestadt, it is more due to the missing street life and poor architectural design, which is considered "boring." A key factor in both cases is the perceived lack of vegetation which people seem to crave as relief from both too much and not enough urban density. In high-density settings, street greenery can create an atmosphere of relaxation and can bring relief from sensory overload. Where density is too low, vegetation can create a comfortable feeling of enclosure and can be a stimulating visual variation.

3.2. Heat Load and Vegetation

3.2.1. Objective Assessment of Heat Load and Vegetation

In both neighbourhoods, the most uncomfortable areas with the highest T_{mrt} values at 2 pm are found in locations without shade (Figure 6). Thorsson et al. (2014) proposed a threshold of 55°C for elevated and 59.4°C for extreme heat stress. Open spaces (B2, M1) and non-shadowed N–S running streets depict T_{mrt} values of 64°C and more. As the building structure in Messestadt is less compact than in Bahnhofsviertel, a larger fraction of the study area falls into the extreme heat stress category due to lack of shade (average T_{mrt} of 60.1°C for Messestadt, 56.4°C for Bahnhofsviertel). The most comfortable areas in both neighbourhoods are located in the shade of trees and buildings (T_{mrt} values from 35–40°C). The small forest in Messestadt M3 (mean T_{mrt} 35–37°C), the park in Bahnhofsviertel B3 (mean T_{mrt} 39–40°C), but also single street trees provide significantly reduced heat loads for residents. Heat loads and cool spots are not evenly distributed across the study areas. In Bahnhofsviertel, the north has higher heat exposure due to the absence of trees. In Messestadt, walkways and the southern meadows (M3) are exposed to heat and thermally uncomfortable.

3.2.2. Subjective Evaluation of Heat Exposure and Vegetation

The subjective heat maps (Figure 6) show that the most comfortably rated places coincide very well with the existing tree stock, whereas the open spaces and almost all streets are perceived as uncomfortable on hot days. This general observation coincides very well with the modelled thermal comfort. In Bahnhofsviertel, more than half of all respondents named "streets" as the most uncomfortable places, followed by the central station (17.1%) and the whole neighbourhood in general (7.9%; Table 1). Heat stress is highest where high density and lack of vegetation are combined with other heat exacerbating factors, like exhaust fumes. Feelings of crowding and perceived heat stress mutually reinforce

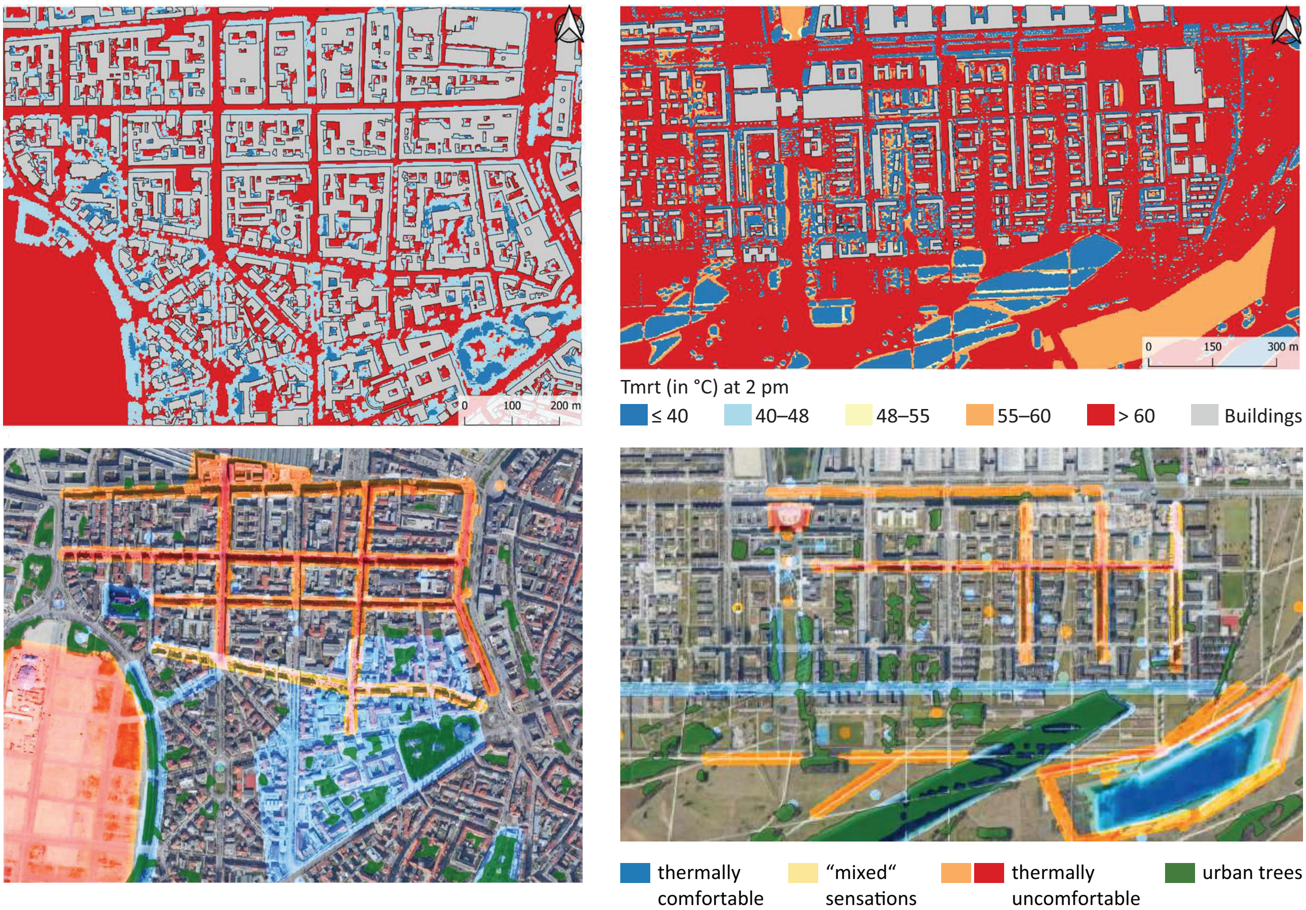

Figure 6. T_{mrt} model results for 25th July 2019 at 2 pm (top) and perceived thermal comfort maps (bottom) for Bahnhofsviertel (left) and Messestadt (right). The colour intensity in the subjective heat maps reflects the number of times the area or location was mentioned.

Table 1. Top three comfortable (left) and uncomfortable (right) sites in hot weather in each neighbourhood.

Messestadt: Top Three Sites Thermal Comfort (n = 68)		Messestadt: Top Three Sites Thermal Discomfort (n = 68)	
Swimming lake M4	54.4%	Willy-Brandt-Square M1	25.0%
Home/Private garden	30.8%	Streets (in general) M2	23.5%
Shopping mall	19.1%	Park M3	10.3%

Bahnhofsviertel: Top Three Sites Thermal Comfort (n = 76)		Bahnhofsviertel: Top Three Sites Thermal Discomfort (n = 76)	
Theresienwiese (area) B2	11.8%	Streets (in general) B1	51.3%
Nußbaumpark B3	10.5%	Central station	17.1%
Fountains	7.9%	Whole neighbourhood	7.9%

each other: "[This street] is such a narrow canyon of houses, or maybe I perceive it as much narrower on such a hot day" (Rebecca). The neighbourhood's compact building structure and narrow streets are, thus, a blessing and a curse at the same time. Narrow streets and tall buildings reduce sun exposure, while wider streets allow for the experience of cool winds and relief from crowded situations. This is also why the large open square Theresienwiese (B2) is the most frequently mentioned of comfortable places in Bahnhofsviertel (11.8%). However, in hot weather, people's use of the area concentrates at the partly tree-lined edges of the square. The Nußbaumpark (B3) was named most comfortable by 10.5% of respondents, followed by fountains in different locations (7.9%).

Conversely, in Messestadt, the site most often mentioned as uncomfortable in hot weather is the large open square Willy-Brandt-Platz (M1; 25%). "Streets" (M2) were named by 23.5% of respondents, followed by the public park (M3; 10.3%), and sports or playgrounds (7.3%). The experience of thermal discomfort in all these places is mainly attributed to a lack of shading trees. Existing trees are perceived as too small or even "puny" and the combination of street and building design reinforces heat stress: "Well, I think that the fact that there are so many white, large houses makes them very radiant. I definitely miss green there" (Maria, 22). One notable exception is a promenade that runs E–W and is lined with tall trees. Several interviewees related that this was always the road they chose on hot days, even if that meant taking a diversion. Notably, people experience heat stress even (and especially) in the park, mainly on the paths (M3), but also around the swimming lake (M4), because there is not enough shade. Nevertheless, the swimming lake is the place most frequently mentioned as pleasant on hot days (54.4%) and is also the only public outdoor space among the top three in the neighbourhood.

In both neighbourhoods, some places are shaded by trees and exhibit low levels of (subjective and objective) heat exposure but whose cooling function is neither used nor appreciated by most people because of their poor quality of stay. The park in Bahnhofsviertel (B3) is rated as a cool place on hot days; however, it is rarely used at all by respondents. Only 27.6% sometimes go there and only 14.5% of all respondents like spending time there. A resident of Bahnhofsviertel explains: "Why should I go there?… I wouldn't use the park… even though it is green, there is just not the atmosphere for me to relax like in a park" (Jürgen). One woman who lives in Bahnhofsviertel describes her feeling about the park as uncomfortable due to the design which is dominated by a lot of old trees and little open space: "Somehow, everything is so dark there. The paths cross each other, it's so opaque, for me there's just such a darkness attached to it that I really don't feel comfortable there and I actually even avoid it during the day" (Rebecca). Other interviewees refer to socially marginalised groups and alcohol and drug use in the park, which makes it unattractive for them. Most interviewees prefer visiting other, more attractive, green spaces instead and do not mind taking on longer journeys to get there. Likewise, in Messestadt, there is a tree-covered public square with some benches, which is evaluated as cool on hot days but is visited only infrequently: "In theory, there is shade, but it is just not comfortable there. I have never felt the impulse to sit down there," says Gertrud. Similarly, the small forest in the park could serve its function as a cool oasis amidst the heat-exposed grasslands if it were not considered hardly accessible, making it "a place for dogs rather than for people to stay'' (Maria).

In summary, the perception of heat stress in both neighbourhoods is influenced most by the supply or lack of shade, especially natural shade by trees. While there is no space for greenery in Bahnhofsviertel, the trees in Messestadt are too small to provide effective shade. Hence, in both neighbourhoods, streets, and most other public spaces are perceived as hot and uncomfortable in summer. This observation corresponds well with the simulation results. Not quite in accordance with the simulation, both parks and potential cool islands do not seem to play a crucial role in individual heat stress adaptation, as their design does not meet users' criteria. Also, Bahnhofsviertel is considered much more uncomfortable in hot weather than Messestadt, which is not supported by the simulation outcomes. This disparity is likely caused by traffic, people density, and visual building characteristics, which clearly influence people's heat perception, but have not been regarded in the objective heat assessment. Again, vegetation seems to have a positive impact on people's perception of heat that goes beyond its simulated cooling effect. We suggest that due to previous experiences and people's general knowledge that plants and trees provide shade and coolness, visual stimuli can provoke those very sensations. The same effect occurs with water. Where urban vegetation is scarce, water takes on an important cooling function, even if it is not "used" in a strict sense. Blue infrastructure (in our cases the lake and the fountains) seems to be able to compensate for the lack of green infrastructure, to some extent (Figure 7).

4. Discussion and Planning Implications

Our results support the idea that urban vegetation not only reduces objective heat loads but also reduces *feelings* of crowding and increases (thermal) well-being. This is in line with other studies that have found positive psychological effects of vegetation for thermal comfort (Klemm et al., 2015; Nikolopoulou & Steemers, 2003), urban stress (Kabisch et al., 2021; Knöll et al., 2018), and health (Kondo et al., 2018).

Depending on the density context, large open public (green) spaces can create an uncomfortable atmosphere of desolation or pleasant sensations of spaciousness and relaxation. Our results indicate that vegetation enhances the quality of stay in low-density settings, which to our knowledge has not yet been investigated in detail and is worth further research. Large open spaces or wide streets in low-density neighbourhoods were often perceived as uncomfortable, which is supported by other studies like Knöll et al.'s (2018), or Kaspar and Bühler's (2009), who found that visual openness is related to higher perceived urban stress and relate it to feelings of exposure. In such sites, vegetation or even additional construction could supply shade and foster feelings of enclosure by creating intimate, small-scale public spaces with a varied and stimulating design.

In our study, building density, as the most popular indicator for density in urban planning, seems to have less effect on perceived heat stress and crowding in public than traffic, or people density. Tall buildings and narrow streets can increase daytime thermal comfort by providing shaded walkways while motorised but also stationary traffic exacerbates heat stress and crowding. Though limited solar access on the streetscape is beneficial during summertime, it increases thermal discomfort during the cold season. Moreover, less compact structures are beneficial for ventilation and nocturnal cooling, as open spaces foster out-going long-wave radiation and turbulent heat exchange (Onomura et al., 2016). This means that decoupling different forms of density can be a highly effective lever to reduce both crowding and heat stress. Where building density is high, we therefore recommend making traffic reduction and walkability a central concern for improvement. The importance of the general attractiveness and appreciation of a place for thermal comfort perception is also highlighted by other research (Lemonsu et al., 2019). Creating space for street trees, e.g., at the expense of parking space, enhances the quality of stay and decreases heat stress and crowding. Deciduous trees are advantageous since they provide shade in the summertime and solar access in winter. In narrow streets, where planting of trees might be impossible and would block ventilation, we, therefore, recommend using visual green elements at eye level (e.g., green facades, shrubs, or planters) to increase the "naturalness" of stressful urban settings, since our results showed positive psychological benefits achieved by urban greenery.

Wherever possible, places to rest combined with vegetation and (natural) shade should be made available, especially for residents with reduced mobility. If greened and made accessible, backyards and roofs bear great potential as high-quality (semi-)public spaces in high-density settings. Our findings support the idea that, in contrast to qualitative factors, building heights "play a relatively small role explaining perceived urban

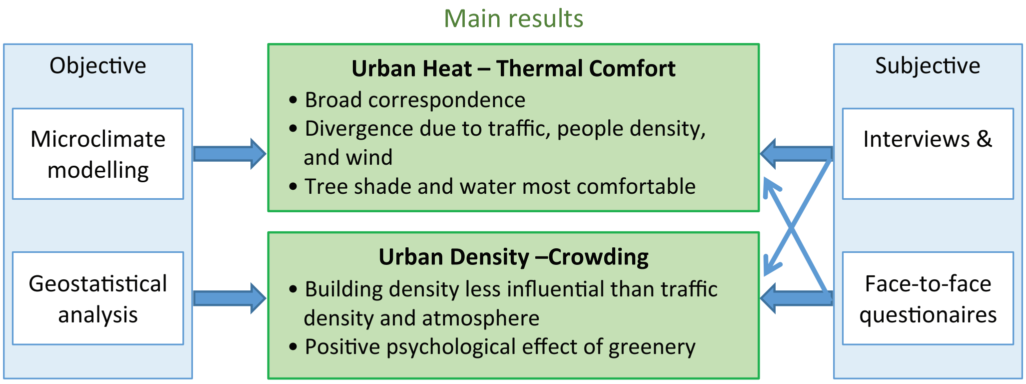

Figure 7. Summary of interaction and main results of the mixed-methods study.

stress" (Knöll et al., 2018, p. 805), while views into the distance are highly valued characteristics, especially among residents of dense neighbourhoods. This suggests that re-densification projects which combine additional storeys with a corresponding redesign of roof areas could result in added value for residents and increased acceptance. As we have seen, urban vegetation is crucial for reducing perceived heat stress, with tall trees providing the most substantial cooling effect. However, the full potential of parks or tree-covered squares for individual heat stress adaptation depends on their accessibility and attractiveness and can only be exploited if set in the right context. Studies by Kyttä et al. (2013) or Klemm et al. (2015) equally highlight that the quality of green space is more important than the quantity. Suburban residents seem to be more selective concerning their use of public space and do not seek peace and quiet to the same degree as residents of dense and highly stimulating neighbourhoods. Also, younger people and people with different cultural backgrounds tend to be more tolerant towards urban density and sensory overload than older citizens. Thus, public parks fulfil different functions in low- and high-density settings, also depending on the amount of private (green) space available and have to be designed bearing in mind the respective requirements of their residents.

In conclusion, our study has shown that the assessment of density parameters and thermal layout does not provide enough information to adequately balance conflicting objectives concerning the use of public urban space. The assessment has to be supplemented by local knowledge to determine the value of these spaces for residents and, thus, their meaning for the ecological and social resilience of cities and their inhabitants (Frerichs & Küpper, 2017). Effective, context-specific, user-centred design of green spaces can increase social and health benefits of UGI in neighbourhoods with different densities.

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Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

Bartesaghi Koc, C., Osmond, P., & Peters, A. (2018). Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. *Solar Energy*, *166*, 486–508. https://doi.org/10.1016/j.solener.2018.03.008

Bavarian State Office for Survey and Geoinformation. (2018). *Digital orthopoto, digital terrain model, digital terrain model and house perimeters of Bahnhofsviertel Munich* [Unpublished data]. Munich.

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, *97*(3), 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006

Chapman, S., Watson, J. E. M., Salazar, A., Thatcher, M., & McAlpine, C. A. (2017). The impact of urbanization and climate change on urban temperatures: A systematic review. *Landscape Ecology*, *32*(10), 1921–1935. https://doi.org/10.1007/s10980-017-0561-4

Cheng, V. (2010). Understanding density and high density. In E. Ng (Ed.), *Designing high-density cities for social and environmental sustainability* (pp. 4–17). Routledge.

Commission of European Communities. (1990). *Green paper on the urban environment—Communication from the commission to the council and the parliament* (EUR 12902).

Debrunner, G., Hengstermann, A., & Gerber, J.-D. (2020). The business of densification: Distribution of power, wealth and inequality in Swiss policy making. *Town Planning Review*, *91*(3), 259–281. https://doi.org/10.3828/tpr.2020.15

European Settlement Map. (2017). *European settlement map 2012—Release 2017*. Institute for Protection and Security of the Citizen—European Commission Joint Research Centre. https://land.copernicus.eu/pan-european/GHSL/european-settlement-map/esm-2012-release-2017-urban-green

Frerichs, S., & Küpper, C. (2017). *Umwelt- und Aufenthaltsqualität in kompakt-urbanen und nutzungsgemischten Stadtstrukturen. Analysen, Fallbeispiele, Handlungsansätze unter Nutzung und Weiterentwicklung des Bauplanungs- und Umweltrechts. Umweltbundesamt* [Environmental quality and quality of stay in compact and mixed-use urban structures: Analyses, case studies, approaches to action using and further developing construction planning and environmental law]. Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-01-29_texte_06-2018_stadtstrukturen.pdf

GeodatenService München. (2020). *Geoinformationsdaten der Stadtgrundkarte* [Geodata from the official city map of Munich]. Geodata-Service Municipal Department of Munich.

Haaland, C., & van den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening*, *14*(4), 760–771. https://doi.org/10.1016/j.ufug.2015.07.009

Hansen, R., & Pauleit, S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *AMBIO*, *43*(4), 516–529. https://doi.org/10.1007/s13280-014-0510-2

Husemann, A. (2005). *Die Wahrnehmung und Bewertung von verdichteten Stadtquartieren* [The perception and evaluation of dense neighbourhoods]. Tenea.

Jabareen, Y. R. (2006). Sustainable urban forms. *Journal of Planning Education and Research*, *26*(1), 38–52. https://doi.org/10.1177/0739456x05285119

Jänicke, B., Meier, F., Lindberg, F., Schubert, S., & Scherer, D. (2016). Towards city-wide, building-resolving analysis of mean radiant temperature. *Urban Climate*, *15*, 83–98. https://doi.org/10.1016/j.uclim.2015.11.003

Kabisch, N., Püffel, C., Masztalerz, O., Hemmerling, J., & Kraemer, R. (2021). Physiological and psychological effects of visits to different urban green and street environments in older people: A field experiment in a dense inner-city area. *Landscape and Urban Planning*, *207*, Article 103998. https://doi.org/10.1016/j.landurbplan.2020.103998

Kaspar, H., & Bühler, E. (2009). Planning, design and use of the public space Wahlenpark (Zurich, Switzerland): Functional, visual and semiotic openness. *Geographica Helvetica*, *64*(1), 21–29. https://doi.org/10.5194/gh-64-21-2009

Klemm, W., Heusinkveld, B. G., Lenzholzer, S., & van Hove, B. (2015). Street greenery and its physical and psychological impact on thermal comfort. *Landscape and Urban Planning*, *138*, 87–98. https://doi.org/10.1016/j.landurbplan.2015.02.009

Klemm, W., van Hove, B., Lenzholzer, S., & Kramer, H. (2017). Towards guidelines for designing parks of the future. *Urban Forestry & Urban Greening*, *21*, 134–145. https://doi.org/10.1016/j.ufug.2016.11.004

Knöll, M., Neuheuser, K., Cleff, T., & Rudolph-Cleff, A. (2018). A tool to predict perceived urban stress in open public spaces. *Environment and Planning B: Urban Analytics and City Science*, *45*(4), 797–813. https://doi.org/10.1177/0265813516686971

Kondo, M., Fluehr, J., McKeon, T., & Branas, C. (2018). Urban green space and its impact on human health. *International Journal of Environmental Research and Public Health*, *15*(3), Article 445. https://doi.org/10.3390/ijerph15030445

Kyttä, M., Broberg, A., Tzoulas, T., & Snabb, K. (2013). Towards contextually sensitive urban densification: Location-based soft GIS knowledge revealing perceived residential environmental quality. *Landscape and Urban Planning*, *113*, 30–46. https://doi.org/10.1016/j.landurbplan.2013.01.008

Landeshauptstadt München. (2018). *Langfristige Siedlungsentwicklung—Zweiter Statusbericht. Sitzungsvorlagen Nr. 14–20/V 12595* [Long-term settlement development—Second status report. Session Papers No. 14-20/V 12595]. https://www.muenchen.de/rathaus/Stadtverwaltung/Referat-fuer-Stadtplanung-und-Bauordnung/Projekte/Langfristige-Siedlungsentwicklung/Naechste-Schritte.html

Lau, K. K.-L., Lindberg, F., Rayner, D., & Thorsson, S. (2015). The effect of urban geometry on mean radiant temperature under future climate change: A study of three European cities. *International Journal of Biometeorology*, *59*(7), 799–814. https://doi.org/10.1007/s00484-014-0898-1

Lee, H., & Mayer, H. (2018). Maximum extent of human heat stress reduction on building areas due to urban greening. *Urban Forestry & Urban Greening*, *32*, 154–167. https://doi.org/10.1016/j.ufug.2018.04.010

Lee, H., Mayer, H, & Kuttler, W. (2020). Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions. *Urban Forestry & Urban Greening*, *48*, https://doi.org/10.1016/j.ufug.2019.126558

Lemonsu, A., Amossé, A., Chouillou, D., Gaudio, N., Haouès-Jouve, S., Hidalgo, J., Le Bras, J., Legain, D., Marchandise, S., & Tudoux, B. (2019). Comparison of microclimate measurements and perceptions as part of a global evaluation of environmental quality at neighbourhood scale. *International Journal of Biometeorology*, *64*(2), 265–276. https://doi.org/10.1007/s00484-019-01686-1

Lindberg, F., Grimmond, C. S. B., Gabey, A., Huang, B., Kent, C. W., Sun, T., Theeuwes, N. E., Järvi, L., Ward, H. C., Capel-Timms, I., Chang, Y., Jonsson, P., Krave, N., Liu, D., Meyer, D., Olofson, K. F. G., Tan, J., Wästberg, D., Xue, L., & Zhang, Z. (2018). Urban multiscale environmental predictor (UMEP): An integrated tool for city-based climate services. *Environmental Modelling & Software*, *99*, 70–87. https://doi.org/10.1016/j.envsoft.2017.09.020

Netek, R., Pour, T., & Slezakova, R. (2018). Implementation of heat maps in geographical information system—Exploratory study on traffic accident data. *Open Geosciences*, *10*(1), 367–384. https://doi.org/10.1515/geo-2018-0029

Neuman, M. (2005). The compact city fallacy. *Journal of Planning Education and Research*, *25*(1), 11–26. https://doi.org/10.1177/0739456x04270466

Nikolopoulou, M., & Steemers, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings*, *35*(1), 95–101. https://doi.org/10.1016/S0378-7788(02)00084-1

Meteorological Institute Munich. (2018). *Weather data station Munich summer 2015* [Unpublished raw data]. Ludwigs-Maximilian-University Munich.

Onomura, S., Holmer, B., Lindberg, F., & Thorsson, S. (2016). Intra-urban nocturnal cooling rates: Development and evaluation of the NOCRA model. *Meteorological Applications*, *23*(3), 339–352. https://doi.org/10.1002/met.1558

Rall, E., Bieling, C., Zytynska, S., & Haase, D. (2017). Exploring city-wide patterns of cultural ecosystem service perceptions and use. *Ecological Indicators*, *77*, 80–95. https://doi.org/10.1016/j.ecolind.2017.02.001

Rapoport, A. (1975). Toward a redefinition of density. *Environment and Behavior*, *7*(2), 133–158. https://doi.org/10.1177/001391657500700202

Staiger, H., Laschewski, G., & Matzarakis, A. (2019). Selection of appropriate thermal indices for applications in human biometeorological studies. *Atmosphere*, *10*(1), 18. https://doi.org/10.3390/atmos10010018

Street Tree Layer. (2018). *Urban atlas: Street Tree Layer (STL) 2018*. Copernicus. https://land.copernicus.eu/local/urban-atlas/street-tree-layer-stl-2018

Thorsson, S., Rocklöv, J., Konarska, J., Lindberg, F., Holmer, B., Dousset, B., & Rayner, D. (2014). Mean radiant temperature—A predictor of heat related mortality. *Urban Climate*, *10*, 332–345. https://doi.org/10.1016/j.uclim.2014.01.004

Wolff, M., & Haase, D. (2019). Mediating sustainability and liveability—Turning points of green space supply in European cities. *Frontiers in Environmental Science*, *7*, Article 61. https://doi.org/10.3389/fenvs.2019.00061

ZENSUS. (2011). *Bevölkerung im 100m-Raster* [Results for the population of the census of 9 May 2011 per grid cell]. https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html

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