# INAUGURAL – DISSERTATION

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Vorgelegt von
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Topic

# *Strengthening the Evidence Base for Urban Planning in the Era of Climate Change*

—

## *An Analysis of Conceptual Frameworks and the Interplay of Heat, Urban Fabric, and Social Structure*

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# Abstract

We are living in a world, in which continuous change is one of few constants. Amidst the transformations taking place, climate change, with its manifold impacts on nature and society, is undoubtedly amongst the most omnipresent ones. In the age of ongoing global urbanization, urban climate change implications, such as the urban heat island (UHI) effect, affect a major part of humanity. Thus, cities as both drivers of and sufferers from adverse conditions are a main focus of climate related research, which can be seen in a constantly growing body of relevant scientific contributions. Associated with that is the necessity of a common understanding of key concepts and definitions. However, as conceptual frameworks are not standardized and furthermore undergo thorough changes, e.g., initiated by the publication of influential IPCC (International Panel on Climate Change) reports, scientific advance is slowed down by varying perceptions, leading to not always comparable results and insights. When analyzing urban heat, there are physical and social factors to be considered. While the former ones can influence the pronunciation of heat, the latter are important to look at in terms of potentially emerging environmental (climate/thermal) injustices. Regarding heat explaining physical variables, a focus of recent research is on land use and land cover characteristics as well as landscape metrics. Urban morphology or fabric as the result of historical developments is rather rarely considered. On the social side, mostly two-sided relationships between, e.g., heat and green supply or green/heat and social status are analyzed. Here, integrated considerations are missing. The research incorporated in the dissertation at hand intends to foster the evidence base for sustainable and resilient urban planning under climate change conditions tackling the before-mentioned shortcomings. The first article featured deals with conceptual and definitional ambiguities in urban climate change research. Amongst others, a strong dominance of certain concepts (e.g., vulnerability) and a huge influence of IPCC reports could be discerned. In the second study, urban morphology and its influence on urban heat is researched for the case of Berlin. Applying a GWR (geographically weighted regression) model, the thermal performance of various urban structure types (UST) could be determined while at the same time obtaining insights on the specific effect of urban morphology parameters on heat intensity. The third article presented is dedicated to explore multi-burden areas in the Ruhr region. Besides heat, green supply as well as social factors are put in relation here via correlations and a cluster analysis. The relationship between heat and social status is found to be ambiguous depending on the city regarded. The cluster analysis could reveal areas suffering from heat, low green provision, and lower social status with a significant amount of the area's population living there (around 27%). In summary, the research featured can be seen as describing three steps necessary in order to achieve resilient cities. A common knowledge base, with common definitions and conceptual framework understandings is needed (1) before the physical urban structure has to be analyzed unleashing adaptation potentials (2). Lastly, the social aspect needs to be included in order to be able to promote tailored solutions in adaptation action benefiting the respective population (3). The outlined procedure can serve as an adaptable blueprint for further research and practice in the area while also exhibiting various connecting points.

# Kurzzusammenfassung

Wir leben aktuell in einer Welt, in der Wandel eine der wenigen Konstanten darstellt. Unter den laufenden Veränderungsprozessen ist der Klimawandel mit seinen vielfältigen Auswirkungen auf Natur und Gesellschaft zweifellos einer der allgegenwärtigsten und prominentesten. Im Zeitalter anhaltender globaler Urbanisierung betreffen städtische Klimawandelfolgen, wie der Hitzeinseleffekt, einen großen Teil der Menschheit. Städte sind dabei sowohl Treiber als auch Leidtragende entstehender ungünstiger Bedingungen und sie stehen damit auch im Mittelpunkt klimabezogener Forschung vieler Fachrichtungen, was sich an einer stetig wachsenden Anzahl relevanter wissenschaftlicher Beiträge ablesen lässt. Dieser *boom* bringt die Notwendigkeit mit sich, ein gemeinsames Verständnis von Schlüsselkonzepten und Definitionen zur Verfügung zu haben. Allerdings sind konzeptionelle Rahmen nicht standardisiert und unterliegen zudem fortwährenden Veränderungen, wie sie beispielsweise durch die einflussreichen Veröffentlichungen des IPCC (Intergovernmental Panel on Climate Change) ausgelöst und initiiert werden. Dies führt zu einer Hemmung des wissenschaftlichen Fortschritts aufgrund unterschiedlicher Auffassungen, was zudem häufig nicht vernünftig vergleichbare und kommunizierbare Ergebnisse und Erkenntnisse zur Folge haben kann. Bei der Analyse von Hitze im urbanen Raum müssen dabei sowohl physische als auch soziale Faktoren berücksichtigt werden. Während erstere die Ausprägung von Hitze beeinflussen können, sind letztere essentiell im Hinblick auf potenziell auftretende Umwelt-, beziehungsweise spezifischer, Klima- und Hitzeungerechtigkeiten. In Bezug auf physische Variablen, die Hitze erklären können, liegt ein Schwerpunkt aktueller Forschung auf Landnutzungs- und Landbedeckungsmerkmalen sowie Landschaftsmetriken. Stadtmorphologie, als das Ergebnis historischer Entwicklungen, wird dagegen eher selten betrachtet. Auf der sozialen Seite sind meist bilaterale Beziehungen zwischen Hitze und Grünversorgung oder zwischen Grünversorgung bzw. Hitzebelastung und sozialem Status Gegenstand der Forschung. Hier fehlen allerdings insbesondere integrierte Betrachtungsweisen. Die in dieser Dissertation präsentierte Forschung soll die Grundlagen für eine nachhaltige und resiliente Stadtplanung unter Klimawandelbedingungen stärken und die zuvor genannten Probleme angehen. Der erste hier vorgestellte Artikel befasst sich dabei mit den begrifflichen und definitorischen Ambiguitäten in der Forschung zum städtischen Klimawandel. Unter anderem wird eine starke Dominanz bestimmter Konzepte (z.B. Vulnerabilität) und ein großer Einfluss der IPCC-Berichte festgestellt. In der zweiten Studie wird die Stadtmorphologie und ihr Einfluss auf städtische Hitze für den Fall von Berlin erforscht. Durch Anwendung eines geografisch gewichteten Regressionsmodells (GWR) konnte die thermische Performanz verschiedener städtischer Strukturtypen ermittelt werden, während gleichzeitig Erkenntnisse in Bezug auf die spezifische Auswirkung von Stadtmorphologieparametern auf die Hitzeintensität gewonnen wurden. Der dritte hier präsentierte Artikel schließlich ist der Erforschung von mehrfach belasteten Gebieten im Ruhrgebiet gewidmet. Neben Hitze (als Proxy für *hazard* beziehungsweise als Teilaspekt/Voraussetzung der Exposition) werden hier auch die Grünversorgung (hitzemindernde Wirkung) sowie soziale Faktoren (als Proxy für Vulnerabilität) in Beziehung gesetzt, indem Korrelationen und eine Clusteranalyse durchgeführt werden. Die Beziehung zwischen Hitze und sozialem Status erweist sich je nach betrachteter Stadt als widersprüchlich. Die Clusteranalyse kann jedoch Gebiete aufdecken, die gleichermaßen von Hitze, geringer Grünversorgung und niedrigem sozialen Status geprägt sind, wobei ein signifikanter Teil der Gesamtbevölkerung des Untersuchungsgebiets in ebenjenen Bereichen lebt (ca. 27%). Zusammenfassend lässt sich konstatieren, dass die hier vorgestellte Forschung drei aufeinander aufbauende Schritte beschreibt, die zur Schaffung resilienterer Städte beitragen. Zuerst ist eine gemeinsame Wissensbasis mit einheitlichen Definitionen und Verständnissen von konzeptuellen Rahmen erforderlich (1), bevor die physische städtische Struktur analysiert werden muss, um Anpassungspotenziale zu identifizieren (2). Schließlich sind auch soziale Aspekte einzubeziehen, um maßgeschneiderte Lösungen in der Anpassungspraxis zu fördern, die der jeweils betroffenen Bevölkerung zugutekommen (3). Das skizzierte Verfahren kann als Vorlage und anpassungsfähiger Leitfaden für die weitere Forschung sowie die Praxis dienen, wobei es gleichzeitig verschiedene Anknüpfungspunkte für die Zukunft bereitstellt.

# Eidesstattliche Versicherung

Gemäß § 11 der Promotionsordnung der Fakultät Raumplanung der Technischen Universität Dortmund erkläre ich folgende Punkte:

1. Bei der eingereichten Dissertation zu dem Thema „*Strengthening the Evidence Base for Urban Planning in the Era of Climate Change*“ handelt es sich um meine eigenständig erbrachte Leistung.
2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken übernommene Inhalte als solche kenntlich gemacht.
3. Die Arbeit oder Teile davon habe ich bislang nicht an einer Hochschule des In- oder Auslands als Bestandteil einer Prüfungs- oder Qualifikationsleistung vorgelegt.
4. Die Richtigkeit der vorstehenden Erklärungen bestätige ich.
5. Die Bedeutung der eidesstattlichen Versicherung und die strafrechtlichen Folgen einer unrichtigen oder unvollständigen eidesstattlichen Versicherung sind mir bekannt.

Ich versichere an Eides statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe.

| | |
|---|---|
| Ort und Datum | Florian Klopfer |

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# List of Abbreviations

| | |
|---|---|
| **ANOVA** | Analysis of variance |
| **AR** | Assessment report |
| **CUHI** | Canopy urban heat island |
| **EEA** | European Environment Agency |
| **GHG** | Greenhouse gas |
| **GWR** | Geographically weighted regression |
| **HSD** | Honestly significant difference |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LCZ** | Local climate zone |
| **LoD 2** | Level of Detail 2 - 3D building model |
| **LST** | Land surface temperature |
| **LULC** | Land use and land cover |
| **MAUP** | Modifiable areal unit problem |
| **NASA** | National Aeronautics and Space Administration |
| **NDVI** | Normalized difference vegetation index / normalized density vegetation index |
| **OLS** | Ordinary least squares (regression) |
| **PCA** | Principal Component Analysis |
| **PRISMA** | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| **ROSES** | RepOrting standards for Systematic Evidence Syntheses in environmental research |
| **RQ** | Research question |
| **SGB II** | *Zweites Buch Sozialgesetzbuch - Grundsicherung für Arbeitsuchende / Bürgergeld*; Social Code Book II - Basic income for job seekers / citizen's benefit |
| **SLR** | Systematic literature review |
| **SREX** | Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation |
| **STURLA** | STructure of Urban LAndscapes |
| **SUHI** | Surface urban heat island |
| **TAR** | Third Assessment Report |
| **UHI** | Urban heat island |
| **UHII** | Urban heat island intensity |
| **UN DESA** | United Nations Department of Economic and Social Affairs |
| **UNEP** | United Nations Environmental Programme |
| **US** | United States (of America) |
| **USGS** | United States Geological Survey |
| **UST** | Urban structure type |
| **WG** | Working Group (IPCC) |
| **ZRR** | *Zukunftsagentur Rheinisches Revier*; Rhenish Mining Region Agency for the Future |

# Part I

# Synopsis

"For the world is changing: I feel it in the water, I feel it in the earth, and I smell it in the air."

Treebeard, Lord of the Rings, The Fellowship of the Ring, J.R.R. Tolkien, (Tolkien, 2009, p. 981).

# Chapter 1

# Introduction

The famous quote at the top of the page by the speaking tree "Treebeard" (not Galadriel as in the movies by Peter Jackson made between 2001 and 2003) in Tolkien's fantasy epic The Lord of the Rings (originally written 1954/55) can be seen as describing some of today's changes in a very accurate manner. First, it illustrates precisely how climate change, one of the biggest challenges prevailing, is perceptible. It is felt in the water, as glaciers are melting and oceans are warming. It is felt in the earth, as droughts and desertification are getting common phenomena in temperate zones and as soils are eroded due to heavy rainfalls or landslides. It is finally felt in the air, as temperatures rise and heatwaves increase in number and intensity. In a more figurative sense, it can also be seen as appropriately portraying structural changes in the aftermath of, e.g., the industrial phase in the Ruhr area or the coal era in the Rhenish mining area (see, e.g., Klopfer et al., 2022) as all three, water, earth, and air, become less impacted by contaminants. Globally, humanity is exposed to a myriad of further changes. Apart from climatic and structural ones, there are demographical changes and more and more other transformations add to these, such as alterations in the energy, the construction, or the mobility sector to name a few. Profound societal, political, and economical transformations and paradigm shifts were moreover triggered by, e.g., the corona pandemic or the Russian aggression in Ukraine.

In urban areas, many of the changes mentioned concentrate and intensify regarding their impacts and implications due to the ongoing global growth of urban populations. While in 2019, globally more than 56% (about 4.3 billion people) were living in urbanized regions, the share was 81% for high-income countries and 33% for low-income countries. In the already highly urbanized higher income regions, annual growth is estimated at 0.7%, while it is 4% for lower income countries (The World Bank, 2019). Thus, in sum, for 2025, the global urbanization rate is expected to be as high as 68.4% (UN DESA, 2019). Some of the largest cities and about 75% of humanity are situated in low and middle-income countries, where especially vulnerable communities are concentrated. In its AR 5, the IPCC stated that key and emerging climate risks accumulate in conurbations. Therefore particularly urban areas need to step up regarding adaptation and resilience promotion (Revi et al., 2014; Bai et al., 2018). Hereby, cities can be seen likewise as driving (e.g., by high GHG emissions) and suffering from adverse climate change induced effects such as increased heat island phenomena (UNEP, 2023).

Concerning climatic changes, the recent IPCC AR 6 concludes that the global warming limit goal of 1.5° over the preindustrial era can still be undershot based on the capabilities present. However, until the 2050s, the surface temperature worldwide is supposed to rise (IPCC, 2021). The IPCC authors furthermore specify a variety of health effects influenced by urban heat and bring up evidence of productivity decreases induced by heat (IPCC, 2022a). Well described are furthermore increased mortalities in the aftermath of heat wave events (Gabriel and Endlicher, 2011; an der Heiden et al., 2020; Vandentorren et al., 2006; Winklmayr et al., 2022). Researching intergenerational disparities regarding extreme climate change induced events (e.g., heat waves, wildfire, crop failures), a recent study finds that children born in 2020 will be exposed to two to seven times more such events (especially heat waves) than people born in 1960 (Thiery et al., 2021). The change of climatic conditions is furthermore regularly displayed impressively by comparing a city's climate projected for a future year to the one of a city today (e.g., in 2070 Berlin will have the climate of Rome today) (for German cities: Crespi et al. (2023). The described actual state and the possible future of urban areas is the stage, foundation, and motivation for the research presented. Although the potential negative effects are massive, especially regarding heat, not many administrative units in Germany have heat action plans. Especially the inter-agency and inter-stakeholder (health, construction, environment, e.g.) collaboration is seen as a major inhibiting factor here (Janson et al., 2023).

Not only factual status quos are, in many ways, subject to change, but also understandings, definitions, and concepts, which has the potential to impede adaptation action. This is observable in the scientifically and medially highly considered complex of climate change. Conceptual as well as applied studies and publications in general use a multitude of concepts and associated definitions. Examples for such concepts are vulnerability, risk, impact, adaptive capacity, exposure, sensitivity, and susceptibility. These, already being defined differently in general, are furthermore related to others in different ways depending on the scientific community a researcher is part of. There are for example big differences between a risk and a vulnerability based approach regarding the assessment of climate change implications (Birkmann et al., 2017). While the IPCC with its comprehensive reports has undoubtedly a great influence, it also changes and adapts understandings and conceptual frameworks from time to time. Not to underestimate is the spatial context of application of these abovementioned concepts. For the evaluation and characterization of, e.g., risks it is of crucial importance whether it is to be done in inner cities or rather rural areas. Different concepts, approaches, or definitions are potentially used there. In summary, disciplines, schools of thought and so on all bring up their own understandings. Key publication for this thematic area is article 1 (review). As urban populations increasingly grow globally (see above) and further societal changes like ageing societies (global north) or informal settlements (global south) are common in wide parts of the world, cities can be seen as ideal study areas of great relevance when it comes to researching climate change effects. As the many and well-described climate change effects are spatially varying phenomena, also on the city level, impacts and effects are not the same everywhere. The UHI is not the same at each place and people are not affected in the same intensity. Here, physical as well as socio-demographic and socio-economic factors play a huge role as determinants. Article 2 and 3 are the key publications dealing with these topics.

The thesis at hand is structured as follows. Following this introduction, Chapter 2 introduces the state of the art relevant for the three publications of this dissertation's framework. At the end of Chapter 2 in 2.4, research questions are derived based upon the identified knowledge gaps and desiderata. Chapter 3 is dedicated to summarizing the articles featured. The next Chapter (4) discusses limitation of the specific papers and the research presented in general. Chapter 5 features the discussion of the results obtained and also draws major conclusions in a synoptic integration of the contributions. The research questions are answered in the framework of this part. The last Chapter (6) is dedicated to future research that, building on the insights of the work at hand, would be needed to further foster the advance in the research areas dealt with here. After a bibliography of works cited, the original papers published are attached in Section II. Appendix A 1 features a list of all the author's scientific works (articles and conference contributions).

# Chapter 2

# State of the Art and Research Questions

The state of the art for the three contributions featured is in parts individual and exclusive to the respective publication while there are also universal and embracing basic aspects important for all three particular thematic focusses. The basic foundation for all the research presented has been laid by shortly touching on the topics of ongoing (urban) climate change, urbanization, and population growth in the previous introductory chapter. The chapter at hand is structured as follows: The specific states of research for the three articles are presented in Chapter 2.1 - 2.3. Finally, in Chapter 2.4 the research gaps identified from the respective state of the arts are presented building upon which research questions are derived.

## 2.1 Describing and Communicating Climate Change Effects

As touched on already above, urban areas are particularly affected biomes when it comes to climate change. Describing, measuring, analyzing, comparing, and communicating about interrelated concepts like impacts, vulnerabilities, and resilience in preparation of adaptation action is aggravated by the magnitude of frameworks as well as by contradicting and/or ambiguous understandings ((Birkmann et al., 2017; Füssel and Klein, 2006; Oppenheimer et al., 2014, specifically regarding vulnerability); (Biesbroek et al., 2018, for adaptation); (Siders, 2019, for adaptive capacity)). Furthermore, definitions and interrelations are also subject to temporal changes and shifts. Exemplary, between their ARs 4 and 5, the IPCC implemented a substantial modification of major concepts. Hereby, the former vulnerability centered conception of climate change adaptation changed to a risk-based one. An achievement in this context was also the harmonization between the climate change adaptation community on the one side with the disaster risk management community as a neighboring discipline on the other side (Connelly et al., 2018). The vulnerability approach in AR 4 (IPCC, 2007) as well as IPCC TAR (IPCC, 2001), is characterized by vulnerability understood as the result of the interaction of the exposure to climate change, a system's sensitivity, impacts, and the respective system's adaptive capacity regarding the impacts (Greiving et al., 2015). In other words, in this framework, vulnerability is a function of exposition, sensitivity, and adaptive capacity. The change was initiated with the 2012 SREX report (Field, 2012) and was then prominently featured in AR 5 (Field et al., 2014). It is mainly upheld also in the recent AR 6 (IPCC, 2022a). According to the "new" understanding, vulnerability and risk are separated (Birkmann et al., 2017). The former became a factor of risk in an exposed system (Field et al., 2014) while risk can

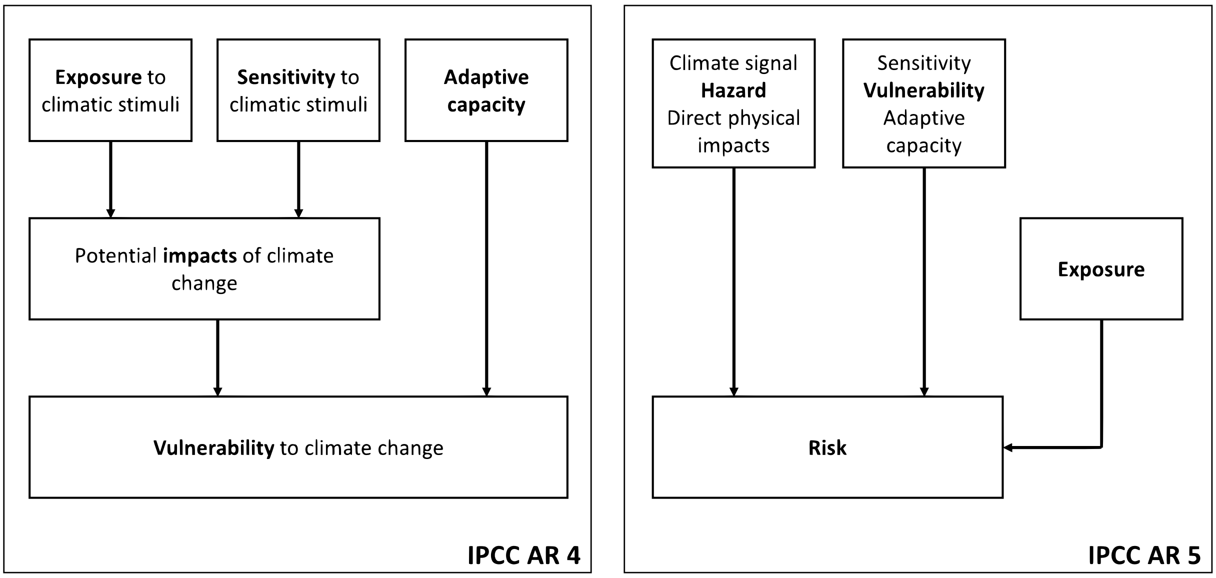

Figure 2.1: Comparison of the AR 4 and AR 5 IPCC risk and vulnerability concept, based on IPCC (2007); Greiving et al. (2015); Field et al. (2014); EURAC research (2017).

be conceived as a function being defined by hazard, exposure, and vulnerability. See Figure 2.1 for a visual representation of this shift.

Especially for (future) comparative studies, the dynamic conceptual diversity outlined above highlights the need for a comprehensive overview of existing conceptual understandings of how climate change effects are assessed. Preconditions for adaptation and prerequisites for adaption action are established by regarding, determining, and analyzing vulnerability and risk as well as studying or assessing adaptive capacity and many more (see, e.g., Di Matteo et al. (2018) for vulnerability assessments as a determinant of what and how to adapt; Siders (2019) for adaptive capacity). Tonmoy et al. (2014) found that regarding climate change vulnerability assessments, the literature originates from a variety of research areas, such as risk assessment, natural disaster management, and urban planning. That makes it challenging to obtain the main directions and key methods in this area. Berrang-Ford et al. (2015) also stated that recent controversy has brought up calls for more standardization and transparency in the methodologies applied to unify climate change research. They furthermore ask for a vigorous conceptual and methodological development of systematic review approaches tackling methodological challenges, such as unifying and monitoring climate change adaptation.

For the dissertation at hand, we follow the definitions provided by IPCC AR 6 for the main concepts, risk, hazard, exposure, and vulnerability (IPCC, 2022a, p. 5). They are listed in the following:

**Risk** is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems.

**Hazard** is defined as the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Physical climate conditions that may be associated with hazards are assessed in WG I as climatic impact-drivers.

**Exposure** is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.

**Vulnerability** in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

## 2.2 Urban Heat and Physical Urban Structures

The need for adaptation in urban contexts is intensified by the combination of climate change and rapid urban population growth, leading to an escalation of urban heat issues with more and more people affected. In this sub-chapter, the UHI effect is introduced before the influence of physical urban structures on urban heat is discussed.

### 2.2.1 The UHI Effect

It has been recognized since the early 19th century that cities tend to experience higher temperatures compared to the surrounding countryside (Oke, 1982). This phenomenon, known as the urban heat island (UHI) effect, alludes to the excess warmth present in the urban atmosphere when compared to non-urbanized areas (Voogt and Oke, 2003). The intensity of the UHI, referred to as the urban heat island intensity (UHII), is determined by the temperature difference between urban and rural regions (Hsu et al., 2021). According to Oke, the UHI manifests as a thermal anomaly with both vertical and horizontal dimensions, influenced by factors intrinsic to the city such as size, population, building density, and land-use distribution, as well as external factors like climate, weather, and seasons (Oke, 1982). To measure UHIs, researchers often use land surface temperature (LST) as a proxy, typically obtained through airborne or satellite-based observations (Voogt and Oke, 2003; Liang et al., 2020).

### 2.2.2 Urban Morphology, Physical Factors, and Urban Heat

Extensive research has been conducted to investigate the influential factors on the UHI phenomenon. Hereby, amongst others, a wide range of urban form parameters has been identified as significant contributors to UHI, which thus have been the subject of intensive study.

#### Urban Morphology

In general, the investigation of urban form and urban morphology originated in Germany during the late 19th century when scholars began to observe and explain the patterns and the development of German cities (e.g., Fritz, 1894; Schlüter, 1899). This historical-geographical approach laid the foundation for the work of M. R. G. Conzen, who introduced the concept of morphological regions (Oliveira, 2016). The study of urban morphology aims to capture the essence of a city's unique spirit, known as *genius loci* (Moudon, 1997). The combination of streets, plots, and buildings, viewed as an interconnected, multilevel structure, is commonly referred to as urban tissue, a term that proves valuable for understanding urban form (Kropf, 2017). Even when undergoing significant functional changes, the fundamental urban form of a city remains evident, in other words cities cannot deny their past (Vance, 1990). At the same time, cities are often considered polymorphogenetic, meaning they are shaped by a variety of styles and trends that contribute to the overall urban structure (Kropf, 2017). US cities, as an example for such a persistent yet individual city type, generally tend to have a more expansive layout (sprawl) compared to their European counterparts, featuring a higher prevalence of suburbs, satellite towns, skyscrapers, a greater reliance on cars, commercial strips along arterial roads, and the presence of exurban areas (Vance, 1990; Jabareen, 2006). Such insights enable the identification of cultural genetic city types (without claiming to be always ideal-typical), a concept particularly prevalent in German urban geography (Heineberg et al., 2017; Hofmeister, 1996). In general, the study of urban form is seen as playing a crucial role in facilitating successful and holistic urban management (Barke, 2018).

### Urban Heat and Physical Urban Structures

As mentioned above, heat and urban form, structure, or morphology are brought together in a variety of ways. When examining the physical aspects related to Urban Heat Islands (UHIs), various determinants and variables receive consistent attention in studies and analyses. To structure our literature review, we classify these factors into three broad categories: urban configuration, land use/land cover (LULC), and urban morphology/geometry.

In the realm of urban configuration, at the wake of modern UHI research, Oke (1973) discovered positive correlations between population numbers and UHI intensity in North American and European cities. He developed equations to predict UHII based on population size and found that adjusted formulas were required for North American and European cities due to variations in the correlation strength, which was weaker for the latter (Oke, 1973). Additionally, indicators such as urban area, contiguity, and density are commonly utilized as well (Chen et al., 2020; Georgescu et al., 2013; Li et al., 2020; Peng et al., 2012).

Within the LULC category, two prominent examples are vegetation and impervious surfaces. Studies have identified a positive relationship between the level of imperviousness (sealed surfaces) and Land Surface Temperature (LST) (Imhoff et al., 2010; Morabito et al., 2016; Yuan and Bauer, 2007). Conversely, numerous studies have explored the negative correlation between UHI and vegetation, often measured using the normalized difference vegetation index (NDVI) (Buyantuyev and Wu, 2010; Chakraborty et al., 2020; Kaplan et al., 2018; Yuan and Bauer, 2007). It is worth noting that the spatial distribution of vegetation, such as its area or edge density, significantly influences LST (Zhang et al., 2009). Moreover, green open space can be seen as a key driver mitigating UHIs (Xu et al., 2019). Water areas or blue infrastructures are another land cover type that receives attention (Larondelle et al., 2014; Žuvela-Aloise et al., 2016). Furthermore, comprehensive studies, encompassing all land covers and land use forms present, are also prevalent (Alhawiti, R. H., Mitsova, D., 2016; Kardinal Jusuf et al., 2007; Zhou et al., 2011). For Phoenix, Arizona for example, Connors et al. showed that heat pronunciation differs in-between land use classes. Applying a regression analysis, they could also reveal varying influences of explaining variables, such as the presence of grass or impervious surfaces, on heat depending on the respective main land use present (Connors et al., 2013).

Urban morphology is generally finding more applications in the fields of urban ecology and microclimate (Kropf, 2017) an thus the urban morphology/geometry category now encompasses a wide range of factors investigated in relation to UHI. In addition to pavement and green plot area, researchers such as Jin et al. (2018) examine aspects like sky view factor, distances to parks/water, and building plot area. The relationship between sky view factor and temperature demonstrates that surface geometry significantly influences air temperature distribution within a city (Unger, 2004). Building density/ratio and building height are also frequently considered in this category (Gao et al., 2022; Kaplan et al., 2018).

The ongoing debate regarding the ideal urban form, considering urban heat islands and the overall urban climate, revolves around whether more compact or sprawling cities are better (Echenique et al., 2012). Oke (1988) previously identified ideal value ranges for urban microclimates, taking into account metrics such as height/width ratio and building density. He argued that the American City, with its dense core and sprawling suburbs, is poorly designed from a climatic perspective (Oke, 1988). However, Echenique et al. (2012) demonstrated that the commonly advocated compact form is not necessarily superior in terms of sustainability, based on their study of three English city regions. The Intergovernmental Panel on Climate Change (IPCC, 2022b) recommends a compact and walkable urban form to achieve significant energy savings. Nevertheless, the discussion surrounding this topic presents pros and cons for both approaches, often influenced by the specific scope and scale of the research conducted (Debbage and Shepherd, 2015; Marshall, 2008; Oke, 1988; Schwarz and Manceur, 2015; Stone et al., 2010). One notable concept that combines urban morphology and heat/climate characteristics is the construct of local climate zones (LCZs). LCZs define regions within a city that have uniform surface cover, structure, material, and human activity, exhibiting distinct screen-height temperature patterns. LCZs typically describe areas in the range of hundreds of meters to several kilometers (Stewart and Oke, 2012). Said concept has been widely utilized in scientific research (Lehnert et al., 2021; Sida et al., 2021) allowing the comparison of both intra-city conditions and entire cities being a main asset (Bechtel et al., 2019). It offers a more comprehensive approach that integrates multiple physical factors relevant to urban heat analysis and avoids the urban-rural differentiation debate. However, there are certain limitations to consider. LCZs cannot capture all the specificities of any urban and rural site, as they provide a reductionist view of the landscape with limited descriptive and explanatory powers. Thus, “ideal” LCZs are improbable to be found in real cities. Moreover, LCZs require a minimum size (Stewart and Oke, 2012), which makes them less suitable for irregularly structured European cities (Oliveira et al., 2020). Another challenge is the resolution of LCZ maps, which often have raster resolutions of 100m (e.g., Demuzere et al. (2021) for Europe), posing difficulties in analyzing densely populated inner-city regions with smaller and irregular spatial scales. In addition to LCZs, another classification concept known as urban structure types (USTs) is prevalent, particularly in Germany. USTs are city-specific typologies that cities usually develop with their own classifications, calculations, and definitions. They incorporate various indicators to quantify and measure different societal structures and specific dynamics (Wendnagel-Beck et al., 2021). Unlike LCZs, USTs provide a higher level of resolution and more precise descriptions of urban morphology, morphological regions, and cultural genetic urban forms. Some city administrations, such as those in Karlsruhe and Berlin, Germany, already consider USTs for climate adaptation strategies. However, the thermal performance of USTs has not been thoroughly investigated when proposing adaptation measures (Wendnagel-Beck et al., 2021). For example, in Dresden, USTs are featured as part of a formula for a settlement heat sensitivity indicator in a climate change adaptation guidebook (Wende, 2014). The city of Leipzig has categorized structure types based on physiognomic similarities to promote sustainable urban development (Wickop, 1999), and these structure types have been studied in terms of indoor and outdoor temperatures (Franck et al., 2013). In Munich, Heldens et al. examined the relationship between land surface temperature (LST) and USTs (Heldens et al., 2013). However, there is a lack of in-depth statistical analyses on the different performance of USTs and the underlying reasons. Nonetheless, USTs are considered an important entry point for analyzing intra-urban variations in physical and social structures and dynamics (Wendnagel-Beck et al., 2021). Currently, there are limited applications that combine USTs and heat analysis, and USTs are not frequently integrated into (adaptation) planning processes. However, the advantages of the UST concept, such as higher resolution, suitability for irregular European cities, and the availability of reliable expert-generated data in cities, make it an appealing approach to complement the LCZ framework. With STURLA (STructure of URban LAndscape), there is a third construct intending to classify urban land uses (applied, e.g., by Kremer et al. (2018); Stewart and Kremer (2022)). STURLA allows for the description of a variety of urban structure combinations. E.g., if a pixel contains trees (t), pavement (p), grass (g), and low-rise buildings (l) the code for this distinct class would be “tpgl” The STURLA approach was found advantageous of the LCZ one as it looks at smaller scales (about 120m²), includes vertical heights (no sky-view-factor estimation needed), and features a potential differentiation in 255 structure types (in the example cited) compared to 17 LCZs (Stewart and Kremer, 2022).

Understanding the climatic performance of local typologies is crucial in urban morphology research (Oliveira et al., 2020). The Intergovernmental Panel on Climate Change (IPCC) recognizes the need for studies that connect urban morphology with the urban heat island phenomenon and its spatio-temporal variability (IPCC, 2022a). Changes in morphology or built form have the potential to mitigate the effects of the urban heat island and alleviate the impacts of heatwaves. However, the IPCC primarily suggests “non-destructive” measures, such as greening or surface albedo changes, and does not propose breaking away from standard urban form arrangements (IPCC, 2022a). Shandas argues that the resistance to change and the lack of adaptive capacity and resilience in cities are often attributed to the rigidity of existing infrastructure, as well as entrenched institutional and political dynamics (Shandas, 2020a). Overall, urban morphology has not been strongly linked to urban planning thus far (Oliveira, 2016). Few studies have examined the effects of urban form on land surface temperature, particularly from an urban planning perspective (Yin et al., 2018), at a spatial level relevant to urban redevelopment and transformation, as opposed to general theoretical constructs. However, Gao et al. provide heat regulation recommendations for urban planners and policymakers based on a block-level analysis and suggest strategies for optimizing block morphology (Gao et al., 2022). In China, regulatory management units with extents of about 150/250m are commonly used, which can be compared to census block groups in the US context and USTs. These units are closely related to urban detail planning (Gao et al., 2022; Lu et al., 2021; Yin et al., 2018).

## 2.3 The Complex Relationship between Heat, Green Supply, and Social Status

The factors under investigation regarding urban heat and urban structure features can be broadly categorized into two main groups: physical aspects (discussed in Chapter 2.2) and societal aspects of the urban fabric (explored in this chapter). The former group primarily aims to elucidate the spatial distribution and underlying causes of urban heat islands and heat hazards. Conversely, the latter group focuses on understanding the exposure and vulnerability of different population groups to UHIs. As mentioned above, we here stick to the definitions provided in the recent IPCC report for the main concepts within the risk framework.

### 2.3.1 Social Factors in Environmental Injustice Research

In addition to studying the connections between heat and physical urban factors, researchers also explore the influence of sociodemographic or socioeconomic structures. The combination of heat islands and rapid urbanization has transformed cities into environments where the adverse effects of global climate change on society are becoming increasingly pronounced. One of the complex challenges lies in the interaction of heat, insufficient green spaces, and the presence of socially disadvantaged urban residents. As climate injustices and potential health problems arise, it is crucial to respond with strong adaptation measures. Between 2015 and 2020, the global urban population experienced a significant growth of nearly 400 million people, with over 90% of this increase occurring in less developed regions (IPCC, 2022a). This process of urbanization has been identified as a factor that heightens vulnerability and exposure to climate change hazards, thereby exacerbating urban risks and impacts. As rapid population growth is primarily concentrated in areas with limited adaptive capacity, those who are already economically and socially marginalized are disproportionately affected by the adverse consequences of climate change (IPCC, 2022a). Studies have demonstrated that the correlation between environmental stresses and the social circumstances of urban residents extends beyond just climate change and urban heat (Bunge and Rehling, 2020; Osberghaus and Abeling, 2022; Ohlmeyer et al., 2022; Mitchell and Chakraborty, 2019; Jafry et al., 2019; Hsu et al., 2021). Environmental burdens such as heat, noise, air pollutants, lack of green spaces, and poor housing conditions tend to be spatially concentrated in socially disadvantaged urban neighborhoods. These areas are characterized by an elevated presence of pathogenic factors like air pollutants and a scarcity of salutogenic factors such as green spaces, which further augment the social vulnerability of residents and negatively impact their overall health (Bunge and Rehling, 2020).

To mitigate the escalating impact of heat stress in urban areas, one effective intervention measure is the strategic incorporation of green spaces and water features to capitalize on their thermal dampening capabilities (Pamukcu-Albers et al., 2021). Predominantly non-paved green and blue areas play a vital role in regulating the local microclimate. Residing in cooler regions with higher vegetation coverage has been linked to a decreased risk of heat-related illnesses and fatalities (Schinasi et al., 2018). It is important to recognize that the adverse consequences of climate change are not limited to generally economically disadvantaged regions, as even in the United States, heat has been the leading cause of natural disaster-related deaths already more than a decade ago (Borden and Cutter, 2008). In Germany, the summer of 2003 witnessed approximately 9,600 deaths attributed to heat-related issues (an der Heiden et al., 2020), followed by around 8,700 deaths in 2018 (Winklmayr et al., 2022).

In order to effectively address the challenges arising here, it is crucial to understand the spatial distribution of heat hazards expressed as UHIs, the factors driving or mitigating urban heat, and the population groups most exposed to excessive heat. This knowledge serves as a foundation for informed urban planning decisions aimed at ameliorating the livability of urban spaces (Rydin et al., 2012; Shandas, 2020b). Furthermore, it is imperative to examine the existence of climate injustice within cities by considering the characteristics of individuals who are potentially at higher risk.

By identifying geographical disparities and co-occurrences, valuable insights can be gained for spatial and urban planning strategies that promote resilient and equitable cities.

### 2.3.2 The Relationship between Social Factors and Green Supply

Urban green infrastructure planning often exhibits a disparity between social demand and social equity. Studies have revealed that low-income areas in urbanized regions of the United States tend to have less tree cover, resulting also in higher temperatures (McDonald et al., 2021). In Atlanta, for instance, there is a significant disparity in access to green spaces among African Americans (Dai, 2011). Analyses conducted in German cities have similarly shown an uneven distribution of urban green, with densely populated and socially disadvantaged neighborhoods often lacking adequate green spaces (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2015; Flacke et al., 2016). Furthermore, these studies indicate that socioeconomically privileged residents are more likely to reside in areas with lower environmental stresses, while less privileged individuals experience higher environmental stresses in their residential areas (Ohlmeyer et al., 2022), leading to heightened health vulnerabilities (Köckler et al., 2020).

From a policy standpoint, it is crucial to prioritize the provision of green spaces in socially disadvantaged neighborhoods. These areas often experience a higher need for public green spaces due to the limited availability of private green spaces, exacerbated by multiple pressures (Voigtländer et al., 2010; Lakes et al., 2014; Schüle et al., 2017; Braubach et al., 2017).

### 2.3.3 The Relationship between Social Factors and Heat

In addition to physical factors, various socioeconomic and sociodemographic indicators are examined in relation to heat, including age, income, and race. Extensive literature, particularly focused on US cities, suggests clear correlations between lower socioeconomic classes and heat exposure (Osberghaus and Abeling, 2022; Hsu et al., 2021; Buyantuyev and Wu, 2010; Dialesandro et al., 2021; Mitchell et al., 2021; Mitchell and Chakraborty, 2018). For instance, a study in Phoenix, Arizona by Buyantuyev and Wu (2010) reveals a weak but significant ($p < 0.001$) negative correlation (0.13-0.25) between income and urban heat islands (UHIs). Another analysis of 20 Southwestern US metro areas demonstrates that, on average, the poorest 10% of neighborhoods are 2.2°C warmer than the most affluent 10%, highlighting unequal heat exposure (Dialesandro et al., 2021). Historical housing policies, such as redlining, continue to contribute to inequalities, including those related to climate. Areas previously impacted by redlining tend to be warmer compared to non-redlined areas (Hoffman et al., 2020; Saverino et al., 2021). People of color are often located in areas with higher UHIs, as indicated by a study examining the 175 largest US urbanized areas (Hsu et al., 2021). Mitchell and Chakraborty's research on the three largest US cities (New York City, Los Angeles, and Chicago) identifies higher heat risks among lower economic status groups (Mitchell and Chakraborty, 2015). However, a study in Philadelphia by Li does not find significant disparities in terms of race/ethnic groups, but highlights that the elderly and high-income individuals tend to live in cooler areas (Li, 2021). The pronounced inequality effects observed in US-focused studies can be attributed to ongoing segregation, resulting in marginalized groups residing in less desirable areas (Mitchell and Chakraborty, 2019). Research in other regions of the world, like, for example, in Delhi, India (Mitchell et al., 2021), Antwerp, Belgium (Burbidge et al., 2021), and Manchester, UK (Kazmierczak, 2016), is not as extensive. Burbidge et al. (2021) find a connection between socioeconomically marginalized communities, urban heat, and the distribution of green spaces in Antwerp, Belgium, indicating heat injustice where socially vulnerable groups tend to reside in less green and hotter areas. In Manchester, UK, climate injustice is observed among diverse communities, individuals living in rental housing, and those in poor-quality housing, who face a greater heat risk, while only a slight trend is found for the elderly and children (Kazmierczak, 2016). A study comparing the relationship between income and heat in 25 cities worldwide reveals that 72% of poorer neighborhoods experience an elevated exposure to heat. For Berlin, the data suggests that poorer households suffer from higher UHIs (Chakraborty et al., 2019). However, a survey on German households by Osberghaus and Abeling does not find differences in heat hazard and exposure based on deprivation levels (Osberghaus and Abeling, 2022). Overall, the reviewed literature indicates that socioeconomically advantaged residents are more likely to reside in areas with lower environmental stress, while socioeconomically disadvantaged individuals are exposed to higher environmental stresses, leading to increased health vulnerability. Therefore, these neighborhoods, in particular, should have a higher proportion of urban green spaces to mitigate the prevailing pressures, such as excessive heat. However, it is important to consider not only residential areas but also other frequented locations like workplaces, where people spend a significant amount of time, in a comprehensive vulnerability and exposure assessment.

The vulnerability to heat among societal groups is influenced by a wide range of socio-demographic and socio-economic factors, as evident in the literature review above. Age is a commonly studied variable, with young children and older individuals (typically under 5/6 and over 65 years) considered more susceptible to the adverse effects of heat (Mitchell and Chakraborty, 2015; Burbidge et al., 2021; Kazmierczak, 2016; Köckler et al., 2020). The elderly population, in particular, experiences significant impacts from heat stress, as previous studies on heatwaves have shown increased morbidity and mortality rates during and after periods of extreme heat (Allex et al., 2013). Socio-economic status is operationalized using various indicators, including income (McDonald et al., 2021; Dialesandro et al., 2021; Mitchell and Chakraborty, 2018; Huang and Cadenasso, 2016), poverty (Kazmierczak, 2016), employment status (Burbidge et al., 2021), and social welfare reception (Flacke et al., 2016; Köckler et al., 2020). Additionally, migration status (Flacke et al., 2016; Köckler et al., 2020), ethnicity/race (Mitchell and Chakraborty, 2015; Kazmierczak, 2016; Huang and Cadenasso, 2016), and minority membership (Dialesandro et al., 2021; Mitchell and Chakraborty, 2018) are considered.

## 2.4 Research Questions

Based on the scientific discourses discussed in the previous chapters, the contributions of this present cumulative dissertation are dedicated to some of the identified processes and changes defining and shaping the future. The focus is here on the assessment and thus on questions regarding the evaluation of the status quo in order to contribute to sustainable futures in urban landscapes in a time of profound changes.

The epistemic interest of this work finds expression in the following research questions, which are answered with the publications written in the framework of this dissertation:

**1. What conceptual frameworks for assessing climate change effects in urban areas are found in the scholarly literature and how are they applied and defined?**

**2. How and why does the thermal performance differ in various USTs? What role does the urban form/morphology play regarding heat in the city? (case study Berlin)**

**3. How is the relationship between heat, green provision, and social status in urban areas? (case study Ruhr area)**

**4. What implications for science and planning can be drawn from RQ 1-3?**

While RQ 1,2, and 3 can be assigned to publications 1 through 3 and will be answered in the respective Chapters (3.1, 3.2, 3.3), answering RQ 4 requires a synthesis of results and conclusions of all three papers, which will be addressed in the discussion Chapter (5). The first article herein deals with conceptual frameworks related to urban climate change and serves as an important groundwork for the work on climate-related topics in an urban context. Especially the multitude of partially contradicting conceptual understandings is analyzed here. Central to the second contribution is the analysis of urban

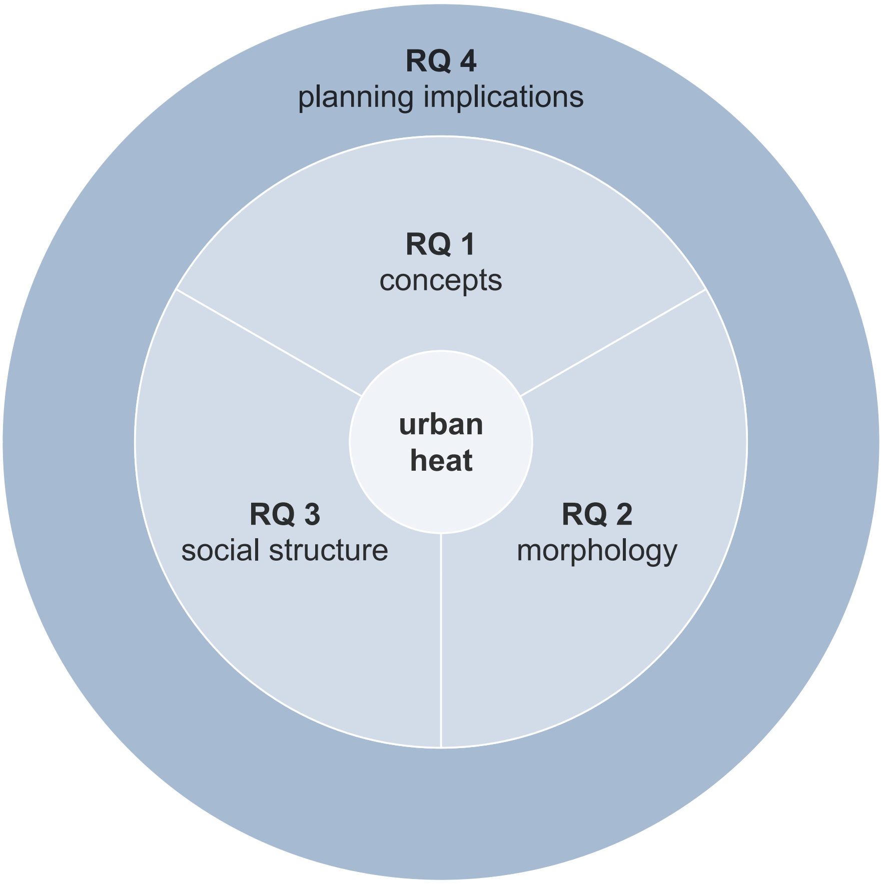

Figure 2.2: Structure of RQs and associated research.

heat in relationship to urban morphology. Adverse heat effects are researched in the context of different USTs in Berlin. This paper's results give hints on how a city can be transformed to achieve fairness and balance in the future. The third article contributes to climate/environmental justice research as it puts urban heat, green provision, and social structures in cities of the Ruhr area in relationship. Figure 2.2 shows the RQs (and thus also the respective publications) and their relationship to each other. While urban heat can be seen as the focal point for the whole dissertation project, RQ 1 through 3 approach this core from different angles that are also the principal subjects of the three papers dedicated to answer these questions. RQ 4 embraces the inner circle parts by asking for planning implications all three former RQs might entail.

Thus, common to all contributions is the desire to initiate changes and to exert influence on planning and politics through insights gained. They are furthermore, on the one hand, also building upon each other and, on the other hand, they exhibit interconnections. Understandings of concepts and frameworks support further research and planning practice in understanding each other, in evaluating and interpreting results, and in potentially transferring findings (1). Knowledge about climatically more or less suitable urban structures helps planning to leave traditions and heritage behind, potentially fostering a paradigm change regarding urban and building design for climate resilient cities (2). The analysis and categorization of areas affected by multiple burdens (hot, socially weak, and less green) facilitates the development of tailored adaptation strategies (3). Lastly, the presented results in combination contribute to a raised awareness and enhance adaptation and mitigation of climate change effects in cities (4).

# Chapter 3

# Scientific Contributions

The following chapter is dedicated to short summaries of the publications generated in the framework of this dissertation. In Section II, which includes the article PDFs, there is an info box featuring the key facts of each document before the respective paper's full-text is following. It contains information on character counts, review modalities, and the author contributions regarding the individual publications. The three articles presented were published between 2021 and 2023 and all are open-access.

## 3.1 Conceptual Frameworks for Assessing Climate Change Effects on Urban Areas - SLR

The first publication[1] in the framework of this dissertation intends to thoroughly investigate the conceptual frameworks applied for the assessment of climate change effects in cities/urban areas. Hereby, an evidence base for both research and adaptation practitioners should be created. The overarching epistemic interest is expressed in the following primary research question (RQ):

What conceptual frameworks for assessing climate change effects in urban areas are applied in the scholarly literature?

Sub questions are elaborated to reveal temporal trends regarding publication activity (RQ 1), to analyze study areas and author provenance (RQ 2), to determine study types and target audiences (RQ 3), and to disclose the frameworks featured in the research and how they are defined (RQ 4).

Systematic and non-systematic literature reviews on conceptual frameworks focusing on climate change effects (in urban areas) are scarce. Those existing are dedicated to rather specific topics like climate change vulnerability assessments in India (Singh et al., 2017) or the threats climate change poses for cultural heritage resources (Fatorić and Seekamp, 2017) to name just two. Even more specialized reviews deal with climate change adaptation and the impact on policies (methods/tools applied) in coastal areas and on small islands (Hafezi et al., 2018) or with climate change vulnerability case studies located in the Canadian Arctic (Debortoli et al., 2018). Bibliometric approaches have been applied already, too (Di Matteo et al., 2018; Zhang et al., 2018). Furthermore, there is also a review of reviews covering climate change adaptation research (Berrang-Ford et al., 2015). When the emphasis is on urban

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[1] The research summarized in this section is based on:
Klopfer, F., Westerholt, R., and Gruehn, D. (2021). Conceptual frameworks for assessing climate change effects on urban areas: A scoping review. Sustainability, 13(19):10794. doi: 10.3390/su131910794.

Table 3.1: Lookup table for the search string creation.

| **Subtopics** | **Climate AND** | **Change AND** | **Climate Change Effect Related Component AND** | **Assessment Component AND** | **Urban Component** |
|---|---|---|---|---|---|
| **keywords** | chang* | climat* | vulnerab * OR risk * OR hazard * OR disaster * OR resilien * OR adapt * OR mitigate * OR expos * OR sensitive * OR impact * OR suscept * OR influenc * OR evidenc * OR effect * OR indicator * OR conceptual framework * | assess * OR evaluat * OR rat * OR estimate * OR measure * OR indicat * OR descri * OR identif * OR analy * OR scan * OR quantif * OR scenario * OR map * OR method * OR approach * OR plan * OR manag * OR index OR indices OR concept * OR strateg * | cit * OR urban * OR settlement * OR communit * |

surroundings, reviews are thematically again often rather narrow focusing on areas like impacts of urbanization and of climate change on urban temperatures (Chapman et al., 2017), urban flooding, and urban water quality (Miller and Hutchins, 2017), or the planning and design of urban drainage systems (Yazdanfar and Sharma, 2015).

For the above described research interest, a systematic methodological approach in the form of a literature review was chosen based on the following rationale. SLR facilitate the evaluation and interpretation of existing bodies of literature to tackle specific research interests or to summarize fields of study (Kitchenham, 2004). Foundations of SLR are both their transparency and reproducibility (Berrang-Ford et al., 2015). Furthermore, a review systematizes general properties of publications, such as number, type, or geographical aspects. Especially for interdisciplinary research and when both quantitative and qualitative methods are applied, a SLR procedure is well-suited (Pickering and Byrne, 2014).

Our approach is mainly based on the well-known and well-established PRISMA framework (Moher et al., 2009) taking into account the components proposed by Berrang-Ford et al. (2015) for reviews in the area of climate change adaptation and the ROSES reporting guidance that was explicitly developed for environmental systematic reviews and maps (Haddaway et al., 2018). The lookup table for the creation of search strings applied for the research in the paper is depicted in Table 3.1 above. Search strings should, as far as possible, cover the field with a broad perspective while the construct remains adaptive and open for the integration of “new” keywords. The databases Scopus and web of science are applied for the literature search. Further criteria for inclusion are the language (English) and the publication time (2014 until December 2020). The process is illustrated as a flow diagram in Figure 3.1, comprising screening titles, abstracts, and the full texts subsequently on the basis of the defined criteria for inclusion or exclusion. This process yielded a final total of 50 publications.

The first major finding derived from analyzing the final literature corpus is the fact that publication activity increased over the time regarded – a trend that can be observed also in general in climate change research and related sub-fields (Haunschild et al., 2016). Much research deals with study areas in Asian (Chinese) and African cities where urban areas also grew and grow the fastest. Authors, however, mainly originate from Europe or North America, which is again a phenomenon that could be confirmed across the field of climate change research. To a certain degree, the global North has an overweight here. The most common study type in our set of publications is the combination of a theoretical framework and a case study. Most of the research was found to be either based on quantitative or mixed

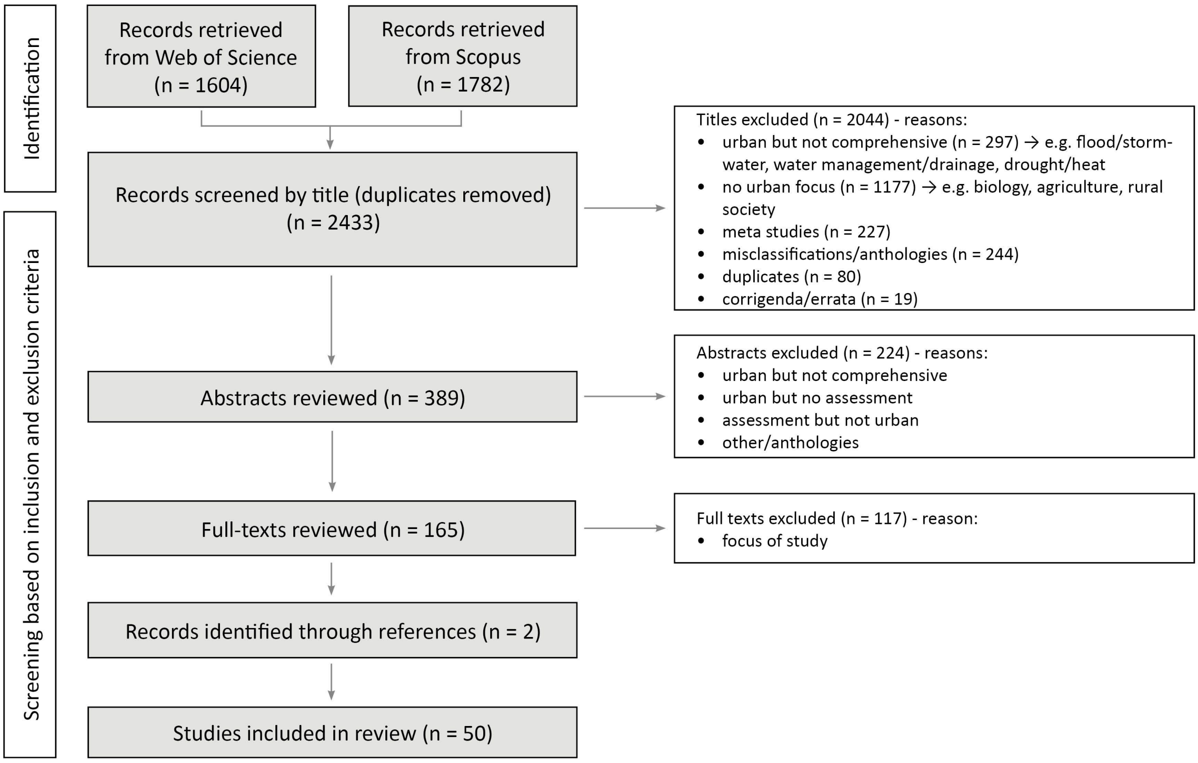

Figure 3.1: Flow diagram for the different phases of the review process; structure based on (Moher et al., 2009).

methods approaches. Many indices described and calculated within the literature are intended to help practitioners rather than the research community. Finally, the concept of vulnerability dominates in our literature corpus (Figure 3.2) with the IPCC publications having a strong influence on the definition and understandings of the respective concepts. Figure 3.3 shows the definitions referred to by the respective authors. The majority is either based on the IPCC definitions of the AR 4 and 5 or these definitions are directly adopted. For our literature corpus, both the *old* and the *new* IPCC framework respectively influenced 28% of definitions used in the investigated studies. Interestingly, however, 24% of the studies regarded do not provide any definitions of the concepts applied.

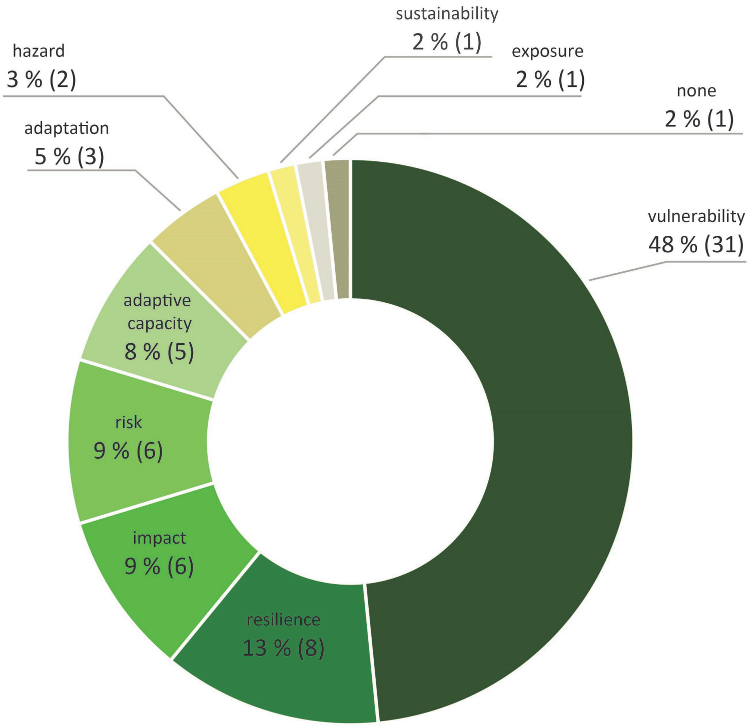

Figure 3.2: Concepts dealt with in the reviewed publications.

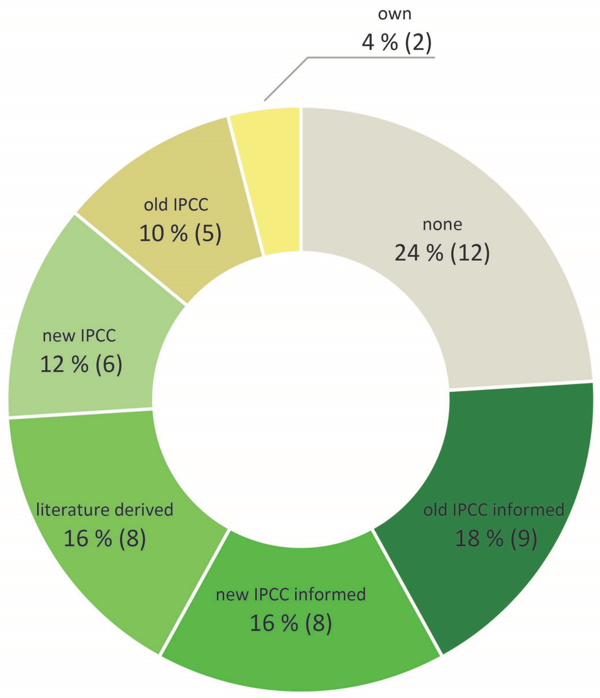

Figure 3.3: Definitions applied for the main concept of the research.

## 3.2 The Thermal Performance of Urban Form – Berlin Study

Unlike the first article, the second paper[2] is not occupied with conceptual considerations but features a case study (Berlin) on the spatially varying presence of heat in urban areas and its connection to the predominant urban morphology in the form of urban structure types (USTs). The analysis furthermore intends to bridge the, oftentimes wide, gap between research and real world planning in the field of climate adaptation and mitigation. Only few applications exist so far researching USTs or urban form on a spatial level relevant for urban transformation and urban renewal in general and their relationship with urban heat (e.g., Gao et al., 2022). Furthermore, USTs in general are not often integrated in urban planning, especially in climate change questions. This is all the more surprising as the analysis of the climatic performance of urban form is deemed a paramount imperative in the current urban morphology research (Oliveira et al., 2020). This is also supported by the IPCC when it calls for studies linking, e.g., urban form and urban heat islands including their spatial as well as temporal variabilities (IPCC, 2022a). While it is well known, that changes in the urban fabric have a significant influence on UHI effects, mostly "non-destructive" interventions (greening, albedo changes, e.g.) are put forward (IPCC, 2022a). This might be due to the durability of present infrastructures as well as passed on institutional and political inheritances (Shandas, 2020a).

The paper described here tackles the emerging research gap with a case study on USTs in Berlin and their thermal performance to derive recommendations for action. By researching the linkages between urban morphology and heat exposure it is possible to deduce spatially precise planning desiderata. The emergence of locally varying heat stresses can thus be better understood and addressed by tailored measures.

The research interest of the discussed study is expressed in the following research questions:

RQ 1: How does the thermal performance differ in various Berlin USTs?

RQ 2: What factors influence the thermal performance in specific USTs in Berlin?

RQ 3: What planning implications can be drawn from RQ1 and 2?

Figure 3.4 shows the applied research design and the methodological steps taken. There are four main phases in this research: data acquisition (1), data preparation (2), descriptive statistics (3), and analysis of variance (ANOVA), correlations and regressions (4). As study city, Berlin is chosen due to the presence of an area-wide UST dataset that is furthermore usable free of charge.

Data stem from various sources: City of Berlin (UST, LoD 2 - 3D building model for building height and building ratio calculation, and boundaries from Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen (2022a,b), USGS (Landsat 8 raw data for LST and NDVI derivation, 30m resolution from USGS (2022b,a), and Copernicus/EEA (imperviousness data from EEA (2018).

Within the framework of data preparation, the UST data was first reduced to six superordinate categories. LST and NDVI are derived from three Landsat scenes obtained for three hot days in the years 2019, 2020, and 2022 applying a widely used methodology (Avdan and Jovanovska, 2016; Kaplan et al.,

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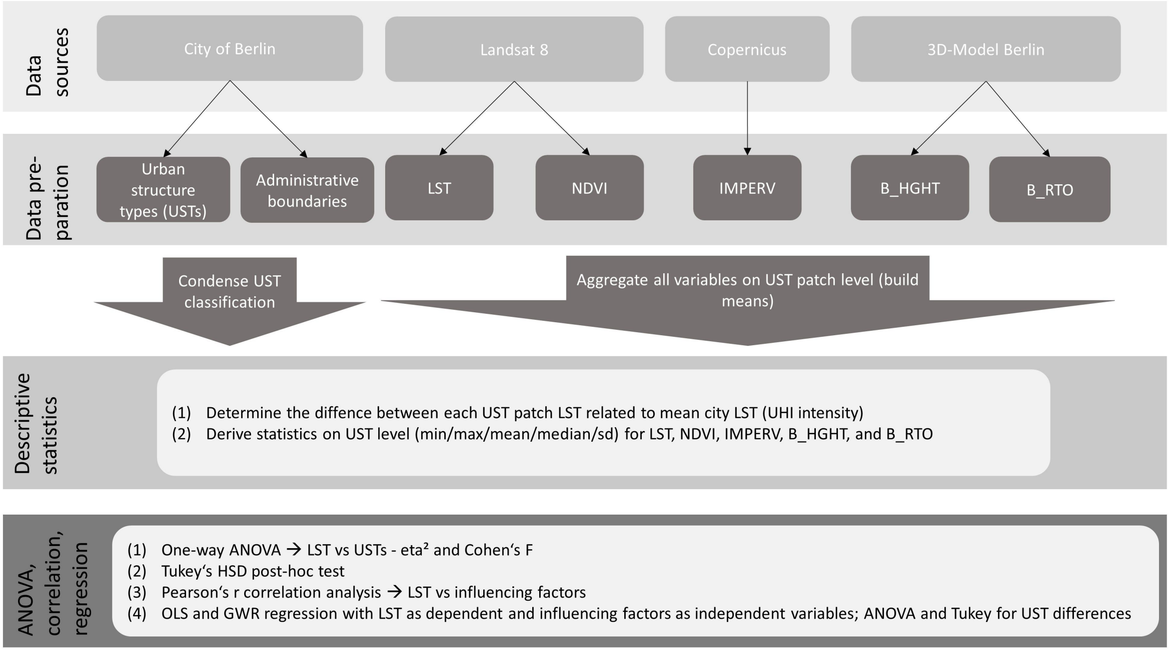
[2] The research summarized in this section is based on:
Klopfer, F. (2023). The thermal performance of urban form – an analysis on urban structure types in berlin. Applied Geography, 152:102890. doi: 10.1016/j.apgeog.2023.102890.



(1) Determine the diffence between each UST patch LST related to mean city LST (UHI intensity)
(2) Derive statistics on UST level (min/max/mean/median/sd) for LST, NDVI, IMPERV, B_HGHT, and B_RTO

(1) One-way ANOVA → LST vs USTs - eta² and Cohen's F
(2) Tukey's HSD post-hoc test
(3) Pearson's r correlation analysis → LST vs influencing factors
(4) OLS and GWR regression with LST as dependent and influencing factors as independent variables; ANOVA and Tukey for UST differences

Figure 3.4: Methodological approach.

2018; Dong et al., 2022). LST, NDVI as well imperviousness are then aggregated on the UST patch level to get one mean value for each variable and patch. Building ratio for each UST patch is finally understood as the percentage of building covered area. Building height for a patch is the mean height of structures in it. After basic descriptive stats are calculated for each variable and UST, an ANOVA with a Tukey post-hoc test is applied to uncover differences between the regarded USTs in terms of thermal performance. The prerequisites that need to be met for the application of an ANOVA examining potentially differing levels of LST among the researched Berlin USTs are also satisfied. LST observations within each UST are independent, normally distributed, and the homogeneity of variance is checked for consistency across USTs. Then, correlation analyses to determine the relationship between LST and the possibly determining factors are executed. We choose vegetation as one of the most frequently used LULC variables (operationalized by the NDVI), imperviousness, and building density and building height as urban morphology indicators. The Pearson correlation approach is suitable for the data at hand as the variables involved are measured at least on the interval scale of measurement and as, furthermore, the data exhibits a tendency towards a near-normal distribution supporting the reliability of the chosen correlation in capturing linear dependencies between the variables. Subsequently, an OLS and a GWR model are fit to determine the effect that NDVI, imperviousness, and building height/ratio have on the pronunciation of heat on UST patch level. The prerequisites for an OLS include non-stationarity of the relationship regarded. As we expect different regression parameters in different patches/USTs we also apply the GWR approach. A GWR allows such non-stationarities as it provides a local regression model for each regarded spatial unit (here UST patches). In this way, for each patch, information on how the influencing factors determine heat can be derived. In other words, the geographical variance in the relationship between dependent and explanatory variables is explored by a GWR (Comber et al., 2022). As a result, a GWR provides intercepts, coefficients, and r²-values for each patch of the analyzed UST dataset. In a final step, another ANOVA with a Tukey HSD test is run to evaluate the differences in GWR results (intercepts, coefficients, r²) on the UST aggregation level. Potentially differing impacts of the explanatory variables applied in various USTs can thus be disclosed.

The ANOVA in addition with the Tukey post-hoc test to determine disparities in the thermal performance of the regarded structure types reveals partly significant differences in the heat exposure. Correlations on the city level yield r-values of 0.67 (LST vs NDVI), 0.71 (LST vs imperviousness), 0.50 (LST vs building ratio), and 0.34 (LST vs building height). Sufficiently high correlation coefficients make the inclusion of all independent variables in the regression models viable. The GWR model improves the r²-value (quasi-global for GWR) clearly from 0.53 (OLS) to 0.83. Regarding locational specific coefficients (means for each UST patch), the GWR offers a differentiated picture. Imperviousness shows the highest positive influence on LST in detached houses and row developments/open blocks and the lowest influence for village cores. NDVI's influence (considering coefficients) is strongest (negative) for village cores and detached houses and weakest for perimeter block development. For the building height, all (negative) coefficients suggest a temperature lowering impact of larger buildings heights. The degree of change a higher/lower level of, e.g., NDVI or imperviousness, induces on the heat varies from UST to UST. For example, our analysis indicates that increasing heights in village areas mitigates LST more than doing so in already more high-rise perimeter block areas with also higher densities. For better illustration, some concrete numbers might help. Having a NDVI value that rises by 0.1 causes a temperature (LST) fall in the detached houses UST by about 0.7°C and 0.4°C in perimeter block areas. When however the building height is 10m higher, LST would go down by 0.2°C and by 0.6°C in detached houses areas and perimeter block neighborhoods respectively. Hereby, it is of paramount importance to consider the respective units and magnitude of change when interpreting results (a 5% increase in impervious area on top of a status quo that is at 10% is to be differentiated from a 5% increase adding to a status quo of 80% impervious surface). The significance of the found differences is checked with another ANOVA and Tukey's post hoc test. Results are depicted in Table 4 and 5 of the Berlin publication. These results show the sophisticated character of the findings obtained here and give many recommendations for tailored adaptation solutions.

Figure 3.5 and 3.6 show the study area wide results for the imperviousness coefficients and the local r² values for the respective GWR model. Imperviousness seems to have the highest positive influence on LST in areas with a lot of green/blue infrastructure (featuring impervious surfaces shares that are very low or even zero) and heterogeneous UST structures. Local r² values are lowest in central city areas and highest further outside of the center. Here, presumably, UST structures are more homogeneous and do not change on a small scale basis. Thus, they are not influenced too much by surrounding varying structures allowing the local regression models to be more accurate (larger r²).

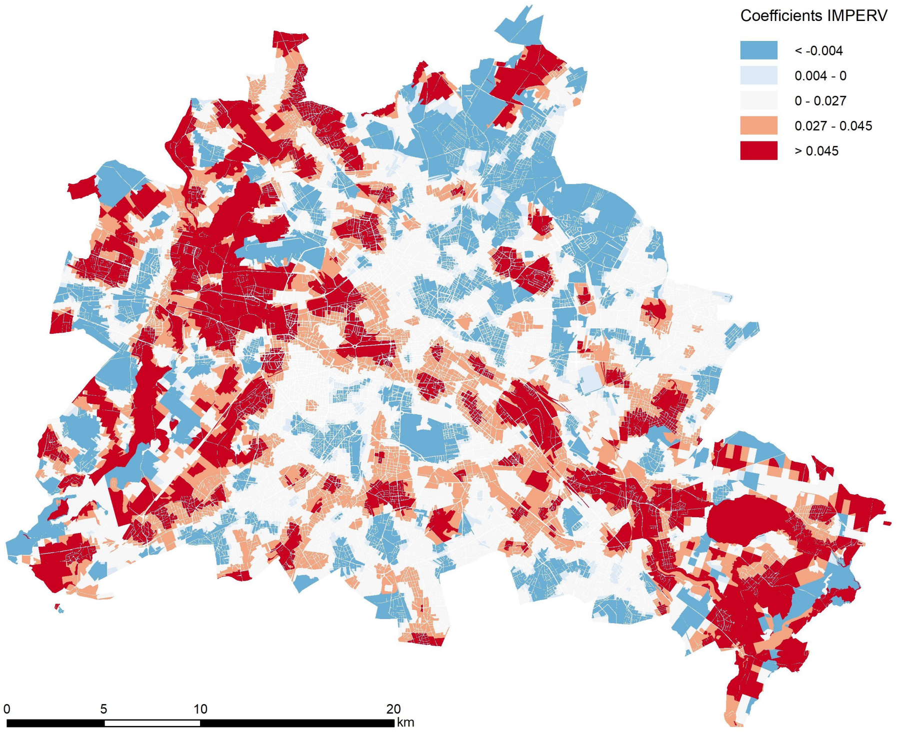


Figure 3.5: Coefficients map for IMPERV.

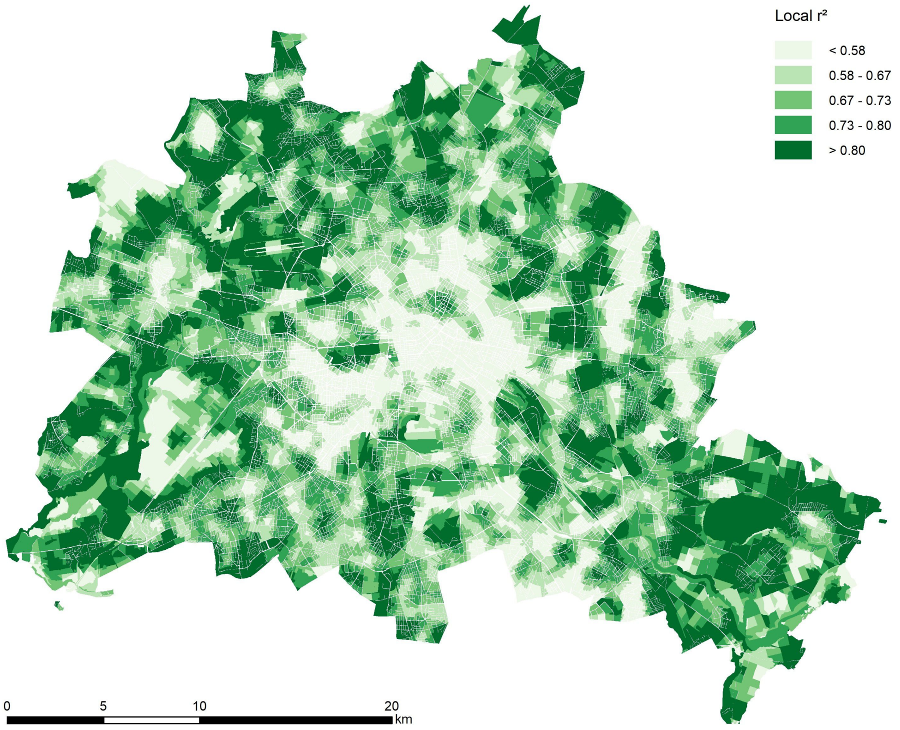


Figure 3.6: Distribution of $r^2$ values.

## 3.3 The Relationship between Heat, Green Provision, and Social Structure - Ruhr Study

Complex challenges arise from the interplay and potential amplification of heat, limited green spaces, and the existence of socially disadvantaged urban residents. Thus, the third study[3] featured here interlinks and analyzes the relationships between heat, green space provision, and social structures. Cities of the Ruhr area in Germany serve as study region (see also Ohlmeyer et al., 2022, with Bottrop as study area in a similar research context). We look at all three two-sided combinations, i.e., heat vs green provision (1), green provision vs social status (2), and heat vs social status (3) in order to determine spatial disparities and potential injustices. Looking at and addressing those connections separately has led to an increase in climate injustices in the past (IPCC, 2022a). Our integrated and comprehensive approach wants to prevent that, as we finally also take an encompassing look at the interplay of all three variables in form of a cluster analysis. The Ruhr region, one of the largest metro areas in Europe and, at the same time, a heterogeneous, polycentric, post-industrial region in an era of structural changes, is an ideal study region for this purpose. Social and economic inequalities arising from the historical evolution from south to north shape the area. The A40 happens to be the equator (Bogumil et al., 2012; Kersting et al., 2009) dividing the whole Ruhr area into a *stronger* south and a *weaker* north. It is important to note here, that the A40 is not a reason for this division but rather a symptom. North of it, is the Emscher zone where the industrial age ended later than in the already widely deindustrialized south. Thus, the south had more time to adjust and to build structures apart from industrial ones (Lengyel et al., 2022; Wehling, 2014). When structural change hit the region, the Emscher, unlike the Hellweg zone in the south, was home to a majority of industrial workers and their families (Kersting et al., 2009). As study cities we therefore chose Bochum, Bottrop, Dortmund, Duisburg, Essen, Gelsenkirchen, Mülheim, and Oberhausen, which are all adjacent to the A40 and partly lie in both described development zones (like Dortmund) or in only one (e.g., Gelsenkirchen only in the north).

The overarching objective of the study described is informing the fight against climate injustices and herewith connected health issues. To achieve that, on the one hand, the UHI distribution must as well be regarded as on the other hand the vegetation cover, in form of highly (multi-)functional and accessible green areas and the social status throughout the study area. Thus, our research questions are the ones listed below and illustrated in Figure 3.7:

RQ 1. What does the relationship between heat and green provision look like?

RQ 2. What does the relationship between green provision and social status look like?

RQ 3. What does the relationship between heat and social status look like?

RQ 4. To what extent are spatial clusters disclosing and depicting similar heat, green supply, and social status conditions in the study area?

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[3] The research summarized in this section is based on:
Klopfer, F. and Pfeiffer, A. (2023). Determining spatial disparities and similarities regarding heat exposure, green provision, and social structure of urban areas - a study on the city district level in the ruhr area, germany. Heliyon, 9(6):e16185. doi: 10.1016/j.heliyon.2023.e16185.

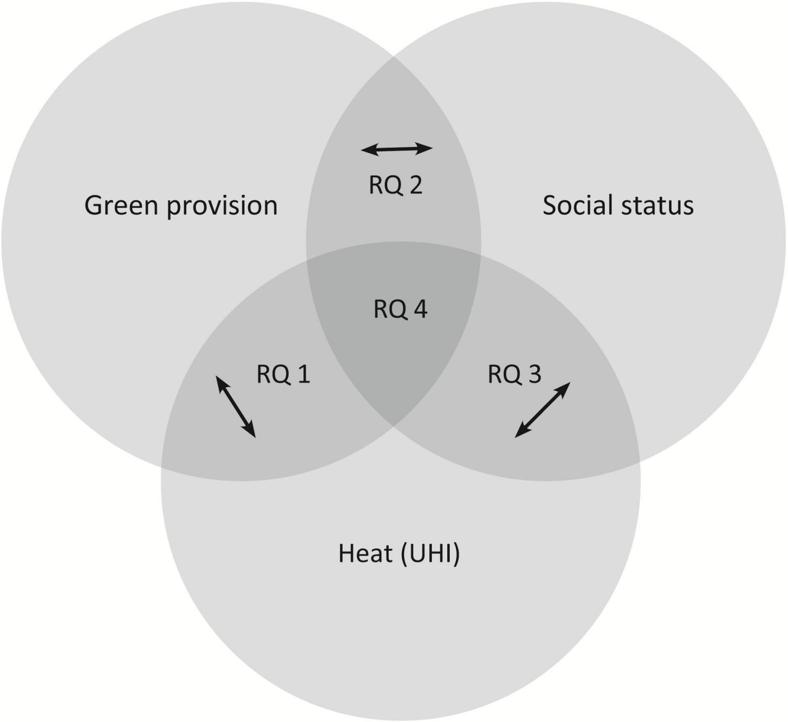

Figure 3.7: Graphical representation of the research questions.

RQ 1 – 3 are dealing with the individual relationships between the factors regarded while RQ 4 builds on them, combining all factors for spatially explicit findings. Again, Landsat 8 derived LST data (30m resolution, USGS, 2022a) is applied as proxy for heat hazard, for green provision, we use NDVI data (also derived from Landsat 8 scenes, USGS, 2022b), and as social factors, indicating a heightened vulnerability, we choose age data (under 6 years and over 65 olds as vulnerable groups), the share of non-German population, and the share of people receiving unemployment benefits (data from the respective city administrations). These social variables are commonly found in existing research (see Chapter 2.3.3).

In a first step, we intend to reduce the social factors to one proxy indicator without losing crucial information. To do so, we check the correlations (Pearson-prerequisites met: metric scale level, normally distributed observations, linear relationship) between all of them. Based on that, we decide for the non-German quota as our single social indicator. It features strong correlations to the social welfare share (SGB II) suggesting a suitable representation of social weakness with also covering probable language barriers. There are also high positive correlations found between the age group of under 6 years olds and the share of non-German population. When looking at the relationship between elderly persons (over 65 years of age) and non-German, correlation coefficients proved to be negative, indicating that a heightened presence of non-German populations does not coincide with higher numbers of older persons in the respective districts. Choosing non-German as single indicator nevertheless is justified by our focus on the links existing between socially deprived populations and LST/NDVI rather than urban dwellers' vulnerabilities generally. Existing research also suggests that, while undoubtedly featuring a higher vulnerability, elderly populations are regularly not characterized by heightened levels of exposure to heat. Appendix Fig. 1 of the article described supports that notion by showing that people over the

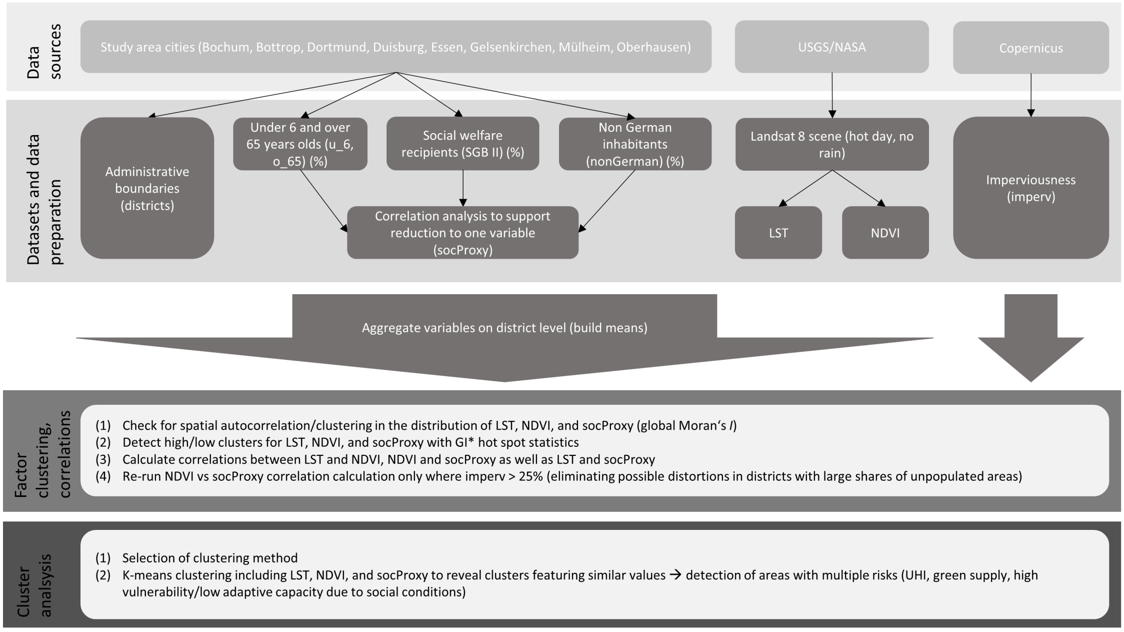

Figure 3.8: Methodological approach.

age of 65 tend to live in generally cooler and greener areas. The correlation approach is favored here over other dimension reduction methods, like PCA, for addressing variables with high intercorrelations because it retains the original variables and simplifies without introducing new constructs. Unlike PCA, which generates new composite variables, correlation analysis preserves one of the original variables as a result, enhancing interpretation and maintaining the connection with the initial dataset.

Next, mean and coefficient of variation (for robustness reasons) are calculated for LST and NDVI in each district. Then, for each city, basic stats are obtained for all three remaining variables (LST, NDVI, non-German as social proxy). These include minimum, maximum, mean, median, and standard deviation. The whole study design and methodology is represented in Figure 3.8.

Furthermore, we run a Global Moran's $I$ and a Gi* calculation to check for the presence of spatial autocorrelation (clustered vs random distribution of values) and clustering of high/low values in the data for each indicator. Following that, we conduct a Pearson correlation analysis for the relationships expressed in RQ 1-3 (heat vs green, green vs social, heat vs social). Finally, the cluster analysis is up. In the two step approach, we first determine the number of clusters via Ward's algorithm (hierarchical cluster analysis) before the k-means cluster analysis follows, aiming at identifying areas with similar characteristics regarding heat, NDVI, and non-German and thus potentially featuring multiple burdens or not. Variables are on the same scale level and the sample size is sufficiently large enabling the application of a cluster analysis.

Regarding the basic descriptive statistics, no peculiarities in the data, such as massive outliers etc., could be discerned. For all three indicators researched, spatial autocorrelation (Moran's $I$ values of 0.6 (LST), 0.5 (NDVI), and 0.47 (non-German)), that means spatial clustering of similar values could be detected. The outcomes of the Gi* furthermore illustrate the presence and the location of high/low value clusters of LST, NDVI, and the share of non-German inhabitants (see Figure 3.9).

The correlation findings suggest a strong negative relationship between LST and NDVI as well as between NDVI and our social proxy with varying intensity from city to city. LST and non-German

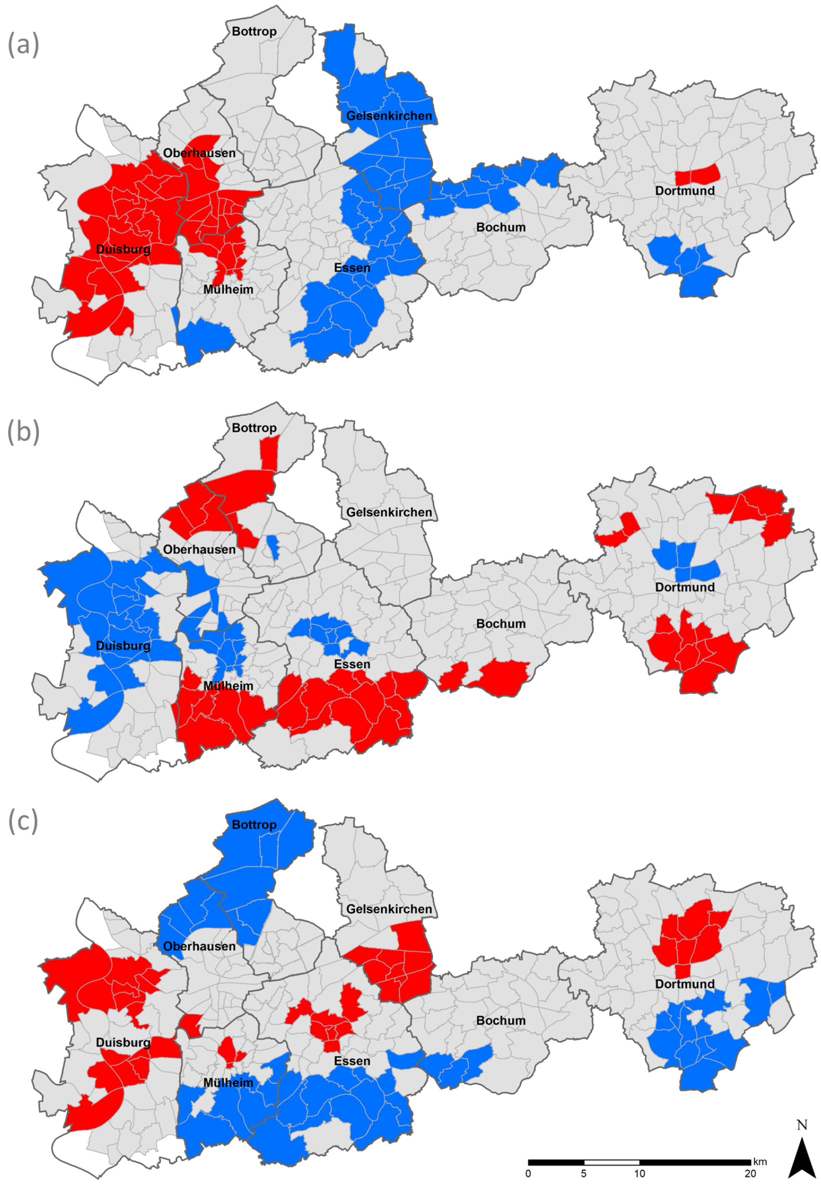

Figure 3.9: Cluster analysis (high-low clusters) with Gi* statistics on the distribution of LST (a), NDVI (b), and the share of non-German inhabitants (c) in the districts of the study area. Red stands for high value clusters, blue for low value clusters.

feature an ambiguous relationship. Correlation coefficients here lie in the range from 0.11 (Bottrop) to 0.6 (Duisburg/Mülheim). Some relationships are not significant (e.g., Bochum) others are on the 0.001 level (e.g., Duisburg). Thus, we can conclude inhomogeneous adverse effects of heat on non-Germans (also indicating lower social status in our case) in our study area. This ambivalent finding is in line with previous studies' conclusions applying similar indicators and finding strong correlations and thus injustices (Dialesandro et al., 2021; Burbidge et al., 2021) or not (Osberghaus and Abeling, 2022; Li, 2021). Finally, the cluster analysis generated six clusters with similar characteristics and pronunciations of our three regarded components.

Here, cluster 1 represents the most unfavorable conditions regarding LST and NDVI (greenery) as well as the highest shares of non-German population indicating environmental injustice and the presence

Table 3.2: Mean factor values within the clusters.

| **Nr.** | **LST** [°C] | **NDVI** | **non-German** [%] | **districts (step 1)** | **districts (step 2)** |
|---|---|---|---|---|---|
| 1 | 30.57 | 0.15 | 47.70 | 30 | 15 |
| 2 | 30.81 | 0.19 | 25.66 | 81 | 54 |
| 3 | 29.68 | 0.24 | 13.11 | 41 | 78 |
| 4 | 26.61 | 0.26 | 21.20 | 60 | 43 |
| 5 | 28.56 | 0.29 | 8.33 | 47 | 69 |
| 6 | 26.03 | 0.35 | 5.75 | 16 | 16 |
| Total | | | | 275 | 275 |

Table 3.3: Population distribution of the clusters.

| **Nr.** | **Number of districts** | **Proportion of residents** [%] | **Number of residents** |
|---|---|---|---|
| 1 | 15 | 6.12 | 170,580 |
| 2 | 54 | 20.89 | 574,079 |
| 3 | 78 | 29.39 | 807,721 |
| 4 | 43 | 19.31 | 530,756 |
| 5 | 69 | 20.73 | 569,889 |
| 6 | 16 | 3.47 | 95,508 |
| Total | 275 | 100 | 2,748,533 |

of large groups that might be more vulnerable to negative influences. On the other hand, low temperatures, high values for green provision, and a low relative presence of non-German people characterize cluster 6. In the end, we can affirm the existence of partially pronounced environmental injustices in the study area cities. When including population numbers, we can also acknowledge that more people live in the unfavorable conditions present in clusters 1 and 2 (ca. 27%) compared to the most favorable conditions in clusters 5 and 6 (ca. 24%). Figure 3.10 illustrates the location and arrangement of the clusters. To examine the clusters and their degree of homogeneity, we calculate standard deviations and variances for the distances to the respective cluster centers for each of the six clusters. Furthermore, we illustrate the distribution of values for LST, NDVI, and the social indicator in the clusters via box plot graph (see Figure 3.11). Here, for example, cluster 1 was found to be rather heterogeneous featuring standard deviations of 8.98% for the non-German indicator, 1.54°C for LST, and 0.04 for NDVI. Other clusters like 3 and 5 are far more homogeneous.

The research conducted here helps administrations responsible for urban planning and climate adaptation in tackling climate injustices in a custom-fit manner. However, for concrete measure planning, detail studies might be a necessity also including further data. Longitudinal studies could also help understanding trends potentially present in the regarded relationships. Yet, we obtained valuable results on a spatial level highly relevant for planning and conversion in urban areas. Three dimensions of segregation are attributed to the Ruhr area: social, demographic, and ethnic, which are a consequence of the history of the region (Kersting et al., 2009; Lengyel et al., 2022; Wehling, 2014). With looking at disparities and co-occurrences of heat and greenery in addition to social aspects, we could add another dimension to the issues arising from the well-known segregation.

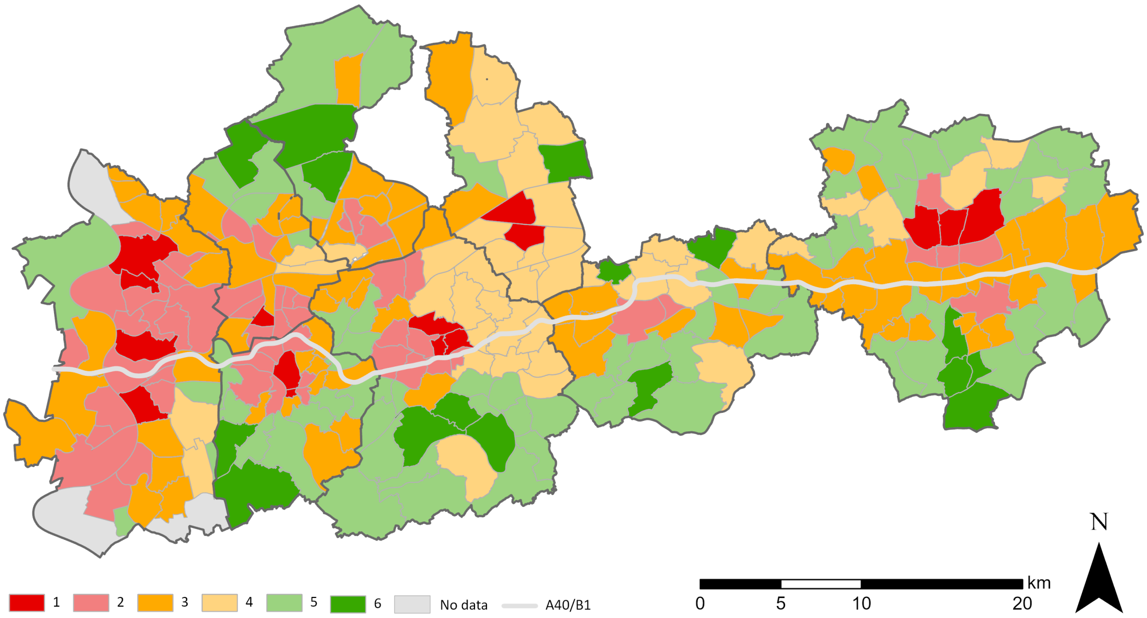

Figure 3.10: Cluster analysis results.

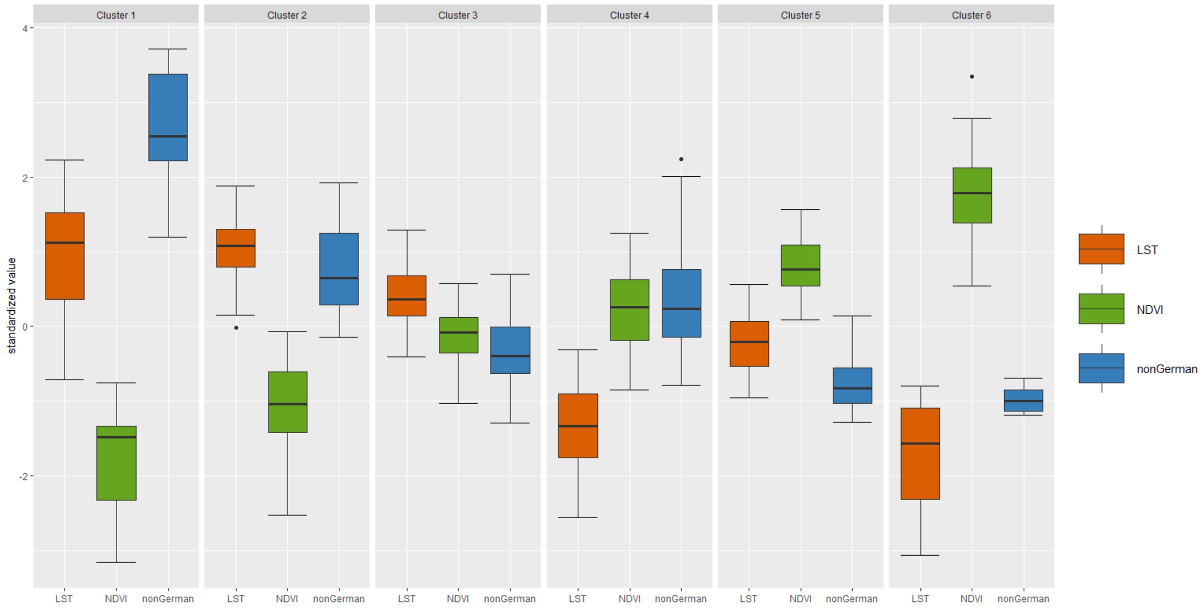

Figure 3.11: Boxplots for the individual clusters.

# Chapter 4

# Limitations of the Research Conducted in the Framework of this Dissertation

It is in the nature of research that it involves deciding on choices and trade-offs, leading to certain limitations. Our research is no exception here. There are shortcomings individual to each contribution featured as well as limitations concerning all three. They are briefly described in the following section.

For literature reviews, a main source of issues is bias, which complicates reproducibility. Findings are subject to minor or major variation resulting from a different set of search keywords or search string creation rationales. Other literature databases, languages, and time frames can also influence the body of literature obtained for analysis. This is as well true for the sections of a publication in which search words/strings need to be present for inclusion. Many options, like title, keywords, abstract, or full text as well as any combination of them, exist here. Detailed documentation and justification of choices made can however ensure a high degree of transparency and also reproducibility. Navigating bias becomes increasingly challenging when making inclusion or exclusion decisions at each individual stage of item reduction, such as title screening, abstract review, and full-text assessment. Furthermore, small adaptations of research focus and thus questions can have a huge influence on the outcome and the conclusions potentially drawn from the research. Overall, the researchers conducting literature reviews with their diverse personalities, experiences, and backgrounds have a huge influence on the setup of the research, the review process, and finally the findings obtained.

Regarding the Berlin study, there are limitations when it comes to the research design as well as the datasets used. Remotely sensed temperatures generally feature uncertainties and are not a perfect substitute for ground measurements representing the felt heat much better. Different LST derivation procedures might furthermore yield different temperature grids/patterns. Refining the results, higher spatial resolution for the LST, NDVI, and also imperviousness data would be necessary. Analyzing what influences the heat in certain USTs might also be enhanced by including more potentially explaining factors and the extension of regarded USTs to non-residential ones. Furthermore, Landsat data stems from the morning hours of the respective recording day, which makes it almost impossible to derive conclusions regarding nighttime UHIs or the UHI pronunciation during the hottest times of the day (late afternoon). Using an aggregation level, like UST patches here, comes also with the so-called modifiable areal unit problem (MAUP - see, e.g., Fotheringham and Wong, 1991). As to the creation of the UST dataset, potential misclassifications have to be kept in mind. Moreover, the application of advanced regression techniques such as mixed Geographically Weighted Regressions (GWRs) as proposed by Comber et al. (2022) and incorporating supplementary statistical analyses to enhance the robustness of the findings can further augment the methodological framework. Additionally, the regression analyses can be strengthened by exploring diverse sets of variables and employing alternative modeling techniques to investigate the target neighborhoods more comprehensively. In any case, the validation of data-driven research, featuring results derived with statistical tools, via ground-truth measurements, and/or on-site field research, including interviews with inhabitants, for example, can be seen as fruitful addition here.

Aggregation level issues are also present in the research executed in the contribution examining the interlinkages between urban heat, urban greenery, and social status. Compared to the application of internally homogeneous UST patches for the urban form paper, using the much coarser level of city districts suggests at least similar potential issues due to this aggregation of data. This is a problem especially for rather heterogeneous districts. Thus, before any adaptation action is taken, more detailed analyses with fine-grained data on a spatially higher resolved level are crucial. Here, as mentioned in the paragraph above, ground-truth data and further investigation approaches can be beneficial. To mitigate the difficulties that might arise from the aggregation using district means, we additionally determine the coefficients of variation for each variable (except for non-German, which is already originally aggregated on the district level) and district. When it comes to data availability, however, desirable datasets, especially regarding socio-economic and socio-demographic factors, for example on health status or income, are widely unavailable. Nevertheless, high-resolution data, also for temperature and greenery, would contribute to possibly more informative and sophisticated results. Another data-related concern, again exhibited also in the Berlin case study, is the combination of datasets stemming from various sources that do not always feature matching spatial and temporal extents. On the methodology side, some of the correlation calculations are based on small $n$ in certain city district, which decreases robustness as sensitivity to outliers is amplified. Moreover, whenever a multitude of potentially influencing factors has to be evaluated, dimension reduction methods such as PCA have to be considered to capture complex data relationships preserving essential patterns and aiding in comprehensibility. Longitudinal studies seem furthermore beneficial here, uncovering trends and extrapolating future developments. Finally, outliers can impair the performance of clustering. Generally, as cluster analyses are merely statistical techniques, further information about the underlying processes and structures are essential for interpretation and the derivation of actionable recommendations.

While for the review, pitfalls are mainly found in the area of comprehensively selecting as well as including and excluding literature, limitations for the other two studies are similar, especially regarding data and aggregation issues.

# Chapter 5

# Discussion of Results and Conclusions

In the following section, the publication-based results are discussed and reconnected to the state of the art, research goals, and research questions in the form of a synoptic integration. The chapter is structured by the four research questions. Subsequently, the contributions to the scientific advance in the research areas touched on are highlighted. Here, the main conclusions and insights gained are furthermore connected and cross links are elaborated. Finally, future research needs and desiderata are identified in Chapter 6.

### RQ 1: What conceptual frameworks for assessing climate change effects in urban areas are found in the scholarly literature and how are they applied and defined?

The literature review (Klopfer et al., 2021) is intended to answer the first RQ posed in the context of this dissertation. Among the concepts applied in relevant studies, vulnerability was found to be dominant, with others, like resilience, risk, or impact being also regularly featured. Generally, mostly concepts prominently highlighted in IPCC publications are also adopted frequently in research (vulnerability being especially omnipresent there). This is supported by the fact that IPCC outputs influenced the definitions of concepts in more than half of our researched literature corpus. The majority of the reviewed literature encompasses applied/case studies while purely conceptual research is scarce. Especially vulnerability is mostly regarded in the framework of vulnerability assessments or the creation of vulnerability indices and is thus integrated from an applied perspective. The lack of conceptual studies attempting to mainstream understandings and use cases is also evident from the fact that various sources (dominance of IPCC) are consulted for definitions. An end or even a mitigation of ambiguities and contradictions in definitional questions is thus not in sight, in particular as the IPCC, notably between AR 4 and 5, changed its own understanding and stance regarding major conceptual frameworks and their relationship to each other contributing to the confusion. The influence of the IPCC is also discernible with respect to publication activity in the field. In the aftermath of IPCC publications, the quantity of relevant scientific output was found to be rising. In general, any new seminal publication, with a potentially changed understanding of concepts, might cause a (somewhat lagged) research activity booster. The much needed clarity, especially on the practical side of climate adaptation, can thus remain in limbo possibly infinitely.

Research on urban climate change is a global phenomenon. However, while, cities in Asia and Africa are frequently case study areas, the scientists conducting the research are predominantly based in Europe or North America. These spatial disparities between research location and researchers might have its foundation in underlying postcolonial tendencies. In the case of Africa, it was found that the amount of "foreign" research is generally particularly high. For instance, in 2018, just under 60% of research conducted on HIV in Africa was done by foreigners (Mawere and van Stam, 2019).

### RQ 2: How and why does the thermal performance differ in various USTs? What role does the urban form/morphology play regarding heat in the city? (case study Berlin)

The study on urban form and its thermal performance in Berlin (Klopfer, 2023) showed that USTs vary mostly significantly regarding their specific temperature patterns. We found various morphological factors (NDVI, imperviousness, building ratio, and building height) making up a UST, to be influential on the LST regime present. The strong correlations between explanatory variables and temperature as well as the complex picture regarding the regression coefficients (GWR) in the different USTs (see Chapter 3.2) allow for a high applicability of the results. The pronunciation of our researched factors (NDVI, imperviousness, etc.) and the changes herein have UST specific influences on heat. For instance, imperviousness having a great influence on LST in some USTs indicates the potential of dampening urban heat in these areas by changing (lowering) the impervious surface area through, e.g., replacing asphalt in courtyards or modifying regular parking lots with more permeable structures. For specific USTs, also "ideal" land use/cover structures can be derived. For example, there might be a building height in perimeter block zones that should not be undershot or exceeded, as that would deteriorate the thermal comfort (i.e., the temperature) of the area. A STURLA based study on Berlin, for instance, found that mid-rise buildings contribute to higher temperatures compared to low and high-rise buildings, which rather function as heat mitigating (Kremer et al., 2018). Considering the particularities of cities across different cultural-genetic urban form types as well as the distinctiveness present within these, it is important to note that individual analyses, adjusted to the specific conditions, are needed for every city and scenario examined. Regardless of that, insights like the ones mentioned before can also help in allocating resources economically as, e.g., at a certain point, more greenery or further changes in the imperviousness might not evoke the significant change effect desired. Money, workforce, and time saved hereby can subsequently be invested in other projects.

### RQ 3: How is the relationship between heat, green provision, and social status in urban areas? (case study Ruhr area)

Heat, green provision, and social status are all exposing individual patterns in the researched study area and the combination of all three does so, too (Klopfer and Pfeiffer, 2023). First, greener areas are generally cooler and vice versa. Second, the analysis of the relationship between green provision and social status exhibited that socially rather deprived population strata live in areas under-supplied with green spaces. Finally, these people also tend to be subject to urban heat effects to a higher degree. However, this last relation is ambiguous. Correlation strength and significances vary from city to city. Subsequently, combining the three aspects, a cluster analysis resulted in six clusters featuring similar properties and being well explainable with background knowledge on the area and its historical development. The cluster analysis revealed that more people in the study area live in unfavorable conditions than in favorable ones (regarding heat and greenery). Thus, the relationship between the analyzed variables indicates environmental (unequal green provision) and climate injustice (unequal heat distribution). With our methodological approach, we could present the issues inherent in the city structure in an illustrative and clear way. The relevance of the problems becomes understandable and can foster much needed debates on urban inequalities. Most important here is the insight that urban inequality regarding socio-economic factors goes along with additional injustices suffered regarding access and proximity to green infrastructures as well as exposure to heat. An urban planning practice that has internalized these connections and co-occurrences can comprehensively address urban grievances in an effective and efficient way rather than dealing with single isolated issues one at a time.

### RQ 4: What implications for science and planning can be drawn from RQ 1-3?

The three scientific contributions featured in the framework of this dissertation can be seen as stages in a three-step process towards enabling comprehensively informed climate mitigation and adaptation executed by administrations and practitioners in urban areas.

First, it is crucial to safeguard that everybody talks about the same and understands concepts and terms the same way when it comes to urban climate change related conceptual frameworks. Unified definitions and consolidated implementation patterns are necessary here for a successful and evidence-based climate change adaptation in cities. On the one hand, this helps practitioners and politics in choosing options, defending them, and talking about them. On the other hand, it fosters scientific advance as comparative studies are facilitated and transferring insights and knowledge would become much easier. Our review goes the first step in this direction by disclosing issues in the status quo. However, one of the conclusions here is that, in the foreseeable future, rather more than less confusion and ambiguity might arise from changed understandings (especially in influential reports and publications) and the unabated surge of publications in the field. Against this background, clarity and unification (to a certain degree) are crucially needed to not endanger progress in climate adaptation by uncertainties and definitional vagueness. Climate adaptation as one of the paramount tasks of our times should not be left lost in translation.

The next stage comprises a thorough investigation of physical conditions in cities that influence heat island occurrences and intensities. Thereby, in a first step, the differentiated impacts that land cover or urban structure types have on the heat pronunciation need to be identified and their relationships described, interpreted, and explained. In a second step, recommendations of action can be derived as to what the climate-resilient urban structure of the future might look like. Most important here is the flexibility and willingness of practitioners and planners to induce change where change is due. Hereby, planning paradigms in the form of traditional building or block types must not hinder adaptation. Whenever, for example, at a specific location, a perimeter block development structure type would be found to increase heat to intolerable levels (according to the specific city's definition or any other legal requirement/guideline) due to its lack of green, its airflow obstructing character, and/or its high impervious surface share, it should be adapted or replaced without all too fiercely clinging to the architectural tradition and planning conventions. Different intensity levels are however recommended considering the individual situation, as historical and architectural heritage should neither be destroyed without proportionality. The best outcome possible might be a symbiosis of retaining traditional structures and a design enhanced by some new features and adjustments. In many cases, like when just a single specific structure, in combination with its building materials, increases the ambient temperature in the direct vicinity, building greenery, green roofs, creating green spaces in the proximity, or the removal of building parts can be sufficient mitigating the heat impact. In other cases, however, when, e.g., a whole neighborhood suffers from excess heat due to a combination of ventilation shortcomings, fast heating surface covers and others more, the whole structure type has to be reconsidered. Taking perimeter blocks as an example again, it might be an option to break up the closed structures to, e.g., create airflow corridors and to connect courtyard greenery to surrounding green infrastructures. Hereby, it is crucial to ensure that potential housing shortages in the respective areas are not aggravated by reducing the number of apartments in buildings subject to adaptation. Naturally, all of this is generally easier to realize at the planning stage of new developments, but should nevertheless also be part of the process in urban renewal activities. The site-specific analysis results in the Berlin study yield a multitude of valuable implications as a starting point for planning and urban design. Our approach enables tailored planning that addresses specific needs by moving away from indiscriminate recommendations for "more green","trees","green roofs" often seen in scattergun approaches. Our analysis empowers decision-makers to come to informed choices, leading to potentially more cost-effective and feasible adaptation solutions. This fosters an economically, ecologically, and socially beneficial paradigm of urban planning, promoting sustainability. The study findings can be seamlessly integrated and implemented within the framework of zoning and master plans, enabling the derivation of specific measures and facilitating regular monitoring of the current state. To date, as demonstrated in the state of the art section, the thermal performance is mostly determined on the basis of land cover/land use typologies. While hereby interesting insights can be gained, most of the results do not have a decisive planning relevance. Thus, the incorporation of USTs and related classification systems (e.g., LCZ or STURLA), in conjunction with a range of geospatial analyses, represents both a valuable spatial level and methodological approach for implementing such measures. Moreover, this approach can be extended and adapted to encompass diverse urban forms in a multitude of cities and regions worldwide. Another potential next step is the expansion of the analysis beyond residential zones and the consideration of social factors. This extension is crucial for developing locally tailored Urban Heat Island strategies that address social thermal injustices, which are often overlooked in existing mitigation planning efforts (Hsu et al., 2021).

As mentioned at the end of the above paragraph, apart from the built structure, the human aspect must be included in the process of creating a future-oriented and climate informed administration and planning practice. Integrating the injustices of heat exposure and green provision in cities into planning helps to determine areas and groups of people that are more vulnerable to adverse heat effects than others. In the third contribution that is part of this dissertation (Klopfer and Pfeiffer, 2023), we researched the complex of relationships between heat, greenery, and social status. The insights gained help localizing necessary measures in order to be beneficial to the public health and to promote environmental/climate justice. Only with the knowledge about "where UHII is strongest and which buildings/neighborhoods are hottest", tailored and human-centered administrative and planning action is possible. We need furthermore information about people affected and how, why, and where that is. While changes in urban morphology patterns can be seen (when implemented in the planning phase) also as part of climate mitigation, research dealing with disparate heat exposure and vulnerabilities is rather exclusively informing adaptation processes. At a broad level, there is a pressing need for efficient and impartial approaches, standardized evaluation instruments, and universally accepted benchmarks. It is crucial to integrate these elements into planning tools such as heat action plans that specifically address climate injustice. To achieve this, e.g., the development of deficit and potential maps, taking into account social perspectives, becomes imperative. By offering a scientific analysis for climate policy decisions and facilitating climate adaptation planning, our work plays a significant role in proactively addressing climate injustice during the early stages of the planning process. This study represents a valuable contribution to the ongoing advancement of procedures and methodologies in the realm of climate adaptation planning, aiming to create resilient, equitable, and healthy cities.

Summing up, particular facets of urban climate change have been addressed by the three contributions featured here. Additionally, the collective of insights in the form of the above-described flexible three-step approach might prove particularly valuable the urban planing processes of the future.

# Chapter 6

# Future Research

Considering the changes and processes addressed in the introductory section of this text and the work presented here, there is still a wide range of topics and directions future research might tackle. Regarding such future research desiderata, there are two ways of connecting to the results and implications presented. First, research is needed that, based on the (isolated) outcomes of the respective papers, expands in the directions outlined and proceeds the (methodological) pathways shown. Second, research is needed that builds on the comprehensive advances all three studies contributed to as a unit, bundling and aligning them to pursue a common compromised direction. Individual future research strands being rather detached from the other studies, however sometimes leading to them, are only exemplarily featured in the following paragraph before comprehensive future work possibilities are highlighted. Some suggestions like the potential of international comparisons will appear multiple times.

In respect to the conceptual frameworks for urban climate change, a unification process needs to be initiated in order to inform future assessments of climate change effects. Taking that as a starting point, one next step can be the characterization of cities to identify the origins for their vulnerabilities or risk for example. Looking at the morphological structure of cities is one beneficial pathway to do so. This was the goal of the Berlin study. Here, the chosen approach including a GWR proved to be meaningful. Future studies examining the influence of urban form on heat exposure might include more explanatory variables and apply further statistical methods to raise the descriptive power of the research. Furthermore, the approach can be transferred to other cities with different historic-genetic urban structure types. Results can also be compared and related to the ones, studies applying, e.g., the concept of LCZ or STURLA, yield. As for the elaboration of planning recommendations, the necessity to integrate factors describing people's vulnerability and to determine who is exposed to heat or green injustice and why leads to the third contribution featured here. Future research building on the determination of the relationships between heat, greenery, and social status again might include more variables and methodological steps. Like the morphology study, comparisons with other population structures in cities around the globe seem promising. Furthermore, detail studies with finer grained data, possibly individually collected, can validate results obtained on a larger level.

Continuous monitoring of the aforementioned relationships is of utmost importance to ensure up-to-date knowledge and to promptly detect any changes that may occur. By actively monitoring these relationships, planners, policymakers, and researchers can stay informed about the dynamics and trends within the studied domains. This monitoring process allows for timely adjustments and interventions, ensuring that urban planning and climate adaptation strategies remain effective and relevant. Furthermore, by closely observing changes, emerging patterns, and potential shifts in the relationships under scrutiny, decision-makers can address new challenges and opportunities in advance whenever they might arise. This proactive approach to monitoring ensures that cities and their inhabitants are better prepared to cope with evolving environmental conditions and make informed decisions for a sustainable and resilient urban development.

Synoptically, for further studies, enhancing robustness, it might be advisable combining multiple Landsat scenes for the LST and NDVI derivation. The Berlin study combined three scenes, however, a more systematic selection of scenes covering multiple years, seasonalities, heat waves and so on might be interesting as it is on the one hand boosting reliability and on the other hand allows for the extraction of more profound information. Generally, nighttime temperatures should be included in following studies. This is mandatory, as nocturnal temperatures during heat waves have a pronounced effect on health (e.g., Laaidi et al., 2012). Urbanization has been found to result in increased night heat stress in the United States, with studies indicating that the UHI effect reaches its peak during nighttime, exhibiting temperature differences of 1.6-4.8°C compared to -0.7-1.4°C for daytime UHI in the respective study areas (Sarangi et al., 2021). Furthermore, hotspot locations differ between day and night regarding the respective land use/cover pattern (Dong et al., 2022). Lately, also the usability of remotely sensed data to inform climate action was questioned demanding the use of air temperature data describing the canopy UHI (CUHI) rather than the satellite derived surface UHI (SUHI). The former being more relevant to public health and the latter overestimating the “real” CUHI (Chakraborty et al., 2022; Venter et al., 2021). Furthermore, as people spend a considerable amount of time indoors, temperatures here are of great importance regarding evaluation of health and comfort impacts. While indoor and outdoor temperatures are found to be closely related, there is an offset of about one day between them, which means that a high air temperature outside manifests itself in a lagged manner in warmer indoor environments (Leichtle et al., 2023).

For both aspects, physical/morphological determinants of urban heat and socio-economic as well as socio-demographic disparities in heat exposure and green provision, in future research, the international perspective can be of great interest. First, cities globally feature very different basic as well as detail structures. The stereotypical cultural-genetic archetype of the US city can be mentioned here exemplarily. Key features of typical US conurbations are the gridiron floor plan, densely built high-rise downtowns, sprawling suburbs, street and car centered development (Bähr and Jürgens, 2005; Hahn, 2014; Heineberg et al., 2017). USTs in the US would thus be very different from the ones in Germany. The thermal performance of these typologies would also be hard to compare to the Berlin/German counterparts. However, comparative studies might reveal structures that are highly climate resilient or temperature dampening in general, potentially also in combination with others. Learning from best practices can thus be enabled. Second, apart from physical urban form, the social fabric is very different around the globe when urban populations are concerned. Looking at the US again here reveals a much more segregated urban community, which is also expressed in climate and environmental injustices. Here, an article revealed uneven distributions of, for example, tree canopies and highly impervious surfaces. According to the said study, Blacks, Asians and Hispanics live in rather unfavorable conditions compared to Whites (Jesdale et al., 2013). Also the persistent effect that historical segregating measures like redlining still have, can be mentioned here (Hoffman et al., 2020; Saverino et al., 2021). Once more, comparing and analyzing similarities and differences in their respective historical and societal embeddedness can help deriving conclusions for current problems and issues.

Studies dealing with other countries and urban cultures might, also from a data perspective, help gaining insights. Here, once again, the US are a good example. Compared to Germany, data availability there is far superior. Highly resolved datasets stemming from the various census surveys are publicly available free of charge. Down to the level of census blocks, data on all kinds of topics like income, ethnic factors, family structures etc. is accessible. On such small scales, much more inferences are possible. Insights gained from studies in regions with better data structures can help designing research also in Germany (or other places with suboptimal data landscapes), as it can be directed in the right direction and data requests can be made targeted and well-founded.

When regarding social aspects in inequalities, a look into further dimensions of segregation might be fruitful. Other than income, ethnicity, or employment status, the relationship and potential connection between higher/lower real estate prices (rental or buying) and higher/lower heat stress has not yet been described. In a conference contribution (Klopfer and Gruehn, 2022), the author presented a preliminary piece of research going in that direction. Regarding the seven largest cities in Germany, correlations between temperature and rent level were conducted. Here, surprisingly, positive relationships could be revealed (hotter neighborhoods are also the more expensive ones). An in-depth analysis for Berlin showed that attractive inner-city areas to-date remain preferred living locations even though they heat up the most. However, this relationship needs to be monitored, as in the future, with more and more heat waves to expect, a shift to negative correlation coefficients and thus negative relationships might be expected. Hereby, also higher resolved data on both the LST (30m at the moment) and the real estate information (currently 1km²) side are desirable. Moreover, various dimensions to look at the mentioned relation might also be fruitful, such as categorizing cities according to their geographical location, their economic affluence, their climate zone, their population and so on.

Furthermore, for more integrated environmental inequality or injustice assessments, further variables have to be included in the process as well. Here, sound data disclosing potential inequalities are thinkable (Trudeau et al., 2023) as well as the intensively researched air pollution components (see, e.g., Jennings et al., 2021; Clark et al., 2014). The more factors in multi-burden analyses are described and operationalized, the easier comprehensive all-encompassing adaptation action is made. Administrations can thus, hypothetically, imply measures that are not only enhancing the thermal comfort of a certain area and potentially simultaneously worsen sound exposure. They are rather enabled to achieve ameliorations throughout a wide range of aspects getting closer to the goal of an entirely livable and healthy city of the future defying the multitude of actual changes and transformations yet to come. Zooming away from rather practical and application-driven considerations, the construct of spatial justice or injustice regarding the set of factors dealt with in this dissertation has to be subject of research activity in the future. Besides varying understandings of justice, the important planning theory question whether spatial planning as such can and should be just (see the following seminal publications as possible entry points to the discussion Davy, 2009; Harvey, 2010) as, e.g., established as a fundamental principle in the German Federal Building Code, or whether it cannot be just or should even be unjust, might also be part of upcoming discussions.

Finally, transdisciplinary approaches play an increasingly pivotal role in science in general and in spatial planning research in particular. Transcending discipline boundaries and trying to generate comprehensive frameworks encompassing multiple knowledge systems is especially benefitial in complex urban planning processes where people from many different backgrounds regularly come together. For example, in the joint research project DAZWISCHEN (Klopfer et al., 2022; Greiving et al., 2022) that the author's organization is participating in, amongst others, urban planners, architects, sociologists, and landscape ecologists are involved as well as practitioners from various administration levels (city and county level, ZRR (Rhenish Mining Region Agency for the Future)). The work on challenging multifaceted planning processes, like managing the manifold structural changes after the coal phase-out in the Rhineland as in DAZWISCHEN, can greatly profit when adopting transdisciplinary approaches, which enhance the prospects of success. Also urban climate change research, as featured in the dissertation at hand, might benefit following such approaches. In this context, the involvement of laypersons in participation processes or as part of citizen science/citizens as sensors approaches as well as bringing together science and administrations at various stages in the respective planning processes are thinkable and potentially fruitful.

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# Part II

# Publications

# Article 1: Key facts and author contributions

| | |
|---|---|
| **Reference** | Klopfer, F., Westerholt, R., and Gruehn, D. (2021). Conceptual frameworks for assessing climate change effects on urban areas: A scoping review. *Sustainability*, 13(19):10794. doi: 10.3390/su131910794 |
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**Signature:**

Florian Klopfer

Date

sustainability

Review

# Conceptual Frameworks for Assessing Climate Change Effects on Urban Areas: A Scoping Review

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**Abstract:** Urban areas are amongst the most adversely affected regions by current and future climate change effects. One issue when it comes to measuring, for example, impacts, vulnerabilities, and resilience in preparation of adaptation action is the abundance of conceptual frameworks and associated definitions. Frequently, those definitions contradict each other and shift over time. Prominently, in the transition from the IPCC AR (International Panel on Climate Change Assessment Report) 4 to the IPCC AR 5, a number of conceptual understandings have changed. By integrating common concepts, the literature review presented intends to thoroughly investigate frameworks applied to assess climate change effects on urban areas, creating an evidence base for research and politically relevant adaptation. Thereby, questions concerning the temporal development of publication activity, the geographical scopes of studies and authors, and the dominant concepts as applied in the studies are addressed. A total of 50 publications is identified following screening titles, abstracts, and full texts successively based on inclusion and exclusion criteria. Major findings derived from our literature corpus include a recently rising trend in the number of publications, a focus on Chinese cities, an imbalance in favor of authors from Europe and North America, a dominance of the concept of vulnerability, and a strong influence of the IPCC publications. However, confusion regarding various understandings remains. Future research should focus on mainstreaming and unifying conceptual frameworks and definitions as well as on conducting comparative studies.

**Keywords:** climate change adaptation; systematic literature review; urban climate; vulnerability assessment

**Citation:** Klopfer, F.; Westerholt, R.; Gruehn, D. Conceptual Frameworks for Assessing Climate Change Effects on Urban Areas: A Scoping Review. *Sustainability* **2021**, *13*, 10794. https://doi.org/10.3390/su131910794

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## 1. Introduction

Climate change is one of the most pertinent global issues to threaten urban areas. In 2019, about 4.3 billion people, and thus more than 56% of the global population, were living in urban environments. For high-income countries, this share is as high as 81%, while for low-income countries, it is still at about 33%. Population growth rates of already urbanized high-income countries are low and at only 0.7% on average, but low-income countries are still growing considerably by 4% per annum [1]. For 2050, estimates show a global urbanization rate of 68.4% [2]. This increase in urban population will promote climate change, and cities with their concentration of inhabitants in addition contribute to a higher degree to the global greenhouse gas (GHG) emissions through their concentration of economic activities compared to rural areas. With about 75% of the global population—including some of the largest cities—being located in low and middle-income countries, climate change will thus become a considerable threat, especially for vulnerable urban communities in the Global South. The Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR) 5, therefore, has concluded a concentration of key and emerging climate risks, especially in urban areas. Conurbations hence need to accelerate their efforts towards climate change adaptation in order to increase their resilience [3,4]. There is no universal understanding of what makes a settlement an urban area. Especially finding a suitable categorization for smaller communities is often difficult [3]. The aim of what follows in this article is to review literature from several national backgrounds. We, therefore, follow the UN understanding of *urban*, meaning that we apply the respective definitions that are used in the countries considered [2]. This kind of approach is often applied in studies with an international outlook. The angle of the present review is hence a broad one covering a range of different types of urban areas.

Numerous definitions, concepts, and ideas have been proposed and applied in the context of assessing climate change effects on urban areas. These concepts and ideas define both universes of discourse and analytical frameworks. However, for terms such as vulnerability, impact, hazard, risk, or resilience, an abundance of definitions and understandings exist, some of which contradict each other ([5–7]—specifically regarding vulnerability; [8]—for adaptation; [9]—for adaptive capacity). Furthermore, concepts and their understandings change over time. Notably, from the IPCC AR 4 to the AR 5, a significant transition took place regarding a variety of definitions and concepts (see also Figure 1). The IPCC went from a vulnerability (AR 4) to a risk-based (AR 5) conception of climate change adaptation. Hereby, it also harmonized the climate change adaptation community with neighboring disciplines, such as disaster risk management [10]. On the one hand, the IPCC AR 4 [11], as well as the IPCC TAR [12] feature a vulnerability approach. Vulnerability thereby represents the outcome of an assessment of the exposure to climate change, the sensitivity of a system, subsequent impacts, and the adaptive capacity of the system to these impacts (see also [13]). Vulnerability can thus be understood as a function of exposition towards a climate signal, sensitivity towards the signal, and the adaptive capacity of the system. On the other hand, the 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) [14] and the AR 5 [15] changed to a risk-based approach. There is now a clear distinction between vulnerability and risk [6]. Vulnerability is understood as a component of the risk of an exposed system [15]. The vulnerability of a system or a society is different from the impact on a system (e.g., temperature rise). For an adequate adaptation, parallel consideration of changes in climate and changes in society is necessary [6]. Risk can be seen as a function of hazard, exposure, and vulnerability. However, the dynamic conceptual diversity outlined above highlights the need for an overview of conceptual understandings for future comparative studies.

Ongoing shifts in conceptual understandings require a comprehensive overview of how climate change effects have been assessed. Preconditions for adaptation and prerequisites for adaption action are built regarding vulnerability and risk as well as studying or assessing adaptive capacity and many more (see, e.g., [16] for vulnerability assessments as a determinant of what and how to adapt; [9] for adaptive capacity). Tonmoy et al. [17] found that regarding climate change vulnerability assessments, the literature originates from a variety of research areas, such as risk assessment, natural disaster management, and urban planning. That makes it challenging to obtain the main directions and key methods in this area. Berrang-Ford et al. [18] also stated that recent controversy has brought up calls for more standardization and transparency in the methodologies applied to unify climate change research. They furthermore ask for a vigorous conceptual and methodological development of systematic review approaches tackling methodological challenges, such as unifying and monitoring climate change adaptation.

The systematic literature review that follows offers a comprehensive overview of frameworks that are used to assess the effects that climate change has on urban areas. The term ‘framework’ as it is used in the remainder of this article thereby describes top-level systems of sub-concepts including vulnerability, risk, or sensitivity that are used in climate change research. In addition, we have chosen to focus on ‘urban’ because we argue that climate change-related research faces different problems in urban areas than in rural areas and that these challenges also play out in different ways at the conceptual level. We thereby follow the arguments of researchers who propose an explicitly urban adaptation of concepts, such as vulnerability and resilience and suggest a systemic and conceptual difference between urban and other areas when it comes to climate change impacts [19,20]. Our goal is to provide a holistic picture instead of focusing only on a few selected concepts or applied fields. We thus investigate the status quo of top-level frameworks applied and reveal trends, inconsistencies, and potential conceptual conflicts. Thereby, we hope to present useful information for both researchers and practitioners in the field alike. It is of note that we do not intend to propose or promote a 'good' framework in an evaluative sense or guidelines for what shall be done and what frameworks and methods practitioners should apply. We rather intend to raise awareness for possible issues and thus to aid future climate change-related research and practice.

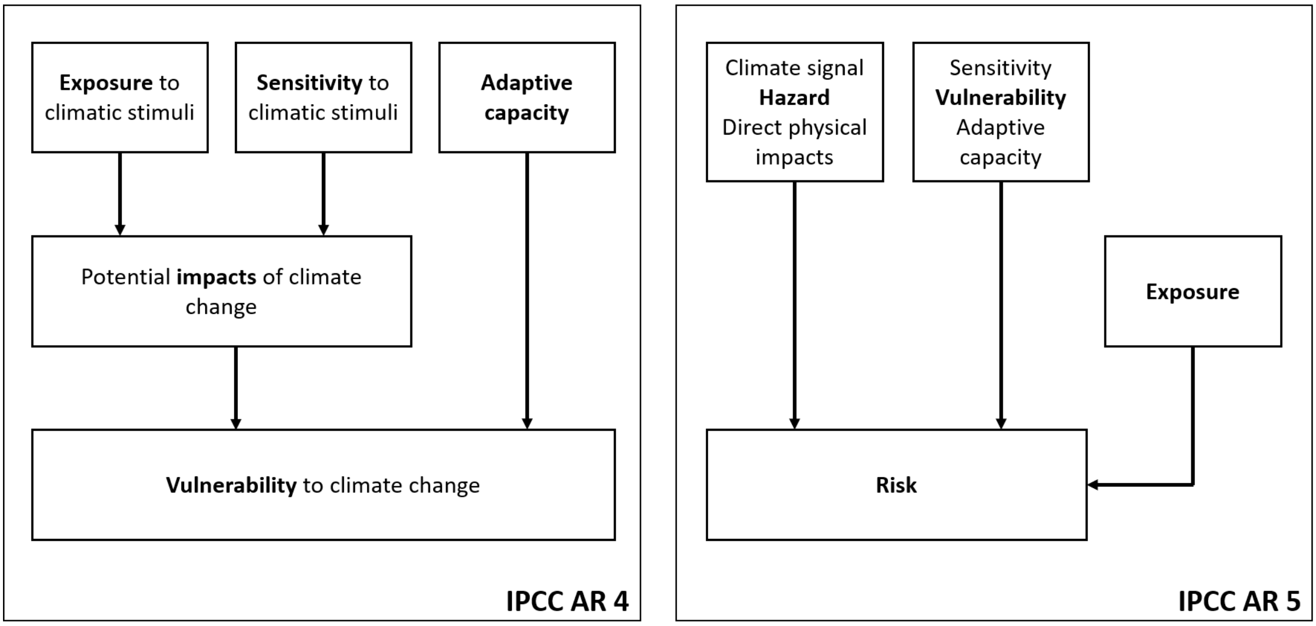

**Figure 1.** Comparison of the AR 4 and AR 5 IPCC risk and vulnerability concept (based on [11,13,15,21]).

Only a limited number of systematic and non-systematic reviews have been undertaken on conceptual frameworks applied to assess climate change effects in urban areas. Our literature review is guided by the following overarching research question:

What conceptual frameworks for assessing climate change effects in urban areas are applied in the scholarly literature?

The literature to be researched in order to address this broad question is narrowed down by applying a number of exclusion and inclusion criteria (see Section 3), such as limiting publication dates to 2014 until today. In addition, several subordinate questions are intended to make answering the broad guiding question more manageable by highlighting specific aspects in each case. These sub-questions are:

RQ 1: Are there trends regarding the publication activity concerning relevant studies in the considered time period, and how can disclosed characteristics be explained?
RQ 2: What are the geographical scopes of respective studies, and where are the authors located?
RQ 3: What study types dominate—case studies or conceptual/theoretical works, quantitative or qualitative analyses, and what target audiences are focused on by the reviewed studies?
RQ 4: What climate change-related conceptual frameworks do authors refer to, and how are they defined?

The remainder of the article is structured as follows. Section 2 presents the state-of-the-art regarding literature reviews touching upon the topic of the review. Section 3 introduces the methodology applied before Section 4 features the results generated from the review and discusses them, while Sections 5 and 6 conclude the paper.

## 2. Reviews in Climate Change Adaptation Related Research

Being applied predominantly in health-related sciences, Berrang-Ford et al. [18], in their review of reviews, showed that the numbers of systematic reviews are on the rise as well in climate change adaptation research. Siders [9] stated that as systematic literature reviews offer objective criteria and transparency, they are useful, especially in climate adaptation, to synthesize results and identify gaps. Possible methods mentioned hereby are qualitative content analysis, bibliometric analysis, and citation network analysis.

Climate change-related literature reviews exist on diverse topics, such as climate change vulnerability assessment in India [22], climate change adaptation, and water resource management [23], or the threatening of cultural heritage resources by climate change [24]. Hafezi et al. [25] did a review on climate change adaptation and the impact on policies (methods/tools applied) in coastal areas and on small islands, respectively. Within their research concerning a systems' network approach for climate change vulnerability assessment, Debortoli et al. [26] also conducted a systematic literature review. Hereby they searched for climate change vulnerability case studies set in the Canadian Arctic in order to select index variables and understand their relationships. Bibliometric analyses of climate change vulnerability assessments were done by DiMatteo et al. [16] and Zhang et al. [27]. Biesbroek et al. [8] intended to systematically capture and assess "the current state of larger-n ($n \geq 20$ cases) comparative adaptation policy literature"(p. 1). Berrang-Ford et al. [18], as touched on above, conducted a review of reviews related to climate change adaptation research. They furthermore introduced guidelines on how to do a systematic review in that field.

When it comes to urban areas and cities, only review studies dealing with particular, relatively narrow issues, such as the impact of urbanization and climate change on urban temperatures [28], urban flooding, and urban water quality [29], or the planning and design of urban drainage systems [30], are found. Hunt and Watkiss, in 2011, also found a majority of single-issue studies in their review, with sea-level rise being the most common [31]. Dhar Khirfan et al. [32] investigated "the extent and the nature of how the urban planning literature has addressed climate change adaptation"(p. 602). They, therefore, reviewed a predefined set of relevant journals.

The aforementioned review by Hunt and Watkiss [31] is titled *Climate change impacts and adaptation in cities: a review of the literature*. However, their primary goal was to identify "the state-of-the-art in the quantification and valuation of climate risks at the city-scale" (p. 13). Hereby, they focused on determining what specific sectors of an urban area are most at risk. Furthermore, their selection and analyses of studies were neither systematic nor exhaustive and focused on major world cities [31]. Thus, to our knowledge, as far as urban areas and cities are concerned, there is no (systematic) literature review assessing how a comprehensive evidence base for adaptation is created apart from the review incorporated in IPCC AR 5 [3].

## 3. Methodology

Systematic literature reviews are used to evaluate and interpret corpora of existing literature, for instance, regarding some specific research question or to summarize a field of research [33]. This is done by applying a methodology that ensures transparency and reproducibility [18]. Thus, systematic literature reviews have some important advantages over *traditional* narrative/meta-analytical assessments. Systematic reviews allow for the thorough determination of general aspects of studies, such as number, type, or geographical aspects. Especially for interdisciplinary research with related literature featuring both quantitative and qualitative methods, this approach is well-suited [34]; for an extensive compilation of motivations, see also [35]. Regarding systematic reviews, there is no *one size fits all*. Even though established guidelines exist, these, at the same time, need to be flexible and adjustable regarding specific cases [18]. We leaned our approach on the well-established PRISMA framework [36] and also embraced the components proposed by Berrang-Ford et al. [18] for reviews in the field of climate change adaptation. We furthermore considered the key components requested by the ROSES reporting guidance that was explicitly developed for environmental systematic reviews and maps [37].

### 3.1. Keywords and Databases

The goal of the present review is to establish a broad understanding of the conceptual frameworks that have been applied to assess climate change effects in urban areas. Therefore, we needed to take a broad perspective. The following Table 1 below gives the keywords that were applied in our review. The keywords presented were the result of a first screening of the literature that was relevant to the topic with respect to the terms included in the IPCC frameworks (see Figure 1), as well as an iterative expansion of the initial set of keywords.

**Table 1.** Lookup table for the search string creation.

| Sub-Topics | Climate AND | Change AND | Climate Change Effect Related Component AND | Assessment Component AND | Urban Component |
|---|---|---|---|---|---|
| **keywords** | climat * | chang * | vulnerab * OR risk * OR hazard * OR disaster * OR resilien * OR adapt * OR mitigate * OR expos * OR sensitive * OR impact * OR suscept * OR influenc * OR evidenc * OR effect * OR indicator * OR conceptual framework * | assess * OR evaluat * OR rat * OR estimate * OR measure * OR indicat * OR descry * OR identif * OR analy * OR scan * OR quantif * OR scenario * OR map * OR method * OR approach * OR plan * OR manag * OR index OR indices OR concept * OR strateg * | cit * OR urban * OR settlement * OR communit * |

When relevant but yet absent keywords appeared recurrent in titles, keywords, and abstracts of the abovementioned literature corpus resulting from the first screening based on IPCC terms, they were added to the list. The same was done when, for example, at the stage of abstract screening, a new keyword was found to recur and to be a key component of research relevant to the review. Thus, the compilation is insofar dynamic at the initial stages of the review as newly identified keywords were included and additionally retrieved literature was integrated into the process. All previously done research steps were then repeated with the new terms that came up. All keywords are to be understood including the respective inflections (e.g., number or case) indicated here by an asterisk (*). The table at hand is arranged in such a way that for each *sub-topic* category of the review, there is a list of synonyms or related terms. For the actual search, at least one keyword from each sub-topic was required (AND), while we allowed for flexibility within the sub-topics (OR). The arrangement of the keywords (Table 1) is a breakdown of the overarching research question, as it comprises components covering climate change, climate change effects, assessment, and urban context. Examples of a query string would thus be *climate change vulnerability evaluation urban* or *climate change resilience analysis cities* (without considering database characteristics and specifications). A total of 1344 search operations was conducted.).

For the following literature corpus collation, the well-established and often employed databases Scopus and Web of Science (WoS) were considered as they constitute the major general-purpose scientific databases (together with Google Scholar) [38] (except for specialized topics for which specialist databases may be preferred). Scopus and Web of Science offer a variety of detailed search options (for instance, Boolean operators and wildcards), cover a wide range of publication types (including journal articles, several book chapters, and major conference proceedings), cover most relevant disciplines, often feature abstracts, and provide functions for the fast and direct integration of bibliographic information into literature management software. Google Scholar was not considered because it does not offer comparable advanced search options and does not allow for sufficiently complex search strings [39]. We applied all components of the query strings to the title of candidate publications. For the urban component (e.g., *cit *, urb **), the abstract and keywords were also scanned as titles tend to be less specific about the respective research settings. Additionally, many studies also name a specific city in their title rather than mentioning terms such as *city*, *cities*, or *urban areas* (see, e.g., [40]). Pre-testing considering all search terms in title, abstract, and keywords led to more than 100,000 retrieved documents (Scopus) meeting the search criteria. This abundance of texts cannot be processed thoroughly in an appropriate time and with reasonable effort. Further steps were therefore undertaken to narrow down the literature corpus further.

### *3.2. Language and Temporal Scope*

We restricted the reviewed literature to English language works published from 2014 onwards. The context of our review is an international one, and we expected the bulk of relevant manuscripts to be available in English. Further, since the IPCC AR 5 was issued in 2014 with the abovementioned profound changes in understanding regarding a variety of climate change-related concepts, we did not look further into the past than that year. This approach is in analogy to Dhar and Khirfan [32], who also chose the year of an IPCC report's publication (2001, third assessment report) as a timely constraint for their review. As mentioned above, the report introduces an updated understanding of vulnerability respectively of how the concepts of vulnerability, exposure, and hazards make up risk [15]. This new interpretation/approach has had a big impact on studies on climate change vulnerability and related concepts. Some researchers adopted the new understandings for their conceptual framework [41], others still apply the older IPCC approach [42]. However, the IPCC is considered the "main scientific organization that leads on climate change" [10] (p. 2). Its concept thus marks the start of a new phase of climate change research. Furthermore, the IPCC report provides both a review of relevant literature to date related to climate change adaptation in general and in urban environments, especially [3,15]. After using these very general criteria, the title, abstract, and full-text screening was carried out in order to select appropriate literatures by applying further inclusion and exclusion criteria.

### *3.3. Record Identification and Screening*

The initial search was conducted in April 2020, with updates done in August and December of the same year. After removing duplicates, a total of 2433 documents was found and organized in the reference management software Citavi.

The first screening step consisted of scanning the titles (see Figure 2 for the entire process). Thereby, documents were considered ineligible when they met at least one of the following exclusion criteria:

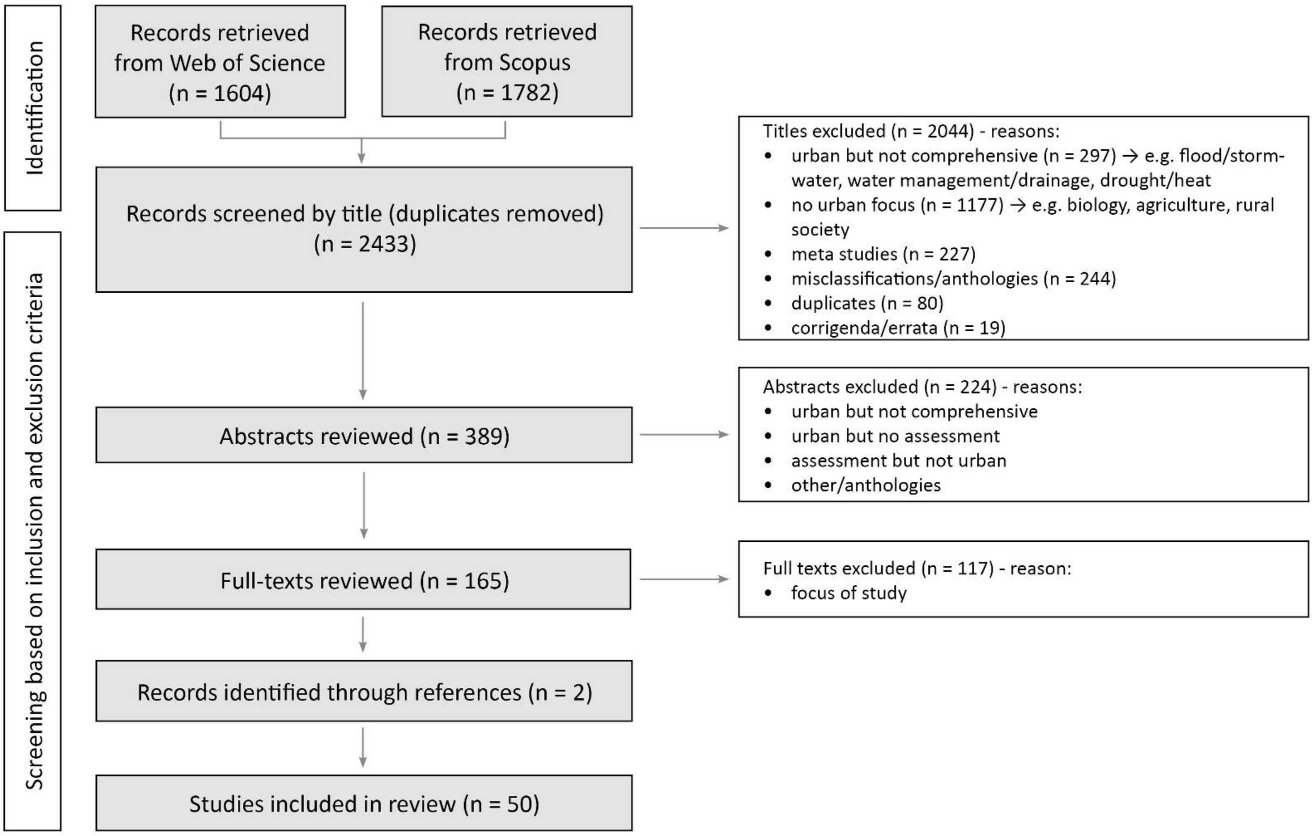

**Figure 2.** Flow diagram for the different phases of the review process; structure based on Moher et al. [36].

First, there were publications that, although looking at cities/urban areas, did not substantially deal with comprehensive evidence base assessments in urban surroundings ($n$ = 297). We are not aiming for a narrow special topic or discipline review approach but rather want to examine frameworks considering urban areas and the climate change effects on them as a whole. Including all studies dealing with the large mass of specific climate change effects, their assessment, and the underlying frameworks led to an unmanageable abundance of literature. Furthermore, it required handling a number of very discipline-specific approaches and technical details. Finally, comprehensive elaborations on conceptual frameworks, such as vulnerability, etc., were not regularly addressed in such studies. Thus, for example, studies dealing with the vulnerability of a specific animal species in an urban context or flooding impacts only were discarded. Flood/stormwater ($n$ = 64) or water management/drainage topics ($n$ = 67) were the most common specializations here. Examples for the flood/stormwater category are Lyle and Mills [43] and Moore et al. [44]. The water management/drainage fraction contained, e.g., Bai et al. [45] and Feilberg and Mark [46]. Other non-comprehensive city studies were, for example, Garcia Sanchez et al. [47] or Rome et al. [48].

Second, there was a large number ($n$ = 1177) of studies dealing with issues located in non-urban areas and often regarding phenomena from a mono-disciplinary perspective, such as biology or political science. The respective category comprised the following subcategories:

- biology, chemistry, ecology: studies focusing on, e.g., flora, fauna, water chemistry, ecosystem services (e.g., [49,50])
- agriculture, forestry, fishery: focus on, e.g., forest management, farmers, yield (e.g., [51,52])

- geomorphology, soil topics, fluvial processes, landscape structure: dealing with, e.g., classical physical geography, coastal change, groundwater, water resources, flood, land cover (e.g., [53])
- (rural) society, villages, human issues, health: focusing on the social science component with, e.g., community studies, coping strategies, social groups (e.g., [54,55])
- politics, organizations, infrastructure, economy, etc.: concentrating on, e.g., political science, governance, management approaches, strategies, planning (e.g., [56])

Third, studies considered as *meta-studies* were discarded (*n* = 227). These publications did not primarily focus on climate change-related issues but rather on side effects, interrelations, or took climate change merely as a setting for other kinds of research (e.g., [57,58].

Fourth, misclassifications, as well as anthologies, were omitted. Sometimes, contributions included in anthologies have separately been published as conference papers, which technically leads to duplicates that we excluded (*n* = 244). Misclassifications sometimes happen with the search algorithm of the database searches (e.g., missing keywords in the title). Furthermore, for example, the fictive title "changing fir growth patterns in boreal climate" meets the criteria that *climate* and *change* have to be found in the publication title. However, the study does not deal with climate change but rather changing patterns of fir growth in the boreal climate zone due to unknown reasons

Fifth, 80 duplicates that Citavi did not detect were excluded alongside corrigenda, errata, and extremely short (and thus uninformative) works (*n* = 19). However, works that apparently covered topics such as vulnerability assessment to climate change in general or for a larger region were also considered for the next screening step as they might contain a significant part on urban environments as well. Generally, whenever it was not possible to undoubtedly sort a study out, it was taken to the following screening phase in order not to lose possibly relevant information.

The next step was to screen the abstracts. Thereby, the evaluation of eligibility criteria was more detailed and laborious. Studies located in urban contexts lacking a comprehensive approach (see title check–aiming for holistic studies) (e.g., [59]) were excluded (*n* = 47). Another 70 publications were sorted in the category *urban, no assessment*, which comprised works, for example, only describing and evaluating adaptation strategies (see, e.g., [60]) and thus featured no assessment component. A total of 52 elements were identified as not being focused on urban areas, and another 55 were discarded for other reasons (containing some anthologies again). These included analogous to the title screening stage, meta-studies such as a review on methodologies for mitigation action evaluation [61], a study on public policy processes in a rural area [62], or a paper evaluating hazard mitigation plans [63]. After checking the abstracts, the full texts of the remaining articles were retrieved (*n* = 165). A total of 48 items were ultimately considered eligible for the review. The other publications (*n* = 117) had an emphasis beyond the scope of the review [64,65] or were not focusing concisely enough on urban areas [66,67]. Literature sections of the eligible full texts were searched for further titles that so far, were not included in the review. Here, two papers were identified. Thus, the final number of publications included for the review was 50. These studies were read and analyzed against the background of the research questions introduced above. Hereby, mainly quantitative analyses in form of descriptive statistics were applied. For answering the questions regarding the main climate change-related concepts and their respective definitions, the qualitative information extracted from the texts was also presented in a quantified form.

### *3.4. Limitations*

Naturally, the methodology applied comes with limitations, and some decisions and approaches are justifiably prone to criticism. Most threats to validity and reliability in systematic reviews arise from bias [35]. To achieve the goal described here, other researchers might have come up with different research questions and other search keywords being searched in alternative databases or languages other than English. Additionally, other time constraints and rationales for applying them are imaginable. The abovementioned search of all keywords in abstracts that leads to an unmanageable amount of literature to review would also possibly yield more research relevant to the topic. This is also true for varying definitions of *urban* or *urban areas*. However, as mentioned above, the process of a systematic literature review allows for a high degree of transparency, reproducibility, and thus comprehension. This is also basically valid for the decisions on whether to include or exclude publications at the respective review stages. That being said, the review at hand offers a systematic overview following previously described traceable steps.

## 4. Results and Discussion

The following section highlights, discusses, and interprets the findings from the analysis of the eligible set of publications guided by the research questions asked.

**RQ 1: Are there trends regarding the publication activity concerning relevant studies in the considered time period, and how can disclosed characteristics be explained?**

The timely distribution of the studies is shown in Figure 3. Starting with 2017, there was a trend upwards regarding the number of works published per year, with an overall peak in 2020 ($n = 11$). The 2021 number was low as the last database search was done in December of 2020, thus only including some publications that date from 2021. Possible reasons for the distribution, albeit based on relatively small numbers, might be found in the publication dates of IPCC reports in 2014 and 2018 [15,68]. These reports could have caused and/or influenced the rising numbers after 2014 and the trend starting in 2017.

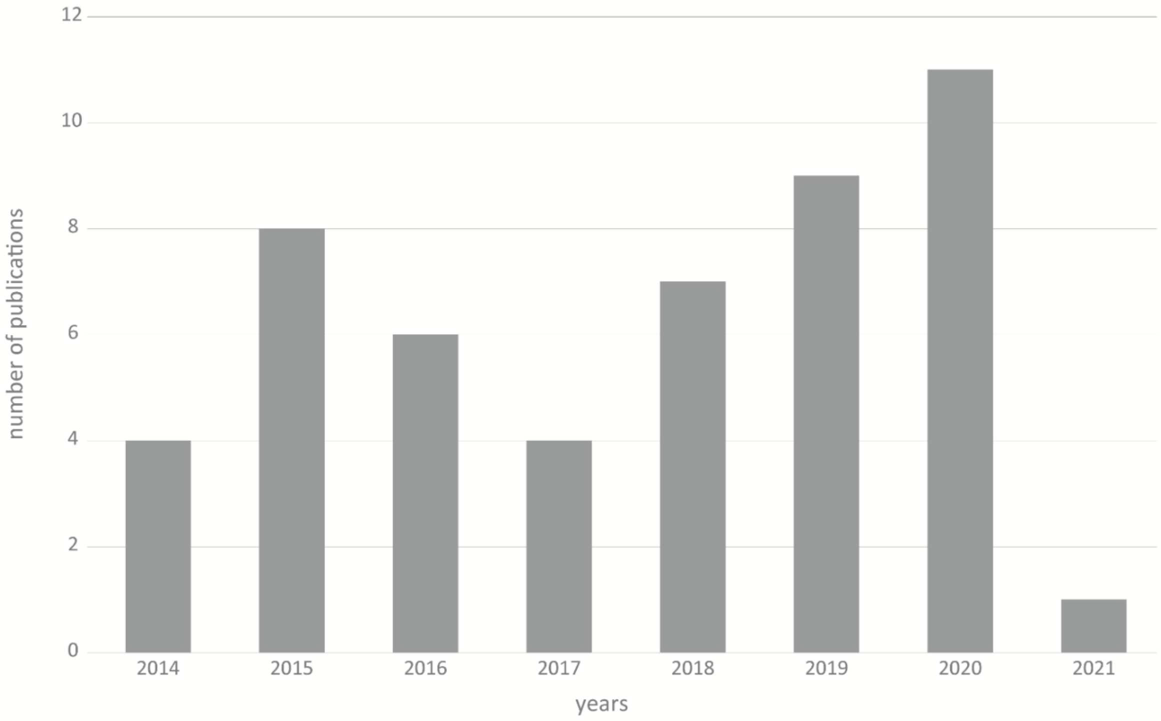

**Figure 3.** Reviewed publications per year. For 2021, the number is incomplete as only some publications assigned to journal issues of that year were found at the end of 2020.

A generally upward tendency was highlighted in existing climate change-related reviews. For the time between 1980 and 2014, Haunschild et al. [69] observed a strongly pronounced overall growth regarding climate change research and also a growth in involved disciplines and subfields, such as adaptation, vulnerability, and impacts. Regarding climate change vulnerability assessment studies, a strong rise in publications between 2006 and 2016 [16], respectively, 2000 and 2011 was observed [17]. Zhang et al. detected a rise in vulnerability assessments in the context of climate change after IPCC 2001, especially between 2005 and 2017 [27]. Siders described a rapid growth in adaptive capacity research starting around 2001 with IPCC TAR [9]. An ascending trend, especially between 2007 and 2016, was also found in research concerning adaptation in the coastal zone respectively on small islands, possibly triggered by the IPCC AR 5′s call for adaptation planning future scenario development and in-depth vulnerability assessment [25]. Haunschild et al. [69] also linked the "exponential growth of climate change literature" (p. 7) disclosed by their analysis to be supposedly induced by IPCC Assessment Reports and their increasing influence on the attractiveness of climate change research. Additionally, they emphasized that climate change effects, impacts, and risks are becoming increasingly tangible.

Regarding our initial set of publications, there was a small bump in the publication totals in 2017 and 2019 (Scopus), respectively a slight bump/stagnation in 2017 and otherwise rising numbers (WoS). Thus, the distribution featured by the 50 publications analyzed in depth was not only found in this subset but rather in the entirety of researched literature. When applying the search terms *climat * chang * adapt ** and searching in title, abstract, and keywords, there was a rise, which in the Scopus case was smaller in 2017 and 2019, while constant for WoS. For *climat * chang * vulnerab **, both databases featured constant rises.

Considering the actuality and significance of climate change-related topics in politics, spatial, and urban planning, as well as in many other areas, it cannot be expected that the number of publications in fields related to climate change adaptation will decrease any time soon.

**RQ 2: What are the geographical scopes of respective studies, and where are the authors located?**

As far as the study areas were concerned, Figure 4a depicts the distribution of studies per continent. A maximum of 18 were located in Asia (11 alone in China). Europe ($n$ = 8), Africa ($n$ = 7), and North America ($n$ = 5) were the runners-up. Four publications regarded localities on multiple continents (e.g., [70]—cities in developing countries), and three featured no explicit study area. On the other hand, Figure 4b shows in which continent the authors' affiliations were located. Hereby, only one occurrence per continent and publication was counted. So, when a paper was written by two authors in China and three in Europe, that counted as one for each of these continents. This was done to avoid overweighting by publications with many authors. Results showed that Europe and Asia topped the list with 22, respectively 18 authorships. China alone accounted for twelve. Following up were North America ($n$ = 12) and Africa ($n$ = 8).

A clear dominance of Asia and especially China was found when it came to the location in which the research was conducted. In addition, Africa was well represented. This is in line with the fact that the world's fastest-growing cities are located in Asia and Africa, and the share of the urban population there is constantly rising. When it comes to bigger conurbations, between 2018 and 2030, the number of cities with 500,000 inhabitants or more is expected to grow by 57% (Africa) and by 23% (Asia), respectively. The number of cities with over five or ten million dwellers is rising fastest in these areas as well [2]. In addition, cities in these regions are among the most affected by climate change influences [3,70,72,73]. However, when it comes to the places the respective authors were active, Europe and North America were overrepresented compared to the case study locations. Africa and Asia were similarly represented as study and author locations. This suggests that a lot of work is done in the region of the regarded case studies. Yet, especially in Europe and North America, researchers frequently worked on out-of-continent study areas. This dominance of western countries (Global North) regarding publication activity in climate change research is discernible in bibliometric analyses as well [69,74]. Sietsma et al. [74] also found "significant topic biases by geographic location" (p. 1). Their study revealed that, according to interviewed experts and the "Big Literature" they reviewed, inequalities between Global North and South are an enduring issue in climate change adaptation research. Applying a database search on Scopus with the search term *climat * chang * africa* (in title, abstract, keywords) from 2014-today yielded about 6140 records for the ten most active country affiliations of the research (database query done in May 2021). The top three nations were the US with about 1900, South Africa with about 1880, and the UK with about 1320 publications. Kenya, with approximately 420 records, is the only other African country in the top ten. When repeating the query with a focus on research done on Asia (*climat * chang * asia*–title, abstract, keywords), there were about 6370 records distributed among the top ten active countries. Here, China with about 2740, the US with about 1900, and the UK with approximately 900 publications make the top three. With Japan on rank 6 and about 600, India on rank 7 with about 580, and South Korea on rank 8 with approximately 380 publications, there are three more Asian countries in the top ten. However, especially when leaving aside China, non-Asian countries were responsible for a large share of research on Asia.

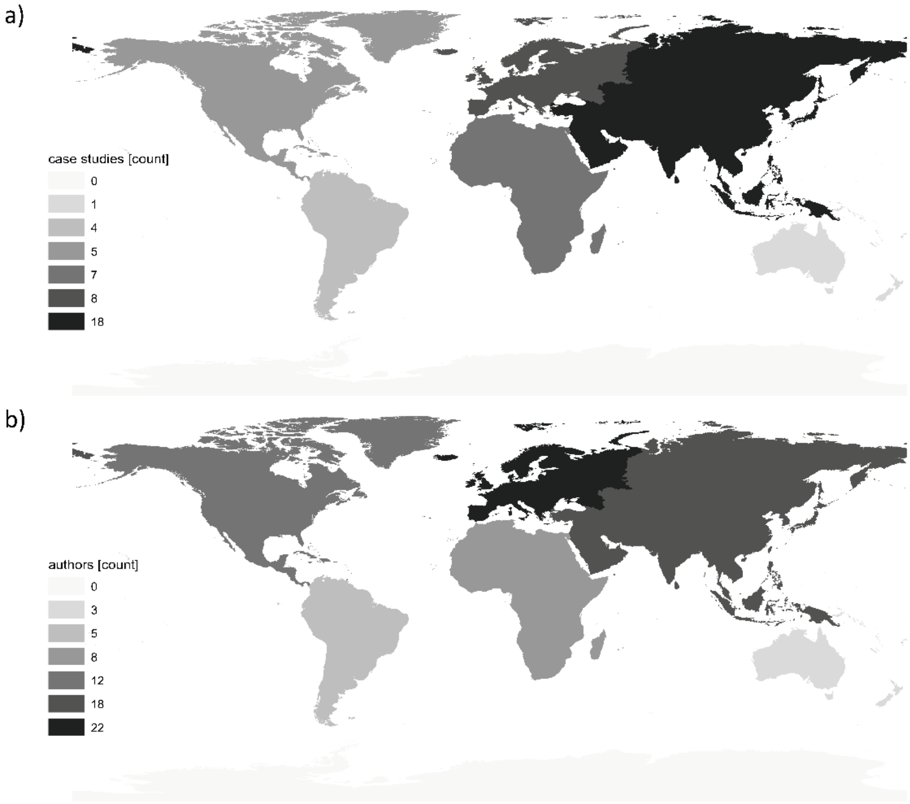

**Figure 4.** Geographical distribution of research focus. Locations of case studies (**a**) and authors (**b**). Map data from Esri [71].

**RQ 3: What study types dominate—case studies or conceptual/theoretical works, quantitative or qualitative analyses, and what target audiences are focused on by the reviewed studies?**

Usually, the reviewed studies encompassed a theoretical framework and a case study. Only a few were merely theoretical and focused on the creation of a conceptual framework ($n$ = 9). Most studies applied a quantitative ($n$ = 17) or mixed methods approach ($n$ = 25, e.g., [70]). Additionally, mostly indicator-based research was done, or the creation of an index was an integral part of the publications. When it came to the target groups, almost entirely decision-makers, politicians, stakeholders, or planners were addressed ($n$ = 49). Only in ten studies was the scientific community targeted explicitly as well. For one publication, it was unclear who was mainly addressed.

The fact that the analyzed set of publications featured mainly case studies often developed indices and addressed almost uniformly practitioners of different kinds supports the notion that climate change adaptation and its evidence base are discerned as rather practical topics. Regarding that, Greiving et al. [13] strongly encouraged closing the science-policy gap by involving stakeholders ("collaborative science") as doing so yields better outcomes. Enhancing the practical utility of risk assessments for policymakers and practitioners is also occasionally the stated goal in climate change adaptation research [10]. The IPCC also encourages a multifaceted stakeholder engagement at the urban scale [3].

The dominance of quantitative and mixed methods approaches is not only found in our compilation. Singh et al. found that about two-thirds of their reviewed studies were either applying quantitative (and index-based) or mixed methodologies [22]. Especially for vulnerability assessments, there is a large quantity of research dedicated to index creation in various sectors [75–77].

**RQ 4: What climate change-related conceptual frameworks are referred to, and how are they defined?**

Figure 5 shows the main concepts dealt with in the studies. Summing up the occurrences, the resulting number was larger than 50. This is because some studies focus on more than one concept (e.g., [78]). The total number of concepts was 64. Vulnerability was the most popular ($n$ = 31), making up for almost half of the total main concepts. Further concepts focused on frequently were resilience ($n$ = 8), risk ($n$ = 6), impact ($n$ = 6), and adaptive capacity ($n$ = 5).

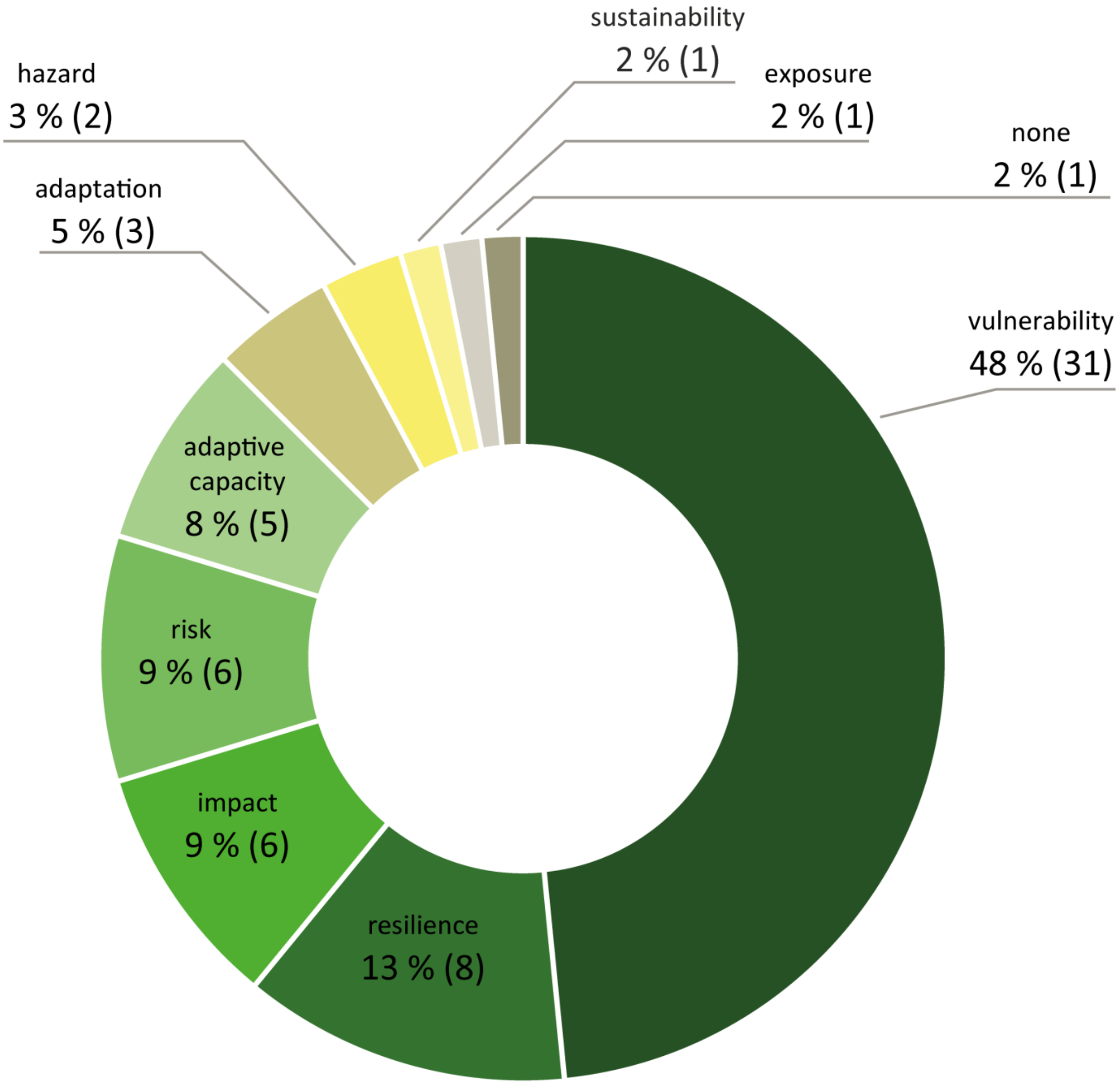

**Figure 5.** Concepts dealt with in the reviewed publications.

Regarding the definitions given in order to specify the main concepts, there was no uniformity. Many concepts were defined in various IPCC Assessment Reports, but we saw a varying understanding of vulnerability, risk, etc., nonetheless. Figure 6 shows a categorization with the classes old IPCC (2007), new IPCC (2014), old IPCC informed, new IPCC informed, own, none, and literature derived. Very often, no explicit definition was given ($n$ = 12). Direct ($n$ = 11) and indirect ($n$ = 17) IPCC definitions were in the majority. Over half of the publications (56%, $n$ = 28) referred somehow to IPCC contents.

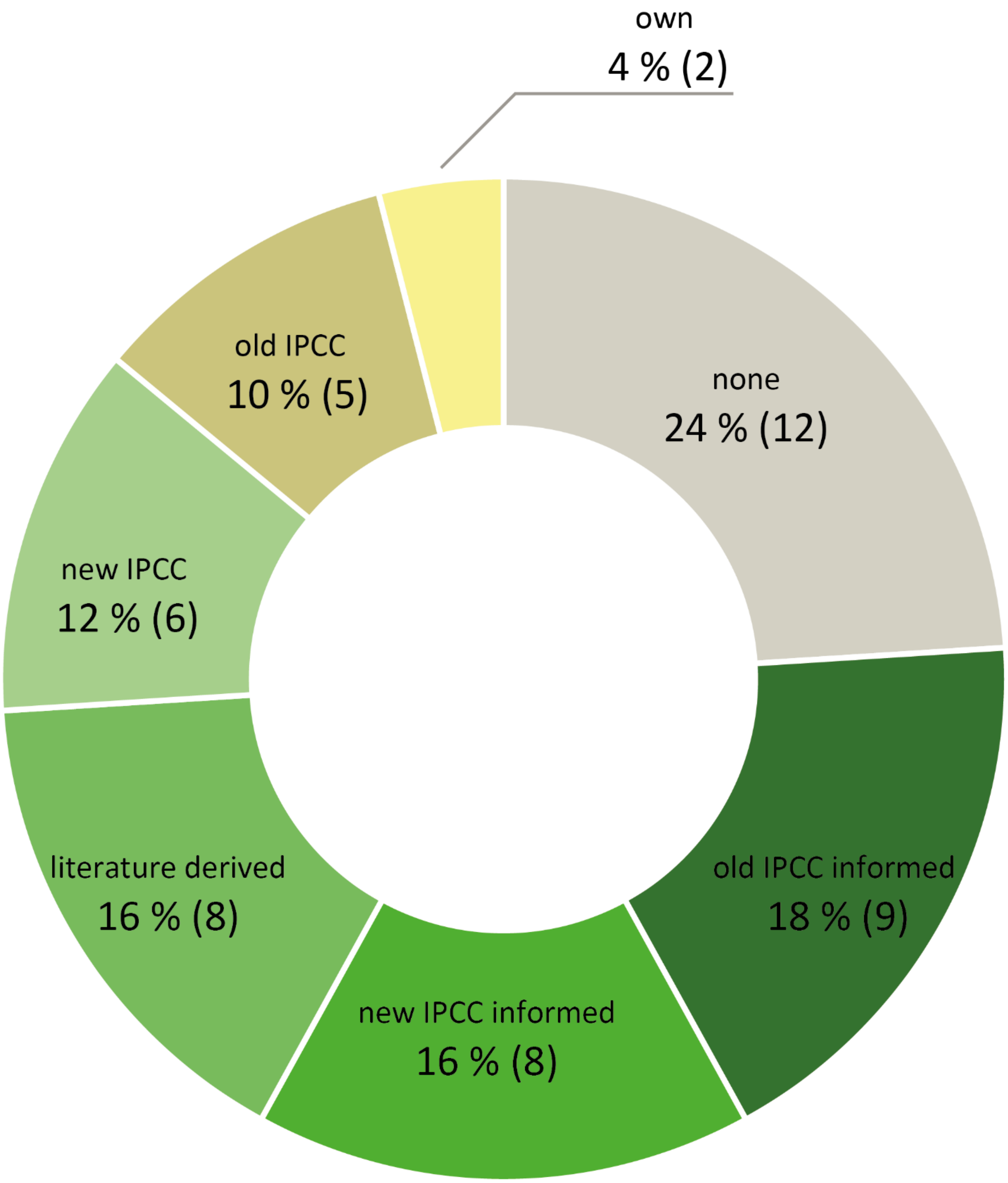

**Figure 6.** Definitions applied for the main concept of the research.

When it comes to the main concepts dealt with in the studies, there was a strong focus on vulnerability while, in total, there was a multitude of different concepts. The dominance of vulnerability can be based on the prominent featuring by the IPCC reports (on which many studies rely when defining concepts). Studies analyzing massive research data related to climate change adaptation also confirmed the outstanding significance of vulnerability as a keyword/topic [74,79]. The plurality and diversity of understandings, however, were still large (see [80]). That made it difficult or even impossible to compare studies that, for example, claimed to deal with vulnerability, but behind this tag, there can be many understandings of what vulnerability is. For vulnerability assessments in India, Singh et al. found that 26% of the reviewed studies related to IPCC definitions, while 25% did not clearly define vulnerability at all [22]. In the findings of her review on adaptive capacity, Siders stated that the field is interdisciplinary, very fragmented, dealing with multiple scales, topical sectors, locations, multiple methods/metrics that are sometimes contradictory [9]. Regarding the notion of exposure, there are also conceptual mismatches [10].

## 5. Conclusions

Our scoping review explored the status quo on conceptual frameworks applied for the assessment of climate change effects in urban areas. We systematically reviewed a number of interdisciplinary publications with a particular emphasis on the usage of terms and concepts. The reviewed field of research was found to be a globally active area with a research focus on under-developed and deprived regions in the Global South (e.g., Africa and Asia), while researchers themselves were often located in Europe and North America. The disclosed dynamics in the field contribute to an ongoing ambiguity concerning the multitude of conceptual frameworks and blurred and sometimes contradictorily used definitions. The dominant climate change-related concept dealt with in the reviewed studies was *vulnerability*. However, related concepts, such as resilience, risk, or impact, were also frequently considered. Definitions for those concepts were found to be informed by various sources, with the IPCC influencing more than half of them.

A possible explanation for the observed temporal trends could be seen in a dependence on IPCC publications. This potential reflection of publication patterns in response to the publication of IPCC reports was also found in existing reviews and studies and their revealed trends (immediate response and triggered, lagged publications). The foci on IPCC reports found in the papers analyzed support this supposed correlation.

The observed discrepancy in the geographical distributions and scopes of researchers versus those being researched can be linked to postcolonial tendencies in research in general. For Africa and research on Africa, Mawere and van Stam showed that scientists “often from countries with unresolved colonial baggage, cast their normalizing shadows over African realities” (p. 168). The dominance of foreign research was often particularly high. As of 2018, for example, almost 60% of HIV research on Africa was found to be done by foreigners—a tendency also found in various other disciplines [81].

In the reviewed set of literature, case studies were found to be dominant with little purely conceptual works. This dominance of applied case studies, employing a variety of concepts and associated definitions, implicates that mainstreaming of conceptual frameworks, definitions, and methodologies is not very advanced and not tackled extensively. Furthermore, the preeminence of *vulnerability* and the ways in which this concept has been used in the literature (vulnerability assessments, e.g.) support the conclusion that the research looked at was mostly driven by applied viewpoints. Vulnerability is also featured strongly in the IPCC reports, which, again, supports the already outlined publication pattern in response to the IPCC publications.

## 6. Outlook

Successfully implementing evidence-based climate change adaptation in urban areas requires a consistent scientific discourse regarding concepts, definitions, approaches, frameworks, and methods. Standardized approaches are especially helpful when a representative selection of cities is observed, facilitating the transfer of insights for other cities in similar regions or with similar characteristics. On that basis, a broad spectrum of more sophisticated studies with increased explanatory power can be initiated [31]. This is also imperative as more studies and research are expected in various world regions and as research addressing policy and practice can only be valuable when it is based on a strong, consistent foundation. Our results contribute to the necessary consensus building ahead through highlighting existing incongruences both at terminological and conceptual levels. The scoping review conducted will thus hopefully support facilitating research and transfer of evidence into policymaking in this timely field of societal relevance. Our obtained results are also intended to inform research and practice likewise. The thorough overview and understanding of conceptual climate change-related frameworks presented in our work will hopefully support evidence-led research and policymaking guided by solid conceptual understandings, including changes and variations of the latter.

Apart from the described unification processes, further research, also preparatory for actual assessments, might focus on characterizing cities in order to understand where their vulnerabilities or resilience originate. Here, a look at regional/cultural genetic city types might be helpful. By doing so, specific characteristics in structure or morphology influencing climate change impacts and effects could be carved out in order to understand them better. When comparing various city types, it is possible to gain an understanding of which structures and morphologies endanger a specific urban area regarding climate change issues and which do not. This can be an important asset for the future of urban planning, including traffic planning, as well as urban design and architecture.

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# The thermal performance of urban form – An analysis on urban structure types in Berlin

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A B S T R A C T

Increasing urban heat issues induced by climatic changes and growing urban populations exacerbate the need for adaptation. The present study intends to foster the so far quite rarely realized transfer from research to real-world planning. Subject of investigation is the thermal performance and characterization of urban structure types (USTs) in Berlin, Germany. Applying Landsat 8 derived land surface temperatures (LSTs), we first determine differences in the temperature patterns of the regarded USTs. Second, after running correlation analyses with LST and potentially influencing factors (NDVI – normalized difference vegetation index, imperviousness, building ratio, and building height), we fit ordinary least square (OLS) and geographically weighted regression (GWR) models. Finally, we relate the GWR results to the USTs and determine the effect of each variable on the respective LST regime. We find significant differences in the thermal performance of USTs, strong correlations between explaining variables and LST, and a sophisticated picture concerning GWR coefficients at various locations. Quasi-global $r^2$ for the GWR (0.83) improves the OLS model value (0.53) considerably. The spatially explicit GWR method in combination with results aggregated on the planning-relevant UST-level provides crucially important information for climate adaptation and planning while being adaptable and transferable to other urban areas.

## 1. Introduction

While the recent IPCC (Intergovernmental Panel on Climate Change) report states that the goal to limit global warming to 1.5° above pre-industrial times until the end of the century can still be achieved, it also points out that the global surface temperature will nonetheless continue to rise at least until mid-century (IPCC, 2021). Moreover, for 2020, the UN estimates the global urban population share to be 56.2%, and projects it at 68.4% for 2050 (UN, 2019). According to the IPCC, urbanization, with a high confidence, is generating vulnerability and exposure in combination with climate change hazards driving urban risk and impacts. The IPCC also lists numerous health effects induced by urban heat, while, furthermore, there is evidence that heat also significantly increases productivity losses (IPCC, 2022a). Higher mortalities related to heat waves in cities are well documented (Gabriel & Endlicher, 2011; Vandentorren et al., 2006). Presumably since the first half of the 19th century it is known that cities feature higher temperatures than the countryside around (Oke, 1982). This urban heat island (UHI) effect is characterized by an “excess warmth of the urban atmosphere compared to the non-urbanized surroundings” (Voogt & Oke, 2003, p. 372). The intensity of an UHI (UHII) is defined as the difference between rural and urban temperatures (Hsu et al., 2021). According to Oke, the UHI is a thermal anomaly with vertical and horizontal dimensions, which’s characteristics are found both in the intrinsic nature of the city (size/population, building density, land-use distribution, e.g.) and external influences (climate, weather, seasons) (Oke, 1982). To quantify UHIs, the land surface temperature (LST), typically acquired airborne or with satellites, is often taken as a proxy (Liang et al., 2020; Voogt & Oke, 2003).

### 1.1. Urban form and UHI – physical influences and association with social factors

Bringing urban heat and urban form, structure, or morphology together is done in a variety of ways. Hereby, the relationships between heat and physical as well as sociodemographic or socioeconomic structures are researched. On the physical side, a few determinants and variables are regularly in the focus of studies and analyses. Being aware of crossover studies and overlapping approaches, for structuring our review of the literature, we apply a rough classification into three categories: urban configuration, land use/land cover (LULC), and urban morphology/geometry factors. At the wake of UHI research, Oke already found positive correlations between population numbers and UHII in

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North-American and European cities (Oke, 1973). Other than population, also indicators like urban area, contiguity or density are used (Chen et al., 2020; Georgescu et al., 2013; Li et al., 2020; Peng et al., 2012). Vegetation and imperviousness are considered prominent examples of the LULC category. Regarding sealed surfaces, positive relationships between the level of imperviousness and LST are detected (Imhoff et al., 2010; Morabito et al., 2016; Yuan & Bauer, 2007). Furthermore, there are numerous studies dealing with vegetation (often operationalized applying the normalized difference vegetation index – NDVI) and its negative correlation with UHI (Buyantuyev & Wu, 2010; Chakraborty et al., 2020; Kaplan et al., 2018; Yuan & Bauer, 2007). It has to be emphasized that the spatial distribution (e.g. area or edge density) of vegetation has a great effect on the LST (Zhang et al., 2009). Another example for a specific land cover type frequently researched are water areas or blue infrastructures (Larondelle et al., 2014, vela-Aloise et al., 2016). From a more general point of view, the entirety of land covers and land use forms are intensely worked on (Alhawiti & Mitsova, 2016; Kardinal Jusuf et al., 2007; Zhou et al., 2011). The urban morphology/geometry category also features a rich variety of factors researched in relation to UHI. Besides pavement and green plot area, Jin, e.g., regard sky view factor, distances to parks/water, and building plot area (Jin et al., 2018). Sky view factor vs temperature shows that surface geometry is a strong determining factor of air temperature distribution in a city (Unger, 2004). Building density/ratio or building height are frequently included here as well (Gao et al., 2022; Kaplan et al., 2018). On a higher level, when it comes to the ideal urban form considering UHI and urban climate in general, there is an ongoing debate whether more compact or more sprawling cities do "better" (Echenique et al., 2012). While The IPCC recommends a compact walkable urban form that could reduce energy use significantly (IPCC, 2022b) there are pros and cons to be found for both sides in the ongoing discussion (Debbage & Shepherd, 2015; Marshall, 2008; Oke, 1988; Schwarz & Manceur, 2015; Stone et al., 2010).

Besides physical factors, a variety of socioeconomic and sociodemographic indicators are put in relation to urban heat. However, unlike the physical ones, they are not directly enhancing or mitigating heat. Their relationship to temperature is rather regarded in order to determine the actual exposure and possible adverse health impacts on variously vulnerable social groups. Such social factors are, e.g., age, income, or race. Clear correlations between weaker societal classes and heat exposure, also quantifying the influence of historic housing policies (redlining) (Hoffman et al., 2020), are suggested by a large body of literature especially, but not exclusively, on US cities (Buyantuyev & Wu, 2010; Dialesandro et al., 2021; Hsu et al., 2021; Mitchell et al., 2021; Osberghaus & Abeling, 2022).

### 1.2. *Urban form classification systems – local climate zones (LCZ) and urban structure types (UST)*

Combining urban morphology and heat/climate characteristics, a comprehensive concept worth mentioning is that of local climate zones. A LCZ describes a region with a uniform surface cover, structure, material, and human activity with a characteristic screen-height temperature regime and reaches from hundreds of meters to several kilometers (Stewart & Oke, 2012). The concept is widely used in science to date (Lehnert et al., 2021; Sida et al., 2021) with its ability to compare intra-city conditions and cities as a whole being emphasized hereby (Bechtel et al., 2019). While it bypasses the notorious urban-rural differentiation debate and improves comparability by integrating many physical factors relevant when analyzing urban heat, there are some significant downsides as well. First, LCZs are not able to capture all peculiarities in every urban and rural site. The view of the landscape is rather reductionist with the descriptive and explanatory powers being limited. Idealized LCZs are unlikely to be found in real world settings. Second, distinct zones need to have a certain size (Stewart & Oke, 2012). Thus, especially in irregularly structured European cities, LCZs seem not always to be the mean of choice (A. Oliveira et al., 2020). Resolution is another issue as comprehensive LCZ maps for example for Europe feature raster resolutions of 100m (Demuzere et al., 2021), which makes the analysis of dense inner-city regions hard, as they often feature changes in smaller and irregular spatial scales.

Another, generically not necessarily climate-related classification concept, present especially in Germany, is the one of urban structure types (USTs). Mostly, cities come up with their own individual classifications, calculations, and definitions of USTs. Typologies can be categorized implementing a variety of indicators used to quantify and measure different societal structures and specific dynamics (Wendnagel-Beck et al., 2021). Compared to the LCZ concept, USTs feature a more city-specific and thus higher resolved and more exact description of urban morphology/morphological regions/cultural genetic urban forms. Some city administrations like in Karlsruhe and Berlin, Germany, already consider USTs for climate adaptation. Yet, they lack a thorough investigation of their thermal performance when suggesting adaptation measures (Wendnagel-Beck et al., 2021). In a guide book for climate change adaptation in Dresden, *Stadtstrukturtypen* (USTs) are also featured as part of a formula for a settlement heat sensitivity indicator (Wende, 2014). For the city of Leipzig, a categorization of structure types was conducted grouping areas of physiognomic similarity, amongst others, in order to ensure a sustainable urban development (Wickop, 1999). These structure types are featured in a study examining indoor and outdoor temperatures differentiated by structure types (Franck et al., 2013). For Munich, Heldens et al., regard the relationship between LST and USTs (Heldens et al., 2013). Profound statistical analyses for the different performance of USTs and the reasons therefore are missing. However, USTs are seen as "an important (…) entry point for the analysis of intra-urban variations, both in terms of physical as well as social structures and dynamics" (Wendnagel-Beck et al., 2021, p. 323). Summing up, only few applications combining USTs and heat exist to date with USTs being not often integrated in (adaptation) planning. We apply the UST concept for being advantageous of the LCZ approach for reasons presented above (e.g., resolution, appropriateness for irregular European conurbations, tailoring to specific cities) and because there are often more reliable expert-generated data existent in cities.

### 1.3. *Objectives and research questions*

Characterizing the climatic performance of local typologies is seen of utmost importance in urban morphology research (A. Oliveira et al., 2020). The IPCC sees a need for studies that connect, amongst others, urban morphology and the urban heat island (and its spatio-temporal variability) (IPCC, 2022a). Changes in morphology or built form can contribute to the reduction of UHI effects and reduce the impacts of heat waves. However, the IPCC itself here merely proposes "non-destructive" measures like greening or surface albedo changes and no breaking up of standard urban form type arrangements, e.g. (IPCC, 2022a). Shandas suggests that the obduracy of existing infrastructure coupled with entrenched institutional and political dynamics contribute to the resistance to change and inhibit adaptive capacity and resilience of cities (Shandas, 2020). In general, urban morphology is not well connected to planning so far (V. Oliveira, 2016). Few studies consider effects of urban form on LST especially from an urban planning perspective (Yin et al., 2018) on a spatial level relevant for urban redevelopment and transformation instead of generally applicable theoretically derived constructs. Gao et al. do so by giving heat regulation recommendations for urban planners and policy makers on a block basis – and by suggesting strategies optimizing block morphology (Gao et al., 2022). In Chinese contexts, regulatory management units are often used (extents of about 150/250m), which can be compared to census block groups and USTs, and like these are related to urban detail planning (Gao et al., 2022; Lu et al., 2021; Yin et al., 2018).

We address the above-mentioned research gap by analyzing urban structures and their thermal performance in a German city context by applying a conceptually and empirically innovative approach. We intend to reveal the connection between urban form and thermal/climatic performance in order to derive locationally accurate planning implications on a planning relevant spatial level for the case of Berlin. By connecting urban morphology with UHII, we can facilitate the understanding of the genesis of local climate stresses and the tackling of these by tailored planning and design action. A geographically weighted regression allows for spatially explicit information and the derivation of UST specific characteristics concerning heat and its influencing factors. As factors, potentially explaining LST, we choose the frequently worked on LULC variables vegetation (operationalized by the NDVI) and imperviousness as well as the urban morphology indicators building density and building height. The methodology applied is furthermore transferable to other locations and adjustable to data availabilities and different epistemic interests.

With the study at hand, we intend to answer the following research questions.

RQ 1: How does the thermal performance differ in various Berlin USTs?
RQ 2: What factors influence the thermal performance in specific USTs in Berlin?
RQ 3: What planning implications can be drawn from RQ1 and 2?

The remainder of the paper is structured as follows. Chapter 2 presents the data used and the methodology applied, before results are presented and discussed in chapter 3. Finally, conclusions are drawn and an outlook is given in Chapter 4.

## 2. Data and methods

The methodological framework for this study is represented graphically in Fig. 1. The approach can be divided in four major steps: data sources/acquisition (1), data preparation (2), descriptive statistics (3), and analysis of variance (ANOVA), correlation and regression procedures (4). Our study area is the city of Berlin, for which a comprehensive UST dataset is freely available.

### 2.1. Data sources

UST and administrative boundary data are obtained from the city of Berlin (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2022b). Landsat 8 scenes with a spatial resolution of 30 × 30 m for the LST and NDVI derivation come from NASA's Earth Explorer platform (USGS, 2022a). The Copernicus program database provides the Pan-European dataset (status of 2018) on imperviousness (IMPERV in %) in a raster resolution of 10 × 10 m (EEA, 2018). For the calculation of building heights (B_HGHT) and building ratios (B_RTO), we use a dataset derived from Berlin's 3D building model (Level of Detail – LoD 2, reporting date April 1st, 2021) (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2022a). Preparing and analyzing the data is done with ArcGIS and RStudio (Esri, 2016; RStudio Team, 2021)

### 2.2. Data preparation

For the analyses, we reduce the original Berlin UST set to six classes. We select only typologies assigned to feature predominantly residential uses and then reclassify those using meta-data and documentations on the dataset provided by the city of Berlin. The resulting UST list is in Table 1 below while definitions and further information on the types used are found in Appendix Table 1.

There are different approaches for capturing the spatial distribution of urban heat. Common is the utilization of satellite data. Hereby, several sources like ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (Buyantuyev & Wu, 2010) and MODIS (Moderate-resolution Imaging Spectroradiometer) (Imhoff et al., 2010; Peng et al., 2012) exist and are used. Today, Landsat 8 is adopted in various locations and with various temperature derivation methods (Yu et al., 2014). We apply the algorithm presented by Avdan and Jovanovska to derive LSTs (Avdan & Jovanovska, 2016; Kaplan et al., 2018).

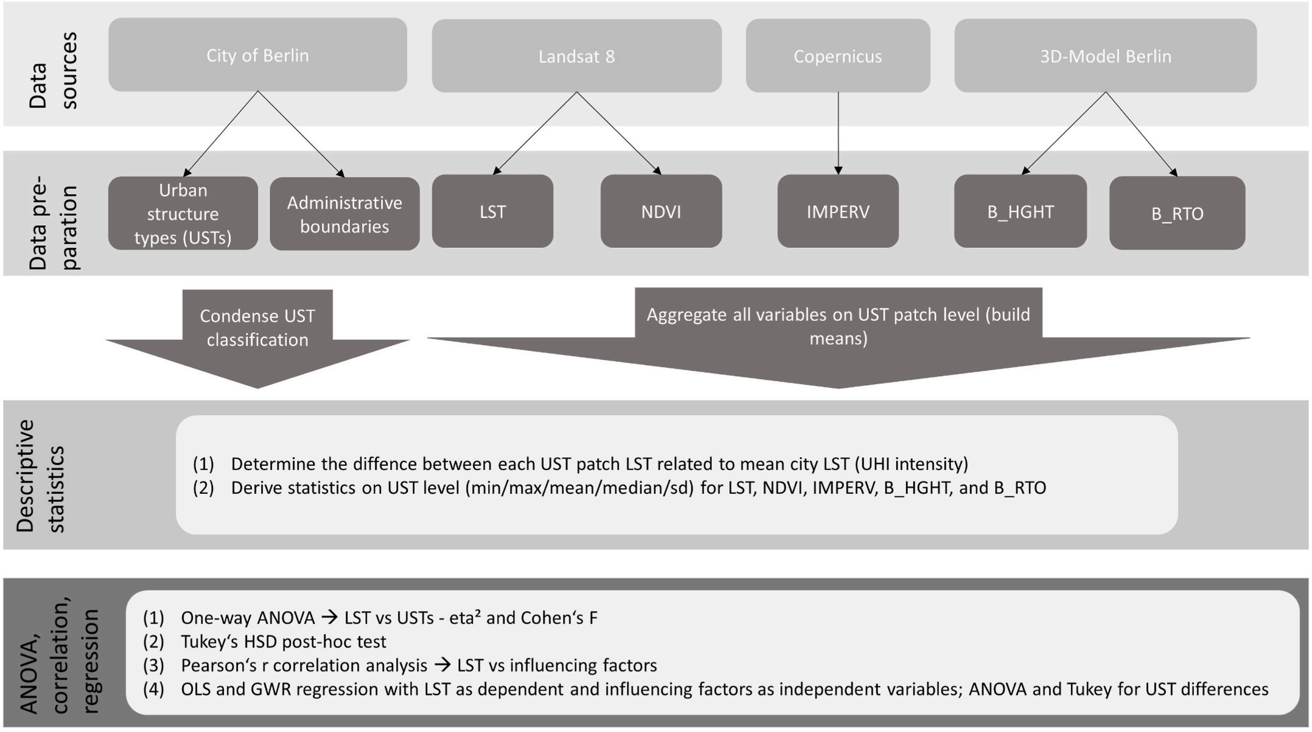

**Fig. 1.** Methodological approach.

**Table 1**
Urban structure types under investigation for Berlin.

| Number | UST name | Short name |
|---|---|---|
| 1 | Perimeter blocks | BLO |
| 2 | Row development, open blocks | ROW |
| 3 | Various multi-story buildings | MSB |
| 4 | Village cores | VIL |
| 5 | Large housing estates | LHE |
| 6 | Detached houses (single family, semi-detached, terraced houses, e.g.) | DTH |

**Table 2**
Specifications of the used Landsat 8 scenes.

| Date | Mean temperature of averaged LST raster for study area | Cloud cover |
|---|---|---|
| 2019/07/26 | 26.81 °C | 0.04% |
| 2020/09/14 | 22.08 °C | 0.10% |
| 2022/06/24 | 21.29 °C | 0.20% |

Therefore, we choose Landsat scenes from three hot days (maximum temperature above 30 °C (dwd, 2022)) in different years. Also, as moisture plays an important role influencing the UHI (Oke, 1982), another inclusion criteria is *no precipitation for two days before the measurement*. Furthermore, we set the maximum cloud cover to 5%. Similar selection procedures are common in UHI research (Buyantuyev & Wu, 2010; Shandas et al., 2019). Table 2 lists the datasets used.

The calculation of NDVI values as a proxy for vegetation density/cover is done using bands 4 and 5 of the said Landsat scenes (USGS, 2022b). We overlay the three LST and subsequently also the three NDVI datasets derived from the original scenes and calculate mean rasters to get robust datasets displaying hot and cold spots and the distribution of vegetation, respectively, with a high certainty. Then, we determine the mean LST/NDVI for each UST patch. For B_RTO (in %), we relate the area covered by buildings in each UST patch to the total area and for B_HGHT (in m) we derive the mean height of structures in a patch. Finally, all indicators are averaged on the UST patches by calculating the respective mean values for each patch. Building and using averages on various (administrative) aggregation levels is common for similar studies. Exemplary units frequently used are census block groups (Buyantuyev & Wu, 2010) or Chinese management units (Gao et al., 2022).

### 2.3. Descriptive statistics

For the following step basic stats (minimum – min, maximum – max, mean, median, standard deviation – sd) are obtained for each UST class (patches dissolved) for LST, NDVI, IMPERV, B_HGHT, and B_RTO.

To avoid the oftentimes hardly defensible differentiation between urban and rural areas, we characterize the UHII at a certain place by calculating the area's LST difference compared to the city average (cf. Kazmierczak, 2016). As we want to compare different USTs in their thermal performance rather than getting absolute magnitudes of UHI, this approach is considered stringent and reasonable.

### 2.4. ANOVA and correlations

For testing the LST differences between UST classes statistically, we perform a one-way ANOVA with eta squared ($\eta^2$) as a measure of significance. We furthermore evaluate the strength of the effects (Cohen's f) according to the thresholds provided by Cohen (Cohen, 1992, 2013). As an ANOVA delivers only insights for the whole dataset, we additionally perform a Tukey's Honest Significant Differences (HSD) test to determine which differences are significant. A correlation analysis (Pearson's *r*) follows. Here, we intend to reveal the relationships between LST and the presumed influencing factors. This also helps deciding on which indicators to include in the regression analyses.

### 2.5. OLS regression and diagnostics

To determine the respective contribution of factors on LST and thus UHI formation, we build a multiple linear regression model. Therefore, we fit an ordinary least square (OLS) regression model. However, spatial data often violate assumptions for a regular OLS regression. Our data supposedly features non-stationarity, as variables are presumably having more/less influence on heat at various locations (USTs). Thus, we believe that the relationship between variables are not global. Whole map regressions tend to make unreasonable assumptions about the stationarity of the regression coefficients under investigation wrongly assuming that regression relationships are the same no matter where one measures them within the study region. In addition, we expect errors to be dependent, causing clustering of similar values at some locations in the data (spatial autocorrelation). This is because heat data, providing continuous information, is considered to be most certainly dependent in its observations suggesting autocorrelation (Yin et al., 2018). Neighboring land uses have also been found influencing local temperatures (Kim & Guldmann, 2014). Although it might ultimately be considered inappropriate, an OLS regression should be the first step in order to be able to later compare other models to it and to analyze its outcomes and residuals (Comber et al., 2022). The formula for an OLS model is the following:

$$y_i = \beta_0 + \sum_{k=1}^{m} \beta_k x_{ik} + e_i, \tag{1}$$

where observations are indexed by $i = 1 \ldots n$, $y_i$ is the dependent variable, $x_{ik}$ is the value of the kth predictor/independent variable, $m$ is the number of independent variables, $\beta_0$ the coefficient for the intercept, $\beta_k$ the regression coefficient for the kth variable, and $e_i$ the random error term.

We first analyze the regression regarding homoscedasticity, which means, residuals should feature a homogeneous variance. To check that, we apply a Breusch-Pagan Test, which, if significant, implies heteroscedasticity. Furthermore, we run a local spatial heteroscedasticity (LOSH) statistical analysis. LOSH can uncover trends in spatial variance and identify cluster boundaries. The level of homo- or heterogeneity in clusters and trends around observations are determined (Ord & Getis, 2012). We combine LOSH and cluster detection results from Getis-Ord Gi* (high/low value clusters) (Getis & Ord, 1992) as done by, e.g., Westerholt (Westerholt, 2021). For the Gi* calculations as well as for Moran's *I* (below) we apply a k-nearest neighbor ($k = 8$) approach to model the neighborhood and to get a spatial weights matrix ($W = (w_{ij})$) for the pairwise comparison of spatial units. By deciding for this approach and against, e.g., distance bands, larger patches are ensured to have neighbors, no NULL values are created, and we are able to capture changing UST neighborhoods on various scales (generally smaller/larger patches and small-scale/large-scale changes in inner/outer-city areas). In analogy to a queen contiguity approach, eight neighbors are considered reasonable, as, even for cities like Berlin with a rather irregular layout, UST patches are more or less rectangular blocks. Finally, errors should be independent, thus not correlated. To check that, we run a spatial autocorrelation analysis on the residuals of the OLS model. Hereby, we apply global Moran's *I* (Getis & Ord, 1992). The *I* values are to be interpreted including the respective p-values and generally reach from $-1$ (negative autocorrelation) to 1 (positive autocorrelation), with values close to 0 meaning no autocorrelation.

### 2.6. Spatial regression models

To address spatial dependencies in errors there are simultaneous autoregressive models like the spatial error (SEM) and the spatial lag model (SLM). While several studies with spatial regression models consider heat as dependent factors (SLM: Agathangelidis et al., 2020; SEM: Dialesandro et al., 2021; Lu et al., 2021; SEM/SLM and others:

Pramanik et al., 2022; Yin et al., 2018), they do not what we need here as they globally include a spatially weighted neighborhood and assume stationarity of the regarded relationships. Thus, we apply a GWR that allows spatial heterogeneities through providing a series of local regression models rather than a single global one. A GWR model examines the potential geographical variance of the relationship between response and predictor variables (Comber et al., 2022). GWR already found some application in explaining urban temperatures (Buyantuyev & Wu, 2010; Gao et al., 2022). For GWR approaches, in a first step, it is important to find a suitable bandwidth that is used to determine the local models. The method generally considered most advantageous therefore is the approach minimizing the Akaike information criterion (AIC) (Comber et al., 2022). However, as our dataset is quite large, the AIC method is not feasible computation-wise, why we apply the leave-one-out cross-validation (CV) technique. The formula for GWR is:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{m} \beta_k(u_i, v_i) x_{ik} + e_i, \tag{2}$$

*where* $(u_i, v_i)$ *are spatial coordinates of observations i,* $\beta_k(u_i, v_i)$ *are the coefficient estimates at these locations (vectors of local coefficients) (Fotheringham et al., 2002).*

The GWR yields intercepts, coefficients, and r$^2$-values for each feature (patch) of the dataset. To determine the, presumably varying, influences of the regarded explaining variables we look at those measures on the UST level aggregation. Therefore, again, we run an ANOVA with a Tukey HSD test to compare USTs and their respective GWR results.

## 3. Results and discussion

### 3.1. Comparing the thermal performance of USTs

The basic statistics for the UST patches in Berlin (Appendix Table 2) give a first overview on the different value ranges for the observed variables. No peculiarities like outliers are identifiable in the data.

The ANOVA to determine whether differences in the LST regime between USTs are significant yields an η$^2$ value of 0.28, and a Cohen's f of 0.63, which, being >0.4, implies a strong explanatory effect. The Tukey post-hoc (HSD) test reveals a more distinguished picture (Fig. 2). Temperature differences are significant on the 0.05 level except between MSB-VIL and MSB-LHE. Comparisons involving VIL have to be regarded with caution generally (low n for this UST). MSB-LHE being not significant indicates similar thermal characteristics in these structures (see Appendix Table 2). The largest differences are generally found when comparing other USTs to BLO (negatively) and DTH (positively). BLO can thus be seen as the hottest and DTH as the coolest UST in our analysis.

These outcomes prove the diversity of USTs in Berlin concerning their thermal performance and thus as well their relative uniqueness in terms of heat. This indicates the fundamental applicability of USTs as aggregation level for UHI analysis and subsequently adaptation action, even though, unlike LCZs, USTs are not classified according to climate-related aspects. Heldens et al. (Heldens et al., 2013) also show clearly different LST levels between USTs in Munich. For districts formerly subject to the racially motivated segregation practice of redlining (another not climate-related division), Hoffmann et al. could prove (also with a Tukey's HSD) significantly higher temperatures than in other areas in US cities, too (Hoffman et al., 2020).

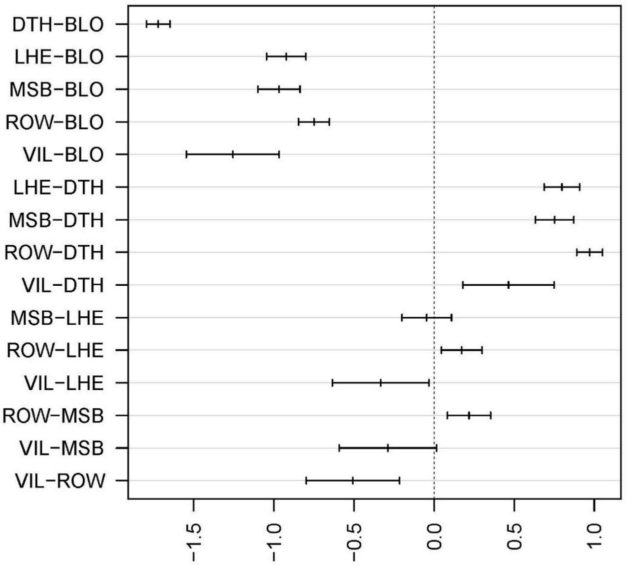

**Fig. 2.** Tukey post-hoc significant differences between UST types for LST difference from city mean.

Correlation analyses for the whole city on the 0.05 significance level yield r-values of −0.67 for LST vs NDVI, 0.71 for LST vs IMPERV, 0.50 for LST vs B_RTO, and 0.34 for LST vs B_HGHT. Inclusion in the regression model is considered viable for all these variables as relatively high correlation coefficients suggest interdependencies. As expected from existing research the coefficients are positive for IMPERV (e.g., due to lower albedo, higher proportion of absorbed radiation), B_RTO and B_HGHT (e.g., due to heat trapping and inhibited air exchange), and negative for NDVI (cooling effects of vegetation). The positive correlation between LST and B_HGHT is contradictory to some other studies' results. Agathangelidis et al. found similar relationships for daytime conditions in Berlin (Spearman Rho): 0.78 for IMPERV, 0.63 for built ratio, and 0.53 for height. In general, height proved to be the most volatile factor, changing signs for day/night in specific cities regarded. The authors attribute these differences, amongst others, to respective micro-climates/background climates. Thus, for height, no generalized influence was derivable (Agathangelidis et al., 2020). The ambiguities regarding building height are furthermore comprehensible when considering the possible opposing effects related to the absolute height as well as the building floor area (sky view factor as exemplary popular measure). Shading might have a cooling effect but dense and high building areas without sufficient ventilation fuel urban heat (Unger, 2004; Yin et al., 2018). This requires in-detail analysis, e.g., on the level of morphologically similar USTs. An explanation for our case's numbers might be the use of heights averaged on the UST area, which leads to BLO (hot) having higher heights due to higher density and to LHE (cooler) being more sparsely scattered in their UST having lower heights.

### 3.2. OLS results and model diagnostics

The results for the OLS regression model are shown in Table 3. Coefficients are highly significant on the 0.001 level (***) except for B_RTO (not significant at 0.05). According to r$^2$, the model explains 53% of the variance.

The check for the abovementioned OLS preconditions homoscedasticity and independence of errors yields the following outcomes. The Breusch-Pagan test result is significant indicating heteroscedasticity. The LOSH and Gi* combination (Fig. 3) shows areas with significant clusters ( ± two or more sd) and overlaying significant LOSH p-values below 0.05. The highlighted areas demonstrate that heteroscedasticity is mostly significant in clusters containing either green/blue or industrial/commercial infrastructures. That means these clusters feature internal differences/high variance changes. Heteroscedasticity in our case is thus

**Table 3**
OLS regression results.

| Intercept | IMPERV | NDVI | B_RTO | B_HGHT | R$^2$ |
|---|---|---|---|---|---|
| 0.47 *** | 0.04 *** | −4.92 *** | 0.0017 | −0.076 *** | 0.53 |

geographically explainable giving a strong indication for a locally adjusted modelling of the regarded relationship with, e.g., a GWR.

Global Moran's *I* for our OLS model residuals is 0.59, exhibiting a significant, strong positive autocorrelation, large enough to follow the alternative hypothesis according to which autocorrelation is present. This also suggests a spatial regression model for the data at hand, as we can suppose a spatially varying relationship between response and predictor variables. All that and the assumption of non-stationarity suggests the applicability of a GWR to be fruitful and advantageous.

### 3.3. GWR results and derived planning implications

The bandwidth determined for the GWR calculation is 347.82m. Resulting coefficient maps, like in Fig. 4, show that values are featuring a wide range and pronounced local differences. This applies also for the $r^2$ distribution maps (Fig. 5), proving the superiority of a local instead of a global regression model. The quasi-global $r^2$ value for the GWR (0.83) presents a strong improvement compared to the OLS model's 0.53, also displaying the advantage of the chosen approach. For the GWR model, lower $r^2$ values are especially found in more central UST patches of the city. Here, the local models explain less variance compared to other areas indicating, for example, missing further explanatory variables and other local effects.

Looking at the coefficient means at the UST level (Table 4) reveals a sophisticated picture. IMPERV has the highest positive influence on LST in DTH and ROW while it is lowest for VIL. NDVI is featuring largest negative values for VIL and DTH and lowest for BLO. Regarding B_HGHT, like in the OLS model, all coefficients are negative indicating a temperature mitigating effect of higher buildings. Highest negative coefficient means are found here for VIL, while DTH features the lowest absolute value. In some USTs, a change in IMPERV, NDVI, or B_HGHT has a relatively strong effect and in some not. B_RTO finally changes signs for three USTs. Like in the OLS case, coefficients for BLO, MSB, and ROW are positive while LHE, DTH, and VIL are now featuring negative values. Naturally, for specific adaptation measures and planning, this needs to be analyzed in detail for any case. For height, for example, density plays a major role. Ideal heights for mitigating heat could be found in certain areas/USTs (see Oke, 1988 suggesting ideal relationships between building heights and street widths). Our small study dataset, e.g., suggests that increasing heights in VIL areas decreases LST more than doing so in BLO areas that already feature high average heights. In the study by Agathangelidis et al. there is a sign change from plus to minus from the OLS model to the SLM one in the Berlin case while generally height features a lot of variability as mentioned above for correlations (Agathangelidis et al., 2020). Looking at the DTH and the BLO classes allows for a better understanding and illustration of the results. An increase of 10% in impervious surface generates, on average, a temperature rise of 0.2 °C in DTH and 0.16 °C in BLO patches. A 0.1 rise in NDVI causes LST in DTH units to fall by about 0.7 °C and 0.4 °C in BLO areas. Increasing B_HGHT by 10m evokes a LST fall by 0.2 °C and by 0.6 °C in DTH and BLO respectively. Regarding B_RTO, a 10% rise means 0.1 °C increase in BLO and 0.05 °C fall in DTH areas. The weakest influence on LST, relatively, is thus featured by B_RTO. For the interpretation, it is of crucial importance to keep the respective units and (relative) magnitudes of change in mind. For example, a 10m rise in height average is relatively massive, especially when the respective area is already densely built-up. Moreover, a 10% increase in impervious surface area from already 80% in a district is different from a neighborhood featuring 20% IMPERV.

The next step consists of checking for the significance of differences in coefficient levels between USTs. An ANOVA features Cohen's f values that are indicating only weak or not significant effects (IMPERV – 0.069, NDVI – 0.15, B_HGHT – 0 0.024, B_RTO – 0.1). Table 5 summarizes the results of the Tukey post-hoc (HSD) test. Only significant differences between UST pairs are depicted. Differences of B_HGHT coefficients are not significant for any comparison. The DTH-BLO and ROW-BLO comparisons are significant for all other coefficients. IMPERV coefficients generally differ less significantly across USTs than NDVI and B_RTO. For our case (Berlin) we can conclude that changing the percentage of impervious surfaces and heights has about the same effect on LST in most USTs. On the other side, changes in NDVI and B_RTO evoke very different effects in the specific USTs. Together with the outcome of Table 4 above this sophisticated picture gives many hints for tailored adaptation solutions while simultaneously indicating the need for

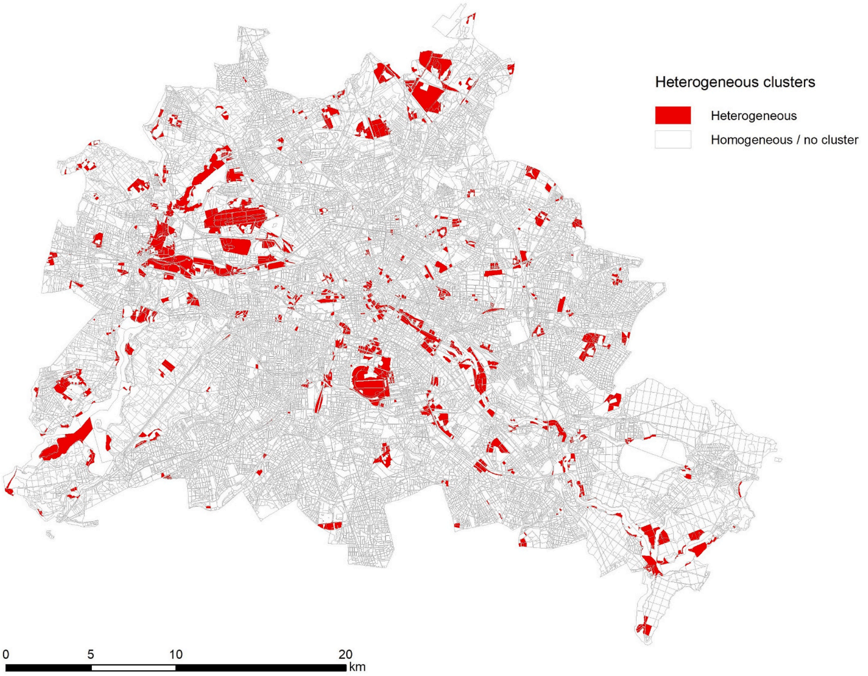

**Fig. 3.** Combined illustration of Gi* and LOSH.

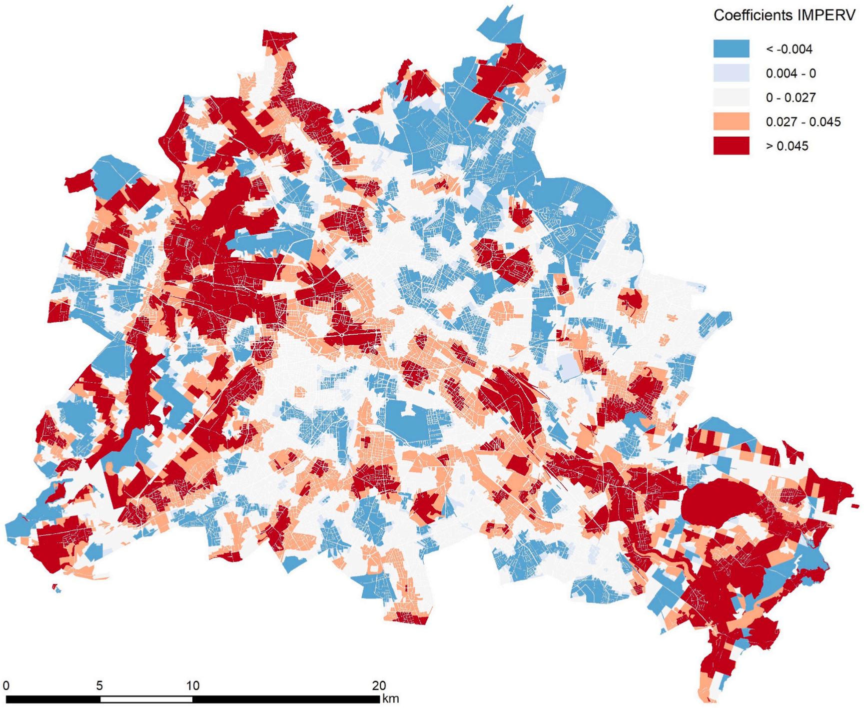

Fig. 4. Coefficients map for IMPERV.

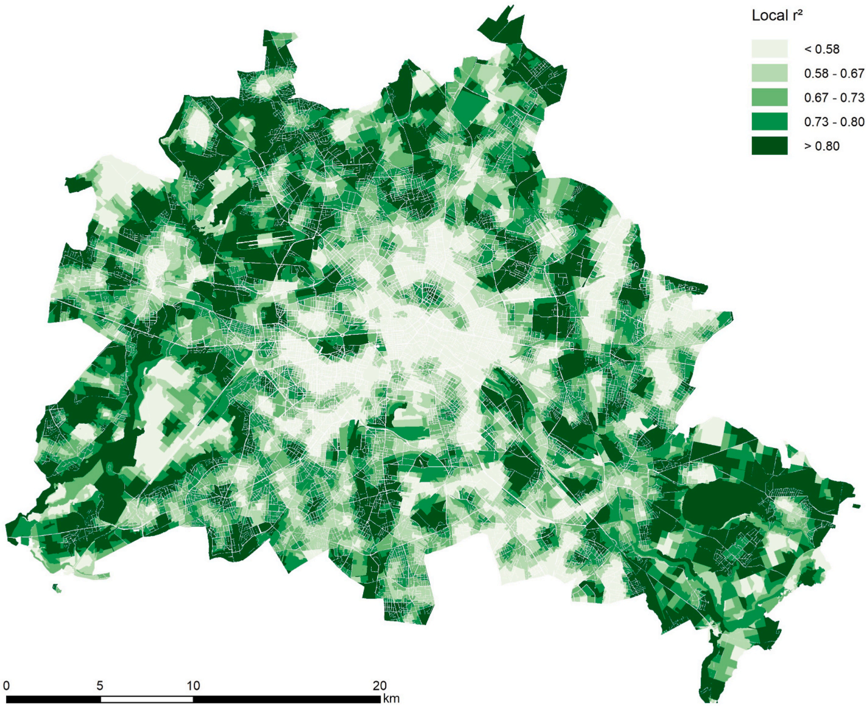

Fig. 5. Distribution of $r^2$ values.

further detail studies.

Like Gao et al., who defined five block group types according to the heat levels in the respective areas and derived tailored planning recommendations for each block group according to GWR results (Gao et al., 2022), our findings allow the deduction of a wide range of planning implications. Based on our results on the different thermal performance of USTs and the various underlying processes, planners can not only make well-informed decisions on where to adapt and initiate changes in urban design, architecture, or morphology, but also how to do so. For example, detected high influences of imperviousness on the LST signalize that increasing/decreasing the impervious surface share there can invoke large effects on the heat in the respective area.

**Table 4**
Ranking USTs according to coefficient means.

| Coefficients | | | |
|---|---|---|---|
| IMPERV | NDVI | B_HGHT | B_RTO |
| DTH 0.020 | VIL -8.162 | VIL -0.100 | BLO 0.009 |
| ROW 0.019 | DTH -6.942 | MSB -0.068 | MSB 0.005 |
| MSB 0.017 | ROW -5.468 | ROW -0.066 | ROW 0.004 |
| LHE 0.017 | LHE -4.940 | BLO -0.060 | LHE -0.003 |
| BLO 0.016 | MSB -4.462 | LHE -0.030 | DTH -0.005 |
| VIL 0.016 | BLO -3.963 | DTH -0.020 | VIL -0.006 |

**Table 5**
Significant differences in UST coefficients according to a Tukey post-hoc test.

| Coefficients | IMPERV | NDVI | B_HGHT | B_RTO |
|---|---|---|---|---|
| Comparisons | DTH-BLO<br>ROW-BLO<br>LHE-DTH | DTH-BLO<br>LHE-BLO<br>ROW-BLO<br>VIL-BLO<br>LHE-DTH<br>MSB-DTH<br>ROW-DTH<br>VIL-LHE<br>VIL-MSB<br>VIL-ROW | | DTH-BLO<br>LHE-BLO<br>ROW-BLO<br>VIL-BLO<br>MSB-DTH<br>ROW-DTH<br>MSB-LHE<br>ROW-LHE |

Furthermore, “ideal” shares and combinations of impervious surfaces, vegetation, building ratio, and building heights can be derived. Going a step further, information on advantages and disadvantages regarding their thermal performance can also lead to a paradigm shift in both future urban planning and design as well as the handling of existing building fabric. That can express itself by a turn away from traditional urban structure types towards the adoption of new, climatically more suitable ones. To do so, an urban morphology classification approach tailored to the respective unique and individual urban structures, instead of globally applicable ones allowing only less customized insights and recommendations for action (like LCZs) offers the best opportunities.

### 3.4. *Limitations*

Our methodological approach and our datasets feature some shortcomings. First, regarding the data, ground measured air temperature as add-on or replacement for a remote-sensed LST derivation might provide a more robust temperature grid. The same applies for alternative LST derivation methods. Furthermore, higher spatial resolutions for LST, NDVI as well as IMPERV data would be desirable refining the results. Data on more UHI influencing factors could potentially increase the fit of the models as would the extension of the USTs regarded to other than residential. Landsat scenes are moreover captured in the morning for the region containing Berlin, thus neither covering night-time conditions nor the hottest times of the day. By using the aggregation level of UST patches our results are exposed to the modifiable areal unit problem (MAUP). This is especially an issue when a grid is used for aggregation instead of evidence-based units (Yin et al., 2018). Finally, when using pre-defined spatial units such as USTs, potential classification shortcomings have to be kept in mind as well.

Second, on the methodology side, there are steps that offer the potential for change, too. While for our purposes, the approach chosen is well suited, adjustments and extensions can be seen as further possible steps worth taking. More elaborated and flexible regression models can be mentioned here as well as additional statistical tests. Especially the GWR approach allows for more sophisticated models such as mixed GWRs (Comber et al., 2022). Including and comparing various sets of variables and neighborhood modelling approaches in the regression models might also be fruitful for further studies.

## 4. Conclusions

Our study showed that the thermal performance of urban morphology in Berlin differs partly significantly among USTs (RQ 1). Furthermore, by applying a GWR, we could determine the degree of influence the regarded factors had on the LST regime at each UST patch site as well as aggregated for the distinct USTs as a whole (RQ 2). For planning and urban design, hosts of valuable implications can be drawn from these site-specific analysis results (RQ 3). GWR proved powerful for exact spatial predictions and modelling. Testing the inclusion of more variables might further improve model fits and explanatory power in future studies. Also calculating models with various indicator sets and combinations seems advantageous (Lu et al., 2021; Yin et al., 2018). However, our approach appears powerful for informing the climate adaptation of built infrastructure and for larger scale future urban planning and (re-)development. Tailored planning for specific needs is facilitated. By enabling a turn away from scattergun approaches’ undifferentiated calls for “more green”, “trees”, or “green roofs”, an analysis like ours allows for informed choices and leads to often presumably cheaper and easier to implement adaptation solutions. An economically, ecologically, and socially benevolent and thus sustainable notion of urban planning is therefore initiated and supported. In the end, knowledge generation from results like the ones presented here can possibly even encourage paradigm shifts regarding the way urban morphology is made climate resilient and historically established urban forms are perceived and handled. Said results can be integrated and operationalized within the scope of zoning and master plans, allowing for the derivation of concrete measures and scheduling a regular monitoring of the status quo. Furthermore, the approach can be transferred to other cities and world regions with various different urban form characteristics. An extension to not only residential zones and by social factors, e.g., is a possible next step as locally tailored UHI strategies are needed also to mitigate social thermal injustices, often present in regions not considered in existing mitigation planning (Hsu et al., 2021). Therefore, USTs, as well as related classification systems established for urban planning purposes, in combination with a variety of geospatial analyses represent a valuable spatial level and methodological approach for such measures.

## Author statement

As single author of the submitted paper Florian Klopfer worked alone at all stages of the article.

## Declaration of competing interest

The author declare that he has 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

**Appendix Table 1**
USTs under investigation for Berlin (adapted from Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2021). Photographs (right row) by Uwe Grützner, TU Dortmund University.

| No. | UST name | Berlin structure types | Example | | Short name |
|---|---|---|---|---|---|
| 1 | Perimeter blocks | 1-3: Mainly built 1870 to 1918, typically 4-6 stories, high density. Characteristic inner yards (varieties: built-up courtyards, closed, half-closed blocks) |  |  | BLO |
| 2 | Row development, open blocks | 4, 5: Constructed between the 1920s and the 1970s. Mostly 2-6 stories. Lower density, more green, large backyards and interstices. |  |  | ROW |
| 3 | Various multi-story,buildings | 8: Multi-family housing developments mainly since the 1990s. Typically 4 stories. Semi-public green and playgrounds. |  |  | MSB |
| 4 | Village cores | 13: Characteristic mixture of new and old structures (e.g., market place). Often local supply centers. Various building heights. |  |  | VIL |
| 5 | Large housing estates | 6: High structures with up to 11 stories and more due to massive shortage of housing space from the 1960s–1990s. Green spaces of variable quality. |  |  | LHE |
| 6 | Detached houses,(single family, semi-detached,terraced houses, e. g.) | 10-12: Various detached and semi-detached house types (terraced houses to generous mansions). Low building density and private gardens. |  |  | DTH |

**Appendix Table 2**
Basic statistical properties of variables in Berlin as total and in the USTs considered.

| Spatial unit | Variable | | | | |
|---|---|---|---|---|---|
| | LST diff (mean, median, sd,min max) | IMPERV | NDVI | B_RTO | B_HGHT |
| Berlin (n = 26,206) | 0.601, 0.996, 2.023, −7.629, 8.514 | 38.975, 38.136, 29.033, 0, 100 | 0.269, 0.273,0.090,-0.069, 0.544 | 17.588, 16.581, 19.936, 0, 99.843 | 2.035, 1.083,3.349,0, 57.347 |
| BLO (n = 2,212) | 2.256, 2.346,0.812,-2.518, 4.621 | 73.784, 75.221,14.523,15.550, 100 | 0.168, 0.165,0.048,0.019, 0.377 | 49.692, 49.780,11.908,9.510, 85.627 | 8.557, 8.743,3.785,0.772, 21.900 |
| ROW (n = 1,741) | 1.507, 1.531,0.867,-2.564, 4.170 | 48.274, 47.676,14.428,7.677, 97.204 | 0.244, 0.245,0.040,0.105, 0,399 | 28.830, 27.028,9.993,6.361, 84.532 | 3.964, 3.413,2.408,0.357, 13.247 |
| MSB (n = 697) | 1.289, 1.351,1.073,-3.470, 4.123 | 66.255, 66.825,20.753,1.870, 100 | 0.204, 0.207,0.058,0.030, 0.400 | 30.260, 28.263,15.541,0.008, 99.843 | 3.636, 2.597,3.276,0.000, 24.802 |
| VIL (n = 114) | 1.001, 1.087,0.842,-1.436, 3.065 | 45.368, 45.168,12.665,8.878, 76.683 | 0.266, 0.268,0.035,0.171, 0.384 | 19.430, 19.083,6.615,0.175, 54.478 | 1.466, 1.317,0.703,0.010, 3.723 |
| LHE (n = 836) | 1.334, 1.333,0.851,-2.414, 4.409 | 52.791, 51.223,15.912,12.881, 100 | 0.229, 0.233,0.049,0.042, 0.374 | 26.316, 23.552,11.823,5.903, 97.298 | 3.590, 2.598,3.137,0.278, 28.810 |
| DTH (n = 7,150) | 0.535, 0.727,1.183,-6.013, 5.496 | 37.862, 37.746,14.857,0, 100 | 0.282, 0.281,0.038,0.110, 0.454 | 18.577, 18.562,5.112,0, 56.710 | 1.575, 1.473,0.742,1.042, 7.541 |

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Research article

# Determining spatial disparities and similarities regarding heat exposure, green provision, and social structure of urban areas - A study on the city district level in the Ruhr area, Germany

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A R T I C L E I N F O

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A B S T R A C T

Heat islands and ongoing urbanization make cities places where the negative impacts of global climate change on society are becoming increasingly evident. Especially the interplay and potential multiplication of heat, low green provision, and the presence of socially deprived urban dwellers constitutes complex challenges. Emerging climate injustices and potential health issues require a powerful counter-reaction in form of adaptation action. For our study, we consider eight cities located in the densely populated and historically highly segregated Ruhr area in Western Germany, which is one of the largest metropolitan areas in Europe with a heterogeneous distribution of socio-spatial problems, economic potential, heat stress, and green infrastructures. We use land surface temperature (LST), data on green provision (normalized difference vegetation index (NDVI)), and social indicators to reveal the relationships between these indicators on the city district level ($n = 275$). Therefore, we first analyze the data regarding spatial autocorrelation (Moran's *I*) and clustering (Gi*) before calculating study area wide and city specific correlations between the three factors regarded. Finally, we conduct a cluster analysis (k-means) to disclose similar areas with or without multiple burdens. Our results show distinct disparities in heat exposure, green availability, and social status between city districts of the study area. We find strong negative correlations between LST and NDVI as well as between NDVI and social status. The relationship between LST and our social indicator remains ambiguous, affirming the necessity of further detailed studies. The cluster analysis furthermore allows for the visualization and classification of districts featuring similar characteristics regarding the researched components. We can discern in parts pronounced climate injustice in the studied cities, with a majority of people living in unfavorable environmental and socio-economic conditions. Our analysis supports governments and those responsible for urban planning in addressing climate injustice in the future.

## 1. Introduction

The interplay of ongoing climatic changes and urbanization creates a variety of challenges for urban areas around the globe. In its latest report the IPCC (Intergovernmental Panel on Climate Change) stresses that limiting global warming to 1.5°C above pre-industrial times until the end of the century is still possible, however, it also points out that the global surface temperature will nonetheless

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continue to rise at least until the 2050s [1]. At the same time, the UN estimates the global urban population share to be 56.2% in 2020 and projects it at 68.4% in 2050 [2]. During the period from 2015 to 2020, urban populations grew by almost 400 million people. Over 90% of this growth took place in less developed regions [3]. Urbanization is considered to induce vulnerability and exposure and in combination with climate change hazards is driving urban risk and impacts. As most rapid population growth is in areas where adaptive capacity is low, the most economically and socially marginalized are most affected by adverse climate change impacts [3]. Not only regarding climate change and urban heat, studies have shown the connection between environmental (multiple) stresses and the respective social situation of urban dwellers [4–8]. The socio-spatial concentration of such environmental burdens (e.g., heat, noise, air pollutants, lack of green spaces, poor housing conditions) corresponds with socially disadvantaged urban neighborhoods. Characteristic is both the increased level of pathogenic (e.g., air pollutants) and the lack of salutogenic (e.g., green spaces) environmental factors in such areas, which further increase the social vulnerability of residents and affects their general health [4]. To counteract increasing heat stress in cities, a fundamental intervention option is the utilization of the thermally dampening potential of green and water areas [9]. Predominantly low-sealed green areas provide important services for the local microclimate. Living in areas which are cooler and feature a higher vegetation cover is also associated with a reduced risk for heat related morbidity and mortality [10]. Adverse climate effects are not limited to generally rather deprived world regions. In the US, already more than ten years ago, heat was the number one natural hazard causing deaths [11]. In Germany, in the summer of 2003, approx. 9600 people died from heat-related issues [12] and approx. 8700 in 2018 [13].

Knowledge about the spatial patterns of heat hazards in form of urban heat islands (UHI), urban heat drivers or inhibiters like green spaces, and urbanites exposed to heat is crucial when it comes to addressing these issues from the planning side. Interventions for adaptation are necessary to meliorate the livability of urban spaces [14,15]. Regarding the characteristics of people potentially at risk, it is important to determine the existence of climate injustice in cities. The objective of this study is to interrelate the crucial factors urban heat, vegetation cover, and socio-demographic/economic indicators by examining and analyzing geographical disparities and co-occurrences to inform spatial and urban planning for resilient and just cities.

## 2. The relationship between urban heat, urban green, and social status

The fact that cities feature higher temperatures than the surrounding countryside is presumably known since the first half of the 19th century [16]. According to Oke, the UHI is a thermal anomaly with vertical and horizontal dimensions, which's characteristics are found both in the intrinsic nature of the city (e.g., size/population, building density, land-use distribution) and external influences (e.g., climate, weather, seasons) [16]. The intensity of an UHI (UHII) is defined as the difference between rural and urban temperatures [8]. The (geographic) location, microclimatic influences, as well as background climate play an important role for the pronunciation of an UHI [e.g., 17,18]. Exemplary individual factors that cause and fuel UHIs are urban canyon geometry, air pollution, heat emission from buildings, traffic and living organism metabolism, as well as building materials [17]. The comprehensive set of factors that are of importance and that are researched intensively can be divided into two main groups: physical and social aspects of the urban composition or fabric. The former category tends to explain where and why UHI/heat hazard is most pronounced. The latter focusses on the exposure and vulnerability side, e.g., trying to find correlations between certain population groups and higher or lower exposure or vulnerability to the UHI (we follow the recent IPCC report for the definitions of, e.g., hazard, exposure, and vulnerability (with the sub-components sensitivity and adaptive capacity) in the risk framework [3]). A proxy often used to quantify UHIs, is the land surface temperature (LST), typically acquired airborne or with satellites [19,20]. One area of focus of this study are the spatial disparities of the vegetation provision and heat pronunciation (Chapter 2.1). Furthermore, our research contributes to two strands of urban environmental (in-)justice literature: analyzing the injustice regarding supply with urban green infrastructure (Chapter 2.2) and examining inequities in the thermal stress considering the socio-economic status of urbanites (Chapter 2.3).

### *2.1. Heat and green*

The spatial distribution of UHI depends on morphological configuration, land use, land cover etc. While the entirety of land cover and land use is also intensely researched [21,22], the negative correlation between heat and vegetation is widely acknowledged and has been thoroughly described [23–25]. Here, the normalized difference vegetation index (NDVI) is often used as a proxy operationalizing vegetation cover and quality [e.g., 23,26].

### *2.2. Social factors and green supply*

Especially in urban green infrastructure planning, we see a misbalance between social demand and social equity. US urbanized areas show less tree cover in low-income areas, which also tend to be hotter [27]. In Atlanta, African Americans have significantly poorer access to green spaces [28]. Various analyses have concluded that urban green is unevenly distributed in German cities, and both densely populated and socially disadvantaged districts are often inadequately supplied with urban green [29,30]. In addition, the studies show that socioeconomically well-off residents are predominantly found in areas with lower environmental stresses, while less privileged people are exposed to higher environmental stresses in their place of residence featuring higher health vulnerabilities at the same time [31]. In terms of policy action, the provision of green space in socially disadvantaged neighborhoods is particularly important. In such areas, the need for public green space tends to be higher due to the generally lower provision of private green spaces, which is further exacerbated by increased multiple pressures [32–35].

### 2.3. Social factors and heat

Besides physical factors, a variety of socioeconomic and sociodemographic indicators are put in relation to heat. These are for example age, income, or race. Clear correlations between weaker societal classes and heat exposure are suggested by a large body of literature especially, but not exclusively, on US cities [5,8,23,36–38]. For Phoenix, Arizona, Buyantuyev and Wu [23] discover a weak but significant ($p < 0.001$) negative correlation (0.13–0.25) between income and UHI. Analyzing 20 Southwestern US metro areas, another study finds that, on average, the 10% poorest neighborhoods are 2.2 °C warmer than the most affluent 10%, representing an unequal exposure to heat [36]. Historic housing policies (redlining) persist in shaping inequalities also in climatic terms. Areas formerly impacted by redlining are found generally warmer than those not subjected to redlining [39,40]. People of color are also often located in areas with higher UHIs as proven by a study examining the 175 largest US urbanized areas [8]. Mitchell and Chakraborty researched the three largest US cities (New York City, Los Angeles, and Chicago) and detect lower economic status groups to be at higher heat risk [41]. In Philadelphia, however, Li does not find significant disparities in terms of race/ethnic groups, but elderly are found to live in cooler areas as well as high-income people [42]. The strong inequality effects found in research focusing on US study areas, according to Mitchell and Chakraborty, roots in the still present segregation. Accordingly, marginalized groups live in less desirable areas [6].

For other world regions, including Europe, there is not as much research to be found to date [Delhi, India: [37], Antwerp, Belgium: [43], Manchester, UK: [44]]. Burbidge et al. connect socio-economically marginalized communities, urban heat, and green space distribution in Antwerp, Belgium, and find heat injustice in so far that weaker social groups tend to live in areas that are less green and thus hotter [43]. In Manchester, UK, climate injustice could be determined as more diverse communities, people living in rent, and poor quality housing make up for a greater heat risk, while for elderly and children only a slight trend is found [44]. Another study compares the relationship between income and heat for 25 cities around the world. Here, 72% of poorer neighborhoods feature an elevated exposure to heat. Amongst other cities, the data for Berlin suggests that poorer households suffer from higher UHIIs [45]. Via a survey on German households, Osberghaus and Abeling, however, do not find differences in heat hazard and exposure for more or less deprived households [5].

Based on the reviewed literature, generally, one can say that socioeconomically well-off residents are predominantly found in areas with lower environmental stress, while socioeconomically disadvantaged are exposed to higher environmental stresses in their place of residence, with higher health vulnerability at the same time. Therefore, these neighbourhoods in particular should have a higher proportion of urban green space to compensate for the prevailing pressures such as pronounced heat. However, it has to be kept in mind that not only residential areas but also other places that people frequent, like the workplaces, where they spend a considerable amount of time, must not be excluded from a comprehensive vulnerability and exposure assessment.

### 2.4. Goals and RQs

The relationships outlined above are often regarded separately leading to the derivation of recommended actions based on the respective results. In the past, climate adaptation measures have also unintendedly led to an increase in climate injustice [3]. In order to avoid that, we follow a stringent integrated approach by regarding all the relationships between urban heat, vegetation, and social status, before combining the three factors in a cluster analysis. Such an approach is purposeful as, for example, the reduction of climate injustice and associated health issues are urgent tasks, for which not only the UHI distribution must be regarded but also the vegetation, especially in form of accessible and highly functional green areas. Thus, we examine the mentioned interplay in a post-industrial, segregated region subject to profound structural changes now and in the future. Our epistemic interest leads to the following research questions.

**RQ 1.** What does the relationship between heat and green provision look like?

**RQ 2.** What does the relationship between green provision and social status look like?

**RQ 3.** What does the relationship between heat and social status look like?

**RQ 4.** To what extent are spatial clusters disclosing and depicting similar heat, green supply, and social status conditions in the study area?

While RQ 1-3 focus on the individual relationships between the factors regarded, RQ4 builds on these findings to combine the factors and to gain comprehensive insights on the interrelations and the spatial arrangement (see Fig. 1).

The remainder of the paper is structured as follows. The next section (Chapter 3) lists and explains the data and methodology applied in the course of this research. Then, Chapter 4 is dedicated to communicating and discussing the results obtained. Conclusions and an outlook complete this article in Chapter 5.

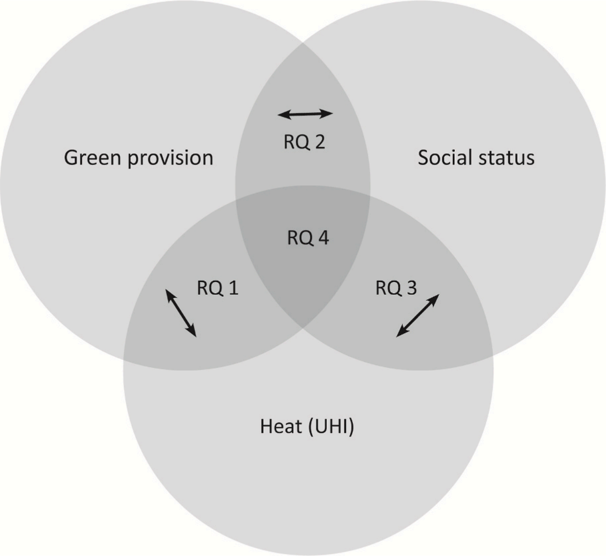

**Fig. 1.** Graphical representation of the research questions.

## 3. Material and methods

In order to answer the research questions, the following methodological approach, visualized in a research design (see Fig. 2), is applied. In a first step, the required data are procured and prepared accordingly. Subsequently, factors are correlated with each other. Finally, the factors are clustered to show underlying spatial structures of similarity and disparity. Preparing and analyzing the data is done with ArcGIS, GeoDa, and RStudio [46–48].

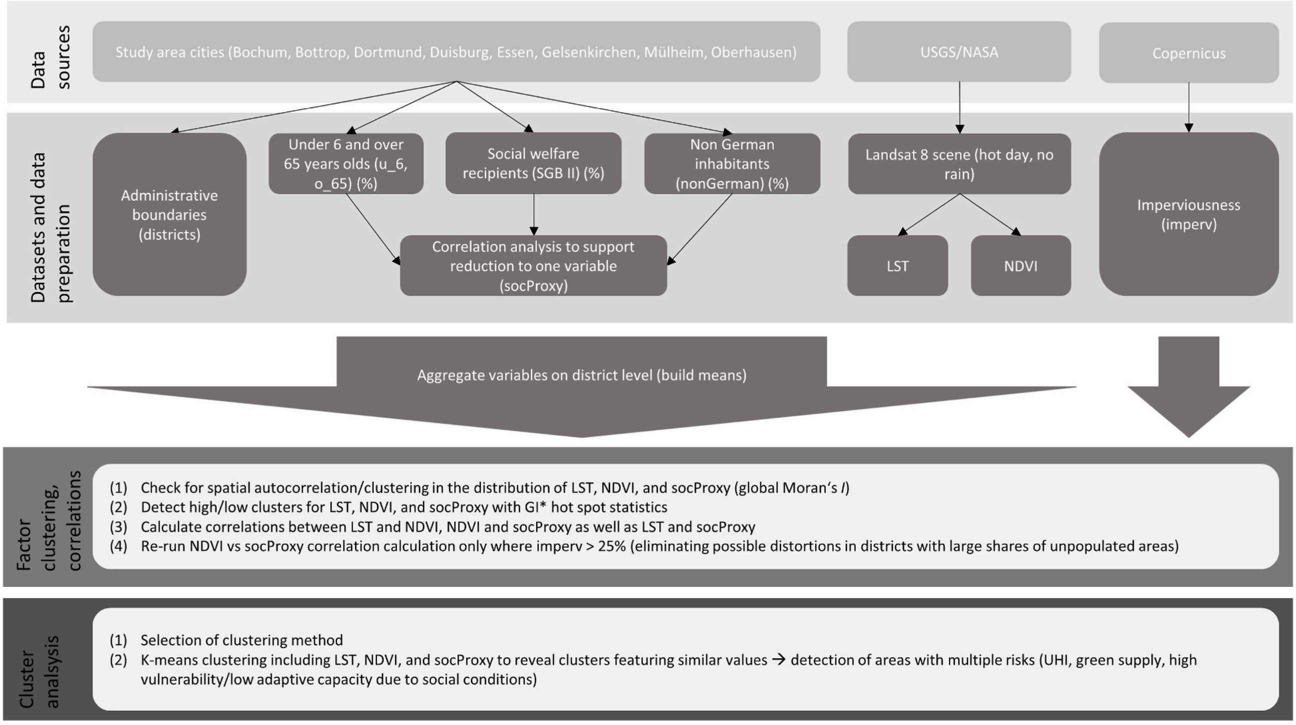

**Fig. 2.** Methodological approach.

**Fig. 3.** Location of the study area in North Rhine-Westphalia.

### 3.1. *Study area*

The research area for this study is the historically highly segregated Ruhr area in Western Germany (see Fig. 3), which is one of the largest metropolitan areas in Europe and densely populated. It is polycentric with a heterogeneous distribution of socio-spatial problems and economic potential. Therefore, it is most suitable for an evaluation of the relationships between heat, green provision, and social status factors. Inequalities in the Ruhr area arising from various historical development steps are particularly evident in a pronounced north-south divide along the federal highway A40 that runs through the whole region and is sometimes referred to as the social equator in both academia and the media [49,50]. It is crucial to note here that the A40 is not a cause but a symptom for the present segregation. The area north of the freeway, the so-called Emscher zone, was hit especially hard by the ongoing and intensifying structural changes as it was home to the majority of industrial workers [50]. The southern parts on the other hand, in the so-called Hellweg zone, where the industrialization took place earlier and that consists of existing older cities and settlement structures, had more time to restructure and adapt [51,52]. Describing this contrast, Wehling speaks of *organized complexity* in the Hellweg zone and of *disorganized complexity* in the Emscher zone [52]. Reflecting the south to north expansion of heavy industry in the Ruhr area, these structural heterogeneities are still perceptible [51]. Our study cities are Bochum, Bottrop, Dortmund, Duisburg, Essen, Gelsenkirchen, Mülheim, and Oberhausen as they all are situated along the mentioned A40. Some of these cities, like Dortmund and Essen, encompass districts in both zones featuring an internal north-south divide themselves while others, like Gelsenkirchen and Bottrop, are located completely in the northern Emscher zone displaying no such internal divide.

### 3.2. *Datasets and data preparation*

There are different approaches for capturing the spatial distribution of urban heat. UHIs and UHII are often operationalized by applying the LST as a proxy [20,22,37,53]. Today, Landsat 8 is adopted in various locations and with various temperature derivation methods [54]. To obtain LSTs representing the spatially differentiated heat hazard and thus also the exposure for people affected, we apply the algorithm presented by, amongst others, Avdan and Jovanovska [55] that is widely applied in the field [24,56–58]. For the aforementioned procedure Landsat 8 Bands 4, 5, and 10 are required. First, the thermal infrared Band 10 is used to derive the top of atmospheric (TOA) spectral radiance, which is then converted to the at-sensor brightness temperature (BT). Combining Bands 4 (red) and 5 (near-infrared), the NDVI is calculated [59], which serves as an input for the derivation of the proportion of vegetation. NDVI and proportion of vegetation are then used to determine the ground emissivity. Finally, the at-sensor temperature and the ground emissivity (as correction factor) are inputs for the final LST calculation. We choose a Landsat scene from a hot summer day in 2018 (maximum temperature above 30 °C [60]). As moisture plays an important role influencing the UHI [16], another inclusion criteria is *no precipitation for two days before the measurement*. Furthermore, we set the maximum cloud cover to 5%. Similar selection procedures are common in UHI research. Shandas et al., for example, chose data from days with maximum temperatures above the 90th percentile of historic averages [61]. Buyantuyev and Wu only included data from days prior to which there was no precipitation for four days and that were cloud-free [23]. The calculation of NDVI values, also part of the LST derivation above, as proxy for vegetation density/cover, and as such either mitigating or promoting heat exposure, is done using bands 4 and 5 of the said Landsat scene [59]. The Landsat 8 scene with its spatial resolution of 30 × 30 m for the LST and NDVI derivation comes from NASA's Earth Explorer platform [62].

There is wide range of socio-demographic and socio-economic factors that are applied describing vulnerability to heat of societal groups. One common variable is age. Here, very young and old people (often under 5/6 and over 65 years as a threshold) are considered more vulnerable to adverse heat effects [41,43,44,63]. In particular, the elderly group is suffering from the impacts of heat stress. Studies about previous heat waves have revealed that the morbidity and mortality rates of the elderly are increased during and post heat periods [64]. Thus, for this study we consider the share of the age groups under 6 (u_6) and above 65 (o_65) years as variables for age as vulnerability indicator.

Socio-economic status is operationalized with indicators like income [27,36,38,65], poverty [44], employment status [43], or social welfare reception [30,63]. Moreover, migration status [30,63], ethnicity/race [41,44,65], or minority membership [36,38] can be mentioned. Due to data availability and up-to-dateness, in our study, we use the social welfare reception (SGB II) and the nationality status (nonGerman) as indicators for the socio-economic status contributing to vulnerability. Unfortunately, there is no free and high resolved data on health status being a factor determining vulnerability. However, one motivation for our research are the potential effects on health that excess heat combined with a low green provision can have on vulnerable groups.

Administrative boundary data (statistical districts) as well as socio-economic and socio-demographic data on age groups, social welfare recipients (SGB II) and nationality status (nonGerman) is obtained from the cities regarded [66–73]. For Dortmund, the reporting date is 12/31/2019, for all other cities it is 12/31/2021 for age data and 12/31/2020 for SGB II and nonGerman. In total, we analyze 275 districts in this research. Three districts in Duisburg could not be included due to insufficient data availability for the social indicators.

For the correlation analyses between heat, vegetation, and social factors, we fathom the possibility of combining or reducing the social factors without losing substantial informative value. To do so, we calculate correlations between the social factors mentioned above for the whole study area and aggregated to the cities within.

**Table 1**
Correlation (r-values) between social factors in the whole study area and for Bochum (BO), Bottrop (BOT), Dortmund (DO), Duisburg (DU), Essen (E), Gelsenkirchen GE), Mülheim (MH), and Oberhausen (OB). *** significant at 0.001 level, ** significant at 0.01 level, * significant at 0.05 level.

| Variables | | 1 u_6 | 2 o_65 | 3 SGB II | 4 nonGerman |
|---|---|---|---|---|---|
| **1 u_6** | All cities | 1 | | | |
| | BO | 1 | | | |
| | BOT | 1 | | | |
| | DO | 1 | | | |
| | DU | 1 | | | |
| | E | 1 | | | |
| | GE | 1 | | | |
| | MH | 1 | | | |
| | OB | 1 | | | |
| **2 o_65** | All cities | −0.595*** | 1 | | |
| | BO | −0.436* | 1 | | |
| | BOT | −0.738*** | 1 | | |
| | DO | −0.478*** | 1 | | |
| | DU | −0.758*** | 1 | | |
| | E | −0.684*** | 1 | | |
| | GE | −0.743*** | 1 | | |
| | MH | −0.779*** | 1 | | |
| | OB | −0.768*** | 1 | | |
| **3 SGB II** | All cities | 0.373*** | −0.554*** | 1 | |
| | BO | 0.712*** | −0.692*** | 1 | |
| | BOT | 0.706** | −0.326 | 1 | |
| | DO | 0.794*** | −0.588*** | 1 | |
| | DU | 0.781*** | −0.854*** | 1 | |
| | E | 0.754*** | −0.817*** | 1 | |
| | GE | 0.499* | −0.163 | 1 | |
| | MH | 0.703*** | −0.853*** | 1 | |
| | OB | 0.873*** | −0.788*** | 1 | |
| **4 nonGerman** | All cities | 0.704*** | −0.681*** | 0.554*** | 1 |
| | BO | 0.538** | −0.887*** | 0.841*** | 1 |
| | BOT | 0.721** | −0.440 | 0.964*** | 1 |
| | DO | 0.684*** | −0.644*** | 0.889*** | 1 |
| | DU | 0.810*** | −0.903*** | 0.925*** | 1 |
| | E | 0.604*** | −0.886*** | 0.848*** | 1 |
| | GE | 0.656** | −0.306 | 0.918*** | 1 |
| | MH | 0.708*** | −0.811*** | 0.916*** | 1 |
| | OB | 0.999*** | −0.732*** | 0.939*** | 1 |

Table 1 shows that relating u_6 and SGB II with the indicator nonGerman features high positive correlation coefficients. Between o_65 and nonGerman, the correlation coefficient proves to be negative (nonGerman population does not coincide with high shares of elderly). Nevertheless, we decide for nonGerman as our single social status indicator/proxy. Our approach focusses rather on the relationships between socially deprived populations and LST as well as NDVI than on urbanites' vulnerability in general. Regarding elderly persons (o_65) there is evidence that, while their propensity to be adversely affected regarding health issues is indisputable (see above), they are often not exposed to heat to a higher degree. For instance, in a study considering Philadelphia this was found by Li [42]. Data for our study area also supports these findings. The cartograms provided in Appendix Fig. 1 reveal, that elderly inhabitants predominantly live in cooler and greener regions of the study area. Thus, excluding the age indicators as standalone (elderly non-German people are still covered) variables is viable for our purposes. Especially its very strong correlation to the social welfare quota (SGB II) makes nonGerman a suitable indicator that, in addition to representing probable social weakness, also covers potential language barriers people might face. Thus, the non-German population can also be seen as more prone to the risk of heightened heat exposure and especially vulnerability regarding adverse health effects connected with urban heat. Although, in the recent past, substantial shares of the non-German population originate from countries with warmer climates potentially featuring both a lowered level of sensitivity and an increased knowledge regarding adaptation strategies, their often precarious economic situation (see correlation with SGB II quotas) prevents them from financially and factually being able to put in value these experiences (e.g., change the place of residence or making adjustments to their homes). While for our aggregation level (districts), nonGerman as a proxy works well for the reasons mentioned above, detailed analyses on a higher resolved spatial level might certainly require other additional factors.

As some, especially peripheral, districts feature only small built-up, developed areas and are otherwise dominated by agricultural land or forests, we repeat the NDVI vs nonGerman correlation calculation (described in Chapter 3.4) with a modified setup including impervious surface data (imperv). The imperv data used is in a raster resolution of 10 × 10 m and stems from the Copernicus database (reporting date 2018) [74].

### 3.3. Descriptive stats and factor distribution in the area

For all variables applied (LST, NDVI, nonGerman) we determine the mean for each district (aggregation). As each aggregation procedure comes with a certain bias, we furthermore calculate the coefficients of variation in the distinct districts to better embrace the situation within the neighborhoods. This also helps interpreting and describing the results from the following cluster analyses. The next step is the calculation of basic stats (minimum – min, maximum – max, mean, median, standard deviation – sd) for each district for LST, NDVI, and the social indicator nonGerman.

We conduct a global Moran's *I* analysis (clustered vs random distribution) and Gi* calculations (reveal locations of high/low value clusters) to examine whether the indicators regarded are clustered and not randomly distributed in the study area [75]. For both processes we apply a queen contiguity (all neighbors sharing a border with the unit regarded are part of the neighborhood) based approach to model the neighborhood and to get a spatial weights matrix ($W = (w_{ij})$) for the pairwise comparison of spatial units. The *I* values are to be interpreted including the respective p-values and generally reach from $-1$ (negative autocorrelation) to 1 (positive autocorrelation), with values close to 0 meaning no autocorrelation. The formulas for the Gi* hot spot statistics as well as the global Moran's *I* are given below:

$$G_i^* = \frac{\sum_j^n w_{ij} \bullet x_j}{\sum_j^n x_j}, \tag{1}$$

*with n being the number of spatial units (districts), and $x_i$, $x_j$ the attribute values at locations i and j.*

$$I = \frac{n}{\sum_{i,j}^n w_{ij}} \bullet \frac{\sum_{i,j}^n w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_i^n (x_i - \overline{x})^2}, \tag{2}$$

where $n$ is the number of spatial units (districts), $\overline{x}$ denotes the average of the observed attribute values, and $x_i$, $x_j$ are the values at locations $i$ and $j$.

### 3.4. Correlation analysis

The answers to RQ 1 to 3 are generated with correlation analyses for the whole study area as well as for the distinct cities therein. For RQ 1 we calculate the correlations (Pearson) between LST and NDVI, for RQ 2 the same is done for the relationship between NDVI and nonGerman, and for RQ 3 finally, we look at LST and nonGerman. In order to eliminate possible distortions in districts with large shares of unpopulated areas, we re-run the analysis with NDVI and nonGerman only where the imperviousness (imperv) is over 25% suggesting an urban structure [76]. Data on population densities as a measure for the presence of people is unfortunately not available in spatial resolutions sufficient for our purposes.

**Table 2**
Basic stats regarding LST, NDVI, and nonGerman for every study city and all cities together.

| Variables | | LST [°C] | | | | | | NDVI | | | nonGerman [%] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spatial unit | Min | Max | Mean | Median | sd | Min | Max | Mean | Median | sd | Min | Max | Mean | Median | sd |
| **All cities (n=75)** | 23.60 | 32.90 | 28.98 | 29.17 | 1.75 | 0.08 | 0.43 | 0.25 | 0.25 | 0.05 | 2.10 | 60.15 | 17.10 | 14.08 | 11.55 |
| **BO (n=30)** | 23.60 | 30.34 | 28.12 | 28.52 | 1.60 | 0.13 | 0.34 | 0.26 | 0.26 | 0.04 | 3.13 | 33.21 | 14.67 | 11.78 | 7.85 |
| **BOT (n=17)** | 25.92 | 31.29 | 29.22 | 29.14 | 1.56 | 0.11 | 0.40 | 0.27 | 0.27 | 0.05 | 2.80 | 27.4 | 11.09 | 10.80 | 7.47 |
| **DO (n=62)** | 24.92 | 31.38 | 28.97 | 29.14 | 1.26 | 0.11 | 0.40 | 0.27 | 0.27 | 0.05 | 3.65 | 59.59 | 15.73 | 12.30 | 13.75 |
| **DU (n=43)** | 26.32 | 32.10 | 30.21 | 30.29 | 1.27 | 0.08 | 0.31 | 0.21 | 0.23 | 0.05 | 4.49 | 60.15 | 22.10 | 18.75 | 13.75 |
| **E (n=50)** | 22.48 | 31.68 | 28.12 | 28.36 | 1.69 | 0.10 | 0.35 | 0.26 | 0.26 | 0.05 | 2.20 | 50.60 | 16.53 | 14.40 | 11.23 |
| **GE (n=18)** | 24.85 | 29.01 | 26.85 | 26.93 | 1.29 | 0.17 | 0.33 | 0.25 | 0.26 | 0.04 | 7.23 | 43.65 | 24.15 | 23.55 | 11.60 |
| **MH (n=28)** | 24.79 | 32.90 | 29.62 | 29.63 | 1.46 | 0.10 | 0.43 | 0.25 | 0.26 | 0.07 | 2.10 | 46.60 | 15.75 | 13.40 | 11.64 |
| **OB (n=27)** | 26.63 | 32.33 | 30.19 | 30.42 | 1.60 | 0.13 | 0.35 | 0.23 | 0.22 | 0.05 | 2.70 | 37.30 | 16.49 | 15.50 | 8.58 |

### *3.5. Cluster analysis*

Building on the previous findings and based on RQ 1-3, our final research question (RQ 4) is dedicated to the detection of areas (district clusters) that feature similar indicator values and can thus describe multiple issues: UHI and overheating through high LSTs, issues with green supply (NDVI), and heightened vulnerability or low adaptive capacity due to social conditions (nonGerman). In a cluster analysis, the allocation algorithms serve the aim of minimizing the variability of the spatial units within a cluster and at the same time maximizing the variability between the clusters. Only by this, generalizable statements about spatially differentiated strategies are possible. In our case, cluster formation is based on the characteristics of the three factors UHI, NDVI and nonGerman. With such a large number of cases ($n = 275$), a suitable number of clusters is usually first searched for, and, in a further step, the cases are (re-)assigned to the clusters – the procedure therefore consists of two steps.

1. Hierarchical cluster analysis (Ward algorithm; optimization of squared Euclidean distances) with the previously determined factor values [77]. The aim is to determine the optimal number of clusters and the cluster centers (average values of the factor values in the districts belonging to the cluster).
2. Cluster center analysis (k-means) with the factor values [78]. The aim is to optimize the cluster affiliation of the statistical districts based on their distance from the cluster center.

By means of hierarchical (agglomerative) cluster analysis, the districts with the smallest Euclidean distance (determined based on the factor values for LST, NDVI, and nonGerman) are grouped together. Ward's method is utilized for the clustering. This method is based on the distance between the respective value and a central point in each cluster, which tends to result in nicely balanced clusters.

Thereafter, the cluster centers are determined for the respective clusters provided in step one. In addition to the number of clusters, these are required to enable the best possible allocation of the statistical districts to clusters based on the cluster center analysis. The cluster center represents the combination of the mean values of the characteristics of the three factor values. In practice, an ideal hypothetical district is formed, representing the center of a cluster.

The k-means algorithm is based on the squared Euclidean distance as the measure of dissimilarity. The districts with corresponding factor values are assigned to the cluster centroid to which they are closest, using a Euclidean (squared difference) dissimilarity criterion. The k-means method uses an iterative relocation heuristic as the optimization strategy. This means that after an initial solution is established, subsequent moves (i.e., allocating observations to clusters) are made to improve the objective function. At each step, the total of the within-cluster sums of squared errors (from the respective cluster means) across all clusters is lowered.

## 4. Results and discussion

### *4.1. Descriptive stats, global autocorrelation, and factor clustering*

Table 2 depicts the basic descriptive statistics for LST, NDVI, and nonGerman for the total study area as well as for the specific cities therein. No peculiarities in the data can be seen here. Cities with more districts (higher n) feature greater differences between min and max than cities with lower n. However, the mean and median values are always close together signalizing the lack of outliers. The same is true for sd values that are all in the same range for the cities and indicators regarded.

As supporting material (e.g., for the intepretation of clusters later on), we provide maps depicting the result of the mean calculation for each district and each of the three parameters applied in Appendix Fig. 2. Furthermore, Appendix Fig. 3 contains two maps showing the coefficients of variation for LST and NDVI on the district level. As nonGerman data was obtained on the (politically relevant) district level without any information on the variation below this spatial level, no coefficient of variation calculation could be conducted.

Moran's $I$ for LST lies at 0.6, for NDVI it is 0.5, and for the share of non-German inhabitants $I$ is 0.47. All three values suggest spatial autocorrelation and thus clustering of similar values in the same region. This assumption is further confirmed by the results of the Gi* cluster analyses. Fig. 4 shows high-low clusters (Gi*) on the district level for LST (a), NVDI (b), and nonGerman (c). Clusters depicted are at least significant on the 95% confidence level and are the result of 999 permutations. On the level of the whole study area, high temperature clusters are found in the densely built and populated northern inner city districts of Dortmund and large parts of Duisburg and Oberhausen in the west. Cooler districts are found in the rural south of Dortmund and Mülheim as well as in the north of Bochum and almost all districts of Gelsenkirchen and the eastern districts of Essen. High NDVI values and thus a higher vegetation cover cluster in many of the norther- and southermost parts of the Ruhr area where more districts with rural spatial structures dominate. Least green areas on the other hand are found in inner city districts that are often characterized by a high level of impervious surfaces and a lack of green/blue infrastructure. The inner/outer city contrast is even more pronounced when the share of nonGerman is regarded. High clusters are found in central city parts, whereas the most distant, rural districts feature the lowest shares and form low clusters.

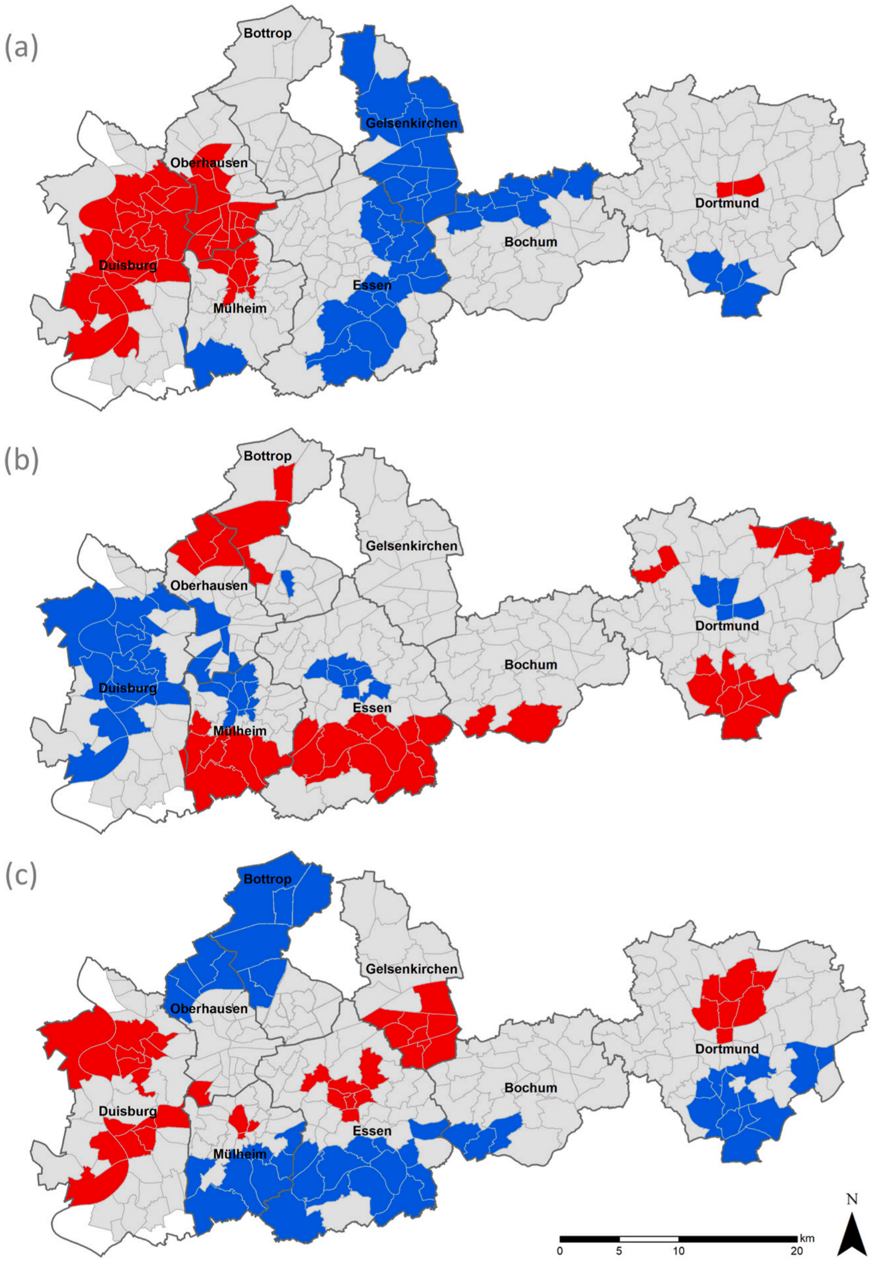

**Fig. 4.** Cluster analysis (high-low clusters) with Gi* statistics on the distribution of LST (a), NDVI (b), and the share of non-German inhabitants (c) in the districts of the study area. Red stands for high value clusters, blue for low value clusters.

### *4.2. Correlation analysis*

Figs. 5–7 show the correlation results for the combinations LST vs NDVI (Fig. 5), NDVI vs nonGerman (Fig. 6), and LST vs non-German (Fig. 7). The LST vs NDVI case (RQ 1) shows correlation coefficients reaching from −0.4 (Bochum) to −0.88 (Mülheim). All correlation results are significant on the 0.001 level except for Bochum and Gelsenkirchen (0.05). The relationship is negative for all cities. This is also what was expected from previous research (see Chapter 2.1).

The NDVI vs nonGerman (RQ 2) shows negative correlation coefficients from −0.5 (Dortmund) to −0.83 (Essen). Here, the assumed relationship between weaker societal status and lower vegetation cover is confirmed (see Chapter 2.2). Except for Gelsenkirchen (0.01) all correlations are significant on the 0.001 level. The differences between cities, however, are quite large. Dortmund obviously features green spaces also in areas inhabited by less Germans. Whereas the opposite is true for Essen, where less nonGermans live in green areas. The re-run of the NDVI-nonGerman correlation analysis features very similar results compared to the original calculation without the imperviousness restriction. This, at first sight somewhat surprising outcome, can be comprehended by looking at the land use/land cover structure of the districts. Low built-up shares mainly occur in rather peripheral districts where the building

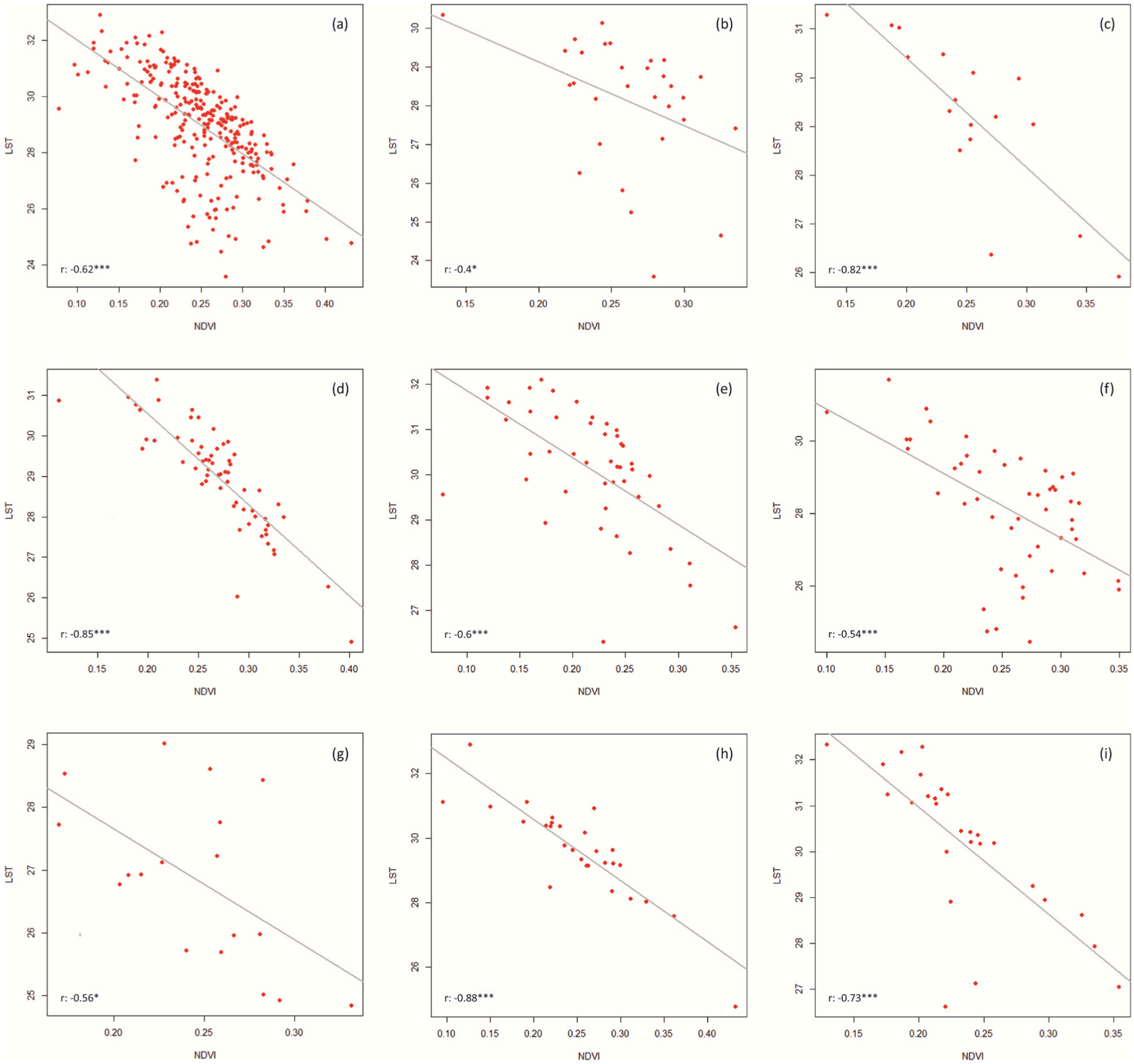

**Fig. 5.** Scatter plots (LST vs NDVI) with linear regression lines for the whole study area (a) and the cities of Bottrop, Bochum, Dortmund, Duisburg, Essen, Gelsenkirchen, Mülheim, and Oberhausen (b–i).

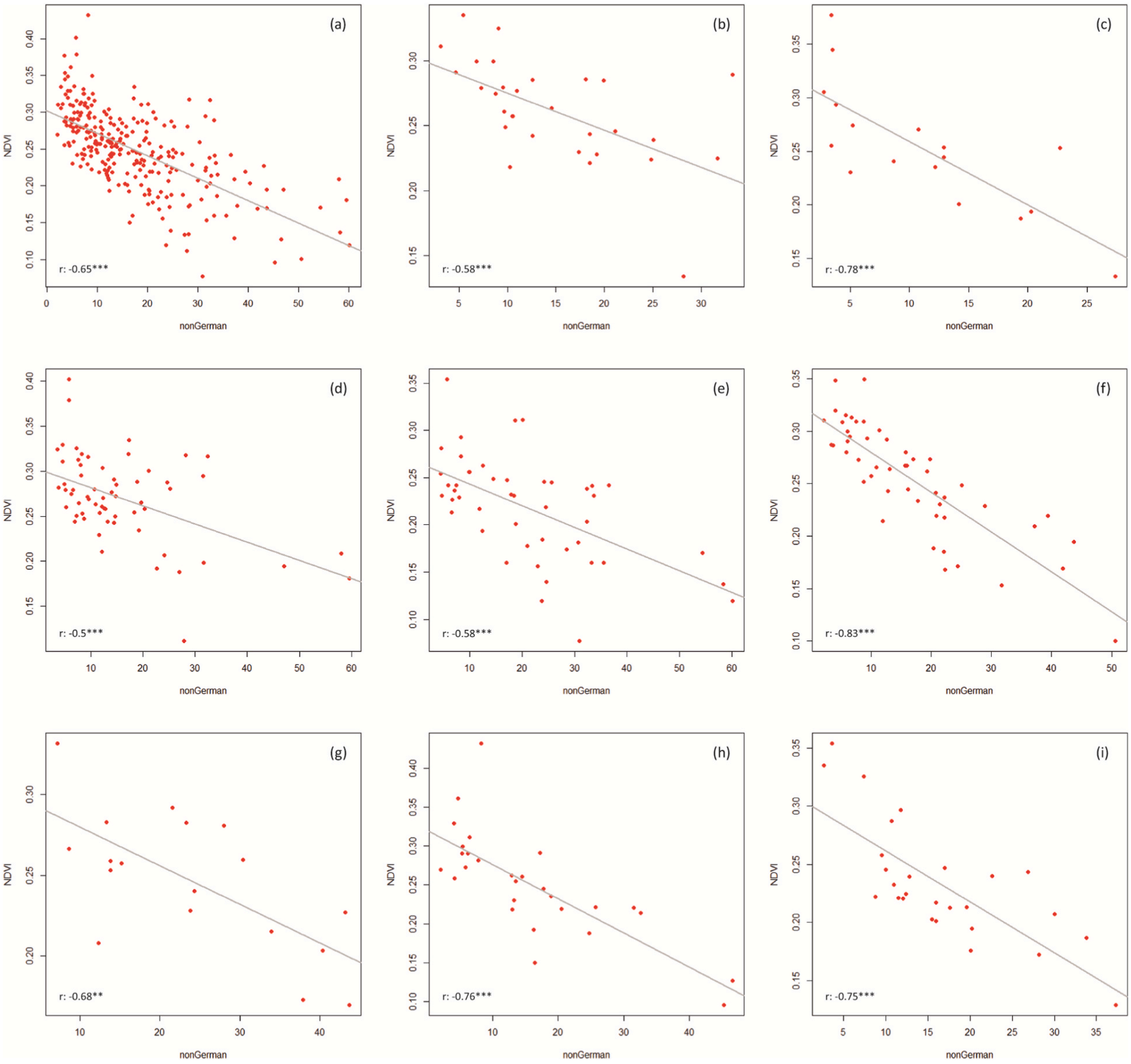

**Fig. 6.** Scatter plots (NDVI vs nonGerman) with linear regression lines for the whole study area (a) and the cities of Bottrop, Bochum, Dortmund, Duisburg, Essen, Gelsenkirchen, Mülheim, and Oberhausen (b–i).

density and population density generally is lower than in central parts. Thus, restricting the NDVI vs nonGerman analysis to only these zones does not change the previously perceived relationship. Furthermore, the social proxy (nonGerman) regularly features higher values in more central parts of urban areas (due to assumed employment opportunities, clustering of functions, and higher availability of living space, e.g.).

When it comes to the LST and nonGerman relationship (RQ 3), the correlation analysis shows an ambiguous picture. Bottrop features a very low correlation coefficient of 0.11, while the highest one is found in Duisburg and Mülheim (0.6). For Bochum, Bottrop, and Gelsenkirchen, the correlation results are not significant, for Essen it is significant on the 0.05 level, for Dortmund and Oberhausen on the 0.01 level, and for Duisburg and Mülheim on the 0.001 level. Non-German citizens are thus heterogeneously impacted by higher temperatures in our study area. These diffuse outcomes match previous studies' findings applying similar indicators, according to which for some cities strong correlation and injustices were found [36,43] and for others this was not the case [5,42]. This reinforces the need for detailed analyses. We can conclude that the relationship between our social proxy (nonGerman) and heat is not area-wide significant and strong, but it is for some cities and possibly also their respective neighborhoods. Our results can serve as first indication for the need of future investigation of certain areas.

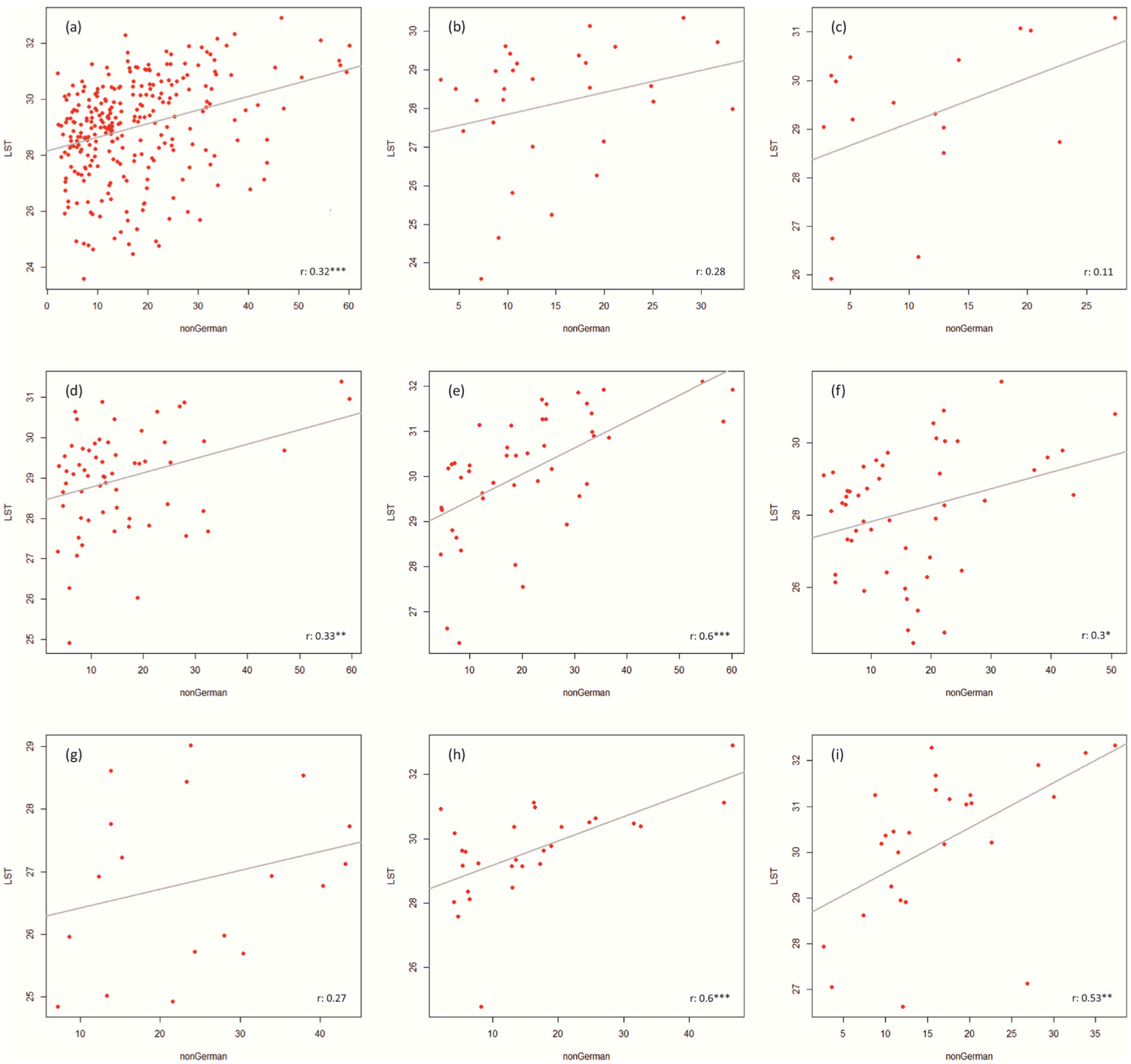

**Fig. 7.** Scatter plots (LST vs nonGerman) with linear regression lines for the whole study area (a) and the cities of Bottrop, Bochum, Dortmund, Duisburg, Essen, Gelsenkirchen, Mülheim, and Oberhausen (b–i).

### 4.3. *Cluster analysis*

Building on the previous correlation analyses and in order to gain more profound insights on the interplay of all three factors we conduct a cluster analysis (RQ 4). This helps visualizing the distribution of UHI taking into account the social structure and green space provision to indicate the need for action. The set number of clusters determined by the hierarchical cluster analysis is six. Fig. 8 shows the spatial distribution of the six clusters. Underlying factors like the historical development, spatial structure or building density of the districts can serve as potential explanations for the resulting clustering. The following six types of clusters can be differentiated:

Cluster 1: districts with high temperatures and high proportions of socially deprived groups, with very low green provision → highly concentrated city center locations, often in the Emscher zone.

Cluster 2: districts with high temperatures and low green provision, but less socially deprived groups → densely built-up and sealed inner city locations.

Cluster 3: districts with relatively high temperatures and low green provision, but significantly less socially deprived groups → peripheral city areas.

Cluster 4: districts with significantly lower temperatures and higher green provision, but still high proportion of socially deprived groups → peripheral areas, mostly in between cities.

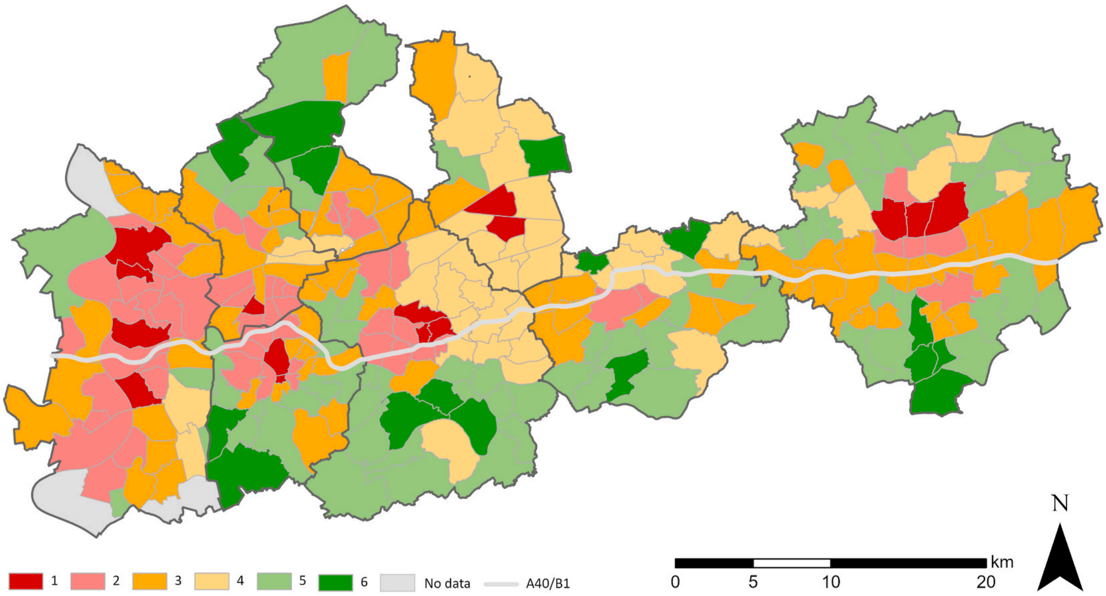

**Fig. 8.** Cluster analysis results.

Cluster 5: districts with low temperatures and a high green provision, as well as low proportion of socially deprived groups → peripheral areas with a rural spatial structure.

Cluster 6: districts with the lowest temperatures and highest green provision as well as lowest proportion of socially deprived groups → peripheral areas with rural spatial structures.

In addition to the mean values of the three factors (LST, NDVI, nonGerman) within the clusters, Table 3 shows the number of districts in the clusters – in each case as a result of the hierarchical cluster analysis (step 1) and after re-sorting as part of the cluster center analysis (k-means). Changes occur in all those districts which's distance to another cluster center is less than the original 'own' center in step 1. Comparing the mean values with each other, one can see the differences of the clusters. There are two clusters (cluster 1 with 30.57 °C and cluster 2 with 30.8 °C) with very high values for the factor LST, but both clusters differ significantly in the case of the social factor nonGerman (cluster 2 with 25,66% and cluster 1 with 47.7%).

Table 4 shows the sd and variance with respect to the distances to the cluster centers within each cluster. In addition to the box plot graphs (Fig. 9), these statistical indicators provide information on how homogeneous a cluster is. While cluster analyses try to minimize the differences within the clusters, there are always outliers, which are not very similar to any cluster center. The final cluster assignment shows that there are more homogeneously occupied clusters with a small dispersion within the cluster and more heterogeneously occupied clusters with a larger dispersion (Table 4).

Through the box plots (Fig. 9), it becomes apparent that cluster 1 is very heterogeneous. The statistical findings in Table 4 underline that: with a standard deviation of 8.98% (nonGerman), 1.54 °C (LST), and 0.04 (NDVI), cluster 1 is by far the most heterogeneous, possibly despite or precisely because of the small number of districts (15) in this cluster. Cluster 3 and 5 are remarkably homogeneous – again despite or precisely because of the large number of districts (78 and 69). The same applies for cluster 4, where there are far fewer districts (43). With standard deviations of 2.00% (nonGerman), 1.17 °C (LST) and 0.0013 (NDVI), the dispersion is low and well below the average at least for the values nonGerman and NDVI (standard deviation of 2.61% and 0.009). For in-depth analyses and interpretation, the maps depicting the coefficients of variation for LST and NDVI on the district level (Appendix Fig. 3) provide valuable additional information. Regarding heat (LST), the variation is generally rather low, reaching a maximum value of about 0.14. Especially warmer, central districts seem to be rather homogeneous regarding LST values, as they feature lower coefficients of variation compared to cooler, more peripheral areas. NDVI coefficients of variation on the other hand are generally much higher, reaching a maximum of 1.47. Roughly speaking, the occurrence of high/low coefficients is inverted compared to the LSTs. Highest NDVI variations are found in the rather central, warmer areas, lower values are often in cooler, peripheral neighborhoods. While the warmest areas seem to feature rather homogeneous temperature regimes due to, e.g., a high general level of imperviousness and building density, the immediate proximity between sealed and unsealed surfaces (parks, gardens etc.) leads to high variations regarding the local NDVI. Cooler, peripheral areas with more mixed and balanced land uses feature more distinguished LST regimes, which results in higher coefficients of variation. NDVI variation is lower especially in districts that are predominantly green with only scattered settlement structures.

The cluster analysis on the aggregation level of statistical districts (Fig. 8) shows that the districts, in which a particularly large number of non-Germans live are mostly concentrated north of the A 40 in the Emscher zone, which is persistent compared to studies using older data [50–52]. The disparities on the green provision also mirror the (rough) bipartite division of the study area. The inner

**Table 3**
Mean factor values within the clusters.

| Nr. | LST [°C] | NDVI | nonGerman [%] | Number of districts (step 1) | Number of districts (step 2) |
|---|---|---|---|---|---|
| 1 | 30.57 | 0.15 | 47.70 | 30 | 15 |
| 2 | 30.81 | 0.19 | 25.66 | 81 | 54 |
| 3 | 29.68 | 0.24 | 13.11 | 41 | 78 |
| 4 | 26.61 | 0.26 | 21.20 | 60 | 43 |
| 5 | 28.56 | 0.29 | 8.33 | 47 | 69 |
| 6 | 26.03 | 0.35 | 5.75 | 16 | 16 |
| Total | | | | 275 | 275 |

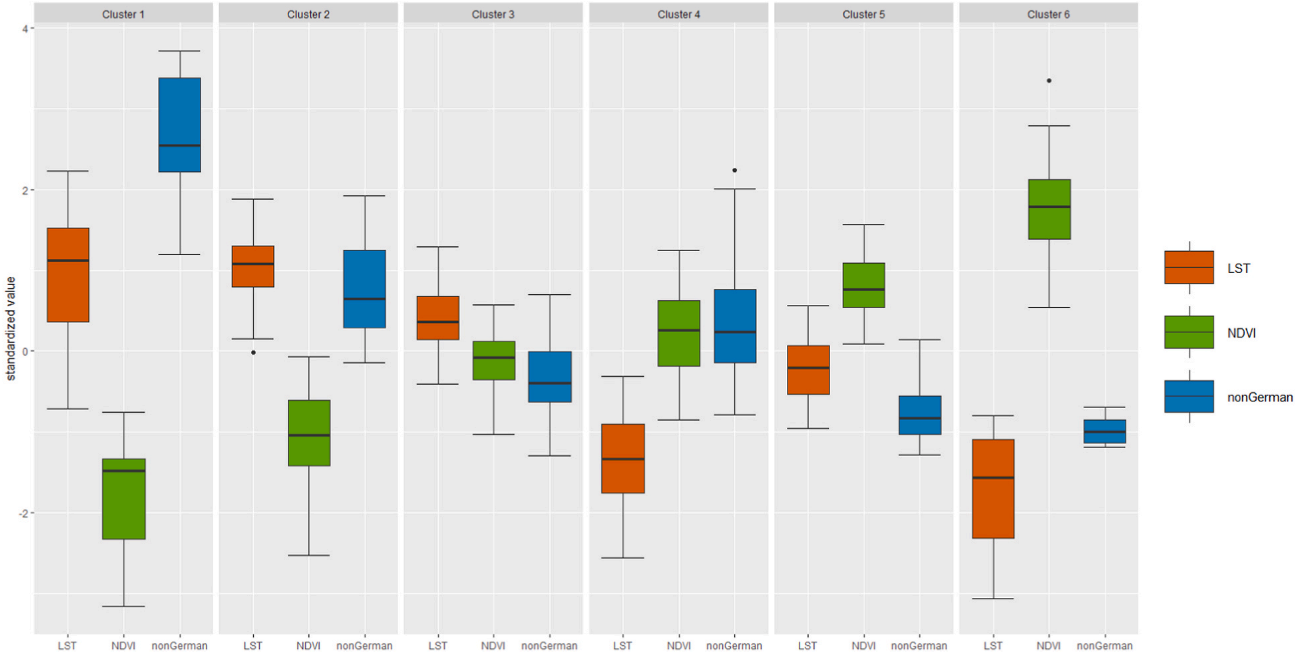

**Fig. 9.** Boxplots for the individual clusters.

**Table 4**
Distances to the cluster centers: standard deviation (sd) and variance.

| Nr. | Number of districts | sd LST [°C] | Variance LST [°C] | sd NDVI | Variance NDVI | sd nonGerman [%] | Variance nonGerman [%] |
|---|---|---|---|---|---|---|---|
| 1 | 15 | 1.54 | 2.36 | 0.040 | 0.0016 | 8.98 | 80.64 |
| 2 | 54 | 0.74 | 0.54 | 0.032 | 0.0010 | 6.31 | 39.83 |
| 3 | 78 | 0.69 | 0.47 | 0.018 | 0.00003 | 5.15 | 26.53 |
| 4 | 43 | 1.08 | 1.17 | 0.029 | 0.0009 | 8.28 | 68.52 |
| 5 | 69 | 0.65 | 0.42 | 0.019 | 0.0004 | 4.14 | 17.17 |
| 6 | 16 | 1.17 | 1.37 | 0.036 | 0.0013 | 2.00 | 4.00 |
| Total | 275 | | | | | | |

**Table 5**
Population distribution of the clusters.

| Nr. | Number of districts | Proportion of residents | Number of residents |
|---|---|---|---|
| 1 | 15 | 6.12% | 170,580 |
| 2 | 54 | 20.89% | 574,079 |
| 3 | 78 | 29.39% | 807,721 |
| 4 | 43 | 19.31% | 530,756 |
| 5 | 69 | 20.73% | 569,889 |
| 6 | 16 | 3.47% | 95,508 |
| Total | 275 | 100% | 2,748,533 |

city-districts, with high densities, and the former old industrial areas with corresponding former old worker's housing estates north of the A40 contain less green spaces. These districts also show higher temperatures. Urban green as a factor in climate adaptation and mitigation against heat stress is not distributed according to the population's needs. Green spaces tend to be least available in districts with a higher share of socially deprived groups. These districts often have an increased need for attention, due to the high density of settlements and their social structure. A closer look at the population distribution in these districts shows that 27.01% (744,659 people) of the population (Table 5) in the case study cities of the Ruhr area live in districts (cluster 1 and 2) that are characterized by high temperatures, low green provision, and a high proportion of socially deprived groups. Only 24.2% (665,397 people) (Table 5) live in districts (cluster 5 and 6) with low temperatures and a high vegetation coverage.

The cluster assignment across the analyzed cities also shows a heterogeneous distribution of the clusters within the cities (s. Fig. 8). Dortmund and Bochum have a more circular historical spatial structure, with, on the one hand densely built-up inner-city districts with prevailing pressures (cluster 1 and 2) and, on the other hand more peripheral districts with rural spatial structures and less heat stress (cluster 5 and 6). Duisburg and Essen as well as Gelsenkirchen have a linear structure, where peripheral districts with rural structures characterized by lower building density and a higher vegetation coverage are located south or north of the city center. Overall, in all cities, the inner-city districts can be seen as hot spots. A closer look at cluster 4 discloses some of the limitations of the aggregation and clustering at district level. Due to the underlying variation of the variables for heat and vegetation coverage, cluster 4 becomes harder to interpret. This cluster consists of districts with significantly lower temperatures and higher green provision, but still high proportion of socially deprived groups in relation to the entire study area. For example to explain the appearance of a "cold belt" in the Emscher zone that encompasses basically the whole city of Gelsenkirchen, more information is needed. The districts of Gelsenkirchen often feature both dense building structures and green areas. On the district aggregation level, these two variables can balance each other suggesting generally less pronounced urban heat effects and thus less issues due to heat stress in these districts. Appendix Fig. 3 shows rather high LST coefficients of variation for Gelsenkirchen suggesting the presence of heterogeneous heat burdens. On a more detailed level potential local hot spots have to be detected in order to inform and guide tailored adaptation measures. Another aspect to be considered is the character of areas that are for example very hot. In the north of Essen there are cluster 2 areas that consist mainly of industrial land uses and not mixed/residential structures as in other cluster 2 regions. While it is important to know that for the selection and prioritization of adaptation action, a focus only on residential areas in order to counter adverse heat effects, such as health impacts, is too narrow, as depending on daytime and phase of life, whereabouts of people are very diverse.

Nevertheless, the analysis shows that, on a level relevant for urban planning, there are spatial clusters depicting similar UHI, green provision, and social status in the study area. Our results represent an addition to the well-described three dimensions of segregation, namely social, demographic, and ethnic, present in the Ruhr area, which are the result of the economic history and thus also land use changes [50–52], by further considering disparities and co-occurrences regarding urban heat and urban green provision. It becomes apparent that there are districts with an urgent need for action regarding the three factors considered. However, there are also districts with less heat stress due to spatial structures and less socially deprived groups. A closer look at the differentiation of the districts shows that each cluster of districts has its own interplay of UHI, NDVI, and nonGerman. Visualizing and analyzing these differences allows specific measures for adaptation and mitigation of heat stress as well as addressing climate injustice in the cities of the Ruhr area.

### *4.4. Limitations*

The data used and the chosen methodological approach exhibit certain limitations. In the German context, data availability, especially on the social status and socio-demographic factors, is unfortunately insufficient in parts, in particular when it comes to high resolution data, therefore not all relevant aspects can be covered with suiting data (e.g., income or health data). Furthermore, more fine-grained data on all ends (LST, NDVI/vegetation coverage, social indicators) would allow for more detailed aggregation levels than districts, potentially exposing different impact and distribution patterns. Due to, in parts strongly, varying district sizes and internal structures, the aggregation via means might bias results. We counter that by additionally calculating the coefficient of variation on the district level allowing inferences on the extent of variability in relation to the mean of the respective variable values. However, more sophisticated normalization procedures might further enhance the transparency and comprehensibility of results. Moreover, temperature and green provision information can probably be made more robust by combining multiple scenes for an average see, e.g., [79]. Finally, combining data stemming from different sources or featuring various spatial resolutions is challenging and a potential source for uncertainties due to the aforementioned necessity of aggregation and the need to compromise regarding the temporal and spatial accuracy of fit.

When it comes to methods, the correlations (especially when n is small) are quite sensitive to outliers leading to misinterpretations. The task for planners and administration is thus to check distributions in detail. In order to determine the influences of certain factors on heat, regression analyses are a future step. Longitudinal approaches, e.g., comparing the last ten years might reveal trends and give hints for future developments, too. Results might also look different when not only social vulnerability is included but health vulnerability in particular or vulnerability as a whole.

The different methods of clustering usually yield very different results. This occurs because of the different criteria for merging clusters (including cases). K-means has trouble clustering data tending to from clusters of varying sizes and densities. Centroids can be dragged by outliers, or outliers might get their own cluster instead of being ignored. Another limitation is that cluster analysis is simply a statistical technique – it assumes no underlying knowledge of the spatial structure. In other words, it is just clustering the data around a series of central points – which way it may or may not make sense once the analysis has been undertaken. The most important part of using the technique is the interpretation of the output to determine suitable strategies and measures to address underling issues by the planning side.

## 5. Conclusions

Our study showed distinct spatial disparities in heat exposure, green availability, and social status between the city districts of the research area. Less green districts are often inhabited by socially weaker populations and are more threatened by heat. Thus, our correlation analyses yielded strong and significant negative correlations between UHII and NDVI as well as between NDVI and the chosen social indicator (nonGerman). Heat and nonGerman, however, are characterized by a diffuse, relationship, varying from city to city (some coefficients indicating weak non-significant and some indicating strong significant positive correlations). Here, detailed studies and the inclusion and testing of further factors might enhance the vulnerability assessment for heat stress. The cluster analysis furthermore generated six distinguishable and spatially explainable clusters with similar characteristics regarding the researched components. We could show that in the study area, more people live in hot and less green districts than in cooler and greener ones. According to this, we can discern differently pronounced climate injustices in the researched cities of the Ruhr area, which will have to be addressed by the administration and planning side in the future.

Our methodical approach is characterized by its high portability and ease of use. Depending on research interest and data availability, other indicators can be included to potentially refine the analyses. Moreover, small-scale studies are needed, e.g., at the block level, as well as the consideration of other factors, such as the building structure or urban morphology in general. In addition, monitoring the described relationships is essential to be up-to-date and to notice changes. The described approach is suitable for presenting inter and intra-urban inequalities and issues in a generally understandable way. The relevance of vulnerability, multiple burdens, and inequality within the city and the region becomes visible, and combined with the local context, stimulates the necessary discussions on justice and the corresponding demands for action. Awareness for the shown spatial patterns and interactions is crucial for customized future urban planning and climate adaptation. On a broad level, we need efficient and unbiased approaches, standardized evaluation tools, and fundamentally accepted orientation values. The integration in planning tools such as heat action plans addressing climate injustice is essential. Therefore, for example, deficit and potential maps, designed also from a social perspective, are required. As a scientific analysis for climate policy decisions and planning in the management of climate adaptation, our work can support addressing climate injustice at an early planning stage. The study at hand is a contribution to the continuous development of procedures and methods in the field of climate adaptation planning for resilient, just and, healthy cities.

### Author contribution statement

Florian Klopfer; Antonia Pfeiffer: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

### Data availability statement

The authors do not have permission to share data.

### Additional information

Supplementary content related to this article has been published online at [URL].

### 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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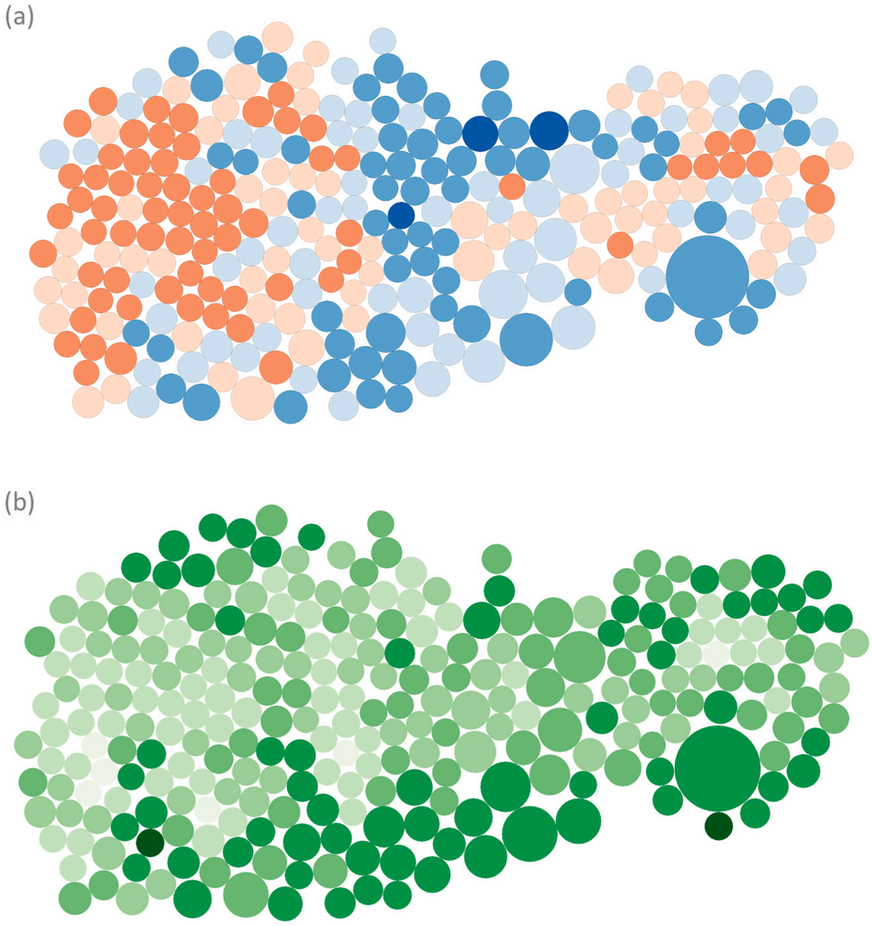
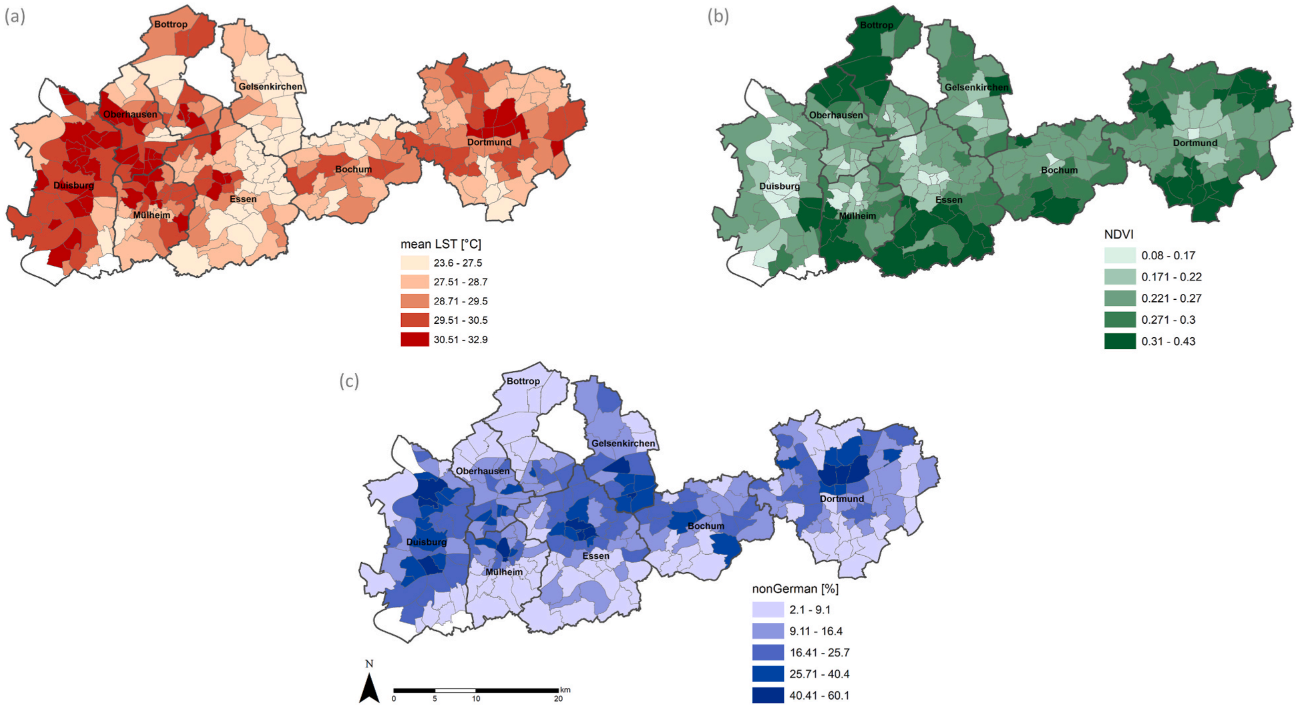
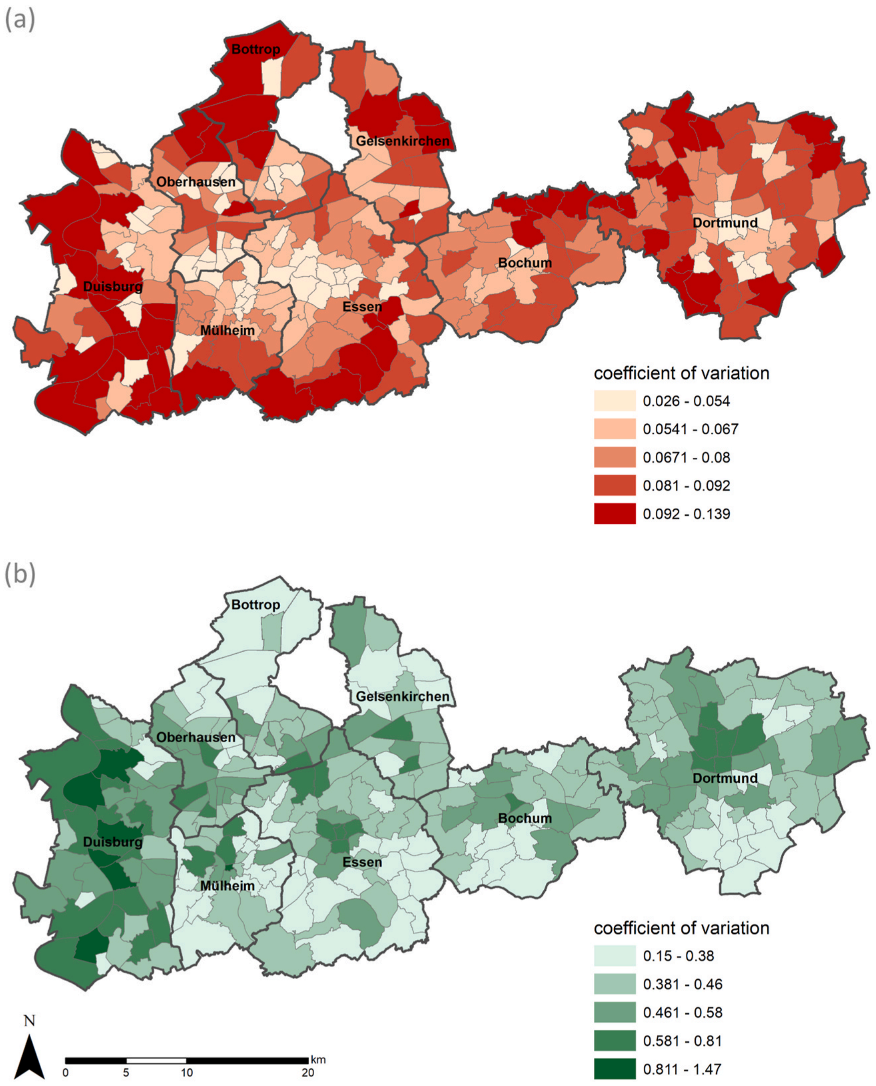
## Appendix



**Appendix Fig. 1.** Cartograms depicting urban heat (LST) (a) and NDVI (b) respectively in combination with the population older than 65 years on a city district level. Circle size represents the share of people over 65 years. Red coloring describes higher LSTs, blue coloring lower LSTs (a). The intensity of the green coloring stands for a higher NDVI (b).



**Appendix Fig. 2.** City district means for LST (a), NDVI (b), and nonGerman (c).



**Appendix Fig. 3.** Coefficients of variation for LST (a) and NDVI (b) on the city district level.

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# Appendix

## A1 Appendix 1

**Publication and conference presentation list**

(a) Peer-reviewed papers:

**Klopfer, F.** and Pfeiffer, A. (2023). Determining spatial disparities and similarities regarding heat exposure, green provision, and social structure of urban areas - a study on the city district level in the ruhr area, germany. *Heliyon*, 9(6):e16185. doi: 10.1016/j.heliyon.2023.e161.

**Klopfer, F.** (2023). The thermal performance of urban form – an analysis on urban structure types in berlin. *Applied Geography*, 152:102890. doi: 10.1016/j.apgeog.2023.10289.

**Klopfer, F.**, Greiving, S., and Gruehn, D. (2022). Creating an evidence base for managing structural change in the rhineland mining area—evaluating open space applying a comprehensive set of indicators. *Journal of Environmental Planning and Management*, pages 1–18. doi: 10.1080/09640568.2022.206231.

**Klopfer, F.**, Westerholt, R., and Gruehn, D. (2021). Conceptual frameworks for assessing climate change effects on urban areas: A scoping review. *Sustainability*, 13(19):10794. doi: 10.3390/su13191079.

**Klopfer, F.**, Hämmerle, M., and Höfle, B. (2017): Assessing the potential of a low-cost 3-D sensor in shallow-water bathymetry. *IEEE Geoscience and Remote Sensing Letters*, 14 (8), pages 1388-1392. doi: 10.1109/LGRS.2017.2713991.

(b) Conference presentations:

Pfeiffer, A. and **Klopfer, F.** (2023): Determining Spatial Disparities and Links in Heat Exposure, Green Supply, and Social Structure of Urban Areas: A Multi-City Study at the District Level in the Ruhr Region, Germany. Presentation, AESOP 2023, 11-15 July 2023, in Łódź (Poland).

**Klopfer, F.** (2023): Entwicklung eines methodischen Ansatzes zur umfänglichen Erfassung, Analyse und Bewertung des Freiraums im Rheinischen Revier unter Einbeziehung von Landschaftsfunktionen und Ökosystemdienstleistungen. Presentation, 6. DOKORP ””Wenn möglich, bitte wenden!” Forschen und Planen für den Sustainability Turn”, 13 February 2023, in Dortmund (Germany).

**Klopfer, F.** and Pfeiffer, A. (2022): Ermittlung von räumlichen Disparitäten der Hitzebelastungen in urbanen Räumen unter Berücksichtigung der Grünraumversorgung und der Sozialstruktur im Ruhrgebiet. Presentation, 5. Community Health Konferenz (CHK 2022), 24-25 November 2022, in Bochum (Germany).

**Klopfer, F.** and Gruehn, D. (2022). Climate (in-)justice in german cities? assessing the relationship between land surface temperature and affordability of housing. presentation. Presented on ISUF 2022 “Urban Redevelopment and Revitalisation. A Multidisciplinary Perspective”, 6-11 September 2022, in Łódź/Kraków (Poland) and online.