Urban Heat:

A Sustainability Challenge Crossing Traditional Boundaries

by

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ABSTRACT

Cities globally are experiencing substantial warming due to ongoing urbanization and climate change. However, existing efforts to mitigate urban heat focus mainly on new technologies, exacerbate social injustices, and ignore the need for a sustainability lens that considers environmental, social, and economic perspectives. Heat in urban areas is amplified and urgently needs to be considered as a critical sustainability issue that crosses disciplinary and sectoral (traditional) boundaries. The missing urgency is concerning because urban overheating is a multi-faceted threat to the well-being and performance of individuals as well as the energy efficiency and economy of cities. Urban heat consequences require transformation in ways of thinking by involving the best available knowledge engaging scientists, policymakers, and communities. To do so, effective heat mitigation planning requires a considerable amount of diverse knowledge sources, yet urban planners face multiple barriers to effective heat mitigation, including a lack of usable, policy-relevant science and governance structures. To address these issues, transdisciplinary approaches, such as co-production via partnerships and the creation of usable, policy-relevant science, are necessary to allow for sustainable and equitable heat mitigation that allow cities to work toward multiple Sustainable Development Goals (SDGs) using a systems approach. This dissertation presents three studies that contribute to a sustainability lens on urban heat, improve the holistic and multi-perspective understanding of heat mitigation strategies, provide contextual guidance for reflective pavement as a heat mitigation strategy, and evaluate a multilateral, sustainability-oriented, co-production partnership to foster heat resilience equitably in cities. Results show that science and city practice communicate differently about heat mitigation strategies while both avoid to communicate disservices and trade-offs. Additionally, performance evaluation of heat mitigation strategies for decision-making needs to consider multiple heat metrics, people, and background climate. Lastly, the partnership between science, city practice, and community needs to be evaluated to be accountable and provide a pathway of growth for all partners. The outcomes of this dissertation advance research and awareness of urban heat for science, practice, and community, and provide guidance to improve holistic and sustainable decision-making in cities and partnerships to address SDGs around urban heat.

Thank you.

To our beautiful Earth, the trees, and all beings living with it.

To all my families—yes plural—wherever you are and have been.

For your selfless, silent, and sound support.

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Here I stand, another branch completed, another seed matured, my forest transformed; all that in a way I was not expecting for it to happen.

Here I stand, not alone, but in the midst of a beautiful, colorful forest of unique individual trees which have influenced my growth.

Here I stand, not only because of what I did, but because of how I was supported and encouraged to keep exploring the unknown—my unknown.

Here I stand, in a space that became a place, a culture once foreign to me, a language we now share, and an experience I will not forget.

Here I stand, thanks to you and the people that were before us.

I want to acknowledge the positionality and privilege that allow me to succeed in the ways I do. As a white, heterosexual, cis-man, born into the German middle-class after the German reunion, I was provided with opportunities and support measures that allowed, allow, and will allow me to succeed with a continuous advantage. I hope that my actions can support justice, equity, diversity, and inclusive efforts on this earth as other peoples' actions helped me succeed.

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CHAPTER 1

INTRODUCTION

1.1 Focus of this work

Ongoing urbanization and climate change cause substantial warming to cities globally with increasing rates of warming expected in the future (Krayenhoff et al., 2018). Heatwaves and elevated temperatures, especially in urban areas, negatively affect human health (Hondula et al., 2015; Howe et al., 2019) and are responsible for more deaths worldwide than any other weather-related event (Larsen, 2015). The changing climate of cities, e.g., increased heat in urban areas, is amplified through urban conditions such as design and human heat sources, which means cities must be considered in more relational, material, historical, and political terms (Rickards, 2019). All city features impact the microclimate, global GHG emissions, and have quality of life implications (Rickards, 2019). Urban heat is responsible for increased per capita water (Guhathakurta & Gober, 2007) and energy use (Akbari et al., 2001; M. Santamouris, 2013). Thus, urban heat is a complex urban sustainability issue that expands beyond the sphere of the urban area since it uses resources beyond its footprint. Sustainability demands transformation in ways of thinking or how cities think (T. Muñoz-Erickson et al., 2017; Sallis et al., 2016). Sustainability demands transdisciplinary interaction during the research process to integrate the best available knowledge (Lang et al., 2012; T. Muñoz-Erickson et al., 2017). Worldwide, cities have increased their focus on local climate adaptation involving citizens (Mancebo & Certomà, 2019) and create partnerships to implement urban resilience (Caughman, 2022), expressing the need for further engagement between scientists, policymakers, and communities (van der Heijden, Certomà, et al., 2019). The outcomes of this dissertation provide a sustainability lens on urban heat, improve the holistic and multi-perspective understanding of heat mitigation strategies, provide contextual guidance for reflective pavement as a heat mitigation strategy, and evaluate a multilateral, sustainability-oriented, co-production partnership to foster heat resilience equitably in cities.

1.2 Background

The United Nations (UN) Sustainable Development Goals (SDGs), set in 2015, are a global agenda for all countries and people to achieve a better and more sustainable future.

SDG #11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable (UN General Assembly, 2015). Specifically, urban sustainability promotes and enables the long-term well-being of people and the planet. Cities are the center of human life for more than 55% of the world's population, and by 2050 the UN expects 68% of all people to live in urban environments (United Nations, 2018). While there is a strong need to mitigate heat, particularly in cities, extreme heat is frequently not perceived as an urgent sustainability issue (Keith et al., 2019). This is especially concerning because urban overheating is a multi-faceted threat to the well-being, performance, and health of individuals, as well as the energy efficiency and economy of cities (Nazarian et al., 2022). It is evident that urban responses to climate change, locally (urban heat) and globally, involve a diverse range of actors and knowledge that cross traditional boundaries (van der Heijden, Bulkeley, et al., 2019). Traditional boundaries refer to the historically and purely academic, disciplinary, or practice-oriented approaches rather than seeking inter- and transdisciplinary interaction which addresses sustainability and complex issues incorporating diverse knowledge such as local and indigenous or user knowledge. Working to achieve SDG #11 cannot occur in a silo; fundamental transformation to address sustainability issues must consider a systems approach that crosses integration of SDGs (Patton, 2023). Current approaches for many academic and non-academic approaches address individual SDGs, without acknowledging the interplay and dependencies (crossing) of multiple if not all SDGs, thus requiring an approach that integrates SDGs with one another.

Extreme heat is considered an invisible and silent threat, which is one of the factors that separates heat from other climate risks such as flooding or wildfires (Keith et al., 2019). Other factors involved in studying urban heat are its spatial and temporal complexity (Coseo & Larsen, 2014), lack of governance (Kaloustian et al., 2016), and compounding effects with other climate risks (Zscheischler et al., 2018). The number of factors results in complexity when determining an appropriate approach for heat mitigation or heat resilience-building. Planners also may face a lack of knowledge on heat and legal or regulatory basis when compared to other climate risks such as flooding which makes preparation and response to heat challenging (Keith et al., 2019). Heat needs to be treated as a complex urban sustainability issue rather than an isolated problem that can be solved with disciplinary or interdisciplinary science. Research shows that new approaches such as co-production (Corburn, 2009) and the creation of usable, policy-relevant science (Kingsborough et al., 2017) address heat as a sustainability issue, which allow a more holistic and sustainable application of heat mitigation strategies and make heat a more mainstream issue (Corburn, 2009; Keith et al., 2019).

To counteract urban overheating, potential heat mitigation strategies include green (urban parks, trees, and other vegetation features), blue (pools, misters, and other water features), and grey infrastructure (pavement, buildings, and other built structures providing shade). Those strategies aim to alleviate heat in cities by reducing surface, and/or air temperature, mitigate heat stress, and improve thermal comfort. It is important to note that recent research has proposed that extreme heat and thermal discomfort should be considered as two separate issues (Leal Filho et al., 2021; Martilli et al., 2020) and that one heat metric alone should not be used as a decision factor (Krayenhoff et al., 2021; Turner et al., 2022). Current mitigation developments that focus on technological solutions as opposed to addressing social inequities in many instances prove to exacerbate issues of injustice (Long & Rice, 2019). Mitigation efforts focus on addressing global climate change rather than local heat challenges (Sailor et al., 2016). Urban overheating affects environmental racism due to higher heat exposure in racially segregated areas (Hoffman et al., 2020) and social injustice due to climate hazard vulnerability, which depends on income, education, and access (Long & Rice, 2019; McDonald et al., 2021).

The effectiveness of heat mitigation strategies studied in relation to the urban heat island (UHI)—the temperature difference between cities and their rural surroundings (Oke, 1982; Taha, 1997)—where the maximum UHI intensity is during nighttime (Oke et al., 2017). But, most heat mitigation strategies have a far higher daytime cooling effect than nighttime (Georgescu, 2015; Krayenhoff et al., 2018; Martilli et al., 2020). Additionally, background climate and local context matter in the efficacy of a heat mitigation strategy (Middel et al., 2020, 2021; Turner et al., 2022). Therefore, recent research aims to change the focus from an urban-rural difference (UHI definition) to an intra-urban difference, which describes urban heat differences within neighborhoods of the city (Martilli et al., 2020). Recent technology and sensor developments can be used to identify local context that affects multiple heat metrics (e.g., air, surface, and mean radiant temperatures) to study urban overheating (Kulkarni et al., 2022; Merchant et al., 2022; Middel et al., 2023; Middel & Krayenhoff, 2019). This context allows recognizing which neighborhoods are particularly vulnerable to heat and applying appropriate equitable heat mitigation strategies where people need them (Keith et al., 2019), including but not limited to neighborhoods facing environmental racism or social injustice. It is important to understand for whom, what, when, where, and why heat mitigation needs to happen (Meerow & Newell, 2019) to be inclusive, safe, resilient, and sustainable and align with SDGs.

Placing new infrastructure, independent of grey, green, or blue, changes the built and natural environment. Research on trade-offs is particularly advanced for green infrastructure (GI) (see e.g., Coutts & Hahn, 2015; Haase et al., 2017; Roman et al., 2020) since it is used in other fields of research as well, such as stormwater management. For example, disservices of trees include infrastructure conflicts, health and safety, aesthetic issues, environmentally detrimental consequences, and management costs (Roman et al., 2021). The possibility of social exclusion and green gentrification has to be considered as well when planning for GI (Haase et al., 2017; Keith et al., 2019; Meerow & Newell, 2019). For urban forestry, negative synergies have been largely ignored (Roman et al., 2021). Similar considerations are needed for cool and reflective pavement (RP). Thus, when planning for heat mitigation strategies one has to consider potential (un-)intended consequences that provide co-benefits or trade-offs such as nighttime visibility improvement or glare, respectively (Akbari et al., 2001; Middel et al., 2020; Roman et al., 2021).

To strategize and apply appropriate equitable heat mitigation strategies where people need them, it is important to recognize which neighborhoods are particularly vulnerable (Keith et al., 2019) and what (un-)intended consequences these strategies create when implemented (Roman et al., 2021). In the process of decision-making, researchers and management often fail to acknowledge the diversity and validity of people’s opinions and experiences, and the reality that disservices even exist (Koop et al., 2017; Shackleton et al., 2016). These failures can cause misidentification and implementation of policies and measures to mitigate heat (Downes & Storch, 2014) leading to potentially unsustainable implementation. Planning for sustainability in general means balancing conflicting goals: economy, environment, and equity (Campbell, 1996). Thus, urban sustainability requires integrative social-ecological-technological solutions as well as transformative and transdisciplinary co-produced, usable science by science, policy, and society to become actionable (Frantzeskaki et al., 2021). To address heat as an urban sustainability issue, many different knowledge types are necessary to ensure sustainable and equitable heat mitigation, which can be brought together by modes such as partnership collaboration. The decision-making process needs to involve a range of actors and agencies within urban climate governance (van der Heijden, Bulkeley, et al., 2019) to ensure equitable planning and empower the voices and users of urban spaces (Mancebo & Certomà, 2019; Patterson & van der Grijp, 2019). Currently, cities are learning how complex the local climate adaptation challenge is and how vital the involvement of citizens is (Uittenbroek et al., 2019). City-university partnerships (CUPs) are a bilateral and transdisciplinary example of a transformation that is needed, involving multiple voices. These partnerships become increasingly important to address complex sustainability problems and develop innovative solutions (Caughman et al., 2020). Beyond that, multilateral partnerships integrate at least three partners involving academics and non-academics, which includes scientists, policy makers, and society at-large. In short, cities and stakeholders require usable, policy-relevant, transferable knowledge (Keith et al., 2019; McNie et al., 2016) that incorporates societal knowledge bodies by crossing traditional boundaries.

Usable science is defined as the science produced to contribute directly to the design of policy or the solution of a problem (Lemos & Morehouse, 2005). It needs to be relevant, credible, and legitimate and involved in boundary-spanning processes such as knowledge co-production (Driscoll et al., 2011; Wall et al., 2017). Co-production is an iterative transdisciplinary process that fosters relationships and trust between the participants and creates a shared vision of what knowledge is usable and policy-relevant (Driscoll et al., 2011). The process connects science and society to address sustainability and inequity problems. It aims to acknowledge and fully integrate the users (community, city staff, etc.) in knowledge production (McNie et al., 2016) and thus can build a comprehensive understanding for informed, sustainable, and equitable decision-making. Examples of co-production include individual projects, where partners aim to achieve a shared goal, or long-term partnerships, which cultivate lasting and meaningful relationships that can create institutional stability to knit projects together over time.

1.3 Research Goals

Current research shows that urban heat and its mitigation are often not addressed in an urgent, sustainable, and equitable manner from science and policy (e.g., Frantzeskaki et al., 2021; Keith et al., 2019; Long & Rice, 2019; Meerow & Newell, 2019). A growing number of scientists calls for more attention and co-production of knowledge in the realm of urban heat. It is unclear how much the perspectives on impacts of heat mitigation strategies vary between science and city practice and what consequences may occur due to diverse understanding or perspectives, especially when disservices are often ignored. New partnerships aim to counteract this potential disconnect between science and policy.

The partnerships build on co-production to co-create knowledge that is usable and policy-relevant to address complex sustainability issues such as heat. But, integrating science and practice in a transdisciplinary scientific process is not guaranteed to be successful in its creation of usable, policy-relevant knowledge. Therefore, a formative evaluation of the process shall help guide the design and decision-making of the partnership to build heat resilience and work towards urban sustainability.

My dissertation has an overall target to advance the research and awareness of urban heat for science, policy, and community. This work further seeks to identify the science-practice disconnect and inequitable implementation of heat mitigation interventions, and to improve holistic and sustainable decision-making in cities to tackle past, present, and future urban heat as sustainability issues to achieve SDG #11.

In summary, my studies herein are focused on urban sustainability, urban heat mitigation, science policy, usable science, co-production, and its evaluation. My dissertation addresses seven (7) goals to support the central research goal:

Goal 1. To add to the scientific and city practice understanding of green infrastructure and reflective pavement;

Goal 2. To identify the science-practice disconnect on heat mitigation strategies by understanding science and city practice perspectives on green infrastructure and reflective pavement co-benefits, trade-offs, and disservices;

Goal 3. To incorporate other knowledge types such as knowledge users/community into the science and evaluation of heat mitigation strategy impacts;

Goal 4. To increase science, policy, and community awareness of co-benefits, trade-offs, and disservices of heat mitigation strategies and their importance for equitable decision-making;

Goal 5. To evaluate a local, multilateral, transdisciplinary, sustainability-oriented partnership and provide guidance to assure successful knowledge co-production and partnership development towards community-based heat resilience;

Goal 6. To adopt a formative bilateral evaluation tool (FAIICES) to guide, cultivate, and foster the design of a multilateral, meaningful partnership ensuring their successful knowledge co-production;

Goal 7. To create new knowledge that will help transform sustainability-oriented, multilateral partnerships for heat resilience approaches to other cities.

My central research target and the seven goals are supported by three individual research projects, outlined in the concept map provided in Figure 1. A detailed discussion of the studies follows in chapter 2, 3, and 4. My dissertation provides a comprehensive understanding of urban heat and how it is underrepresented as an urban sustainability challenge in science and practice.

In chapter 2, my research identifies the different perspectives of science and practice on heat mitigation strategies' co-benefits, trade-offs, and disservices with a focus on GI and RP. Identifying the disconnect allows the creation of efforts to improve collaboration, trust-building, and understanding between science and practice in transdisciplinary environments, which is of essential guidance to address complex sustainability issues such as heat (Figure 1, middle).

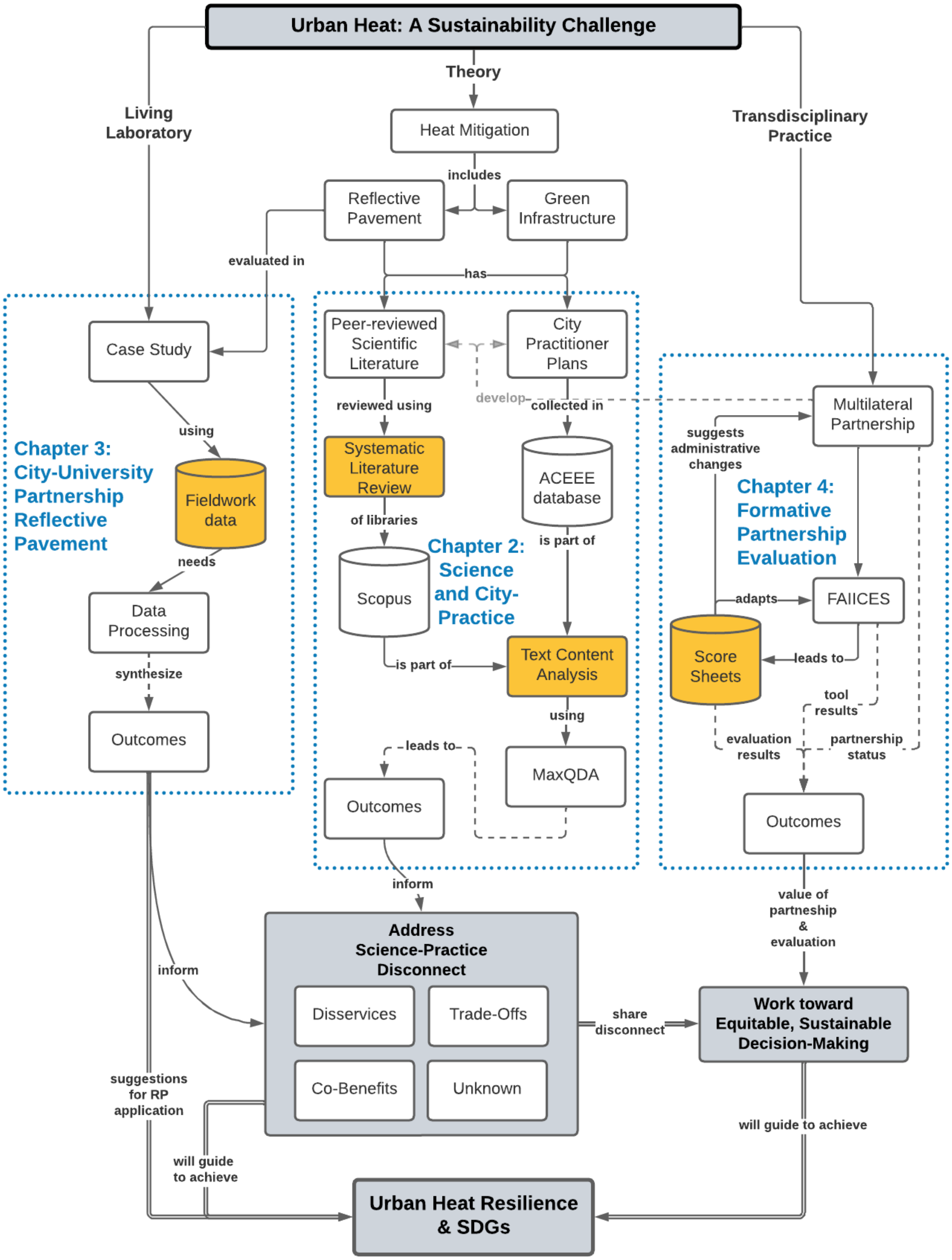


Figure 1: Concept map of dissertation research by Florian A. Schneider.

In chapter 3, my research comprehensively assesses RP in the City of Phoenix, with findings supporting a better understanding of the physical impacts at different times of the day and community perceptions of the used technology. A synthesis of the results with the neighborhood conditions and technology performance will support a better understanding of sustainable heat mitigation (Figure 1, left).

In chapter 4, I formatively evaluate the projects and the relationships of a newly-formed community-based, transdisciplinary, multilateral partnership using the FAIICES tool to guide the design and management of the partnership. An additional contribution is the suggestion of adaptations to FAIICES to improve applicability in a multilateral context (Figure 1, right).

CHAPTER 2

SCIENCE AND CITY PRACTITIONER LITERATURE PERSPECTIVES ON GREEN INFRASTRUCTURE AND REFLECTIVE PAVEMENT: A DISCONNECT?

2.1 Abstract

Written communication of and between scientists and practitioners is key to building resilience against human health threats such as extreme (urban) heat. Urban heat mitigation demands transformation in ways of thinking and asks to involve actors from outside academia. Scientists and city practitioners, as two relevant stakeholders in the process of the creation of usable science, are expected to have diverse and potentially competing views on urban climate governance including heat mitigation strategies and how they are communicated. I hypothesize that a science-practice disconnect exists in written communication potentially preventing holistic decision-making when increasing resilience against urban heat.

This work showcases the results of a systematic literature and content analysis of scientific peer-reviewed literature and US city practitioner literature. The study focuses on understanding the science and practice perspectives on the impacts of green infrastructure (GI) and reflective pavement (RP) as heat mitigation strategies. Additionally, I determine the potential science-practice disconnect in the written word. This study identifies 191 GI impacts and 93 RP impacts across both literature groups. Impacts are classified as environmental, social, or economic, as co-benefit, trade-off, disservice, or neutral impact, and are grouped based on similarity and detail to 65 GI and 30 RP impact groups. The identified impacts are compared for GI between both literature universes to draw conclusions about the science-practice disconnect. RP impacts cannot be compared due to the lack of impacts being discussed in the US city practitioner literature. The outcomes of this study add to the understanding of GI and RP, and to the understanding of options to bridge the science-practice disconnect on heat mitigation strategies, thus contributing to urban climate governance. Identifying these differences and integrating knowledge from different agents is critical to inform future transformational ways of thinking and the creation of usable science in urban heat mitigation and urban climate governance.

2.2 Introduction

Communication of and between scientists and practitioners on urban climate governance is key to improve resilience against human health threats such as extreme (urban) heat (Collins & Ison, 2009; T. A. Muñoz-Erickson, 2014). Urban heat mitigation and city planning in general demands transformative thinking (T. A. Muñoz-Erickson, 2014; Sallis et al., 2016) and asks to involve actors from outside academia (users) crossing traditional boundaries using a diverse range of actors and agencies (van der Heijden, Bulkeley, et al., 2019) to integrate best available knowledge into policy-making (Sallis et al., 2016), thus creating needed usable science (McNie et al., 2016). Scientists and practitioners, as two relevant stakeholders in the process of the creation of usable science, are expected to have diverse and potentially competing views on urban climate governance including heat mitigation strategies and how they are communicated. Integrating knowledge from different agents, especially their tacit knowledge, may bridge views and potentially create more holistic and acceptable outcomes (Sallis et al., 2016; van der Heijden, Bulkeley, et al., 2019) with respect to urban heat mitigation.

Urban heat mitigation strategies aim to cool the built environment and potentially reduce heat morbidity and mortality, which are increasing globally (Zhao et al., 2021), more so in developing countries (Broadbent et al., 2020). Green Infrastructure (GI) and highly reflective materials such as Reflective Pavement (RP) are the most commonly used heat mitigation strategies (Taleghani, 2018). Research has shown that GI can cool cities, create comfort spaces, create cleaner air, improve local health, produce economic benefits (Mat Santamouris et al., 2018), and provide other co-benefits related to water, food, medicine abilities, infectious disease modulation, climate regulation, physical activity, mental health, and social capital (Coutts & Hahn, 2015). However, not all heat-burdened cities have the water capacity or space for GI, and current urban expansion tend to continue to deplete urban green resources rather than sustain them. Depletion of urban green resources may be exacerbated in rapidly urbanizing developing countries (Leal Filho et al., 2021) which also are considered to carry a greater burden in terms of future heat exposure (Broadbent et al., 2020). The questions of mitigating heat for whom, what, where, when, and why are essential in the provision of sustainable and equitable heat mitigation (Meerow & Newell, 2019).

An alternative option, which is recently explored in real-world applications, is RP (Middel et al., 2020). RP is a type of cool pavement, which refers to multiple technologies that create a cooler surface than regular concrete or asphalt. RPs have a higher surface reflectance (albedo) in the solar spectrum and reduce solar radiation absorption leading to lower surface temperature (Akbari et al., 2001; Erell et al., 2014; Mohegh et al., 2017; M. Santamouris, 2013). Thus far, research shows that in general, RP reduces the surface temperature, increases solar radiation exposure, and has limited air temperature impacts as shown by a study performed in 2020 in Phoenix, AZ, USA (Schneider et al., 2023). The research results confirm that reducing single heat metrics alone, such as the air temperature, should not be the goal, but rather an improvement of the overall thermal conditions and a reduction of negative impacts (Krayenhoff & Voogt, 2010; Martilli et al., 2020).

When focusing on reducing negative impacts, decision-makers identify priorities for benefits and potential trade-offs or even negative impacts. These decision-makers are stakeholders which have unique goals. Depending on the stakeholders, their main goal may not be to reduce heat or the effects of global climate change, but may be to reduce cost or the local climate action image, for example (van der Heijden, Bulkeley, et al., 2019). Thus, it is relevant to understand which information is communicated about heat mitigation strategies. People tend to search for and selectively choose the information that confirms their beliefs and attitudes due to confirmation bias or motivated reasoning, which prevents contradicting and potentially diverse information from being considered in their evaluations (Kenski, 2017). Missing communication or information from stakeholders, even if unintentionally, could lead to consequences that outweigh the intentional heat mitigation impact when considering cost, population health (Choumert & Salanié, 2008; Gocheva et al., 2019; Hansen & Pauleit, 2014; Maes et al., 2019; Pataki et al., 2011), or climate justice, and affect minority groups and poorer populations disproportionally (Anguelovski et al., 2019). Limited and biased communication may create an inequitable and unsustainable implementation of actions (Driscoll et al., 2011; Pouyat et al., 2010).

The basic-applied paradigm (Sarewitz & Pielke, 2007), or here science-practice disconnect, refers to the disconnect between scientists as the traditional form of knowledge producers (basic) and stakeholders such as city staff or practitioners, as the traditional form of knowledge users (applied). Cities often ask for more science to justify their needs, yet, the linear model of science in policy and politics—here urban climate governance—curbs attention to alternative policy options such as the transformational way of thinking and in doing so supports stealth issue advocates pursuing a hidden agenda (Pielke Jr, 2007) due to different levels of agency which contest empowerment in this transformation (van der Heijden, Bulkeley, et al., 2019). Science policy lacks a formal conception of research that acknowledges and fully integrates users in knowledge production and their perspectives (McNie et al., 2016), which creates a difficult environment to produce usable science using a boundary-crossing transformational way of thinking (T. A. Muñoz-Erickson, 2014; van der Heijden, Bulkeley, et al., 2019).

It is paramount to consider and expand the knowledge on the holistic consequences of implementing GI and RP as a heat mitigation strategy in research and practice, especially to find geographically appropriate solutions (Georgescu et al., 2014), and avoid unintended effects, information that will be valuable to decision-making (Frantzeskaki et al., 2019). The identification and communication of co-benefits, trade-offs, disservices, and unclear/neutral impacts of these strategies must not only be researched using a diverse set of methodologies and stakeholders but also communicated between science and practice to lead to a fair and sustainable implementation via practitioner plans and actions, which are currently in high demand (Keith et al., 2019, 2021; Meerow & Keith, 2022).

The focus of this review is GI and RP. GI is a well-researched heat mitigation strategy with widespread implementation in the real world while RP is starting to gain traction in research studies, but lacking real-life implementation though new developments are emerging (Middel et al., 2020; Schneider et al., 2023).

While there have been many literature reviews on heat mitigation strategies (Krayenhoff et al., 2021; Lai et al., 2019), research has not yet been undertaken to understand the written scientific and US practitioner perspectives on impacts of heat mitigation strategies. It is critical to collect more evidence about the nature of implementation and how this affects or distorts the intended services (Frantzeskaki et al., 2019). Following the need to determine if and where the science-practice disconnect exists surrounding urban heat mitigation strategies, it is important to understand how written communication perspectives of the scientific peer review and US city practitioner literature differ. I hypothesize that a science-practice disconnect exists for heat mitigation strategies in written communication, which may prevent holistic decision-making that simultaneously encompasses the urban environment, society, and economy for increasing urban heat resilience. To test this hypothesis, a systematic literature review using a text content analysis is completed that addresses three research questions:

- RQ1: What are the communicated (un-)intended co-benefits, trade-offs, and disservices of green infrastructure and reflective pavement as heat mitigation strategies?
- RQ2: How does the written perspective of co-benefits, trade-offs, and disservices of the same heat mitigation strategy differ between the scientific peer-reviewed and US practice literature universes? Where is agreement and where is a disconnect?
- RQ3: Which co-benefits, trade-offs, or disservices have mostly been neglected in either or both literature universes?

2.3 Materials and Methods

This study was conducted in two phases (Figure 2): In phase I, the scientific GI and RP literature of the SCOPUS database was systematically reviewed to identify relevant work for phase II. The city practitioner literature was retrieved from the American Council for an Energy-Efficient Economy (ACEEE) State and Local Policy Database on city-municipal heat mitigation (American Council for an Energy-Efficient Economy, 2021). In phase II, an inductive and deductive text content analysis in MaxQDA was performed to identify impacts of heat mitigation strategies (co-benefit, trade-off, disservice, and neutral impacts) as outlined in the selected literature. My data collection includes scientific and city practitioner literature between 2010 and 2021 (2022 for practitioner’s work) to keep the work limited to the most recent full decade.

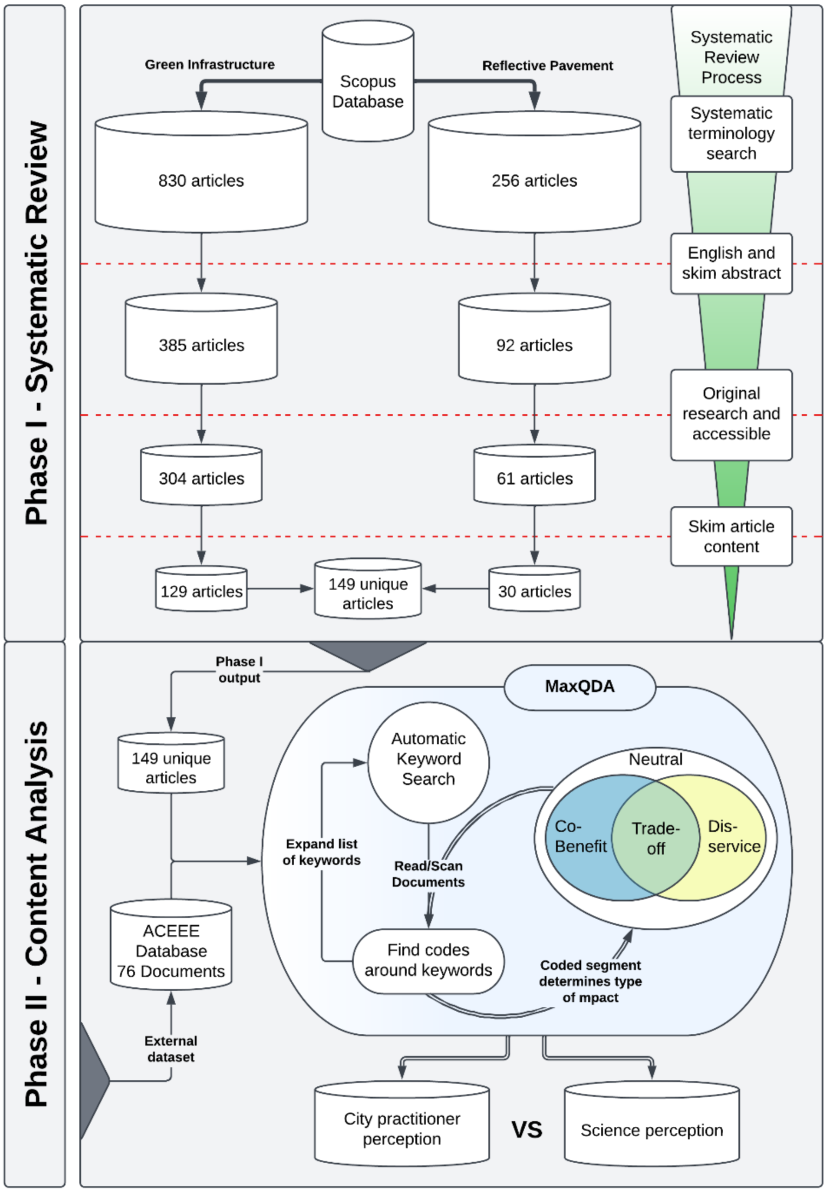


Figure 2. Methodology Phases I (Systematic Review) and II (Content Analysis). Phase I includes the data collection portion in which the Scopus database was systematically searched using keywords. Matching articles are filtered using three filters: English and abstract of relevance; original research and accessible; and article of relevance that does not mainly use remote sensing. The resulting articles and the ACEEE practitioner literature are then analyzed for their content in Phase II using an inductive and deductive coding approach, which includes an automatic keyword search (deductive) to identify words/paragraphs of interest with respect to green infrastructure and reflective pavement. The areas of interest were then inductively coded for their impacts and classified into Disservice, Trade-Off, Neutral, or Co-Benefit.

2.3.1 Phase I—Systematic Review of Scientific Literature

The SCOPUS database was searched for GI literature using the following key in the title, abstract, and keywords only: “urban” AND (“urban heat” OR “extreme heat”) AND ("green infrastructure” OR "green space" OR "tree*" OR "vegetation") AND ("heat mitigation" OR "mitigate heat" OR "cool*"). For RP literature, the following key was used: “urban” AND ("urban heat" OR "extreme heat") AND "pavement" AND ("heat mitigation" OR "mitigate heat" OR "cool*"). Both searches were limited to the most recent and complete 12 years (2010 to 2021). The systematic search yielded a total of 830 articles related to GI and 256 articles related to RP. All publications went through a 3-tier filter process (Figure 2). The first filter excluded all articles that were not written in English or did not focus on heat mitigation through GI or RP as determined by reading the abstract. The second filter removed all articles that were not original research and/or not accessible through the library network of Arizona State University. The remaining 304 GI and 61 RP articles were read and removed if the methodology mainly employed remote sensing (i.e., the article investigates surface temperature, not air temperature), or the focus was not on heat mitigation. Literature focused on cool but not reflective pavement (e.g., permeable pavement) was removed as well. After filtering, 129 GI articles and 30 RP articles between 2010 and 2021 remained. Ten articles covered both GI and RP, resulting in 149 unique articles.

For metadata analysis, I identified the origin of scientific articles based on the first-author affiliation and practitioner work based on their city affiliation to identify clusters of research origin and whether those are similar between GI and RP research and city practice. To visualize the differences, I mapped those origins which can be found in the supplementary material.

2.3.2 Practitioner Literature—ACEEE Heat Mitigation Database

The ACEEE State and Local Policy Database includes references to climate action plans, resiliency plans, urban forest management plans, sustainability plans, and minor policy and planning documents (ordinances, zoning codes) for 67 US cities. All documents in the database were checked for up-to-date versions and if they focused on heat mitigation and/or strategies. 60 cities have eligible documents. For the given 60 US cities, I also used Google to search for most recent practitioner literature such as climate action plans, sustainability plans, or similar which are not updated or included by the ACEEE. Of the provided database, only major policy and plan documents such as climate action plans, comprehensive plans, heat mitigation plans, resiliency plans, stormwater management plans, sustainability plans, urban forest management plan, and other plans were included; ordinances, zoning codes, and other minor policy documents or presentations were dismissed. This process yielded 76 documents for the practitioner dataset.

2.3.3 Phase II—Impact Identification via Deductive/Inductive Content Analysis using MaxQDA

Phase II used a combination of a deductive and inductive coding technique to identify communicated impacts of GI and RP as heat mitigation strategies. MaxQDA was used to assist with the coding process. The codebook was developed first for deductive codes (keywords) to autocode for GI and RP in all eligible SCOPUS and ACEEE documents to highlight areas for potential inductive codes, which are the impacts to be identified. An initial list of codes was developed based on existing scientific knowledge of urban heat and heat mitigation strategies, with specific focus on GI and RP. The code list was expanded and amended during the content analysis process due to new knowledge on terminology and distance between impacts and the strategy being mentioned. A single statement could include multiple codes. The initial definition of deductive codes adapted throughout the coding process as new terminology was identified and expanded the autocoding for GI and RP. After autocoding, each identified area of interest +/- three sentences were read for potential impacts and relationships. If one was found, either a new inductive code was created or one prior found inductive code was applied. Based on the context in the sentences around an autocode, sentences were coded for an inductive impact type. Codes were categorized as neutral, trade-off, disservice, or co-benefit. The four categories overlap, as indicated in Figure 2, and were identified based on the context given around the autocoded section.

At first all impacts are considered neutral; hence the neutral impact incorporates all other definitions of impact categories. A neutral impact is an impact that is mentioned without any or any clearly interpretable positive or negative effects. Co-benefit is defined as an impact that has only positive communication within the found section thus leading to a benefit to either the environment, society, economy, or all. Disservice is defined as an impact that has only negative communication within the found section thus leading to a disservice to either the environment, society, economy, or all. An impact is considered a trade off if both a co-benefit and disservice are mentioned concurrently within the same section of code and in relation to one another. The Venn diagram within the "neutral" circle depicts the definition relationship of all four categories.

The coding process was performed in the order: GI SCOPUS literature, RP SCOPUS literature, and ACEEE practitioner literature. During the process, the codebook was continuously expanded for inductive codes. A single appearance of a code was sufficient to consider this impact represented in the document.

After analyzing all literature, all inductive codes (impacts/relationships) were grouped within their type in different classes. The level-1 class organized each code as an economic, a social, or an environmental impact. Level-2 codes grouped sub-codes that have similar impacts, such as impacts on the thermal environment, costs, safety, urban design solution/detriment, air quality, or their cooling potential. Level-3 codes grouped sub-codes (level-4) that are similar, but specify time, location, or are particularly specific. Levels 2, 3, and 4 include single-standing codes as they do not fit into other super-codes.

2.4 Results

2.4.1 Literature metadata

The GI scientific literature used here arose from Asia (n=61), Europe (n=39), North America (n=17), Australia (n=10), and North Africa (n=2). RP scientific literature is from Asia (n=12), Europe (n=12), and North America (n=6). Using the ACEEE State and Local Policy Database for UHI Mitigation goals, the practitioner literature was focused on the USA and is distributed across 60 cities from 31 US-States, including Hawaii, and 1 US-District.

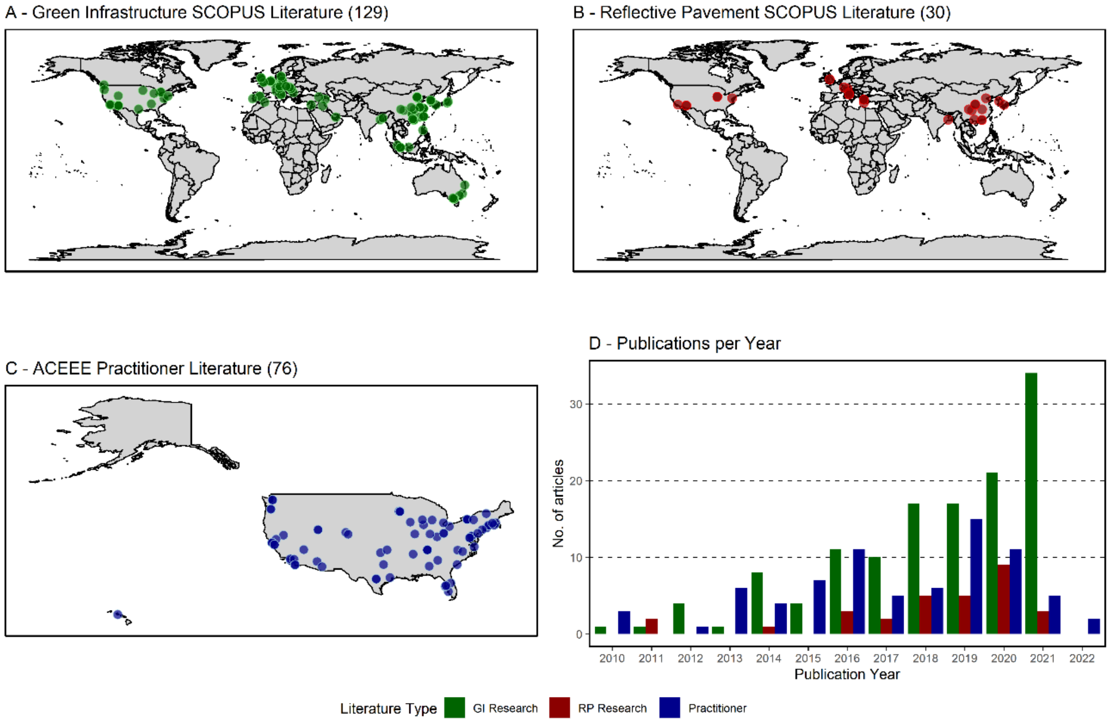


Figure 3. Distribution of literature origin and publication year sorted by GI research, RP research, and practitioner literature between 2010 and 2021 (2022 for practitioner). A shows the GI research literature origins across the world (129 articles); B shows the RP research literature origins across the world (30 articles); C shows the practitioner literature distribution within the United States; D shows the number of articles published by literature type for each year between 2010 and 2021 (2022 for practitioner).

The number of publications on GI and RP within the filtered database increases over time between 2010 and 2021, though higher numbers of publications per year are almost always prominent for GI compared to RP (exception is 2011; Figure 3). Practitioner works (city plans) relevant to heat mitigation on GI or RP were published between 2010 and 2022 without a particular emphasis on more recent works.

2.4.2 Green infrastructure communication in the scientific and US city practitioner literature

A total of 191 GI impacts were identified and grouped into social, economic, and environmental (Level 1) co-benefits, trade-offs, disservices, and neutral impacts.

For GI, I summarized all 191 GI impacts into 65 Level-2 GI impact groups, which incorporate Level-3 and Level-4 impacts due to similarity or similar impact areas. Figure 4 shows a Venn diagram for all Level-2 GI impacts and depicts the overlap of found impacts between the written communication in the science and city practitioner literature. An impact appearing on the left (right) side means that the impact is only communicated in the science (practice) literature. An impact in the center of the Venn diagram means it was found in both the science and practice literature. Neutral or unclear impacts (white), with the exception of “Modification of thermal environment” were only found in the scientific literature. The practice literature communicates more economic (+5) and social (+4) co-beneficial GI impacts (blue). All found trade-off impact groups (green) are discussed in both literature universes. Some disservices (4, yellow) are discussed by both literatures, but both science and practice literature communicate also about other disservices (6 each) unique to each perspective.

Both scientists and US city practitioners communicate GI positively using various co-benefits even though those differ between the science and city practitioner literature groups as shown in Figure 4. Table 1 shows that 100% of all documents in both science and practice literature analyzed for GI include any kind of co-benefits, while disservices are included in 47% and 30% and trade-offs are included in 69% and 67% of the scientific and practice literature, respectively. US city practitioners included almost always social (97%), economic (95%), and environmental (100%) GI co-benefits while 64%, 52%, and 100% of the scientific literature included social, economic, and environmental GI co-benefits, respectively.

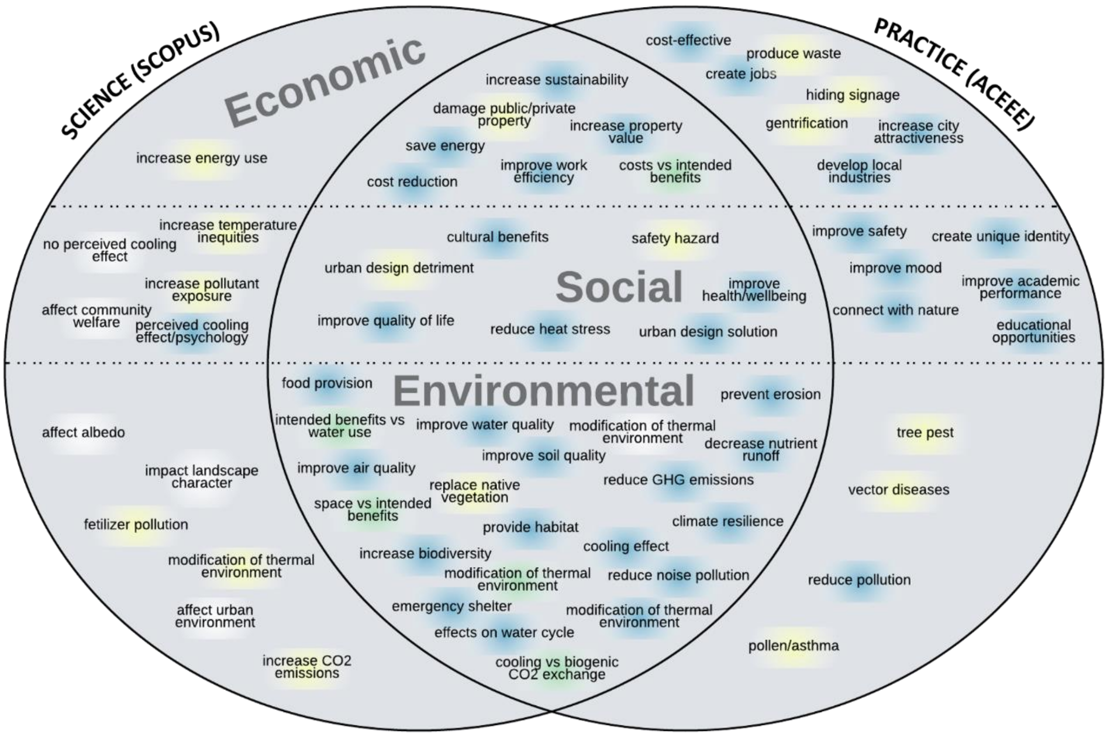


Figure 4. Venn diagram for green infrastructure (GI) that depicts the overlap of found impacts between the written communication of science (Scopus literature) and practice (ACEEE archive). Impacts in the diagram are sorted by their economic, social, and environmental influence. The color code is: blue is co-benefit; green is trade-off; yellow is disservice; white is a neutral impact. This depiction shows whether an impact was found in either literature universe, but not how often.

Of the scientific literature that discusses GI trade-offs, there is no communication about social trade-offs (n/a), 30% communicate economic trade-offs, and 93% communicate environmental trade-offs. These are depicted in an opposing manner in the practice literature (except for social trade-offs (n/a)) with 88% including economic trade-offs and 27% including environmental trade-offs. Disservices of GI are included in 47% of the scientific literature and of those documents 20%, 8%, and 88% mention social, economic, and environmental disservices, respectively. For the practice literature that discusses disservices, 52%, 61%, and 43% of the documents communicate social, economic, and environmental disservices, respectively. Neutral or unclear impacts are communicated in 71% (3%) of all analyzed scientific (practice) literature, with 98% (100%) of all documents communicating environmental impacts, and 3% (n/a) communicating social impacts. No economic neutral impacts were found in either of the literature groups.

Across all groups (co-benefits, trade-offs, disservices, and neutral impacts) and both the scientific and city practice literature included in the GI content analysis, environmental impact representation is dominant, except for trade-offs in the city practice literature where economic trade-offs dominate (Table 1).

For the scientific literature, the level 2 impact group “Modifications of thermal environment” is mentioned as co-benefit, trade-off, neutral impact, and disservice within the same document. This impact group includes the largest group of sub-codes related to thermal

Table 1. Number of science (n_{GI} = 129; n_{RP} = 30) or practice (n_{ACEEE} = 76) documents (#Doc) for green infrastructure (GI) and reflective pavement (RP) that include neutral, disservice, trade-off, or co-benefit codes organized by type (social, economic, environmental). The first column for each combination of impact and document type shows the number of documents (#Doc), the second column the total relative occurrence (%), and the third column the relative occurrence within documents that include codes of that combination (rel.).

Type		Neutral						Disservice					
		Science			Practice			Science			Practice		
		#Doc	%	rel.	#Doc	%	rel.	#Doc	%	rel.	#Doc	%	rel.
GI	All	91	71	100	2	3	100	60	47	100	23	30	100
	Social	3	2	3	0	0	n/a	12	9	20	12	16	52
	Economic	0	0	n/a	0	0	n/a	5	4	8	14	18	61
	Environmental	89	69	98	2	3	100	53	41	88	10	13	43
RP	All	14	47	100	0	0	n/a	18	60	100	0	0	n/a
	Social	0	0	n/a	0	0	n/a	3	10	17	0	0	n/a
	Economic	0	0	n/a	0	0	n/a	2	7	11	0	0	n/a
	Environmental	14	47	100	0	0	n/a	18	60	100	0	0	n/a

Type		Trade-Off						Co-Benefit					
		Science			Practice			Science			Practice		
		#Doc	%	rel.	#Doc	%	rel.	#Doc	%	rel.	#Doc	%	rel.
GI	All	89	69	100	51	67	100	129	100	100	76	100	100
	Social	0	0	n/a	0	0	n/a	83	64	64	74	97	97
	Economic	27	21	30	45	59	88	67	52	52	72	95	95
	Environmental	83	64	93	14	18	27	129	100	100	76	100	100
RP	All	14	47	100	0	0	n/a	30	100	100	12	16	100
	Social	1	3	7	0	0	n/a	11	37	37	2	3	17
	Economic	5	17	36	0	0	n/a	16	53	53	2	3	17
	Environmental	11	37	79	0	0	n/a	30	100	100	12	16	100

environment changes such as air, surface, or mean radiant temperature or thermal comfort changes. The general “Cooling effect” and other impacts such as “Save energy”, “Urban design solution”, or “Improve health/wellbeing” are discussed as co-benefits within the same document. “Cooling effect” includes impacts with respect to “UHI mitigation”, “Heat mitigation”, “PCI” (Park Cool Island), or the type of cooling such as “Cooling shade”. The most common trade-offs apart from the thermal modification being discussed in research literature are “Costs vs intended benefits”, “Intended benefits vs water use”, and “Space vs intended benefits”. Unclear statements leading to neutral impacts such as “Affect urban environment” are mentioned. Disservices are isolated from other impact groups in the scientific literature. Some documents discuss individual disservices and include impacts such as “Damage public/private property”, “Replace native vegetation”, and “Safety hazard”.

The network analysis of the city practitioner literature revealed that co-benefits are often mentioned together. 30+ level 2 co-benefits are mentioned within the same document and most of them across many documents. Disservices and trade-offs are less discussed but appear in combination with many different impacts across the city practitioner literature. Like in the scientific literature, US city practitioners discuss impacts such as “Cooling effect”, “Modifications of thermal environment”, “save energy”, “Urban design solution”, and “Improve health/wellbeing”, but go further to include more social and economic co-benefits such as “Improve safety”, “Create unique identity”, “Increase property values”, or “Increase sustainability”, which aligns with the findings in Table 1. The network analysis revealed that social and economic impacts are more often discussed together with environmental impacts when communicating about GI than within the scientific literature.

2.4.3 Reflective pavement communication in the scientific and US city practitioner literature

A total of 93 RP impacts were identified and grouped into social, economic, and environmental (Level 1) co-benefits, trade-offs, disservices, and neutral impacts.

For RP, I have summarized all 93 RP impacts into 30 Level-2 RP impact groups, which incorporate Level-3 and Level-4 impacts due to similar impact areas. Figure 5, similar to Figure 4, shows a Venn diagram for all Level-2 RP impacts and depicts the overlap of found impacts between the written communication in the science and city practitioner literature. There are no impacts that are uniquely found in the US city practitioner literature. Neutral or unclear impacts (4), trade-offs (5), and disservices (7) were only found in the scientific literature. The scientific literature communicates more economic (+2), social (+2), and environmental (+3) co-beneficial GI impacts.

Both scientists and US city practitioners communicate RP positively using various co-benefits even though the scientific literature is more comprehensive as shown in Figure 5. Table *1* shows that 100% of all science documents and 30% of all practice documents analyzed for RP include any kind of co-benefits. Trade-offs, disservices, and neutral impacts are communicated in 37%, 60%, and 47% of the scientific literature, respectively, and are not mentioned in the US city practitioner literature. 3% of the US city practitioner literature included social and economic co-benefits and 16% included environmental co-benefits. Compared to the practice literature, 37% of the scientific literature included social co-benefits, 53% included economic benefits, and 100% included environmental co-benefits.

Across all groups (co-benefits, trade-offs, disservices, and neutral impacts) and both the scientific and city practice literature included in the RP content analysis, environmental impact representation is dominant (Table 1).

The network analysis for GI reveals that “Modifications of thermal environment” are discussed as co-benefits, trade-offs, disservices, and neutral impacts, though co-benefits are most represented in the scientific literature. “Cooling effect” is by design the most considered impact group due to the heat mitigation focus when choosing eligible literature, followed by “Modifications of thermal environment”, “Save energy”, “Reduce heat storage”, “Reduce pavement damage”, and “Urban design detriment”, which is a social disservice impact group consisting of detrimental impacts such as “Increase glare” or “Decrease outdoor recreation”. The most discussed economic trade-off is “Costs vs intended benefits”. It is noted that the scientific literature communicates neutral impacts such as “Not effective in all conditions” and “Affect urban environment”. Some impacts such as disservices like “Reduce water permeability”, “Increase

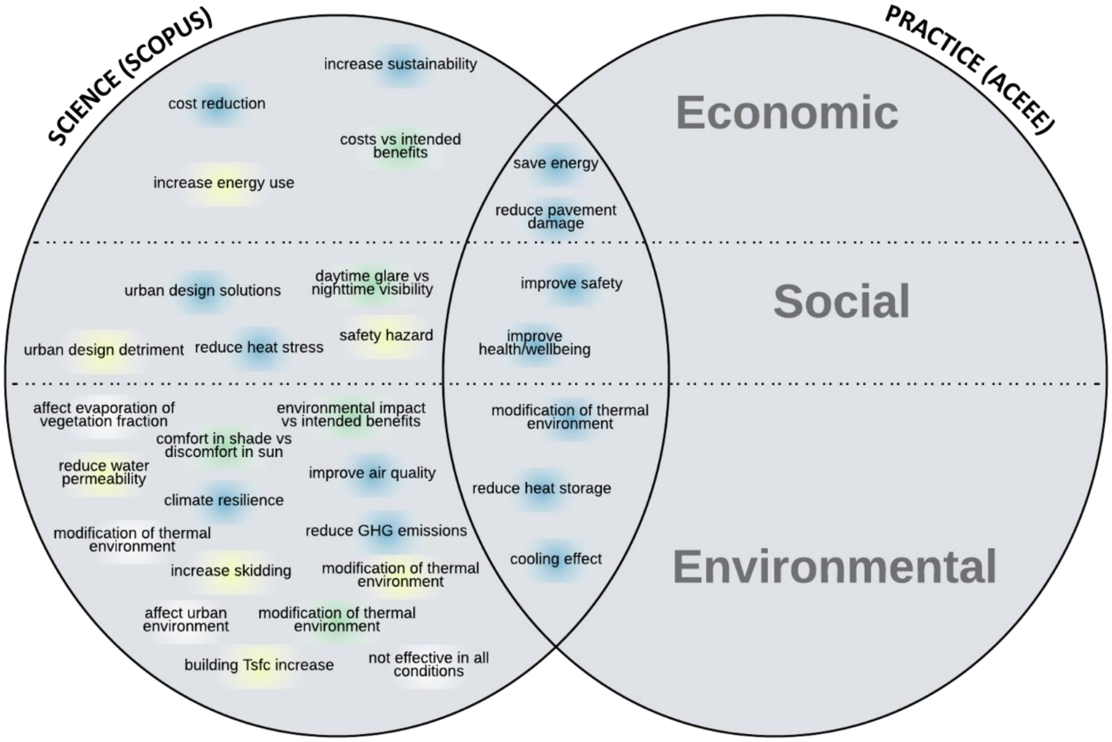


Figure 5. Venn diagram for reflective pavement (RP) that depicts the overlap of found impacts between the written communication of science (Scopus literature) and practice (ACEEE archive). Impacts in the diagram are sorted by their economic, social, and environmental influence. The color code is: blue is co-benefit; green is trade-off; yellow is disservice; white is a neutral impact. This depiction shows whether an impact was found in either literature universe, but not how often.

skidding", and "Safety hazard", and co-benefits such as "Reduce heat stress" and "Urban design solutions" are mentioned rarely.

The network analysis of the US city practitioner literature shows that RP is mentioned in 16% of all practice literature as a "Cooling benefit" strategy, but impacts are mentioned alone and not in combination with others. Trade-offs, neutral, and disservices are not communicated.

In general, it is recognizable that all but one social ("Daytime glare vs nighttime visibility") and economic ("Reduce pavement damage") impact group that have been found for RP, have been found for GI as well, yet GI level 2 impact groups include many other social (e.g., "Increase temperature inequities", "Create unique identity", "Educational opportunities", and "Improve quality of life") and economic (e.g., "Gentrification", "Damage public/private property", "Create jobs", and "Increase property values") impacts. Most of the RP environmental impacts communicated are also communicated for GI, except for RP technology specific impacts such as “Increase skidding” or “Reduce water permeability”. GI research and practice communicates about many other environmental impacts (e.g., “Effects on water cycle”, “Provide habitat”, “Prevent erosion”, or “Replace native vegetation”) that could be relevant for further knowledge expansion of RP.

2.5 Discussion

2.5.1 RP lacks practice representation

Historically, more original research on GI than RP as a heat mitigation strategy has been completed and continues on a yearly basis (Figure 3D), which suggests that more social, economic, and environmental impacts should be discussed across the literature for GI (191) than for RP (93) in urban spaces. Yet, all types of environmental impacts are a focus in both GI and RP scientific literature (co-benefits, trade-offs, and disservices) with social and economic impacts mostly being discussed as co-benefits alone. A comparison between practice communication of RP and GI is not possible due to the limited use of RP in practice and thus limited communication about it, which confirms the recent piloting and ongoing research of this technology (Feng et al., 2023; Ko et al., 2022; Middel et al., 2020; Mohegh et al., 2017; M. Santamouris et al., 2017; Schneider et al., 2023). Any lessons learned about GI impact communication may be valuable for future RP research and city practitioner communication efforts. Including learned lessons could be of interest for a more holistic and RP research with stronger evidence-base and practice leading to improved and informed decision-making and thus urban climate governance.

2.5.2 The science-practice disconnect

More GI impacts are communicated in the practitioner literature (Table 1 and Figure 4). A higher representation of impacts in city practitioner documents than scientific journal articles could be due to different incentives and dynamics of publishing. Scientists are evaluated based on criteria such as number of publications, citations, grants, and patents, which is not related to societal benefits that the society expects to receive by investing into science (Bozeman & Sarewitz, 2011; Meyer, 2011) while practitioners apply a wider perspective to their work to consider co-benefits and justify them for their motivation (Sippel & Jenssen, 2009; van der

Heijden, Bulkeley, et al., 2019). City practice using GI adds an emphasis on social and economic co-beneficial impacts that have not been found in the research literature, e.g., “Create jobs”, “Develop local industries”, “Increase city attractiveness”, “Connect with nature”, “Create unique identity”, “Educational opportunities”, and “Improve safety”. The emphasis on social and economic dimensions for city practitioners aligns with the highly political (Hughes et al., 2020) and fiscal nature within urban climate governance (Sippel & Jenssen, 2009; Vedeld et al., 2021). Co-benefits that are solely represented within the practitioner literature should be carefully considered. The methodology used to filter eligible literature in this study may have excluded works that would have made larger interdisciplinary or transdisciplinary connections to the social and economic impact fields that are not focusing on heat mitigation, but other aspects of GI technology.

GI disservices and trade-offs are not communicated equally in both literature universes compared to co-beneficial impacts (Table 1). This finding aligns with the confirmation bias that is applied by individuals in science and practice (Kenski, 2017) and the general narrative that research and practice want to achieve some good with their actions (Hughes et al., 2020). Notably, scientific literature communicates about neutral or unclear GI impacts indicating that scientific literature is communicating about potential impacts without weighing it positive or negative, while US practitioners do not mention neutral codes. This observation may be beneficial for practice because it shows that practice is not communicating about unclear outcomes, thus not hypothesizing, and may prevent unintended consequences, or ignoring important impacts of which the contribution has not been identified.

Science is providing suggestions, a future research agenda, and impacts that have not been evaluated yet, while practice provides evidence-based suggestions and learns from other real-world practice implementations (Hölscher & Frantzeskaki, 2021).

2.5.3 Involvement of users and creating awareness

Finding the various economic, social, and environmental impacts in the GI scientific and city practitioner literature raises the question if it is reasonable to expect that either type of literature can communicate beyond the science-practice disconnect about the co-benefits, trade-offs, disservices, and potential neutral impacts.

There is a disconnect between science and practice in how positive or negative consequences are communicated, yet it may not be beneficial to overcome this communication gap due to distinct differences in purpose. City practitioners communicate GI from a co-beneficial social, economic, and environmental perspective that is more holistic than science, but they may not communicate about the trade-offs and disservices as science literature does. The lesser amount of disservices and trade-offs confirms former findings by Shackleton et al. (2016), which state that researchers and practice often fail to acknowledge the diversity and validity of people's opinions, experiences (Shackleton et al., 2016), and the urban system complexity. It could be beneficial to include more trade-off and disservice communication into practice by incorporating users as well as mediators and honest brokers, who can provide an alternative pathway to solve a problem by involving new perspectives (Pielke Jr, 2007).

McNie et al. (2016) stated that the basic-applied paradigm, or the science-practice disconnect found here, limits recognition of processes that address both knowledge creation (science) and participation (applied; practice). Such processes involve users who are not recognized in the decision-making (McNie et al., 2016). Incorporating a holistic communication perspective in both the scientific and practice literature may not be beneficial and may lead to an overload of information that cannot transfer key messages to the audience, who often is a user of the provided knowledge or action. Users such as vulnerable groups underestimate their heat risk in the US already (Howe et al., 2019) and awareness is critical for their heat resilience. Overcoming the science-practice disconnect in the traditional sense by providing more information may trigger negative outcomes. Creating a transformative approach to produce usable science that is co-created between users, scientists, and practitioners is recommended. Usable science connects science and society and fully integrates users in knowledge production (McNie et al., 2016). Research on sustainability issues such as urban heat require usable, policy-relevant, and transferable knowledge (Keith et al., 2019; McNie et al., 2016). My findings suggest that the scientific and city practitioner literature has not made the step towards usable science yet, and thus is disconnected. It is imperative to find educational and awareness pathways to address the user and thus involve them in not only the science, but the decision-making as well. This involvement may require a fiscal and political change to allow partnerships between cities, universities, and communities to be established.

2.5.4 So, what?

Transformational thinking is needed to address urban issues (T. A. Muñoz-Erickson, 2014; Sallis et al., 2016). I observed that the science-practice disconnect exists in the written communication—confirming my hypothesis—and that science and practice require bridging communication and mutual understanding of various impacts (including disservices and trade-offs) to find an alternative pathway around the science-practice disconnect. What could such a bridge look like? Are there approaches and perspectives already being discussed?

Transformational approaches such as usable science and co-production have been introduced in the last decade by research (Driscoll et al., 2011; Lemos & Morehouse, 2005; Wall et al., 2017), but they have either not been applied or not led to a change in written communication by GI heat mitigation science or the city practitioner literature on heat mitigation. The existing communication disconnect and the largely observed disregard of scientific evidence around disservices and trade-offs suggests that the literature of both investigated groups still needs to adapt to the transformative approaches by involving users, mediators, and/or honest brokers. New developing partnerships can be studied of their use co-productive approaches and identify whether their written communication is more holistic and inclusive of disservices and trade-offs. City-university-community partnerships acknowledge that research needs to be specific and rigorous and that practitioners focus on money and selling innovation to people, thus finding balance between potentially conflicting goals (Campbell, 1996). Partnerships co-create an agenda while not ignoring individual needs. Additionally, city-university-community partnerships embrace the basic-applied paradigm and instead co-create usable, policy-relevant science that can be readily applied (Keith et al., 2019; McNie et al., 2016), thus overcoming the communication disconnect from the source.

Comparing the communication status quo between GI and RP, there is a unique opportunity for the upcoming studies and application of RP and other innovative strategies with respect to their research, impacts, and practice communication. Involving practitioners and community in the research process of a strategy early on may prolong the research process, but it will allow the research results to be communicated as usable, policy-relevant, and potentially readily actionable in practice.

2.5.5 Limitations

The identified scientific literature does not cover the breadth of all science for GI and RP due to the exclusion of remote sensing works. This reduction of literature was necessary for this study to be manageable. A future step in this research could be the use of AI which may make this process more inclusive as done in a similar content analysis study (Fung et al., 2021); however, they did not code inductively, which would be a challenge to overcome.

The city practitioner literature is limited to the collection of plans that were provided in the ACEEE database, thus creating a bias based on the database itself. An additional search for plans based on their focus on RP may allow a more inclusive comparison between impacts of GI and RP. Additionally, many additional plans or policy documents may exist outside of cities in non-governmental organizations, non-profits, or other institutions that can inform heat mitigation strategies. This assessment focused on city practitioner plans only and thus has a unique perspective. It is worth noting that city practice includes a set of different plans that combine to create a comprehensive communication tool, which focus on individual challenges and actions (Meerow & Keith, 2022). Instead of studying individual practitioner literature, as I did, what would the communication be like if all documents are combined as a master document?

As shown in Figure 3D, not all countries and languages are represented. This is likely due to the language and accessibility filter. An expansion to adding further languages into the database and by purchasing research literature would create a more inclusive database. Again, there is an opportunity for AI to be used to analyze content of literature across languages.

Original research, by default, is meant to be specific and has historically been siloed research rather than inter- or transdisciplinary. Literature reviews, which have been excluded due to their different nature from original research, can be an opportunity to bridge different fields, include further impacts such as co-benefits, disservices, and trade-offs in the discussion, and point out gaps in the literature that may be related to those impacts. An additional analysis of literature reviews may reduce the observed science-policy disconnect due to literature reviews synthesizing information as practitioners would need to.

Overall, there is an opportunity for this work to be not only expanded on the communication of heat mitigation strategies, but also in identifying if suggested partnerships can successfully provide usable, policy-relevant science for such urgent needs like sustainable and equitable urban heat mitigation.

2.6 Conclusion

To overcome the science-practice disconnect in urban heat mitigation strategies to ensure useful science crosses traditional boundaries, it is important to understand how the written communication perspectives of the individual stakeholders (science and city practice) may differ.

I found 191 GI and 93 RP impacts that were communicated in the science and US city practitioner literature. Across all groups (co-benefits, trade-offs, disservices, and neutral impacts) and both the scientific and city practice literature, environmental impact representation is dominant, except for GI trade-offs in the city practice literature where economic trade-offs dominate. Practitioner literature had a stronger emphasis on social and economic co-beneficial impacts than the scientific literature, which aligns with its highly political and fiscal responsibility. Science provides suggestions and a future research agenda for the impacts that have not been evaluated yet, i.e., neutral impacts. A comparison between practice communication of RP and GI is not possible due to the limited use of RP in practice, which confirms the recent piloting and ongoing research of this technology. Yet, expanding RP research and practice on those impacts from the GI literature could be of interest for a more holistic and better evidence-based RP research and practice leading to potentially improved decision-making.

The results and analysis of the GI literature confirm the disconnect between science and practice and how impacts are communicated, yet it may not be beneficial to overcome it due to the distinct differences in purpose of the scientific and practice literature. Additionally, disservices and trade-offs are mentioned less often. I synthesize that even though research on usable science and co-production are brought forward, they are not yet implemented or recognized within the scientific or practice literature to encourage holistic and user-influenced written communication.

The outcomes of this study include a definition of how co-benefits, trade-offs, disservices, and neutral impacts are identified in written and oral communication, add to the understanding of GI and RP, and to the understanding of options to bridge the science-practice disconnect on heat mitigation strategies, thus contributing to urban climate governance. Both scientists and US practitioners are expected to have a differing understanding of heat mitigation strategies and their co-benefits, trade-offs, and disservices. Identifying these differences is critical to inform future transformational ways of thinking and the creation of usable science in urban climate and urban climate governance.

Overall, there is an opportunity for this work to be not only expanded on the communication of heat mitigation strategies by including more datasets and using an advanced AI methodology, but also by identifying if suggested partnerships can successfully provide usable, policy-relevant science for such urgent needs like sustainable and equitable urban heat mitigation and urban climate governance.

CHAPTER 3

EVIDENCE-BASED GUIDANCE ON REFLECTIVE PAVEMENT FOR URBAN HEAT MITIGATION IN ARIZONA

3.1 Abstract

Urban overheating is an increasing threat to people, infrastructure, and the environment. Common heat mitigation strategies, such as green infrastructure, confront space limitations in current car-centric cities. In 2020, the City of Phoenix, Arizona, piloted a “cool pavement” program using a solar reflective pavement seal on 58 km of residential streets. Comprehensive micrometeorological observations are used to evaluate the cooling potential of the reflective pavement based on three heat exposure metrics—surface, air, and mean radiant temperatures—across three residential reflective pavement-treated and untreated neighborhoods. In addition, the solar reflectivity of reflective pavement is observed over 7 months across eight residential neighborhoods. Results are synthesized with the literature to provide context-based reflective pavement implementation guidelines to mitigate urban overheating where common strategies cannot be applied. The three most important contextual factors to consider for effective implementation include urban location, background climate type, and heat exposure metric of interest.

3.2 Introduction

Cities globally have experienced elevated temperatures due to anthropogenic heat sources and the built environment (Taha, 1997), which results in an Urban Heat Island (UHI) by adding or retaining more energy within the urban system (Oke, 1982; Oke et al., 1991). This urban-induced warming together with climate change result in increasing temperatures in cities (Georgescu et al., 2014). Urban overheating, a recently introduced concept, is of particular concern within already-hot cities experiencing extensive urban heat stress for their residents, such as the City of Phoenix, Arizona, USA (Chow et al., 2012; Harlan et al., 2006). These concerns are intensified due to unequal distribution of heat exposure resulting from past and current marginalization and contemporary urban design decisions (Hoffman et al., 2020; Hsu et al., 2021). For example, neighborhood-level decisions involving heat mitigation strategies affect residential heat exposure and energy use (Keith et al., 2019; Meerow & Keith, 2022; Sinha et al., 2021), which are impacted by environmental racism and historical neighborhood redlining (Hoffman et al., 2020; Schell et al., 2020). While there has been extensive past focus within the scientific literature on the UHI concept (Nazarian et al., 2022), quantifying the magnitude and impact of *intra*-urban heat variability is a more meaningful way to understand drivers affecting human health, energy use, and water use, among other impacts.

Urban overheating constitutes a multi-faceted threat to the well-being, performance, and health of individuals, as well as the energy efficiency and economy of cities (Nazarian et al., 2022). Numerous heat mitigation strategies have, or will be, deployed and tested to counteract overheating in cities worldwide. Heat mitigation strategies, such as increased tree canopy or urban green spaces, are seen as compelling solutions to cool the urban environment based on various heat exposure metrics (including 2m-air, surface, and mean radiant temperatures) while creating aesthetically appealing spaces that include other co-benefits, such as increased shade, property value, recreation space, and ecosystem services (Bartesaghi-Koc et al., 2021; Endreny, 2018; Livesley et al., 2016; Zölch et al., 2019). However, urban green spaces can only provide these amenities if well-watered, maintained, and accessible (Meili et al., 2021; Teskey et al., 2015). Cities in hot and dry environments, such as the City of Phoenix, face water shortages that could affect the ability to maintain trees and grass and thus jeopardize their cooling potential (He et al., 2021). Additionally, many cities are car-centric, with extensive use of paving. In Phoenix, a high surface area (36%) covered by streets and parking lots (Hoehne et al., 2019) makes large-area implementation of urban green spaces more difficult. Paved surfaces have high thermal storage capacities and sensible heat fluxes (Hoehne et al., 2022), two major components responsible for the additional urban heat and thus the higher overall heat load.

Reflective coatings are one strategy to reduce surface temperature and heat storage by pavements and roofs (M. Santamouris, 2013). Additionally, a reflective coating may increase road service life under normal operating conditions because asphalt-based pavements wear and develop cracks due to higher surface and internal temperature ranges. Yet, reflective coatings or pavement have not been evaluated as a feasible heat mitigation strategy for car-centric spaces where urban green spaces cannot be implemented.

Reflective coatings have a higher albedo (reflectance across the solar radiation spectrum) and thus reduce solar radiation absorption yielding lower surface temperatures (Akbari et al., 2001; Erell et al., 2014; Mohegh et al., 2017; M. Santamouris, 2013). Reflective coatings are generally easy to apply to existing paved surfaces (e.g., spray, squeegee) and, in most cases, use light-colored pigments and materials (such as nanoparticles) to increase albedo (Middel et al., 2020; Qin, 2015; M. Santamouris, 2013; Sen et al., 2019; Synnefa et al., 2007). The technology is a low-cost measure, which is particularly important as the cost-effectiveness of heat mitigation strategies is key to widespread implementation, but tends to be neglected (Pomerantz, 2018). Reflective coatings are stated to require minimal maintenance (Gilbert et al., 2017; Synnefa et al., 2007), do not need water to be effective (Vahmani & Jones, 2017) (which is of particular interest to water-strained areas), and can be applied city-wide (Akbari et al., 2001), including areas that cannot be used for urban green spaces to provide cooling. City-wide application of reflective pavement (RP) may be restricted to use on roads with certain (lower) speed limits and roads not requiring line striping/traffic paint, following city practice based on industry safety guidance.

A conventional seal coat returns the road surface to a low albedo (~5%) and ages over time to approximately 12-13% reflectivity, while the reflective coating can be 6 to 7 times (and more) as reflective as the initial albedo (at 30-35%). Even higher albedos are possible. However, since highly reflective coatings at ground-level (e.g., pavements) may have adverse effects such as glare(Yang et al., 2015), it is advisable to consider moderately reflective coatings (e.g., with solar reflectance <50%). When applied on roadways for heat mitigation, these coatings are called “cool” or “reflective” pavements (CP and RP, respectively). CP often refers to multiple technologies that create a cooler surface than traditional concrete or asphalt concrete (AC). RP is one of these CP technologies accomplished via coatings (Erell et al., 2014; M. Santamouris, 2013), with further CP technologies including phase-change material pavement (Qin, 2015), highly conductive pavements (Qin, 2015), pavement as solar collectors (Nasir et al., 2021; Xu et al., 2021), and permeable pavement, i.e., porous pavement (M. Santamouris, 2013) and water-retentive pavement (Qin et al., 2018).

Research on reflective urban materials, particularly roofs, under hot daytime summer conditions has been growing in recent years using models and simulations (Akbari et al., 2001; Erell et al., 2014; Middel et al., 2015; Mohegh et al., 2017; M. Santamouris et al., 2017; Taha et al., 1988), microclimate observations (Hardin & Vanos, 2018; Ko et al., 2022; Middel et al., 2020), and laboratory studies (Synnefa et al., 2007). Further real-world field studies are warranted to understand RP thermal performance, specifically concerning the interaction between different heat exposure metrics, i.e., surface (T_{sfc}), air (T_{air}), and mean radiant temperature (T_{mrt}). T_{mrt} is the weighted sum of short and longwave radiation that a human experiences at a given place and time, and is considered the most significant heat exposure metric in hot and dry spaces (Johansson et al., 2014; Kántor & Unger, 2011).

As a daytime heat mitigation strategy with potentially lasting effects throughout the night, it is of particular interest to understand the thermal performance of RP in hot and dry areas where solar radiation is abundant. Numerous questions remain surrounding the effect of RP on localized T_{sfc}, T_{air}, and T_{mrt} in real-world conditions across different times of day. Surface temperature reduction due to RP has been demonstrated successfully through observations and modeling, but the effect on air temperature is still contested due to the scale of interventions (Millstein & Levinson, 2018) and accurate albedo values applied in models. A recent review of modeling studies found a 0.2–0.6°C T_{air} reduction per 0.1 increase in albedo, on average, of the entire neighborhood (Krayenhoff et al., 2021). However, even if higher albedo results in T_{air} reduction, a trade-off may exist with increased T_{mrt} adversely affecting pedestrians in the daytime resulting from the added reflection of solar radiation towards people (Erell et al., 2014; Lai et al., 2019). However, T_{mrt} is rarely used as a heat exposure metric to quantify the human-experienced impacts of heat mitigation technologies. Different heat exposure metrics impacting the overall thermal load experienced by people have not been compared in neighborhoods that received RP. Moreover, there is minimal empirical research on the impacts of RP on nighttime cooling of T_{air}.

This study evaluates a large-scale implementation of RP in the City of Phoenix, Arizona, USA between August and October 2020, where the city applied RP to 58 km of residential neighborhood streets and one public parking lot. The applied RP is a water-based asphalt emulsion seal coat designed to achieve lower pavement surface temperatures on streets through its lighter color and higher albedo. This City-University collaborative project—titled the Cool Pavement Pilot Program (CPPP)—systematically evaluates the performance of the RP to understand its localized heat mitigation potential across extreme heat days based on T_{sfc}, T_{air}, and T_{mrt}. The RP is compared to conventional and commonly used, yet aged, AC sealcoats. The performance evaluation of the RP addresses the following research questions:

1. Compared to weathered/aged AC, how does RP alter T_{sfc}, T_{air}, and T_{mrt} across four times of day in three neighborhoods during late summer in Phoenix, AZ?
2. How does the surface reflectivity of the RP change over time (7 months) compared to AC in Phoenix, AZ?

We provide innovative neighborhood-scale RP evaluation results, potential impacts on nighttime heat mitigation of RP, possible trade-offs between the use of multiple heat exposure metrics, unintended consequences when using a wrong heat metric, and surface reflection changes over time. Critical recommendations are provided to support optimal location selection of RP based on shade presence and urban form (e.g., height-to-width ratio), as well as human exposure based on time of day, to counteract urban overheating in a hot and dry city using abundant car-centric space that cannot be used for alternative heat mitigation strategies.

3.3 Results

3.3.1 Heat Metrics Overview

Weather conditions on data collection days (August 18, September 5, and September 20, 2020) were clear, sunny, and hot, with calm-to-light winds. The daily profiles for mesoscale T_{air}, relative humidity (RH), and wind speed from the Phoenix airport are provided in Figure 6. The T_{air} during the individual measurement transects in the neighborhoods (Figure 7) was consistent during the pre-sunrise and the afternoon transect, increased during the noon transect, and decreased during the post-sunset transect. The maximum (minimum) T_{air} at Phoenix Sky Harbor airport on these days was 46.1°C (32.2°C), 45.6°C (28.9°C), and 41.1°C (25.6°C) on August 18 (Garfield), September 5 (Maryvale), and September 20 (Westcliff), respectively. All transect measurements occurred at RH levels between 9 to 20% apart from pre-sunrise measurements.

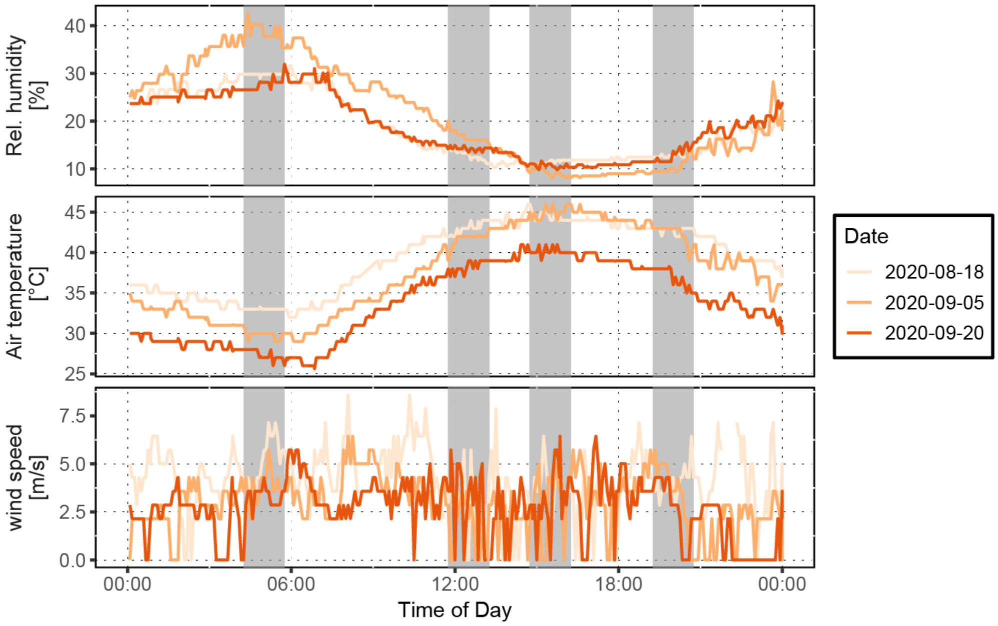


Figure 6. Diurnal meteorological data profile for Phoenix. Diurnal meteorological data profile from Phoenix Sky Harbor airport for mesoscale meteorological conditions. Relative humidity, air temperature, and wind speed are shown for the three days when data were collected (August 18, September 5, and September 20, 2020). Grey highlighted areas denote the time windows during which data collection in the three neighborhoods occurred.

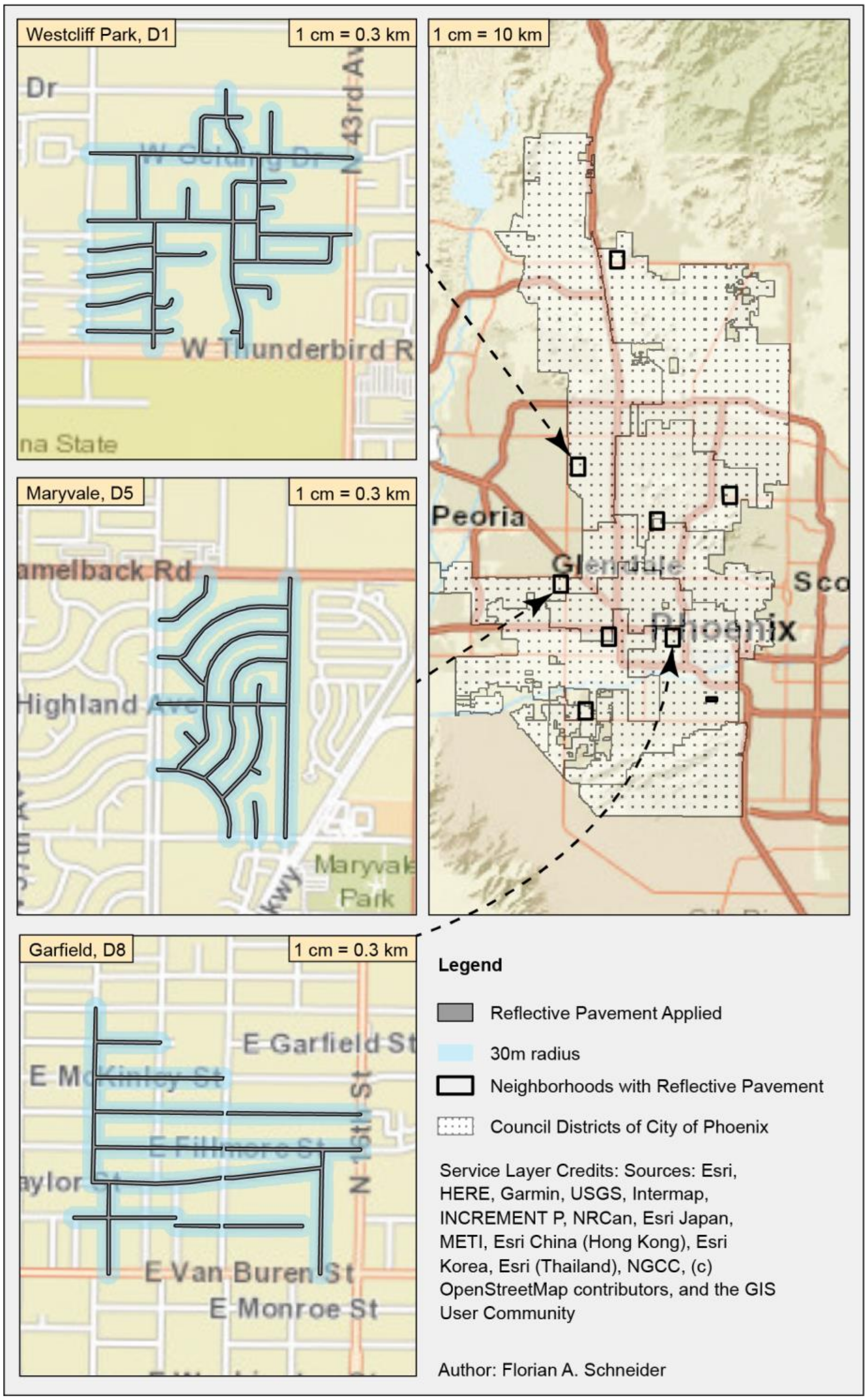


Figure 7. Areas of application of reflective pavement in Phoenix. Map of the Council Districts (D1–D8) within the City of Phoenix (right), the neighborhoods where CoolSeal was applied (black rectangles), and a close-up for those neighborhoods where in-situ measurements were performed (left). Blue highlighted roads received the reflective seal treatment. The council district boundaries were downloaded from the open access Phoenix Open Data platform via https://mapping-phoenix.opendata.arcgis.com.

Wind speeds were consistently between a calm and moderate breeze (Beaufort scale: 0–4). All three days had similar synoptically uninterrupted profiles.

Detailed results comparing each heat exposure metric by neighborhood and time window are provided below and in Figures 8–10. Overall, significant within-neighborhood differences in T_{sfc} between RP and AC were observed across all four periods. T_{air} differences were within the uncertainty of the instruments between RP-treated and AC areas across the full day. At the same time, T_{mrt} was elevated over RP-coated streets during the noon and afternoon hours compared to AC, and slightly lower at sunrise and sunset.

3.3.2 Surface Temperature (T_{sfc})

During vehicle traverses across the four in situ measurement periods, the highest mean T_{sfc} of 66.7°C was found on the AC in the Garfield neighborhood during the afternoon transect (hottest T_{air} time of the day; Figure 8). At this time and day, the RP reached a mean T_{sfc} of 61.6°C in Garfield. The minimum T_{sfc} values occurred just before sunrise, with Westcliff—which had

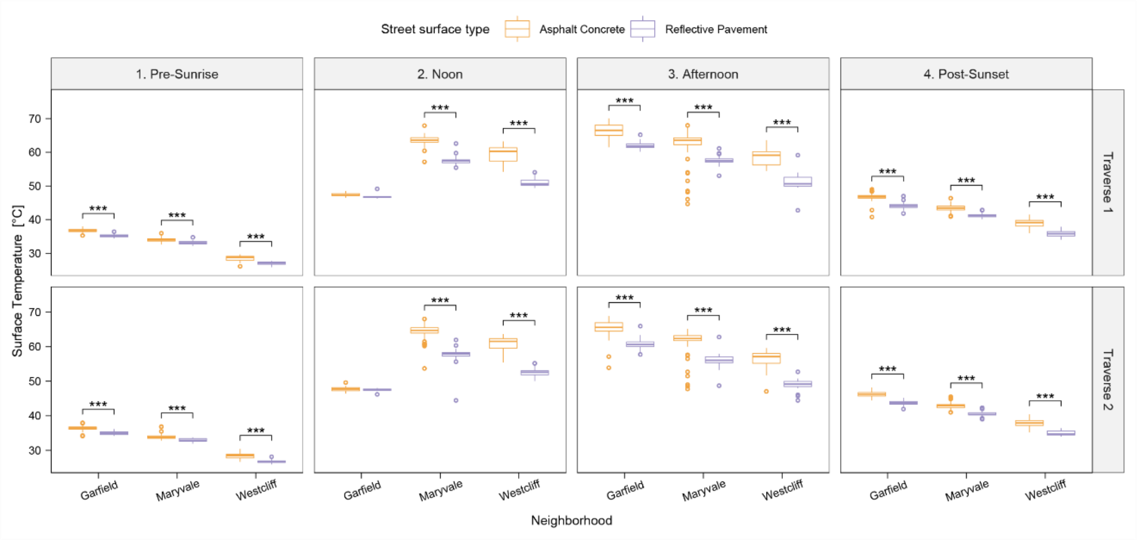


Figure 8. Overview of surface temperature measurements for all areas and times. Car transect-derived surface temperature panel for all neighborhoods, transects, and traverses in box-whisker plots. Center line=median; box limits=upper and lower quartiles; whiskers=1.5x interquartile range; points=outliers. Asphalt concrete, AC (orange), and reflective pavement, RP (purple), surface temperature distribution and the statistical significance of the difference between those surface types is shown: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$. Note: The infrared temperature monitor failed during the noon measurements in Garfield, however, data from the MaRTy cart downward facing infrared sensor were used for surface temperature comparisons.

shorter days, less intense sunlight, and the lowest average T_{air} (Figure 6)—showing the lowest average minimum T_{sfc} (28.3°C for AC, which was 1.3°C higher than the RP T_{sfc} minimum for Westcliff).

The T_{sfc} values of the RP were, on average, significantly lower than those of AC during all measurements (Figure 8). The highest T_{sfc} difference between RP and AC (i.e., $T_{sfc,RP}$ – $T_{sfc,AC}$) of –8.4°C was found in the Westcliff neighborhood during the noon transect for vehicle traverse 1 (and –8.2°C for vehicle traverse 2), with similarly large differences found during the afternoon transect in the same neighborhood (–7.4 and –7.3°C for traverses 1 and 2, respectively). The lower T_{sfc} of the RP was evident during the noon and afternoon periods for all neighborhoods, reaching maximum differences of –6.8°C (noon, traverse 2) and –4.5°C (afternoon, traverse 2), respectively, in Maryvale and Garfield. T_{sfc} measurements during the noon transect in Garfield indicate a T_{sfc} difference of –5.4°C. The largest T_{sfc} differences were measured during the noon transect in all neighborhoods. The T_{sfc} differences were lowest, yet significant, before sunrise, with differences ranging from 0.9 to 1.6°C cooler on the RP across all neighborhoods.

3.3.3 Air Temperature (T_{air})

T_{air} data was collected using 1–3 T-type thermocouples at 2m height on a vehicle performing two traverses four times a day within the three neighborhoods. The highest mean T_{air} in each neighborhood was found in the afternoon, with 45.5°C in Garfield over AC, 44.1°C in Maryvale over RP, and 39.2°C in Westcliff over AC (Figure 9). Minimum T_{air} for all neighborhoods occurred before sunrise, with small variations in T_{air} across neighborhoods.

The 2m T_{air} difference between RP and AC locations (i.e., $T_{air,RP}$ – $T_{air,AC}$) was highest on average, just after sunset, averaging –0.3°C across neighborhoods (ranging from –0.6°C to +0.1°C). Across all neighborhoods and traverses, the T_{air} cooling effect of RP only reached a significant difference of –0.7°C in the afternoon in Maryvale (traverse 1). Daytime differences averaged –0.2 and –0.1°C above the RP during noon and afternoon, respectively. Significant warming was found before sunrise during traverse 1 in D5, Maryvale (+0.2°C).

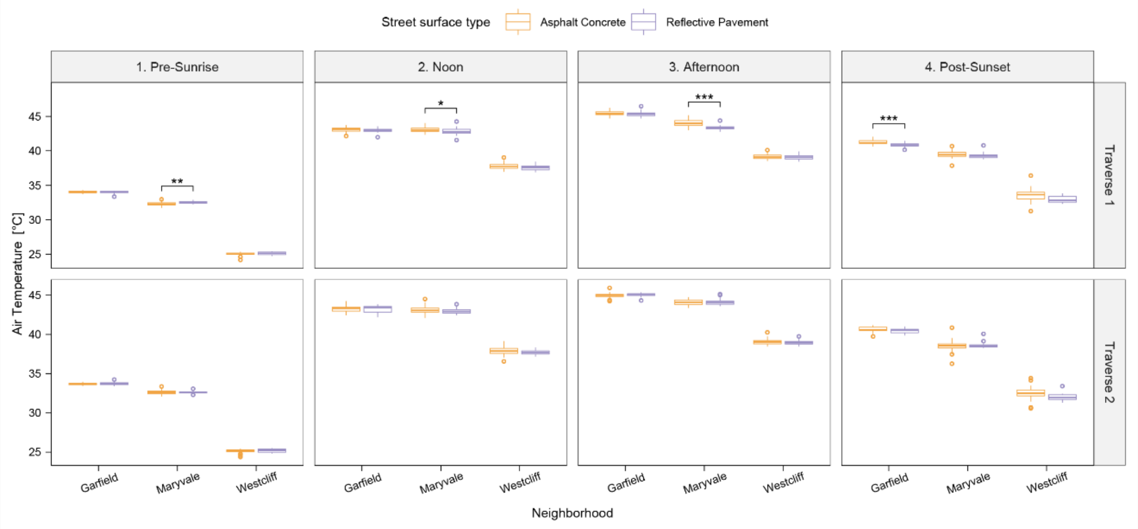


Figure 9. Overview of air temperature measurements for all areas and times. Car transect-derived air temperature panel for all neighborhoods, transects, and traverses in box-whisker plots. Center line=median; box limits=upper and lower quartiles; whiskers=1.5x interquartile range; points=outliers. Asphalt concrete, AC (orange), and reflective pavement, RP (purple) surface temperature distribution and the statistical significance of the difference between those surface types is shown: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$.

In summary, the 2m T_{air} over RP was cooler or equivalent to that over AC after sunset in all neighborhoods. Excluding the pre-sunrise measurements, an insignificantly lower, yet varied 2m T_{air} (–0.19°C ± 0.05°C) was predominantly found over RP compared to AC in all neighborhoods.

3.3.4 Mean Radiant Temperature (T_{mrt})

T_{mrt} data were collected with a six-directional net radiometer setup on the mobile MaRTy cart (Middel & Krayenhoff, 2019) at the pre-defined locations and time windows in all neighborhoods. On average, T_{mrt} was elevated over RP compared to AC during noon and afternoon hours (Figure 10). The largest T_{mrt} difference between RP and AC ($T_{mrt,RP}$ – $T_{mrt,AC}$) of 5.1°C was found in the Westcliff neighborhood at noon, showing the elevated T_{mrt} above the RP. T_{mrt} differences were minor before sunrise and after sunset, where AC and RP performed nearly equal.

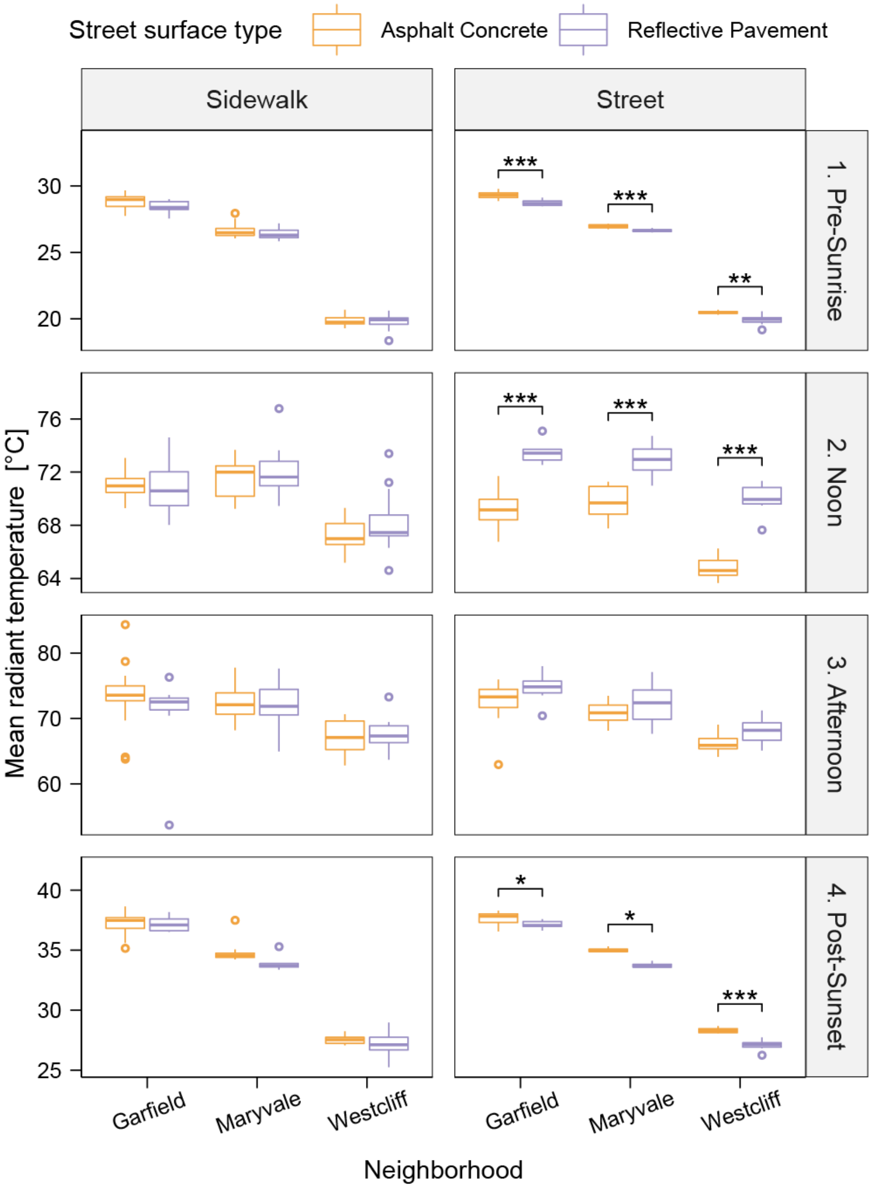


Figure 10. Overview of mean radiant temperature measurements for all areas and times. Average MaRTy-derived mean radiant temperature (Tmrt) across all neighborhoods and transects, delineated by positions (on adjacent sidewalk (left) versus on road (right)) for asphalt concrete, AC (orange), and reflective pavement, RP (purple) in box-whisker plots. Center line=median; box limits=upper and lower quartiles; whiskers=1.5x interquartile range; points=outliers. Significance tests denote the difference between the RP and AC surface (*** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$).

The highest average T_{mrt} levels were found standing on the RP-coated road in the Garfield neighborhood during the afternoon (74.6°C), which was the hottest time of the day

(Figure 10). At this time, T_{mrt} was 2.3°C lower (72.3°C) on the AC. During the afternoon in Maryvale, T_{mrt} was 1.4°C higher over RP compared to AC, but T_{mrt} was equally high over the adjacent sidewalk next to RP or AC or when standing on RP. Similar to T_{sfc}, minimum T_{mrt} values occurred just before sunrise, with Westcliff showing the lowest average T_{mrt} (~19.0–20.0°C), approaching T_{air} due to the absence of direct solar radiation. After sunset, T_{mrt} was 0.5 to 1.3°C cooler over RP due to reduced upwelling longwave radiation compared to AC.

3.3.5 Surface Reflectivity in the Solar Spectrum

Monthly solar reflectivity measurements with a spectroradiometer were performed between November 2020 and May 2021 at fixed RP locations in all eight neighborhoods (D1-D8) plus one AC control (Asphalt X) location. Figure 11 shows reflectivity results over seven months (November 2020 to May 2021) across the eight Phoenix Council Districts (each with one neighborhood receiving the RP). On average, the measured treated roads in Council District 3(D3), District 2 (D2), and District 1 southside (D1S) were the most reflective (average reflectivity of 34%, 33%, and 31% of the incident shortwave radiation, respectively). At the same time, RP in District 8 (D8), District 1 north-side (D1N), and District 4 (D4) had the lowest reflectivity (average reflectivity of 24%, 25%, and 28% of the incident shortwave radiation, respectively). These reflectivity values are higher than the average AC reflectivity of ~12–13% in the control segment (Asphalt X, Figure 11). Throughout the seven months, all Districts saw decreases in reflectivity (Figure 11a), with an all-District average change from 34% to 25% for near-infrared (NIR; 700–2500nm) and 26% to 18% for visible (VIS; 400–700nm). These decreases varied by District, where the reflectivity of the surface in D1S, D2, D5, and D6 showed an absolute reduction of 10–12% in seven months, yet D4, D7, and D8 had an absolute reflectivity decrease of 5–6% across the measured spectrum (350–2500nm).

Rainfall and street sweeping from December 20–25, 2020 increased the reflectivity in three Districts temporarily (D2, D3, D7), supporting the increase in overall reflectivity in Figure 11b, yet the remaining Districts were unaffected. Rainfall on March 25, 2021 resulted in increased reflectivity in D4.

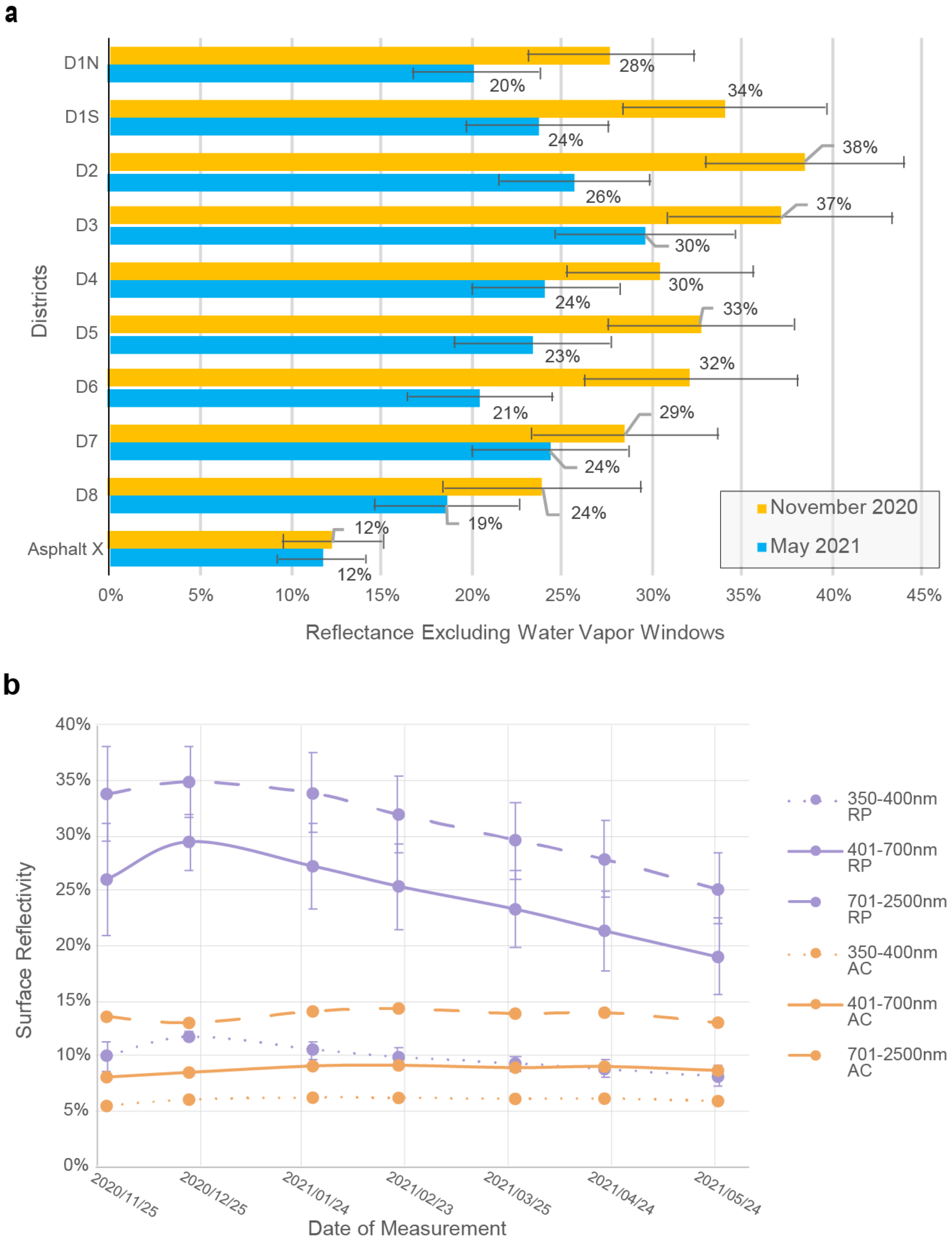


Figure 11. Surface reflectivity measurements in all areas (a.) and over time (b.). a. Reflectivity in November 2020 compared to May 2021 across all wavelengths, excluding strong water vapor and carbon dioxide absorption windows (1350–1450nm; 1800–1950nm; 2300-2500nm). b. Solar reflectivity over time for reflective pavement (RP) and asphalt concrete (AC) across three wavelength ranges: dotted line—ultraviolet A (UVA; 350–400nm), solid line—visible (VIS; 400–700nm), and dashed line—near infrared (NIR; 700–2500nm). RP data represents averages for all 8 Districts, and error bars represent the standard deviation. Figures a. and b. are modified for colors and readability from figures 11 b) and 12 of the Cool Pavement Pilot Program report by Middel et al. (2021) published under a CC BY-NC-ND 4.0 license and available at https://hdl.handle.net/2286/R.2.N.160731.

3.4 Discussion

3.4.1 Heat metrics matter

To better understand how RP affects different heat exposure metrics experienced within a residential neighborhood, this study investigated the differences in $T_{sfc,}$ $T_{air,\ and}$ T_{mrt} between RP and AC. In-situ comparisons with two mobile measurement platforms were performed four times per day in three residential neighborhoods. T_{sfc} was significantly reduced at all observed times on RP-treated roads compared to AC, while T_{mrt} was reduced after sunset and before sunrise, yet, higher during the noon and afternoon observations.

The significantly lower T_{sfc} indicates that the RP-treated roads absorb less heat than AC roads, which helps to reduce overall urban heat levels and thus should lead to reduced T_{air} (Krayenhoff & Voogt, 2010) and T_{mrt} at nighttime due to the lower upwelling infrared radiation from the surfaces. The overall magnitude of the RP T_{sfc} reduction agrees with observations in Los Angeles that showed a moderate T_{sfc} cooling of 4–6°C for a similar change in albedo (Ko et al., 2022; Middel et al., 2020).

While T_{sfc} is reduced significantly by increasing surface solar reflectivity, it comes with a trade-off wherein the radiant heat load is increased due to more solar radiation exposure at the pedestrian level (Erell et al., 2014; Lai et al., 2019; Middel et al., 2020). The higher T_{mrt} above the RP (middle of road) at noon and afternoon hours is in line with prior modeling (Erell et al., 2012; Qin, 2015; M. Santamouris, 2013) and fieldwork studies (Middel et al., 2020). Our results also show that T_{mrt} values on the sidewalk do not differ significantly between RP and AC, but differ significantly when on the road, which is thus a concern for those walking, living, and/or working on the road. The overall solar load (incoming and outgoing) on the human body is the primary contributor to heat stress and thermal discomfort in hot, dry urban microclimates (Middel & Krayenhoff, 2019). Given that RP functions best where solar radiation is abundant, this enhanced T_{mrt} will be an ongoing consideration in determining the optimal placement of RP.

Significantly lower radiant heat exposure was found before sunrise, indicating that the lower T_{sfc} leads to a continuously lower T_{mrt} throughout the night in the investigated neighborhoods, though the magnitude of the cooling effect fades over time. Thus, it is essential to consider the time frame when T_{mrt} could be elevated in already hot environments. One should assess the T_{sfc} and T_{mrt} trade-off based on time of day, pedestrians' behavioral patterns, presence of sidewalks and additional mitigation strategies such as shade (Middel et al., 2021), and vulnerable populations such as unhoused individuals and outdoor workers. Additionally, it remains unclear how much the additional reflected radiation affects vertical structures, such as buildings next to the street, and whether it could create a higher energy need for indoor cooling (Erell et al., 2014; Schrijvers et al., 2016).

We did not observe significant differences in 2m T_{air} at any time of day averaged over all neighborhoods, indicating no significant neighborhood-scale T_{air} cooling by the RP. Overall, results show minor decreases in T_{air}, agreeing with prior modeling studies that found a cooling of 0.2–0.6°C (Krayenhoff et al., 2021). Biophysically, a lower $T_{sfc,}$ and thus less sensible heat flux to the air volume above the surface, supports this decrease. Reasons for minor T_{air} differences between the RP and AC include a potential displaced cooling effect due to the combination of diffusion and advection, leading to a downwind cooling effect (where no sensors were placed). Additionally, the scale of the intervention (RP treatment) may not be large enough to significantly cool the well-mixed air volume moving over the treated surfaces (Millstein & Levinson, 2018). Other reasons for small decreases in T_{air} include lack of control for various types of land use throughout the two areas (e.g., grass versus xeriscape), urban design, shading, and irrigation variability across the neighborhood, and more mixing by the time the air reaches 2m height versus sensing closer to the ground. Furthermore, the sensor uncertainty is large (+/- 1.0 C), potentially obscuring the cooling effect.

Our observational study agrees with prior and current urban climate modeling (Krayenhoff et al., 2021) and the Los Angeles observational studies on single (Middel et al., 2020) and multiple RP types (Ko et al., 2022) concerning the overall heat impact of RP use in a neighborhood. This agreement is promising when considering the challenges of accurately measuring or modeling large-scale urban effects across entire neighborhoods.

3.4.2 Degrading solar reflectivity

Over the seven-month period, monthly measurements indicate that the solar surface reflectivity of the RP reduces from 33–38% to 19–30% across the eight neighborhoods. Similar reflectivity degradation was found by Ko et al. in Los Angeles (Ko et al., 2022). These reflectivity reductions may result in a lower cooling effect for T_{sfc} and thus T_{air}, yet an improvement for T_{mrt}. For comparison, an untreated AC surface had a consistent reflectivity of 12%, reflecting half as much solar radiation as the aged RP surface, and a third as much as the new RP surface. Reduction in reflectivity for RP is likely due to wear, dust accumulation, rubber residual, and other materials (Zheng et al., 2020). Dust may be a frequent issue for the region where measurements were performed due to regular monsoonal dust storms (haboobs) in Arizona, USA, with a frequency of 9.6 storms per year (Eagar et al., 2017). After rain and street sweeping events, higher reflectivity values were present, suggesting that cities can use street sweeping to help maintain RP; this benefit of surface cleaning was also observed in a laboratory study (Synnefa et al., 2007). The largest decrease in average reflectivity occurred in neighborhoods with either high traffic volume and/or generally more dust/dirt accumulation (Figure 11). Notably, the reflectivity is highly variable by neighborhood, road, or nearby. For example, the surface reflectivity of locations D1N and D1S differ by ~6%, yet are merely 5 m apart. This result is likely due to street design, where the northern side (D1N) is trafficked much more than the street's southern side (D1S), which leads to more rubber residue and wear on the surface.

Fading reflectivity via wear and tear is an important consideration given the demand for more cleaning and maintenance, i.e., to restore higher solar reflectivity (Ko et al., 2022; Synnefa et al., 2007), which helps maintain lower T_{sfc} in the residential neighborhood (this demand may be less in areas that receive more rain and less dust). Notably, the reflectivity results should be interpreted with caution since they only refer to a portion of the roadway (northern side, except location D1S) near the curb that experiences less traffic. Other areas of the road with more traffic may exhibit lower reflectivity. Future work that leverages airborne and spaceborne/satellite imaging spectroscopy can overcome these limitations/drawbacks and provide more spatially-resolved (VSWIR) reflectance data on the variability of the RP reflectance across all neighborhood roads (Herold & Roberts, 2005; Schnebele et al., 2015).

Additionally, the first reflectivity measurements were performed in November, while the RP-treatment was performed between August and October, which could explain aging differences among the different surfaces measured in all neighborhoods. Even so, a statistical relationship between the age of the surface and its reflectivity could not be found.

3.4.3 Limitations

In-situ measurements for the three neighborhoods were performed on different dates with slightly different atmospheric conditions (Figure 6), different RP age, and different reference AC properties. To account for these differences, we compared intra-neighborhood heat exposure metrics for the RP-treated and non-treated sections rather than assessing absolute values. Neighborhood differences were particularly prominent in T_{sfc} results. Although we chose similar micro-environments concerning tree canopy cover and urban morphology in the AC and RP-treated neighborhoods, urban form and vegetation differences still influenced the measurements. Such factors may explain the different magnitudes for the T_{mrt} between RP-treated and non-treated residential neighborhoods.

T_{air} differences between AC and RP-treated neighborhoods were within the sensor uncertainty (+/- 1.0 C), which obscures potential cooling effects. The strongest T_{air} cooling is expected close to the RP surface, diminishing as one moves away from the surface, specifically considering turbulence in the urban canopy layer. The turbulent air volume of the urban canopy layer may have restricted us from measuring a significant cooling effect at our measurement height of 2m, yet the cooling effect may be measurable at lower heights.

3.4.4 Reflective Pavement Implementation Guidance

Prior to implementing RP, numerous potential co-benefits or trade-offs (e.g., nighttime visibility improvement or morning glare, respectively (Akbari et al., 2001; Middel et al., 2020)) must be considered based on climate type, land use, urban form and design, road types and speeds, and pedestrian time-use patterns of a specific location. The following recommendations are presented based on current study findings synthesized with available peer-reviewed literature for practical and effective application of RP for heat mitigation:

- RP is most effective in hot mid/low latitude cities with low annual cloud coverage and a large surface area of roads and parking lots, i.e., in low traffic areas, which keep the reflectivity from degrading.
- RP is effective in residential neighborhoods with low- to mid-rise buildings and open streets where shade structures, buildings, and trees do not shade the streets; thus, solar radiation can escape the boundary layer when reflected. Trees, overhangs, and canopies may (and should) still be used to provide shading for sidewalks for pedestrian heat stress mitigation. The use of RP cannot replace the benefits of shade trees for pedestrian cooling. RP in urban canyons (high-rise downtown areas) is ineffective for heat mitigation due to a lack of direct incoming solar radiation.
- RP is a convenient and affordable alternative to conventional AC and may extend the life of the pavement (long-term research studies are needed).
- RP should not be used on surfaces with high daytime pedestrian use as it will increase heat load on the body. Those spaces include playgrounds, recreational areas (e.g., basketball courts), courtyards, and plazas. Heat exposure mitigation should focus on shading, such as trees and engineered shade, in these areas.

Optimizing the placement of heat mitigation strategies should consider for whom, what, when, where, and why those strategies will be implemented at a specific location and time (Meerow & Newell, 2019). In addition to weighting co-benefits and tradeoffs, community perceptions of a given heat mitigation strategy should also be considered. Determining what the final users—the community experiencing the resulting effects—think about a given heat mitigation strategy and potential unseen considerations is valuable to city decision-makers. As heat vulnerability is higher for people of color and people below the poverty line (Gabbe et al., 2022), who may have faced historical environmental racism, efforts to understand community perception are critical to address heat equity (Hsu et al., 2021), as well as enhance cost-benefit or tradeoff assessments.

This innovative approach of RP addresses areas responsible for added heat in the urban environment and how those can be cooled when urban green spaces are not a viable solution. RP, as a heat mitigation strategy on public property—residential streets—may be an opportunity to be provided equally in all residential neighborhoods, independent of socioeconomic background, because residential streets are prevalent in all neighborhoods of Phoenix, AZ, and implementation does not rely on the wealth of individuals.

3.4.5 Future Challenges

Following this study numerous areas of future research arise. These include:

- Investigating the effect of RP on T_{air} at different heights sensors that have an accuracy that is larger than the expected magnitude of the cooling effect (<1.0°C)
- Assessing the heat mitigation performance of different RP materials for all heat exposure metrics and the trade-offs of increased T_{mrt} above and adjacent to the surface
- Examining the effect of additional solar radiation exposure on neighboring vegetation and buildings, which has been called for prior (Sankar Cheela et al., 2021) (e.g., the buildings' associated indoor conditions).
- Investigating potential downwind effects of the RP on T_{air}, which may be displaced due to the small intervention scale(Sen & Khazanovich, 2021), and whether the cooling effects can be enhanced when the scale of the intervention is increased.
- Assessing seasonal, background climate, and local climate zone effects to support multi-model studies for more accurate use in urban planning and city decision-making. Such work may also include understanding the interactions between mixed approaches using multiple heat mitigation strategies (Sen & Khazanovich, 2021).
- Investigating the in-situ interaction between trees and RP and how effective RP is in the direct influence area of trees. A modeling study suggests that RP cannot contribute significantly to local urban heat mitigation when a tree or building shades the road (Chatterjee et al., 2019).

3.5 Reflective Pavement Assessment

The current study comprehensively assessed RP cooling potential in the hot, dry climate of Phoenix, AZ, considering three heat exposure metrics: T_{sfc}, T_{air}, and T_{mrt}. Based on our findings, we provided context-based suggestions to inform the use of RP to counteract urban overheating while minimizing unintended consequences.

RP is designed to minimize heat gain in an urban environment in locations where alternative cooling strategies, such as urban green spaces and water features, cannot be placed. Such heat reduction is particularly important for car-centric cities with wide streets and large parking lots. Results comparing untreated to RP-treated neighborhoods show a significant reduction in T_{sfc}, no significant impact of RP on T_{air}, and mixed results based on time of day concerning T_{mrt} (i.e., significantly elevated around noon, slightly lower at night). These differences may also affect energy use, health, and water usage, yet future work is needed.

The large reduction in T_{sfc} may support a general cooling of the air (shown minimally in the current study), and could thus be used to help counter urban overheating in places where solar radiation is abundant; however, seasonal, background, and local climate effects need to be investigated further to determine the effect and magnitude of RP on the heat exposure metrics when used in other cities and circumstances. The time-of-day T_{mrt} impacts provide important contextual guidance for locational use of RP based on knowledge of the time use of a specific urban space, wherein spaces with high foot traffic midday (parks, plazas, playgrounds) should avoid RP coatings due to heightened T_{mrt} (and thus heat stress) while locations with low foot traffic (roads, parking lots) can provide cooling benefit overnight with RP use. Despite the measurements taken within one local climate zone (open low-rise), similar results are expected in areas with little shade and low cloud coverage—in such locations, the additional reflectivity of RP would result in the greatest changes to the heat exposure metrics tested here, including lasting effects into the night.

Overall, each city must evaluate the potential impact and sustainability of RP to mitigate heat compared to current conditions alongside other strategies. Our synthesis of results and literature provide three important takeaways for cities to consider when assessing the cooling performance of any type of reflective seal. First, the heat metric matters —that is, cooling of the surface occurs throughout most times of the day, yet T_{mrt} is elevated during the day, while T_{air} may see no changes. Second, the location in which RP is applied must ensure that reflected radiation can escape the urban area, and some locations will see greater deterioration (and thus performance decrements) than others. Third, background climate matters, wherein hot, dry, and clear climates will see a greater difference between RP versus conventional seal coats versus warm, humid, more cloudy climates. Finally, RP may not be suitable for certain locations with high pedestrian foot traffic midday given elevated T_{mrt}.

3.6 Methods

3.6.1 Study Area

The City of Phoenix, AZ (33°27’N, 112°04’W) is the capital of and most populous city in Arizona and the heart of the Phoenix metropolitan area (population 4.95 million) in the Southwestern U.S.A. The city has eight Council Districts (Figure 7), covers an area of 1,344.50 km^2, and experiences a hot desert climate (Köppen Climate Classification subtype Bwh) with, on average, 299 sunny days per year. Summers are hot and dry for three months (June, July, and August), with a climatological average (1991–2020) maximum daily T_{air} above 40°C (104°F). The area experiences higher humidity during the monsoon season from June 15 to September 30. The average minimum T_{air} from May through September remains above 20°C (68°F).

3.6.2 Study Setup

Data were collected to assess (1) the impact of RP on heat metrics across three neighborhoods and (2) long-term solar reflectivity in eight neighborhoods (Figure 7). All neighborhoods are classified according to Stewart & Oke (2012) as open low-rise local climate zones (Wang et al., 2018). In-situ heat measurements were performed in the neighborhoods of Garfield (District 8 – D8; 5.6 km RP; 6.5 km AC; 0.8 km Concrete), Maryvale (District 5 – D5; 4.5 km RP; 8.0 km AC), and Westcliff Park (District 1 – D1; 5.5 km RP; 12.2 km AC).

3.6.3 In-Situ Data Collection

Three residential in-situ field campaigns collecting heat metric data were conducted on clear-sky, hot days in August and September of 2020 in the Garfield (August 18, 2020), Maryvale (September 5, 2020), and Westcliff (September 20, 2020) neighborhoods (see Figure 6). Those neighborhoods are in Phoenix Council Districts 8 (D8), 5 (D5), and 1 (D1), respectively. To assess the impact of RP on the urban micro-environment compared to traditional AC in each neighborhood, high-resolution T_{sfc}, 2-m T_{air}, and T_{mrt} were acquired using two mobile platforms: vehicle (T_{air} and T_{sfc}) and human-biometeorological carts (T_{mrt}) (see Table *2* for instrument and evaluation details). Data were collected across four 1-hour time windows: pre-sunrise (transect to

Table 2. List of instruments used to measure each heat metric and the solar reflectivity of the RP.

Instrument	*Accuracy*	*Response Time*	*Height (m)*	*Heat Metric*	*Statistical Test*	*Stationary (S) or Mobile (M)*
1–3 T-type Thermocouples (car)	±1.0°C	< 0.1 s	2.0 m	T_{air}	Mann-Whitney U test	M
Platinum Resistance Thermometer (MaRTy)	±0.2°C at (23°C); ±0.5°C at (-40/60°C)	< 22 s	1.7 m	T_{air}	descriptive	S
Apogee SI-111 Infrared Radiometer (car)	±0.2°C at (-10/65°C); ±0.5°C at (-40/70°C)	< 1 s	0.10 m	T_{sfc}	Mann-Whitney U test	M
Downward facing Pyrgeometer – IR01 (MaRTy)	±2.4% on T_{sfc} on daily sum	< 18 s	0.99 m	T_{sfc}	descriptive	S
3 NR01 Hukseflux 4-Component Net Radiometers oriented in 6 directions (MaRTy)	±2.4% on T_{mrt} on daily sum	< 18 s	1.11 m	T_{mrt}	descriptive	S
ASD FieldSpec 4 Wide-Res Field Spectroradiometer	3 nm (VNIR) 30 nm (SWIR)	N/A	1.0 m	N/A	descriptive	S

be finished 30 mins before sunrise; ~4:30–5:30), high sun (~12:00–13:00), high air temperature (~15:00–16:00), and directly post-sunset (transect to be started 30 mins after sunset; ~19:30–20:30).

A vehicle was equipped with an Apogee SI-111 Infrared Radiometer positioned on the front of the car perpendicular to the road to monitor T_{sfc} and 1–3 T-type thermocouples to monitor 2-m T_{air}; data were recorded at 1sec intervals on a vehicle moving at ~25 km h^{-1}. This speed allowed the vehicle to complete two traverses of the full neighborhood per hour, stay within speed limit ranges, ensure airflow over the sensors, and to take a representative number of samples in each area. A time-synchronous GPS system was attached to the car and time-matched with each temperature measurements. The movement of the vehicle aspirated the sensors. Traverse measurements while the vehicle was stopped (e.g., at intersections) were excluded from the analysis, as recommended by a similar study (Hart & Sailor, 2009).

For T_{sfc} measurements, which were taken directly (sensor at 10 cm height) over the AC and RP surfaces, the thermal emissivity of diverse AC surfaces lies between 0.93 and 0.98 (Marchetti et al., 2004). Thermal emissivity has a significant effect on T_{sfc}, yet a thermal emissivity difference of 0.03 leads to less than 0.5°C change in T_{sfc} (Gui et al., 2007). The infrared radiometer used a default emissivity of 0.95 for all measured surfaces to account for minor thermal emissivity differences. The introduced error is comparable to the error margin of the sensor itself.

A human-biometeorological cart (MaRTy) (Middel & Krayenhoff, 2019) measured T_{mrt} based on a six-directional net radiometer setup, T_{air}, relative humidity, wind velocity, and GPS location at 2-sec intervals (Table *2*). Within the 1-hour traverses, stationary MaRTy measurements occurred at pre-defined locations over and on the sidewalk adjacent to the RP and AC. The cart stopped at each location for 45-60 seconds to account for sensor lag(Häb et al., 2015).

3.6.4 Long-term Reflectivity Measurements

Monthly solar reflectivity measurements were performed on clear days between November 2020 and May 2021 at fixed locations in all eight neighborhoods plus one AC control

(D3) location. Measurements were taken with an ASD FieldSpec 4 Wide-Res field spectroradiometer and started when RP was 1–3 months old, depending on the neighborhood. This instrument provides solar reflectance data between 350–2500 nm. The monthly dataset provided critical pavement reflectivity performance based on real-world conditions, including seasonal impacts, surface wear, traffic flow and type, and dust and dirt.

Up to ten data points per surface were measured. These measurements were collected on the North side of the road next to the sidewalk to minimize the effect of varying traffic intensities between the neighborhoods, and hence the impact of traffic on road conditions.

3.6.5 Data Analysis/Statistics

The mobile temperature observations (T_{air}, T_{sfc}, and T_{mrt}) were time-detrended to account for temporal changes in atmospheric conditions. Time-detrending for MaRTy data (T_{air}, T_{mrt}) uses a reference location at the start and end of the transect that assumes a linear T_{air} change within the transect hour. Time-detrending of T_{air} and T_{sfc} of the vehicle traverses is based on a microclimate grid-detrending method developed for this study. Microclimate grid-detrending averages T_{air} and T_{sfc} data points in an area of 50 m x 50 m during the first and second vehicle traverse (traverse from now on). The difference between the traverse averages of T_{air} or T_{sfc} is used to create a linear temperature difference between each temperature value in the first and second traverse. The heat difference results from additional heating or cooling over time; hence, the results of the two traverses are kept separate. However, the slopes for each T_{air} and T_{sfc} are used to linearly time-detrend the respective temperatures for each grid cell during the first traverse to the average time of the first traverse, and similarly for the second traverse. This processing allows comparing the T_{air} or T_{sfc} across the whole neighborhood incorporating spatial and temporal changes of the heat metrics during measurements. After detrending, the average differences between AC and RP were calculated.

Table 3. N-th observation “n” and the resulting number of observations “#obs” that could be used in statistical analysis to avoid autocorrelation for each neighborhood, transect hour, and car-derived heat metric.

Neighborhood	Transect hour	Tair				Tsfc			
		Traverse 1		Traverse 2		Traverse 1		Traverse 2	
		n	#obs	n	#obs	n	#obs	n	#obs
Garfield	Pre-sunrise	44	27	22	58	12	101	11	116
	Noon	35	38	48	24	69	21	36	33
	Afternoon	33	35	28	42	19	63	13	90
	Post-sunrise	25	50	37	35	11	113	16	79
Maryvale	Pre-sunrise	28	63	25	67	18	98	22	76
	Noon	17	94	22	93	13	122	11	186
	Afternoon	19	92	12	99	10	174	9	132
	Post-sunrise	32	50	25	60	15	106	17	87
Westcliff	Pre-sunrise	71	28	50	35	33	60	26	67
	Noon	27	67	22	83	30	60	28	65
	Afternoon	14	109	13	113	31	50	25	59
	Post-sunrise	65	25	45	31	29	55	27	51

Due to the nature of the continuously collected T_{air} and T_{sfc} data during each traverse and the potential temporal autocorrelation, an autocorrelation test (Durbin-Watson test) for both traverses of each transect hour was applied using microclimate grid-detrended T_{air} (averaged above all 1–3 sensors used) and T_{sfc}. We found high temporal autocorrelation, which could artificially inflate statistical power. To minimize the impact, the iterative autocorrelation test method using every n-th observation described in Vanos et al. (2020) was used. After correcting for autocorrelation (p-value for both traverses: $p > 0.05$), the n-th observation for both T_{air} and T_{sfc} traverses was identified. The value for n was different for each transect hour, neighborhood, and heat metric. An overview of the autocorrelation parameters is provided in Table *3*, which shows the n-th observation used for each transect hour, neighborhood, and heat metric, as well as how many observations for each traverse were available for statistical analysis after adjusting for temporal autocorrelation.

The reduced datasets were tested individually for statistical significance concerning the underlying surface type (AC and RP) using the non-parametric statistical Mann-Whitney U test.

All statistical tests and data management were conducted in RStudio version 1.3.1073 (RStudio Team 2020). The DHARMa package was used for the temporal autocorrelation test (Hartig, 2021). The dplyr package was used for the non-parametric statistical Mann-Whitney U test (Wickham et al., 2018). Statistical significance of differences between surface types is calculated and indicated in Figures 8–10 with * for statistical significance ($p < 0.05$), ** for good statistical significance ($p < 0.01$), and *** for high statistical significance ($p < 0.001$).Spectroradiometer-derived surface reflectivity was processed by excluding the solar radiation signal for strong water vapor and carbon dioxide absorption windows (1350–1450nm; 1800–1900nm; and 2300–2500nm) to prevent very low but strongly varying signals that would introduce strong noise to the data analysis when comparing them to the white surface reference of the spectroradiometer. All data points were then averaged (maximum of 10) for each surface, location, and time measured. In addition to the spectral profiles, reflectance data were grouped into three wavelengths and averaged to show reflectance for particular wavelength spectra: 350–400 nm (UV-A, ultraviolet-A), 400–700 nm (VIS; visible), and 700–2500 nm (NIR; near-infrared). Street sweeping and rainy days were identified in the dataset to determine whether surfaces were cleaned by these processes and thus potentially changed or influenced solar reflection properties. Although no measurements were taken directly after rain or road sweeping, the effects of those events could have a prolonged impact. Due to the low number of data points at each given measurement date, there was low power to perform statistical testing; thus, descriptive statistics are provided between the different RP-treated neighborhoods and AC.

3.7 References

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X

Bartesaghi-Koc, C., Haddad, S., Pignatta, G., Paolini, R., Prasad, D., & Santamouris, M. (2021). Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. Solar Energy, 216, 564–588. https://doi.org/10.1016/j.solener.2020.12.043

Chatterjee, S., Khan, A., Dinda, A., Mithun, S., Khatun, R., Akbari, H., Kusaka, H., Mitra, C., Bhatti, S. S., Doan, Q. Van, & Wang, Y. (2019). Simulating micro-scale thermal interactions in different building environments for mitigating urban heat islands. Science of The Total Environment, 663, 610–631. https://doi.org/10.1016/j.scitotenv.2019.01.299

Chow, W. T. L., Brennan, D., & Brazel, A. J. (2012). Urban Heat Island Research in Phoenix, Arizona: Theoretical Contributions and Policy Applications. Bulletin of the American Meteorological Society, 93(4), 517–530. https://doi.org/10.1175/BAMS-D-11-00011.1

Eagar, J. D., Herckes, P., & Hartnett, H. E. (2017). The characterization of haboobs and the deposition of dust in Tempe, AZ from 2005 to 2014. Aeolian Research, 24, 81–91. https://doi.org/10.1016/j.aeolia.2016.11.004

Endreny, T. A. (2018). Strategically growing the urban forest will improve our world. Nature Communications, 9(1), 1160. https://doi.org/10.1038/s41467-018-03622-0

Erell, E., Pearlmutter, D., Boneh, D., & Kutiel, P. B. (2014). Effect of high-albedo materials on pedestrian heat stress in urban street canyons. Urban Climate, 10(P2), 367–386. https://doi.org/10.1016/j.uclim.2013.10.005

Erell, E., Pearlmutter, D., & Williamson, T. (2012). Urban microclimate: designing the spaces between buildings. Routledge.

Gabbe, C. J., Mallen, E., & Varni, A. (2022). Housing and Urban Heat: Assessing Risk Disparities. Housing Policy Debate, 1–19. https://doi.org/10.1080/10511482.2022.2093938

Georgescu, M., Morefield, P. E., Bierwagen, B. G., & Weaver, C. P. (2014). Urban adaptation can roll back warming of emerging megapolitan regions. Proceedings of the National Academy of Sciences, 111(8), 2909–2914. https://doi.org/10.1073/pnas.1322280111

Gilbert, H. E., Rosado, P. J., Ban-Weiss, G., Harvey, J. T., Li, H., Mandel, B. H., Millstein, D., Mohegh, A., Saboori, A., & Levinson, R. M. (2017). Energy and environmental consequences of a cool pavement campaign. Energy and Buildings, 157, 53–77. https://doi.org/10.1016/j.enbuild.2017.03.051

Gui, J. (Gavin), Phelan, P. E., Kaloush, K. E., & Golden, J. S. (2007). Impact of pavement thermophysical properties on surface temperatures. Journal of Materials in Civil Engineering, 19(8), 683–690. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:8(683)

Häb, K., Ruddell, B. L., & Middel, A. (2015). Sensor lag correction for mobile urban microclimate measurements. Urban Climate, 14, 622–635. https://doi.org/10.1016/j.uclim.2015.10.003

Hardin, A. W., & Vanos, J. K. (2018). The influence of surface type on the absorbed radiation by a human under hot, dry conditions. International Journal of Biometeorology, 62(1), 43–56. https://doi.org/10.1007/s00484-017-1357-6

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. Social Science & Medicine, 63(11), 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030

Hart, M. A., & Sailor, D. J. (2009). Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. Theoretical and Applied Climatology, 95(3–4), 397–406. https://doi.org/10.1007/s00704-008-0017-5

Hartig, F. (2021). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models (p. R package version 0.4.4). http://florianhartig.github.io/DHARMa/

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., & Bryan, B. A. (2021). Future global urban water scarcity and potential solutions. Nature Communications, 12(1), 4667. https://doi.org/10.1038/s41467-021-25026-3

Herold, M., & Roberts, D. (2005). Spectral characteristics of asphalt road aging and deterioration: implications for remote-sensing applications. Applied Optics, 44(20), 4327. https://doi.org/10.1364/AO.44.004327

Hoehne, C. G., Chester, M. V., Fraser, A. M., & King, D. A. (2019). Valley of the sun-drenched parking space: The growth, extent, and implications of parking infrastructure in Phoenix. Cities, 89, 186–198. https://doi.org/10.1016/j.cities.2019.02.007

Hoehne, C. G., Chester, M. V., Sailor, D. J., & King, D. A. (2022). Urban Heat Implications from Parking, Roads, and Cars: a Case Study of Metro Phoenix. Sustainable and Resilient Infrastructure, 7(4), 272–290. https://doi.org/10.1080/23789689.2020.1773013

Hoffman, J. S., Shandas, V., & Pendleton, N. (2020). The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. Climate, 8(1), 12. https://doi.org/10.3390/cli8010012

Hsu, A., Sheriff, G., Chakraborty, T., & Manya, D. (2021). Disproportionate exposure to urban heat island intensity across major US cities. Nature Communications, 12(1), 2721. https://doi.org/10.1038/s41467-021-22799-5

Johansson, E., Thorsson, S., Emmanuel, R., & Krüger, E. (2014). Instruments and methods in outdoor thermal comfort studies – The need for standardization. Urban Climate, 10, 346–366. https://doi.org/10.1016/j.uclim.2013.12.002

Kántor, N., & Unger, J. (2011). The most problematic variable in the course of human-biometeorological comfort assessment - The mean radiant temperature. Central European Journal of Geosciences, 3(1), 90–100. https://doi.org/10.2478/s13533-011-0010-x

Keith, L., Meerow, S., & Wagner, T. (2019). Planning for Extreme Heat: A Review. Journal of Extreme Events, 06(03n04), 2050003. https://doi.org/10.1142/S2345737620500037

Ko, J., Schlaerth, H., Bruce, A., Sanders, K., & Ban-Weiss, G. (2022). Measuring the impacts of a real-world neighborhood-scale cool pavement deployment on albedo and temperatures in Los Angeles. Environmental Research Letters, 17(4), 044027. https://doi.org/10.1088/1748-9326/ac58a8

Krayenhoff, E. S., Broadbent, A. M., Zhao, L., Georgescu, M., Middel, A., Voogt, J. A., Martilli, A., Sailor, D. J., & Erell, E. (2021). Cooling hot cities: a systematic and critical review of the numerical modelling literature. Environmental Research Letters, 16(5), 053007. https://doi.org/10.1088/1748-9326/abdcf1

Krayenhoff, E. S., & Voogt, J. A. (2010). Impacts of Urban Albedo Increase on Local Air Temperature at Daily–Annual Time Scales: Model Results and Synthesis of Previous Work. Journal of Applied Meteorology and Climatology, 49(8), 1634–1648. https://doi.org/10.1175/2010JAMC2356.1

Lai, D., Liu, W., Gan, T., Liu, K., & Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. Science of The Total Environment, 661, 337–353. https://doi.org/10.1016/j.scitotenv.2019.01.062

Livesley, S. J., McPherson, E. G., & Calfapietra, C. (2016). The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. Journal of Environmental Quality, 45(1), 119–124. https://doi.org/10.2134/jeq2015.11.0567

Marchetti, M., Muzet, V., Pitre, R., Datcu, S., Ibos, L., & Livet, J. (2004). Emissivity measurements of road materials. Proceedings of the 2004 International Conference on Quantitative InfraRed Thermography, 1(1). https://doi.org/10.21611/qirt.2004.012

Meerow, S., & Keith, L. (2022). Planning for Extreme Heat. Journal of the American Planning Association, 88(3), 319–334. https://doi.org/10.1080/01944363.2021.1977682

Meerow, S., & Newell, J. P. (2019). Urban resilience for whom, what, when, where, and why? Urban Geography, 40(3), 309–329. https://doi.org/10.1080/02723638.2016.1206395

Meili, N., Manoli, G., Burlando, P., Carmeliet, J., Chow, W. T. L., Coutts, A. M., Roth, M., Velasco, E., Vivoni, E. R., & Fatichi, S. (2021). Tree effects on urban microclimate: Diurnal, seasonal, and climatic temperature differences explained by separating radiation, evapotranspiration, and roughness effects. Urban Forestry & Urban Greening, 58, 126970. https://doi.org/10.1016/j.ufug.2020.126970

Middel, A., AlKhaled, S., Schneider, F. A., Hagen, B., & Coseo, P. (2021). 50 Grades of Shade. Bulletin of the American Meteorological Society, 102(9), E1805–E1820. https://doi.org/10.1175/BAMS-D-20-0193.1

Middel, A., Chhetri, N., & Quay, R. (2015). Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. Urban Forestry and Urban Greening, 14(1), 178–186. https://doi.org/10.1016/j.ufug.2014.09.010

Middel, A., & Krayenhoff, E. S. (2019). Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: Introducing the MaRTy observational platform. Science of The Total Environment, 687, 137–151. https://doi.org/10.1016/j.scitotenv.2019.06.085

Middel, A., Turner, V. K., Schneider, F. A., Zhang, Y., & Stiller, M. (2020). Solar reflective pavements—A policy panacea to heat mitigation? Environmental Research Letters, 15(6), 064016. https://doi.org/10.1088/1748-9326/ab87d4

Millstein, D., & Levinson, R. (2018). Preparatory meteorological modeling and theoretical analysis for a neighborhood-scale cool roof demonstration. Urban Climate, 24, 616–632. https://doi.org/10.1016/j.uclim.2017.02.005

Mohegh, A., Rosado, P., Jin, L., Millstein, D., Levinson, R., & Ban-Weiss, G. (2017). Modeling the climate impacts of deploying solar reflective cool pavements in California cities. Journal of Geophysical Research: Atmospheres, 122(13), 6798–6817. https://doi.org/10.1002/2017JD026845

Nasir, D. S., Pantua, C. A. J., Zhou, B., Vital, B., Calautit, J., & Hughes, B. (2021). Numerical analysis of an urban road pavement solar collector (U-RPSC) for heat island mitigation: Impact on the urban environment. Renewable Energy, 164, 618–641. https://doi.org/10.1016/j.renene.2020.07.107

Nazarian, N., Krayenhoff, E. S., Bechtel, B., Hondula, D. M., Paolini, R., Vanos, J., Cheung, T., Chow, W. T. L., de Dear, R., Jay, O., Lee, J. K. W., Martilli, A., Middel, A., Norford, L. K., Sadeghi, M., Schiavon, S., & Santamouris, M. (2022). Integrated Assessment of Urban Overheating Impacts on Human Life. Earth's Future, 10(8), e2022EF002682. https://doi.org/10.1029/2022EF002682

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

Oke, T. R., Johnson, G. T., Steyn, D. G., & Watson, I. D. (1991). Simulation of surface urban heat islands under “ideal” conditions at night part 2: Diagnosis of causation. Boundary-Layer

Pomerantz, M. (2018). Are cooler surfaces a cost-effect mitigation of urban heat islands? Urban Climate, 24, 393–397. https://doi.org/10.1016/j.uclim.2017.04.009

Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. Renewable and Sustainable Energy Reviews, 52, 445–459. https://doi.org/10.1016/J.RSER.2015.07.177

Qin, Y., He, Y., Hiller, J. E., & Mei, G. (2018). A new water-retaining paver block for reducing runoff and cooling pavement. Journal of Cleaner Production, 199, 948–956. https://doi.org/10.1016/j.jclepro.2018.07.250

Sankar Cheela, V. R., John, M., Biswas, W., & Sarker, P. (2021). Combating Urban Heat Island Effect—A Review of Reflective Pavements and Tree Shading Strategies. Buildings, 11(3), 93. https://doi.org/10.3390/buildings11030093

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments. Renewable and Sustainable Energy Reviews, 26, 224–240. https://doi.org/10.1016/j.rser.2013.05.047

Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., & Synnefa, A. (2017). Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. Solar Energy, 154, 14–33. https://doi.org/10.1016/j.solener.2016.12.006

Schell, C. J., Dyson, K., Fuentes, T. L., Des Roches, S., Harris, N. C., Miller, D. S., Woelfle-Erskine, C. A., & Lambert, M. R. (2020). The ecological and evolutionary consequences of systemic racism in urban environments. Science, 369(6510). https://doi.org/10.1126/science.aay4497

Schnebele, E., Tanyu, B. F., Cervone, G., & Waters, N. (2015). Review of remote sensing methodologies for pavement management and assessment. European Transport Research Review, 7(2), 7. https://doi.org/10.1007/s12544-015-0156-6

Schneider, F. A., Cordova Ortiz, J., Middel, A., Vanos, J. K., Sailor, D. J., Hondula, D. M., Wright, M. K., Kaloush, K. E., Medina, J., Campbell, B., Epel, E., Rice, B., & Garcia, R. (2023). “Phoenix Cool Pavement Heat Exposure Metrics”, in City of Phoenix Cool Pavement Evaluation (COPE). DesignSafe-CI. https://doi.org/https://doi.org/10.17603/ds2-71a1-n812 v2

Schneider, F. A., Cordova Ortiz, J., Vanos, J. K., & Middel, A. (2023). “Phoenix Cool Pavement Surface Reflectivity”, in City of Phoenix Cool Pavement Evaluation (COPE). DesignSafe-CI. https://doi.org/https://doi.org/10.17603/ds2-a1nj-z717 v2

Schrijvers, P. J. C., Jonker, H. J. J., de Roode, S. R., & Kenjereš, S. (2016). The effect of using a high-albedo material on the Universal Temperature Climate Index within a street canyon. Urban Climate, 17, 284–303. https://doi.org/10.1016/j.uclim.2016.02.005

Sen, S., & Khazanovich, L. (2021). Limited application of reflective surfaces can mitigate urban heat pollution. Nature Communications, 12(1), 3491. https://doi.org/10.1038/s41467-021-23634-7

Sen, S., Roesler, J., Ruddell, B., & Middel, A. (2019). Cool Pavement Strategies for Urban Heat Island Mitigation in Suburban Phoenix, Arizona. Sustainability, 11(16), 4452. https://doi.org/10.3390/su11164452

Sinha, P., Coville, R. C., Hirabayashi, S., Lim, B., Endreny, T. A., & Nowak, D. J. (2021). Modeling lives saved from extreme heat by urban tree cover. Ecological Modelling, 449, 109553. https://doi.org/10.1016/j.ecolmodel.2021.109553

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

Synnefa, A., Santamouris, M., & Apostolakis, K. (2007). On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy, 81(4), 488–497. https://doi.org/10.1016/j.solener.2006.08.005

Taha, H. (1997). Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. Energy and Buildings, 25(2), 99–103. https://doi.org/10.1016/S0378-7788(96)00999-1

Taha, H., Akbari, H., Rosenfeld, A., & Huang, J. (1988). Residential cooling loads and the urban heat island-the effects of albedo. Building and Environment, 23(4), 271–283. https://doi.org/10.1016/0360-1323(88)90033-9

Teskey, R., Wertin, T., Bauweraerts, I., Ameye, M., Mcguire, M. A., & Steppe, K. (2015). Responses of tree species to heat waves and extreme heat events. Plant, Cell & Environment, 38(9), 1699–1712. https://doi.org/10.1111/pce.12417

Vahmani, P., & Jones, A. D. (2017). Water conservation benefits of urban heat mitigation. Nature Communications, 8(1), 1072. https://doi.org/10.1038/s41467-017-01346-1

Vanos, J. K., Wright, M. K., Kaiser, A., Middel, A., Ambrose, H., & Hondula, D. M. (2022). Evaporative misters for urban cooling and comfort: effectiveness and motivations for use. International Journal of Biometeorology, 66(2), 357–369. https://doi.org/10.1007/s00484-020-02056-y

Wang, C., Middel, A., Myint, S. W., Kaplan, S., Brazel, A. J., & Lukasczyk, J. (2018). Assessing local climate zones in arid cities: The case of Phoenix, Arizona and Las Vegas, Nevada. ISPRS Journal of Photogrammetry and Remote Sensing, 141, 59–71. https://doi.org/10.1016/j.isprsjprs.2018.04.009

Wickham, H., Francois, R., Henry, L., & Müller, K. (2018). dplyr: A Grammar of Data Manipulation (p. R package version 0.7.6). https://cran.r-project.org/package=dplyr

Xu, W., Jimenez-Bescos, C., Pantua, C. A. J., Calautit, J., & Wu, Y. (2021). A Coupled Modelling Method for the Evaluation of the Impact of Pavement Solar Collector on Urban Air Temperature and Thermal Collection. Future Cities and Environment, 7(1), 2. https://doi.org/10.5334/fce.109

Yang, F., Lau, S. S. Y., & Qian, F. (2015). Cooling performance of residential greenery in localised urban climates: A case study in Shanghai China. International Journal of Environmental Technology and Management, 18(5–6), 478–503. https://doi.org/10.1504/IJETM.2015.073098

Zheng, N., Lei, J., Wang, S., Li, Z., & Chen, X. (2020). Influence of Heat Reflective Coating on the Cooling and Pavement Performance of Large Void Asphalt Pavement. Coatings, 10(11), 1065. https://doi.org/10.3390/coatings10111065

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

CHAPTER 4

SUSTAINABILITY PARTNERSHIP EVALUATION: TRANSITION FROM A CITY-UNIVERSITY TO A CITY-COMMUNITY-UNIVERSITY PARTNERSHIP

4.1 Abstract

City-university partnerships (CUPs) are a bilateral, transdisciplinary example of a transformation that is becoming increasingly important to address complex sustainability problems through the development of innovative solutions. Recently, the City of Tempe-Arizona State University CUP has been expanded to a multilateral partnership by including the community as a partner. To understand the relationships and systems within this expanded partnership, the newly-amended CUP must be formatively evaluated, allowing the partnership to enact active adjustments. The Foundation, Actions, Impact, and Interpersonal Context and Empowering Supports (FAIICES) evaluation tool offers a way to formatively evaluate a sustainability-oriented CUP to guide the partnership's design and management, yet, it has not been tested or adjusted for multilateral partnerships. Thus, I apply the FAIICES tool to the expanded CUP between the City of Tempe, Arizona State University, and the local community to identify the status of the partnership and project relationships with a focus on equity and sustainability for heat resilience. Additionally, I reflect on how well the FAIICES tool is designed for this purpose and propose tool amendments. Throughout the process, the status of the partnership is discussed as to how far the transition toward an equitable multilateral partnership has processed. The outcomes of this study seek to improve the multilateral partnership evaluated, the FAIICES tool, and the design for complex sustainability and solutions-oriented partnerships.

4.2 Introduction

Urban responses to sustainability and climate resilience transcend traditional boundaries of agency and decision-making (Frantzeskaki et al., 2021), involving diverse consequences for different social groups without guaranteeing an improvement to their well-being (van der Heijden, Bulkeley, et al., 2019). Transformative approaches across these traditional boundaries involve multilateral partnerships between cities, universities, and communities (Caughman et al., 2020), yet, it is unclear how those partnerships fare to enabling co-production of usable, policy-relevant science and decision-making including a range of diverse knowledge types.

Traditionally, emphasis is put on problem identification and solution, which regularly ends up with unintended consequences (Verweij & Thompson, 2006). In the process of decision-making, researchers and management often fail to acknowledge the diversity and validity of people's opinions and lived experiences (Shackleton et al., 2016). Sustainability issues, such as urban heat, demand transformation in how people and cities think (T. Muñoz-Erickson et al., 2017); sustainability demands transdisciplinary interaction before, during, and after the research process to integrate the best available knowledge (Lang et al., 2012). Knowledge from diverse groups in a multilateral partnership, including academic, policy, and societal knowledge at large. Involving community experience can be part of expanding equity and inclusion in sustainability research and practice but asks for flexible program design and an institutional culture that embraces risk-taking in learning as keys to success (Groulx et al., 2021). Transdisciplinary teams should include diverse voices and knowledge such as the local communities who know the real limits of a neighborhood, rather than the administrative limits provided by the city (Mancebo & Certomà, 2019). This work uses the definition of transdisciplinarity provided by Lang et al. (2012): "Transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge."

Lang et al. (2012) state that transdisciplinary research focuses on societally relevant problems, enables mutual learning among participating parties in- and outside of academia, and aims to create usable solution-oriented knowledge. Indeed, decision-making for heat resilience, like planning for sustainability in general, means finding some balance between conflicting goals: economy, environment, and equity (Campbell, 1996). In short, cities and stakeholders require usable, policy-relevant, transferable knowledge (Keith et al., 2019; McNie et al., 2016) that requires societal knowledge. Usable science is defined as the science produced to contribute directly to the design of policy or the solution of a problem (Lemos & Morehouse, 2005). Usable science needs to be relevant, credible, and legitimate, including boundary-spanning processes such as knowledge co-production (Driscoll et al., 2011; Wall et al., 2017).

Co-production is an iterative transdisciplinary process that fosters relationships and trust between the participants and creates a shared vision of what knowledge is usable and policy-relevant (Driscoll et al., 2011). The process connects science and society to address sustainability and equity problems, which is particularly important for multilateral partnerships. Co-production aims to acknowledge and fully integrate the users (community, city staff, etc.) into knowledge production (McNie et al., 2016), with the ability to build a comprehensive understanding for informed, sustainable, and equitable decision-making. City-university partnerships (CUPs) are a bilateral, transdisciplinary example of a needed transformation that is increasingly important to address complex sustainability problems through innovative solutions (Caughman et al., 2020). They can lead to a better understanding of the dynamics of phenomena, independent of whether they are desired or not; they focus on learning (Mancebo & Certomà, 2019). Yet, the nature of CUP relationships is essential to transfer solutions (best practices) between CUPs (Withycombe Keeler et al., 2018). To understand the relationships and systems within CUPs, they need to be evaluated. A successful transformative CUP administration matches the structure of their partnership to their sustainability goals and calls for understanding how to think systematically and manage within systems (Caughman et al., 2020).

Scientific processes, such as transdisciplinary co-production, are not guaranteed to be successful as a whole or from each participating party’s perspective, even if planned for appropriately (Lang et al., 2012; Marek et al., 2015). Transdisciplinary co-production can involve a single project or research process and lead to desired and not desired outcomes, if the co-production is not successful. Additionally, co-production takes significantly longer due to its difficulty to encompass all the actors, take into account micro-decisions made by individuals, and consider that all actors must see each other as legitimate (Mancebo & Certomà, 2019). Thus, we need partnerships to develop long-term relationships beyond the individual transdisciplinary project that can focus on reframing collaboration between the co-production partners in a transformative partnership. Transformative partnerships such as CUPs need to develop effective monitoring and evaluation techniques that allow adjustment, management, learning, and implementation of interventions within the partnership (Caughman et al., 2020). Formative evaluation that is conducted throughout the partnership provides information that allows correction, adaptation, and learning during the partnership. Essential approaches to formative evaluation are participatory, responsive, educative, and should be integrated effectively throughout the partnership (Hall et al., 2014). If it is not guaranteed to be successful for CUPs, what will the status be for a further expanded partnership that involves the community in a multilateral partnership?

The Foundation, Actions, Impacts, and Interpersonal Context and Empowering Supports (FAIICES) evaluation tool offers a way to formatively evaluate a sustainability-oriented CUP to guide the partnership's design and management (Caughman et al., 2020). FAIICES was developed by Caughman et al. (2020) and is a research-based, real-time evaluation tool for CUPs working on urban sustainability and resilience transformations. FAIICES is chosen over other frameworks such as the relationships, climate, and expectations (RCE) framework or the extent of collaboration (EC) framework. Those frameworks can assess the partnership's attributes like trust, respect, and communication, but do not guide partners on evaluative practices, relate assessments to outcomes, or integrate findings in ongoing partnerships, which is especially needed in sustainability-oriented partnerships working towards prolonged change. FAIICES supports agile decision-making and learning (Plummer & Armitage, 2007). The formative evaluation informs and increases intended and evidence-based, user-oriented decision-making to allow cities and citizens to equitably co-produce urban climate governance. Co-management, institutional alignment, and process are the core metrics investigated by the tool that can be applied in a wide range of collaborative efforts, though it is unclear how FAIICES might be applicable in contexts other than CUPs (Caughman et al., 2020). FAIICES allows ongoing, iterative data collection on both project-based and relationship-based components of the partnership with immediate, tangible, useful results for adept management of partnership initiatives in real time (Caughman et al., 2020).

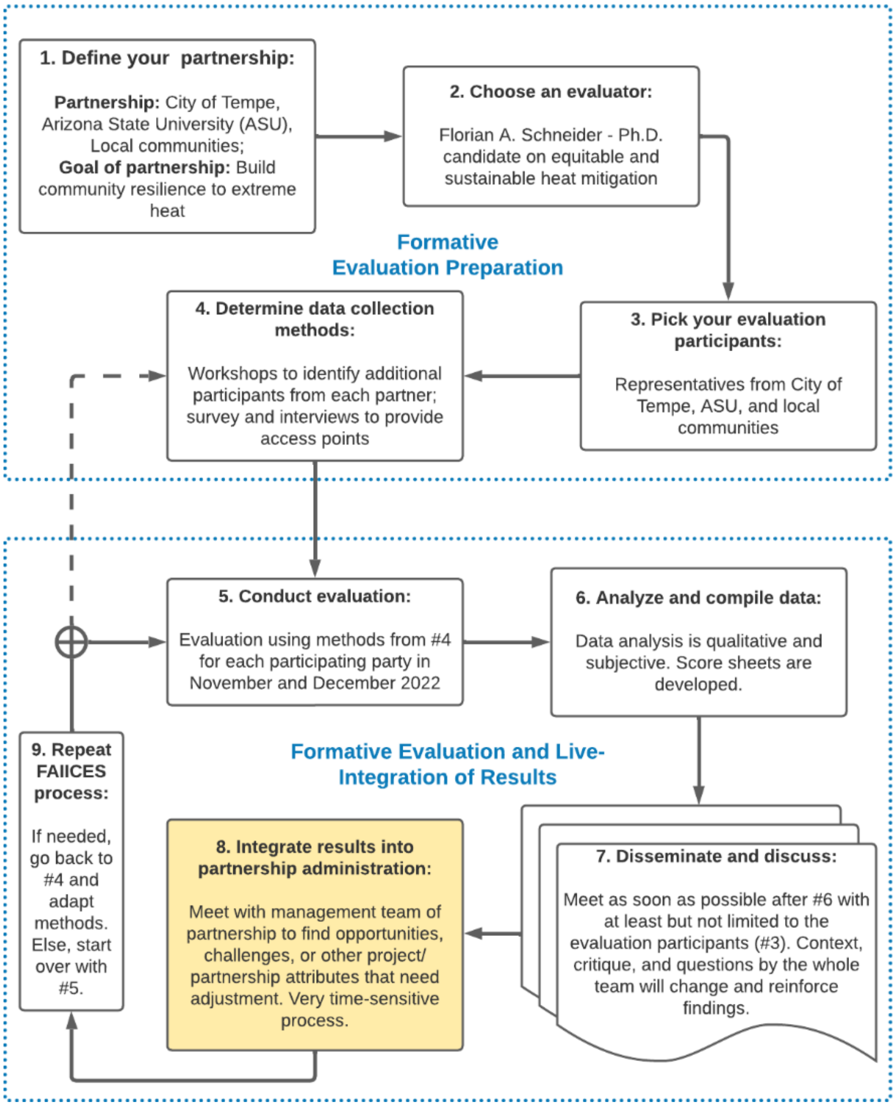
This study formatively evaluates the relationships within a newly-formed community-based, transdisciplinary, and multilateral partnership focusing on the perceptions of collaborative projects and of the partnership itself. The studied partnership expanded from a bilateral CUP between the City of Tempe, AZ, and Arizona State University (ASU) to a multilateral partnership between the City of Tempe, ASU, and the local community (a variety of sub-groups) and aims to co-produce usable, policy-relevant knowledge with an emphasis on changing the perspective from local to collective heat resilience and sustainability. A principle contribution of this study is the adaptation of the evaluation framework (FAIICES) from a bilateral to a multilateral process to evaluate how FAIICES may be applicable in a multilateral context. The study focuses on answering the following three research questions:

- According to the FAIICES framework: “How is the multilateral partnership functioning, what is working well, and where are improvements needed?” in the co-production environment of the evaluated multilateral partnership in Tempe, AZ.
- How well does the FAIICES framework accommodate this multilateral partnership?
- What are adoptions to the CUP serving framework that would make it better able to evaluate multilateral partnerships?

Throughout the process, the status of the partnership is discussed as to how far the transition toward an equitable multilateral partnership has processed.

4.3 Materials and Methods

The multilateral, co-production partnership between the City of Tempe, ASU, and the local community is formatively evaluated using the qualitative FAIICES tool. The partnership has developed from three different CUP partnership projects between the City of Tempe and ASU that merged under “Cool Kids, Cool Places, Cool Futures”. One partnership focused on extreme heat and resilience, another one on emergency management, and a third one on climate action planning. This partnership expanded to involve community within the project “Cool Kids, Cool Places, Cool Futures” and brought community partners and youth to participate under a focus of indigenous design that shall focus on decolonizing and indigenizing. Tangential to the project, the City of Tempe brought Unlimited Potential as a community organization to the partnership with a focus on climate justice within the city’s climate action plan, which expanded the now city-community-university partnership even further. Under the project of “Cool Kids, Cool Places, Cool



1. Define your partnership:
Partnership: City of Tempe, Arizona State University (ASU), Local communities;
Goal of partnership: Build community resilience to extreme heat

2. Choose an evaluator:
Florian A. Schneider - Ph.D. candidate on equitable and sustainable heat mitigation

3. Pick your evaluation participants:
Representatives from City of Tempe, ASU, and local communities

4. Determine data collection methods:
Workshops to identify additional participants from each partner; survey and interviews to provide access points

5. Conduct evaluation:
Evaluation using methods from #4 for each participating party in November and December 2022

6. Analyze and compile data:
Data analysis is qualitative and subjective. Score sheets are developed.

7. Disseminate and discuss:
Meet as soon as possible after #6 with at least but not limited to the evaluation participants (#3). Context, critique, and questions by the whole team will change and reinforce findings.

8. Integrate results into partnership administration:
Meet with management team of partnership to find opportunities, challenges, or other project/ partnership attributes that need adjustment. Very time-sensitive process.

9. Repeat FAIICES process:
If needed, go back to #4 and adapt methods. Else, start over with #5.

Figure 12. Flowchart depicting and describing the individual steps of the FAIICES evaluation. Visualized and adapted for this study from “Box 1. Step-by-step guide for getting started with the FAIICES evaluation scheme” by Caughman et al. (2020).

Future", which was the nucleus for this multilateral development, the partnership expanded from a CUP to a multilateral partnership that plans to focus on sustainability-driven, multilateral, and equitable decision-making toward collective heat resilience.

The chosen tool allows us to understand the project-based and relationship-based components of the partnership from the different perspectives involved and creates immediate, tangible, useful results to guide and foster the partnership as it happens (Caughman et al., 2020). With the help of the FAIICES tool, both the perception of the collaborative project and the perception of the partnership functioning are evaluated simultaneously. For a more in-depth understanding of the FAIICES tool and its indicators, see Caughman et al. (2020). Measuring subjective perceptions of and perspectives on the indicator areas (FAI and ICES) is an informative comparison of perspectives to guide the partnership but needs to be critically reflected due to its subjective nature.

The FAIICES tool was initially designed for CUPs on complex urban sustainability and resilience but it does not have specific constraints of municipal governments or research universities. Therefore, this study applies the tool to a multilateral partnership to understand its functioning; what is working well, and where are improvements needed? The FAIICES tool is applied following the steps visualized in Figure 12.

After initial IRB approval in October 2021, the partnership was not able to meet or interact until the Summer of 2022—dynamics within the partnership changed, requiring amendments to the formerly approved IRB. The amendments were accepted on October 19, 2022. Once the IRB was approved, step "5. Conduct evaluation" began; a survey with a consent form, Likert scale questions based on a rating system, and open-ended questions was deployed in November 2022 (Appendix A) to workshop participants from workshops that took place between June and November 2022. Participants in the survey included community members, city staff, and university researchers. In December 2022, a total of eleven (11) semi-structured interviews (approximately 30 minutes) were taken and audio-recorded from community members, city staff, and university researchers who were in leadership positions of the partnership and/or workshop/survey participants. The audio recordings were transcribed and anonymized, before the recordings were destroyed. A set of example interview questions is provided in Appendix B.

During January and February 2022, step “6. Analyze and compile data” was performed. Likert-scale survey results were averaged for each group (city, community, university) and analyzed descriptively. Open-ended survey responses and transcribed semi-structured interviews were analyzed using a text content analysis. The text content analysis was performed with the assistance of MaxQDA and text segments were subjectively coded using a pre-developed codebook and the indicators provided by the FAIICES tool. The codebook includes the measures of perception according to Caughman et al. (2020) for each of the five indicators which were utilized when performing the text content analysis. First, the foundation indicator measures participants’ perception of interest, competency, capacity, motivation, knowledge, processes, and resources. Second, the actions indicator assesses participants’ perception of planning, implementing, goals, partnership, co-management, methodology, and co-production. Third, the Impact indicator evaluates participants’ perception of outcomes, achievements, and future prospects. Fourth, the interpersonal context indicator measures participants’ perception of collaborative history, interest to engage, motivation to engage, and the mutual understanding of need. Lastly, the empowering support indicator assesses participants’ perception of the formalization of the partnership, the mechanisms of the partnership, and the resource commitment of partners within the partnership.

The results of all data analysis were compiled. Step “7. Disseminate and discuss” was performed in mid-February and led to essential feedback and reinforced findings, including project and partnership relationships, and partnership design. Throughout the process, the FAIICES tool was assessed for its efficacy and whether or how the FAIICES tool can be adapted to better serve multilateral partnerships if needed. The latter portion is part of the discussion.

Outcomes of the evaluation were presented to the administration and integration of changes is up to leaders within the partnership.

4.4 Results

4.4.1 Project: Foundation, Actions, and Impact

The first part of the Likert-scale responses from the survey shows how satisfied city staff, community, and university researchers are with the project. All groups show strong interest in the topic of the Cool Kids project and its workshops. The researchers are most satisfied with the heat resilience impacts that Cool Kids is producing, and the city staff is satisfied. The perception of university and city capacities is considered high by the other partners, while the community is judged to have the lowest capacity among the three. The same perception exists for the co-management of the partners. All partners perceive medium satisfaction with respect to the actions and outcomes taken by the project. Researchers have the highest satisfaction with the progress and functioning of the project and workshops, while the community has a high satisfaction with the progress and a medium satisfaction with the functioning of the project, and the city reports medium satisfaction with both the progress and functioning of the project.

Incorporating the text content analysis of the interviews, the score sheet for the Foundation, Actions, and Impact indicators were drawn, as shown in Figure 13. It shows that the city staff has the greatest foundation, followed by the university researchers, and the community

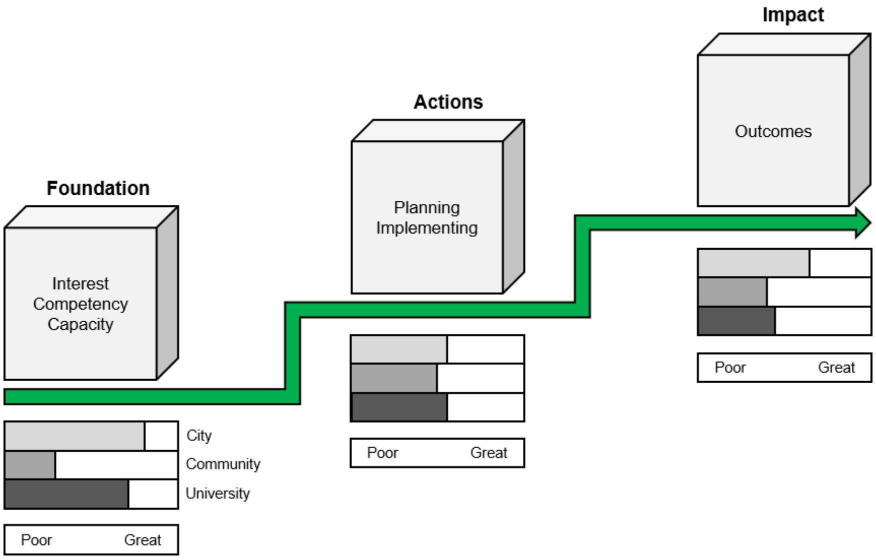


Figure 13. Score sheet for the comparison of partners' perspectives of multilateral project functioning across the FAIICES scheme. Shows the three core areas of the project functioning evaluation (FAI). Adapted from Caughman et al. (2020).

Table 4. List of summary statements drawn from the text content analysis of the interviews and open-ended survey questions for each FAIICES indicator. Left column to right column: Foundation (F), Actions (A), Impact (I), Interpersonal Context (IC), and Empowering Support (ES). MOU stands for memorandum of understanding. IGA stands for intergovernmental agreement. The order and the fact that there are six statements for each indicator does not carry any weight and is for a summary and visual purpose only.

Foundation (F)	Actions (A)	Impact (I)	Interpersonal Context (IC)	Empowering Support (ES)
Interest big; different focus; missing communication	Communication and planning mainly between city-university and city-community	Communication is positive but may not be solution-oriented	Collaborative history strong between city and university; acknowledgment and trust	MOU and IGA are formal agreements for process.
Position turnover is disruptive, i.e., community	Position turnover running concern; breaks relationships	Position turnover exacerbates achievement communication	High interest to engage; also, in self-critique	Lack of accountability measures to ensure equity and learning
Good capacity and competency	City and university see successful implementation	Need for outfacing reports and journal articles	Lacks humility for mutual understanding of needs	Mechanisms of partnership in need of improvements
Need for accountability, flexibility, bureaucracy, language use, action vs research, partnership reflection	University focuses on acknowledgment while the city focuses at self-critique and improvement	The city achieves milestones but partners are not aware of them. Lack of communication of goals and thus achievements.	Motivation to engage is perceived high by university and community. City focus on process improvements	Resource Commitment is acceptable between partners but not transparent
All agree: Can't be done alone	The city struggles with ambiguous goals	Learning of needs: goals, staffing, commitment, communication, resources	Mutual understanding of heat resilience and collaboration is acknowledged	Resources are unclear to many actors creating accountability concerns
City capacity increased while university capacity decreased over time	A full-time staff of the city allowed structured action	Permanent impacts on the city and community; not on the university	Critical gaps in language use and missing accountability measures	All agree: Lack of humility, acknowledgment, and achievements

with the worst foundation by comparison. As the foundation includes interest, competency, and capacity, the statements listed in the first column of Table *4* were drawn from the analyzed interviews and surveys.

Results with respect to the “Actions” indicator focus on the perception of planning (including goals) and implementation of the involved partners. All partners are perceived to have comparable, average project performance for these indicators. The statements listed in the second column of Table 4 were drawn from the analyzed interview and surveys.

Results with respect to the “Impact” indicator focus on the perception of outcomes, achievements, and future prospects of the involved partners. The city is perceived to have the greatest “Impact”, with the university researchers and the community perceived as lacking impact on the project’s outcomes. The statements listed in the third column of Table *4* were drawn from the analyzed interviews and surveys.

4.4.2 Partnership: Interpersonal Context and Empowering Support

The second part of the Likert-scale responses from the survey shows how satisfied city staff, community, and university researchers are with the partnership. The city and community are highly satisfied with the historical collaboration of the university. The historical collaboration of the City of Tempe and its community is perceived as satisfactory by the other partners. The community perceives lower levels of mutual understanding from the university and city, with the least credit given to university researchers. Researchers show a higher satisfaction with the community’s understanding of mutual needs than the city staff. The university researchers report the highest satisfaction with respect to the commitment of the community and city staff to the partnership. City staff are satisfied but express the least amount of satisfaction among all partners regarding the progress, functioning, and overall structure of the partnership.

The third part of the Likert-scale responses report the level of trust, communication, and commitment that was perceived between the partners. The level of trust is perceived as similar across the partners at a strong level, with space for improvement. In terms of communication, the community perceived the communication between the university and city to be acceptable, a perception substantiated by the city and university who state strong communication with each other. The university partner perceives communication with the community as weaker than that of the city staff with the community. The level of commitment between the city and university and the city and community are perceived by the city as “strong to very strong” and “strong”, respectively. Community perceives the level of commitment between acceptable and strong for both the university and the city, while university researchers perceive a strong commitment between all partners.

Results for the “Interpersonal Context” indicator focus on collaborative history, engagement, and mutual understanding of needs between partners. The statements listed in the fourth column of Table *4* were drawn from the analyzed interviews and surveys.

Results for the “Empowering Support” indicator focus on formalization and mechanisms of partnership as well as resource commitment to partners. The statements listed in the fifth column of Table *4* were drawn from the analyzed interviews and surveys.

4.4.3 Problems and Successes using FAIICES

The FAIICES tool provided the necessary guidance throughout the process (Figure 12) while allowing flexibility based on the partnership design, participants, and evaluator preferences concerning data collection and dissemination. The formative evaluation, evaluator, and FAIICES tool were introduced at the beginning of the partnership but they were not formally addressed or written into the formalized partnership documents and agreements. The aforementioned evaluation tools were formally written into the IRB documents for approval as the chosen method and rationale behind the necessity for human-subject data. The missing formality of the evaluation process within the partnership created missing accountability for when the evaluation happens and when certain analysis and dissemination sessions are needed. It is acknowledged that a multilateral partnership has many moving parts that operate outside of the control of the leaders of the partnership because the moving parts operate at different sub-levels.

Using the indicators of the subjective FAIICES tool gives the evaluator ease of access to perform a text analysis. Analyzing data was not a weakness of the FAIICES tool in the context of the multilateral partnership, yet, the flexibility of the tool in terms of when it can be applied created an opportunity for any partner to inhibit an effective evaluation. This is another argument for a more formalized accountability measure that is missing from the FAIICES framework. The multilateral partnership that developed from the historical collaboration between the city and the university added not one, but many different entities that can be categorized community partners. Thus, compared to a CUP, the multilateral partnership has less transparency as to who are participants from all partners in addition to realizing that individuals may not represent one partner alone and have a shared agency in the space of the multilateral partnership.

4.5 Discussion

4.5.1 Status of Evaluated Partnership

The performed evaluation led to a project and partnership status overview involving all partners' perspectives. On the project indicators (Figure 13), the partnership lacks foundational support (knowledge, capacity, processes, competency) for projects, especially on the community side. Further, the university's capacity has lowered over time due to a purported lack of interest, resources, and an apparent loss of engagement toward the research component of the partnership. A weak foundation leads to compromised project actions and impact due to missing communication and understanding, making it more difficult for the partnership to thrive in the latter stages (Caughman et al., 2020). The foundational concern of position turnover does not only disrupt commitment and competency, but it can simultaneously break relationships and trust, worsening general communication. This communication breakdown is especially pertinent to achievements if people are not aware of goals when joining the partnership. The partnership's communication and acknowledgment of goals and the co-management of projects are areas of improvement. Specifically, the city needs to identify how non-tangible goals such as relationships and trust can play a role in partnership building. Co-production and communication mostly happen between two out of three partners at a time. University and community currently lack a co-productive relationship and operate based off of a work/service relationship. An important step in building actions was the commitment to full-time staff from the city as acknowledged by all partners. The different projects that participants and partners relate to having created outcomes of value, with some being already permanent such as new relationships and trusted environments due to the projects between partners and full-time staffing as well as more funding and time as resources. On the other hand, there is a need to create solution-oriented outcomes for all partners, including official reports and journal articles, as well as communicate and acknowledge milestone achievements. As stated by Groulx et al. (2021) for community-university partnerships, adding community involves highlighting flexibility, equity and inclusion, and the ability to take risks in learning and teaching. The openness to learn and teach is an avenue for the evaluated multilateral partnership to improve and thus invite all perspectives equitably with unique knowledge and language.

The multilateral partnership developed from a CUP, which has a strong collaborative history with a strong shared interest to engage the community. Yet, there is a perceived lack of humility to the diverse perspectives that have joined this partnership and a deficit of acknowledgment of roles and resources that all individuals come from. The interpersonal context of the partnership is strong between the university and city but fragile between the community and original partners, even though the motivation to engage is strong. There is a mutual understanding from all partners of this heat resilience effort that collaboration is needed, but the partnership shows critical gaps in interpersonal language use and a lack of accountability measures to ensure trust. The partnership was designed with formal agreements to provide empowerment mechanisms that create a shift in power, such as memorandums of understanding and intergovernmental agreements, yet these simultaneously constructed boundaries and inflexibility. It is important to recognize that the formal process in the partnerships allowed both empowerment and disempowerment. Empowerment via the creation of citizen awareness by involving the community which creates support for action and via the cultivation of narratives of action to support the initiative/partnership (Patterson & van der Grijp, 2019). Disempowerment occurred via lack of awareness from language discontinuity between partners, which makes it difficult to support action and via institutional voids (e.g., bureaucracy) that make it more difficult for community partners to gain traction in the partnership (Patterson & van der Grijp, 2019). Thus, accountability measures and risks to learning and teaching are areas of need in the partnership to address the shifts in power appropriately and not as tokenism (Arnstein, 2019). Additionally, partners commented that each partner commits resources at an acceptable rate but the flow of resources is unclear or nontransparent, exacerbating accountability concerns. The multilateral partnership can be described as a routine partnership that is still identifying and finding each other to discuss opportunities and further engagement (Caughman et al., 2020).

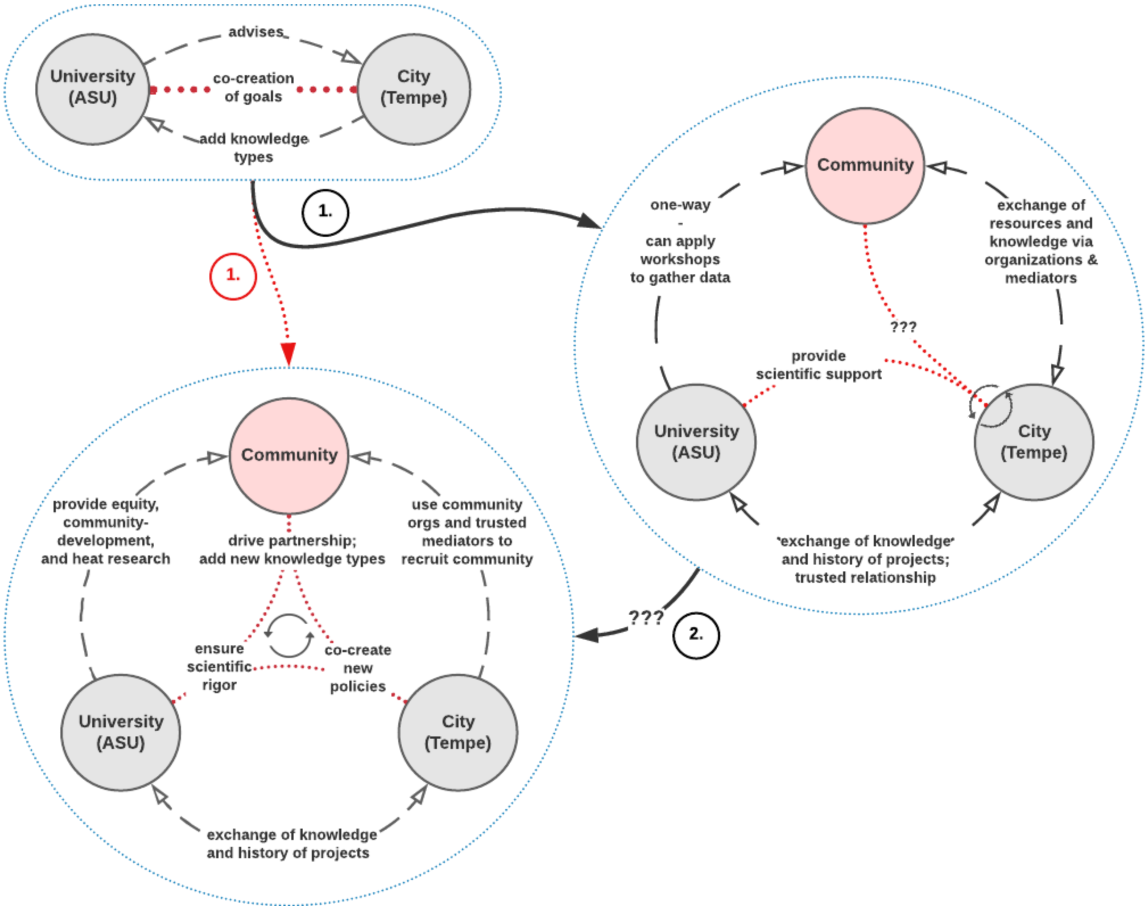


Figure 14. Evaluation of transition from city-university partnership to city-community-university partnership, depicting that the direct pathway to a transformative partnership was not achieved (red circle with “1”). There is at least one intermediate step (black circle with “1”) via a bifurcated partnership (right circle). The question marks at the black circle with “2” indicate that the transition from bifurcated to multilateral is not clear.

Suggestions for the partnership administration after dissemination included a stronger focus on the shift of power, summed up as: co-production, co-management, and co-leading at all levels of the partnership. The partnership has achieved some permanent and sustainable outcomes in terms of relationships and the first tangible outcomes on heat resilience for all partners, with different emphases. The deep engagement that was initiated between all partners enhances respect and trust between the groups and opens further shared decision-making pathways in the future (Meerow et al., 2019). Despite this important first steps of building shared resilience, further improvements around continued research engagement and a focus on shared load between research and community action are suggested. Positive engagement could best be achieved via formal accountability measures and stronger communication of smaller milestones (goal setting) rather than focusing on the large end goal alone. Additionally, the pitfalls of the bureaucracy can be avoided through acknowledgment of all actors in their different capacities, utilizing identified resource pathways to create action, and formalizing the process. Resource utilization should be communicated to all partners, including communication on barriers to achieving more trust and satisfaction. Recognizing barriers such as bureaucracy and trying to resolve them to provide necessary acknowledgment to partners such as universities is an important factor for the long-term improvement of university engagement via additional resources.

Reflection via evaluation was perceived as a crucial mechanism to recognize differences in perceptions, yet the evaluation is not part of the formalized partnership. Considering reflection as a key component without including it in the foundation via resources may create a lack of commitment and could derail any evaluation processes and accountability to it. Using the FAIICES tool to identify perceptions of the projects and partnerships of all partners is a key component to provide this essential feedback and informs the tool itself to assist in the design of complex and solutions-oriented partnerships or those that strive to achieve them.

4.5.2 Transition from CUP to Multilateral

A more general question after evaluating this partnership and identifying its status is: What does the transition from a CUP to a multilateral partnership involving the community look like? Using the case study, it was identified that there is no direct pathway from a bilateral partnership without community (CUP) to a multilateral partnership with community (Figure 14). The partnership is not at a transformational stage when using the definition provided by Caughman et al. (2020) because, even though a clear framework was designed, collaboration and resources are not transparently provided. Collaborative efforts are not co-created between all partners but between the city and university and between the city and community in isolation, which creates two co-producing project partners within a larger partnership. The former CUP can be identified as a strategic partnership with numerous collaborative efforts, strong shared interests and missions, and some shared resources (Caughman et al., 2020). The same level of partnership exists within the larger multilateral partnership between the two co-producing subgroups (city-community; city-university) but on the level of the multilateral partnership, partners are still identifying and finding each other where they discuss opportunities and engagement in limited joint efforts, which makes the investigated partnership a routine multilateral partnership (Caughman et al., 2020). Currently, the city holds the majority of resources in terms of funding and relationships with other partners, which means communication goes via the city and not directly from the community to the university and vice versa. The detour via the city creates a power differential within the partnership and puts the greatest responsibility on the city. Community and university interacted in workshops in a one-way communication more or less, and not in the co-creation of usable science since the researchers were not preparing the workshop with community members. In the end, instead of reaching a multilateral partnership that is co-productive in the curation of usable science, the first transition from expanding the CUP with community partners led to a bi-furcated partnership via the center of relationship and power holder.

4.5.3 A necessary stop? – Bi-furcated partnership

The bi-furcated partnership design and how the design is part of the transition from CUP to a multilateral partnership is shown in Figure 14. It is important to recognize where the arrow circle within that partnership lies. That is where administrative leadership, resources, responsibility, and power are centered. The bi-furcated partnership as a middle step shows a new partner (community in this case) and that led to a shift in responsibility and power to the partner that is most responsible for holding and building the relationships (the city in this case). Considering that adding community requires flexibility which is hard to provide from a bureaucratic and formal perspectives within the city and university, the in-between step to a bi-furcated partnership is logical since those hurdles need to be overcome by those who construct them. In addition, relationships are initiated and held by the administrative leadership which, in this case, was perceived to be the city, even though the partnership was not initially designed that way. As a result of the evaluation, the city would like to share the leadership role. Co-leading can only work if everyone provides the capacity and competency to provide leadership in the complex partnership environment. Co-leadership is one of the next steps suggested to achieve a stronger connection between the university and the community, which may lead to a co-productive partnership between them. Once the third co-productive subgroup is established, relationships and goals are aligned between the two partners. Bringing the conversation to the center (Figure 14, bottom left) would be the next step to align goals, resources, and responsibilities between all partners and thus achieve a transformative multilateral partnership that co-creates with strong influence on the strategies of all partners involved. Multiple suggestions for administrative changes were made to the partnership leadership to advance the design toward a multilateral partnership, should that be the desired relationship. Sharing those suggestions may not lead to success, since cities fail to define partnership-based resilience work consistently and implementation is not guaranteed to be successful (Caughman, 2022). Future research should continue to explore the pathway to identify different stages of the transition from a bilateral to a potential multilateral partnership and whether a further transition is actually of advantage for complex sustainability-focused partnerships. How does an ideal multilateral sustainability-focused partnership operate?

4.5.4 FAIICES tool adaptation

The formative evaluation process using the FAIICES tool with a multilateral partnership having three partners (city, university, and community) has shown to be an effective pathway for providing essential feedback and reflection on the partnership, even though it was not a partnership with two but three partners. The tool has been provided, as suggested by the tool designer Caughman et al. (2020), as a guiding mechanism to inform the design and management of a sustainability and resilience-oriented partnership. They indicated that the tool may be useful for a much broader context, including the interpretation to use it for a multilateral partnership, as done in this study. Thus, it can be confirmed that the tool has the potential to achieve suggested outcomes for not only CUPs, but also for a multilateral partnership that includes the community and developed from a prior CUP.

Additionally, outcomes of this study suggest that the tool requires adjustment for some minor aspects to serve multilateral partnerships. One aspect requires the evaluator and the tool to become part of the formalized partnership, and thus are recognized as an entity. Hence, some accountability for the reflection and evaluation process should be given to the tool and evaluator. This step is best done between steps #2 and #3 (see Figure 12), when an evaluator for the given partnership is chosen, and before participants for evaluation are selected, especially since step #3 can change based on position turnover. In addition to making the evaluation part of the formal process, which means to co-design formally when the evaluation should be conducted and allowing some flexibility, but not too much, due to extensive delays of individual projects of the partnership. In short, align the evaluation on time windows of individual projects rather than on partnership steps.

Another suggested change is to evaluate partnerships between two of the three partners in parallel to identify relationships and perceptions between the partners in subprojects. Outcomes of the subgroup evaluations will provide context for the larger multilateral partnership, such as was given in this study. Even though this step was not exclusively performed, it was recognized that the dynamics between each sub-partnership matters in the larger scheme of the multilateral partnership and its development.

The FAIICES tool provides a convenient pathway on how to approach the individual evaluation with almost too much flexibility which may create conflicts since the partnership also needs to become more flexible when involving the community. Thus, findings suggest that the data collection method involves direct feedback questions about the data collection, which can be justified when the method is a formal part of the evaluation.

One general concern that has yet to be addressed is the ambiguity of the community partner and its many different identities and entities. Even though the investigated partnership is considered a three-partner partnership, it is clear that the community represents more than one single voice. Finding a recognition and pathway to incorporate the multitude of diverse voices equitably into the evaluation is needed.

4.5.5 Limitations of this work

Using the FAIICES tool was a choice based on what partnership design was approached. The tool is designed for partnerships with complex sustainability and solution-oriented goals. It is acknowledged that other frameworks exist and there may be additional insights applying a different evaluation perspective to this same case. For example, the EASIER model by Berrone et al. (2019) focuses on public-private partnerships that contribute to sustainable development goals and may unveil differing perspectives. It could be interpreted that the investigated partnership also involves private partners within the community and that the EASIER model with six indicators, compared to FAIICES with five indicators, could provide a better sustainability perspective in terms of engagement, access, scalability, inclusiveness, economic impact, and resilience (Berrone et al., 2019). Yet, EASIER does not focus on the partnership design indicators for interpersonal context and empowering support as FAIICES does, which are crucial components for a sustainability and equity-driven partnership (Caughman et al., 2020).

Apart from the tool used to evaluate, considering the transition from a CUP to a multilateral partnership within one step or adding another step (bi-furcated partnership) may be idealistic. Due to the idealism, a question mark was left in Figure 14 at the black circled number two. It is of interest to further evaluate the partnership to identify partnership design milestones that are achieved and can be approached as goals by other new partnerships aspiring for a multilateral solution. It is important to recognize that the discussed evaluation is a case study on a single evaluation of a partnership between the City of Tempe, ASU, and the local community. A different foundational setup between partners, a different engagement of individuals within the groups and between them, a different amount of resources at hand, and other variations may well show a slightly different picture of how the bi-furcated middle step may look. Maybe it is not the city in a different partnership that holds the relationships, finances, and resources. Maybe it is a community-university partnership expanding to the city. What happens if community holds the money and provides opportunity to city and university? The solution for sustainability planning through a collaborative approach depend on the characteristics of the local communities and recognizing that there is no one-size-fits all solution (Mancebo & Certomà, 2019). Yet, it will be interesting to further research alternative partnerships that approach a multilateral design between city, community, and university to identify additional steps or expand from the steps provided in Figure 14. The case study also showcased that evaluation is extremely dependent on the progress of the partnership and the multilateral partnership had many reasons for delays in different subprojects and at-large including but not limited to the COVID-19 pandemic, positional turnover, workshop rescheduling, matching availability between partners, and funding development. Results indicate that future evaluations need to be integrated into the partnership and be executed at times independent of whether all projects can achieve the milestones of interest simultaneously. Waiting for the projects to align takes away important insight and opportunities to learn from the evaluation and potentially adjust the partnership toward creating a sustainable and equitable multilateral partnership.

4.6 Conclusion

City-university partnerships (CUPs) are a bilateral, transdisciplinary example of a transformation that is needed and becomes increasingly important to address complex sustainability problems and develop innovative solutions. Recently, the City of Tempe-Arizona State University CUP has been expanded to a multilateral partnership by including the community as a partner. This study applied the FAIICES evaluation tool to the multilateral partnership between the city, community, and university in November and December of 2022 to identify the partnership and project perception of all involved partners and provide guidance on the partnership and project status.

Results show that the partnership is a routine partnership at the multilateral level but at the sub-levels, where two partners operate together, the city-university and the city-community partnership co-produce usable science and outcomes, but the community-university partnership utilizes one-way communication for data collection from the university. The partnership lacks foundational substance, especially for the community even though interest is high from all partners. Lacking foundation has lasting implications for actions and impact, which lack overall communication on planning and implementation, co-management, and a clear perception of each other's goals, specifically smaller milestones. Even though the city and university see successful implementation happening, the city struggles with ambiguous (non-tangible) goals. This lack of clear goal setting is one of the risks when building multilateral partnerships with multiple partners involving the community. It turns out that the partnership is not yet a multilateral partnership with equal or fair contribution—it is a bi-furcated partnership with the responsibility, resources, and power close to the city. Multiple suggestions for administrative changes were made to the partnership leadership to advance the design toward a multilateral partnership if the partners desire that result. Future research should further investigate the transition from a bilateral to a multilateral partnership and whether a further transition is actually an advantage for complex sustainability-focused partnerships.

Throughout the process, the FAIICES tool was reflected and a couple of suggestions toward its application were made when handling multilateral partnerships, including sub-partnership evaluation, formalizing the evaluation as part of the partnership, and identifying how to involve the diverse perspective of community members as one partner. The outcomes of this study inform the multilateral partnership evaluated, the FAIICES tool, and the design for the transition of complex sustainability and solutions-oriented partnerships.

CHAPTER 5

SYNTHESIS AND SUMMARY

Three different research studies were performed to provide a comprehensive understanding of urban heat as a sustainability challenge.

A systematic literature review with a text content analysis of scientific and city practitioner literature confirms the written communication disconnect between science and city practitioner literature for green infrastructure (GI) and that it may not be beneficial to overcome the disconnect due to distinct differences in the purpose of each literature group. Additionally, disservices and trade-offs are less often communicated than co-benefits, leading to a concern that science and practice fail to acknowledge the urban system's complexity and the diversity of people. Outcomes of the content analysis demonstrate that even though research on usable science and co-production are brought forward, they are not yet implemented or recognized within the scientific or practice literature to encourage holistic and user-influenced written communication. GI as a heat mitigation strategy is more comprehensively discussed than reflective pavement (RP), which is also due to RP not being utilized in cities as much. Future research should look into utilizing AI to expand the literature groups and topics, and thus involve, at some point, the user perspective as well. Additionally, investigating oral communication between different perspectives should be considered as well, to understand if the same disconnect exists in the oral space. The key outcome of the first study for this dissertation can be summarized to the following statement: "Awareness of communication disconnect may allow for fiscal and political recognition of partnerships that cross traditional boundaries and bring in diverse knowledge sources for a holistic and equitable implementation of urban heat mitigation."

One example of a reflective pavement living laboratory study was performed for this dissertation. Here, RP was assessed for its impacts on multiple heat metrics to understand the potential side effects of reducing heat. This project was a city-university partnership (CUP). The assessment revealed that RP decreases heat gain of road surfaces in an urban environment and could be used to counter urban overheating where solar radiation is abundant when background climate and local context are considered. Specifically, RP reduces surface temperature but increases pedestrian heat load based on mean radiant temperature during the day. Thus, RP is of increasing interest in locations where alternative cooling strategies, such as GI, cannot be placed, yet where exposure to the additional radiative heat is reduced to a minimum. That includes but is not limited to areas where pedestrians foot traffic is minimal and where cyclists and e-scooter riders are not affected negatively. The synthesis revealed that the heat metric used for evaluation, the location in which RP is applied, and the background climate matter when determining whether RP is a suitable heat mitigation strategy. Future research should investigate air temperature at different heights, in different cities and background climates, for mixed-strategy approaches, and for larger implementation projects. Additionally, different RP materials and neighboring buildings and vegetation as well as the human-material interaction need to be studied. Each city must evaluate the potential impact and sustainability of RP to mitigate heat compared to current and future conditions alongside other strategies to receive equitable heat reduction while including future transformation of the city including increased walkability and public transportation. A foundational CUP from the project commencement, or other partnership design, is encouraged. Involving community into the evaluation- and decision-making process on RP includes the user of RP in the neighborhood and provides local knowledge and motivation to create a co-produced solution that creates heat resilience locally and at a city scale, centering the design around people. The key outcome of the first study for this dissertation can be summarized to the following statement: ” Cities must evaluate RP (or other strategies) for multiple heat metrics, beyond the environmental perspective, to current and future conditions, and consider RP alongside other strategies.”

A transdisciplinary study evaluating a multilateral, sustainability-oriented, heat resilience partnership revealed that the multilateral partnership operates as a routine partnership. The partnership lacks foundational substance, especially for the community contribution, which has lasting effects on actions and impacts of the partnership and its projects to achieve collective heat resilience. The evaluation disclosed a lack of clear goal setting and continued commitment to all partners' goals. Missing acknowledgment and accountability were major concerns. It was identified that the partnership is still transitioning toward a multilateral co-production partnership and is currently in a state of a bi-furcated partnership, where the city holds power, resources, and responsibility, and leads the bilateral co-productive partnerships with the university and community. The study revealed that the FAIICES tool could use some minor changes to better serve multilateral or transitioning partnerships. This study is an observation of how urban heat can be addressed as a complex sustainability issue involving diverse voices: in a co-productive, user-informed way, yet, it takes time, resources, and commitment. Future research should further investigate the transition from bilateral to multilateral partnership and whether a further transition beyond the bi-furcated stage is actually an advantage for complex sustainability-focused partnerships. The key outcome of the first study for this dissertation can be summarized to the following statement: “Community-oriented multilateral, sustainability partnerships cross traditional boundaries and are key for heat resilience efforts that serve the users, but they need to be built over time, be accountable, and require reflective evaluation tools.”

In conclusion, this dissertation is timely due to climate change and continued urbanization and provided new knowledge towards the seven (7) goals that were outlined in the introduction. This work advances the research and awareness of urban heat for science, policy, and community, to identify the science-practice disconnect and inequitable implementation of heat mitigation interventions, and improves holistic and sustainable decision-making in cities to tackle past, present, and future urban heat as sustainability issues to achieve SDG#11. I found different perspectives on co-benefits, trade-offs, and disservices of GI and RP, which may enhance communication between city practice and science in the future, allowing for potentially better collaboration between partners to achieve SDGs related to urban heat. I found that RP as a strategy for heat mitigation must be assessed in the context of its location and for multiple heat metrics to involve the user—the pedestrian or driver—perspective, and that air temperature reduction may not be the sole focus alone to achieve sustainable outcomes. I found that a multilateral partnership development takes time, constant evaluation, flexibility, and accountability, and, in my case, led to a bi-furcated partnership with the power, resources, and responsibilities lying in one partner’s hand. This potential in-between step of a bi-furcated partnership may develop further and should be continuously monitored to identify development stages for transitioning partnerships and empowerment/disempowerment.

Based on the outcomes and synthesis of the three studies, especially considering the key takeaways that bridge across the study itself, I encourage the following four procedures to address urban heat as a traditional boundary-crossing sustainability challenge:

1. I encourage co-productive partnerships that involve user-based knowledge to ensure equitable and sustainable heat mitigation;
2. I encourage to include social and economic dimensions in addition to the environmental dimensions in the urban space when researching and communicating heat;
3. I encourage to make decisions based on need rather than convenience—facing the hard truth;
4. I encourage to cross traditional research and practice boundaries and approach community-based research and practice even if it takes longer and is more cost-intensive.

My results guide research and partnerships, and thus, decision-making toward a resilient urban future on urban heat as an acknowledged complex sustainability issue and related SDGs. Urban heat mitigation is for the people that live in our cities – so let them be part of it.

REFERENCES

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, *70*(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X

American Council for an Energy-Efficient Economy. (2021). *ACEEE - State and Local Policy Database*. https://database.aceee.org/city/mitigation-urban-heat-islands

Anguelovski, I., Connolly, J. J. T., Pearsall, H., Shokry, G., Checker, M., Maantay, J., Gould, K., Lewis, T., Maroko, A., & Roberts, J. T. (2019). Why green "climate gentrification" threatens poor and vulnerable populations. *Proceedings of the National Academy of Sciences*, *116*(52), 26139–26143. https://doi.org/10.1073/pnas.1920490117

Arnstein, S. R. (2019). A Ladder of Citizen Participation. *Journal of the American Planning Association*, *85*(1), 24–34. https://doi.org/10.1080/01944363.2018.1559388

Bartesaghi-Koc, C., Haddad, S., Pignatta, G., Paolini, R., Prasad, D., & Santamouris, M. (2021). Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. *Solar Energy*, *216*, 564–588. https://doi.org/10.1016/j.solener.2020.12.043

Berrone, P., Ricart, J., Duch, A., Bernardo, V., Salvador, J., Piedra Peña, J., & Rodríguez Planas, M. (2019). EASIER: An Evaluation Model for Public–Private Partnerships Contributing to the Sustainable Development Goals. *Sustainability*, *11*(8), 2339. https://doi.org/10.3390/su11082339

Bozeman, B., & Sarewitz, D. (2011). Public Value Mapping and Science Policy Evaluation. *Minerva*, *49*(1), 1–23. https://doi.org/10.1007/s11024-011-9161-7

Broadbent, A. M., Krayenhoff, E. S., & Georgescu, M. (2020). The motley drivers of heat and cold exposure in 21st century US cities. *Proceedings of the National Academy of Sciences*, *117*(35), 21108–21117. https://doi.org/10.1073/pnas.2005492117

Campbell, S. (1996). Green Cities, Growing Cities, Just Cities?: Urban Planning and the Contradictions of Sustainable Development. *Journal of the American Planning Association*, *62*(3), 296–312. https://doi.org/10.1080/01944369608975696

Caughman, L. (2022). Characterization of partnerships and collaborations in US cities' urban resilience plans. *RAUSP Management Journal*, *57*(4), 362–381. https://doi.org/10.1108/RAUSP-09-2021-0180

Caughman, L., Withycombe Keeler, L., & Beaudoin, F. (2020). Real-Time Evaluation of City–University Partnerships for Sustainability and Resilience. *Sustainability*, *12*(21), 8796. https://doi.org/10.3390/su12218796

Chatterjee, S., Khan, A., Dinda, A., Mithun, S., Khatun, R., Akbari, H., Kusaka, H., Mitra, C., Bhatti, S. S., Doan, Q. Van, & Wang, Y. (2019). Simulating micro-scale thermal interactions in different building environments for mitigating urban heat islands. *Science of The Total Environment*, *663*, 610–631. https://doi.org/10.1016/j.scitotenv.2019.01.299

Choumert, J., & Salanié, J. (2008). Provision of urban green spaces: Some insights from economics. *Landscape Research*, *33*(3), 331–345. https://doi.org/10.1080/01426390802045996

Chow, W. T. L., Brennan, D., & Brazel, A. J. (2012). Urban Heat Island Research in Phoenix, Arizona: Theoretical Contributions and Policy Applications. *Bulletin of the American Meteorological Society*, *93*(4), 517–530. https://doi.org/10.1175/BAMS-D-11-00011.1

Collins, K., & Ison, R. (2009). Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. *Environmental Policy and Governance*, *19*(6), 358–373. https://doi.org/10.1002/eet.523

Corburn, J. (2009). Cities, climate change and urban heat island mitigation: Localising global environmental science. *Urban Studies*, *46*(2), 413–427. https://doi.org/10.1177/0042098008099361

Coseo, P., & Larsen, L. (2014). How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago. *Landscape and Urban Planning*, *125*, 117–129. https://doi.org/10.1016/j.landurbplan.2014.02.019

Coutts, C., & Hahn, M. (2015). Green Infrastructure, Ecosystem Services, and Human Health. *International Journal of Environmental Research and Public Health*, *12*(8), 9768–9798. https://doi.org/10.3390/ijerph120809768

Downes, N. K., & Storch, H. (2014). Current Constraints and Future Directions for Risk Adapted Land-Use Planning Practices in the High-Density Asian Setting of Ho Chi Minh City. *Planning Practice & Research*, *29*(3), 220–237. https://doi.org/10.1080/02697459.2014.929835

Driscoll, C. T., Lambert, K. F., & Weathers, K. C. (2011). Integrating Science and Policy: A Case Study of the Hubbard Brook Research Foundation Science Links Program. *BioScience*, *61*(10), 791–801. https://doi.org/10.1525/bio.2011.61.10.9

Eagar, J. D., Herckes, P., & Hartnett, H. E. (2017). The characterization of haboobs and the deposition of dust in Tempe, AZ from 2005 to 2014. *Aeolian Research*, *24*, 81–91. https://doi.org/10.1016/j.aeolia.2016.11.004

Endreny, T. A. (2018). Strategically growing the urban forest will improve our world. *Nature Communications*, *9*(1), 1160. https://doi.org/10.1038/s41467-018-03622-0

Erell, E., Pearlmutter, D., Boneh, D., & Kutiel, P. B. (2014). Effect of high-albedo materials on pedestrian heat stress in urban street canyons. *Urban Climate*, *10*(P2), 367–386. https://doi.org/10.1016/j.uclim.2013.10.005

Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban microclimate: designing the spaces between buildings*. Routledge.

Feng, J., Haddad, S., Gao, K., Garshasbi, S., Ulpiani, G., Santamouris, M., Ranzi, G., & Bartesaghi-Koc, C. (2023). Fighting urban climate change—state of the art of mitigation technologies. In *Urban Climate Change and Heat Islands* (pp. 227–296). Elsevier. https://doi.org/10.1016/B978-0-12-818977-1.00006-5

Frantzeskaki, N., McPhearson, T., Collier, M. J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., van Wyk, E., Ordóñez, C., Oke, C., & Pintér, L. (2019). Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making. *BioScience*, *69*(6), 455–466. https://doi.org/10.1093/biosci/biz042

Frantzeskaki, N., McPhearson, T., & Kabisch, N. (2021). Urban sustainability science: prospects for innovations through a system's perspective, relational and transformations' approaches. *Ambio*, *50*(9), 1650–1658. https://doi.org/10.1007/s13280-021-01521-1

Fung, A. A., Zhou, A., Vanos, J. K., & Schmid-Schönbein, G. W. (2021). Enhanced intestinal permeability and intestinal co-morbidities in heat strain: A review and case for autodigestion. *Temperature*, *8*(3), 223–244. https://doi.org/10.1080/23328940.2021.1922261

Gabbe, C. J., Mallen, E., & Varni, A. (2022). Housing and Urban Heat: Assessing Risk Disparities. *Housing Policy Debate*, 1–19. https://doi.org/10.1080/10511482.2022.2093938

Georgescu, M. (2015). Challenges Associated with Adaptation to Future Urban Expansion. *Journal of Climate*, *28*(7), 2544–2563. https://doi.org/10.1175/JCLI-D-14-00290.1

Georgescu, M., Morefield, P. E., Bierwagen, B. G., & Weaver, C. P. (2014). Urban adaptation can roll back warming of emerging megapolitan regions. *Proceedings of the National Academy of Sciences*, *111*(8), 2909–2914. https://doi.org/10.1073/pnas.1322280111

Gilbert, H. E., Rosado, P. J., Ban-Weiss, G., Harvey, J. T., Li, H., Mandel, B. H., Millstein, D., Mohegh, A., Saboori, A., & Levinson, R. M. (2017). Energy and environmental consequences of a cool pavement campaign. *Energy and Buildings*, *157*, 53–77. https://doi.org/10.1016/j.enbuild.2017.03.051

Gocheva, K., Lü, Y., Li, F., Bratanova-Doncheva, S., & Chipev, N. (2019). Ecosystem restoration in Europe: Can analogies to Traditional Chinese Medicine facilitate the cross-policy harmonization on managing socio-ecological systems? *Science of The Total Environment*, *657*, 1553–1567. https://doi.org/10.1016/j.scitotenv.2018.11.192

Groulx, M., Nowak, N., Levy, K., & Booth, A. (2021). Community needs and interests in university–community partnerships for sustainable development. *International Journal of Sustainability in Higher Education*, *22*(2), 274–290. https://doi.org/10.1108/IJSHE-03-2020-0086

Guhathakurta, S., & Gober, P. (2007). The Impact of the Phoenix Urban Heat Island on Residential Water Use. *Journal of the American Planning Association*, *73*(3), 317–329. https://doi.org/10.1080/01944360708977980

Gui, J. (Gavin), Phelan, P. E., Kaloush, K. E., & Golden, J. S. (2007). Impact of pavement thermophysical properties on surface temperatures. *Journal of Materials in Civil Engineering*, *19*(8), 683–690. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:8(683)

Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., Brenck, M., Fischer, L. K., Frantzeskaki, N., Kabisch, N., Krellenberg, K., Kremer, P., Kronenberg, J., Larondelle, N., Mathey, J., Pauleit, S., Ring, I., Rink, D., Schwarz, N., & Wolff, M. (2017). Greening cities – To be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat International*, *64*, 41–48. https://doi.org/10.1016/j.habitatint.2017.04.005

Häb, K., Ruddell, B. L., & Middel, A. (2015). Sensor lag correction for mobile urban microclimate measurements. *Urban Climate*, *14*, 622–635. https://doi.org/10.1016/j.uclim.2015.10.003

Hall, J., Freeman, M., & Roulston, K. (2014). Right timing in formative program evaluation. *Evaluation and Program Planning*, *45*, 151–156. https://doi.org/10.1016/j.evalprogplan.2014.04.007

Hansen, R., & Pauleit, S. (2014). From Multifunctionality to Multiple Ecosystem Services? A Conceptual Framework for Multifunctionality in Green Infrastructure Planning for Urban Areas. *Ambio*, *43*(4), 516–529. https://doi.org/10.1007/s13280-014-0510-2

Hardin, A. W., & Vanos, J. K. (2018). The influence of surface type on the absorbed radiation by a human under hot, dry conditions. *International Journal of Biometeorology*, *62*(1), 43–56. https://doi.org/10.1007/s00484-017-1357-6

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine*, *63*(11), 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030

Hart, M. A., & Sailor, D. J. (2009). Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theoretical and Applied Climatology*, *95*(3–4), 397–406. https://doi.org/10.1007/s00704-008-0017-5

Hartig, F. (2021). *DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models* (p. R package version 0.4.4). http://florianhartig.github.io/DHARMa/

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., & Bryan, B. A. (2021). Future global urban water scarcity and potential solutions. *Nature Communications*, *12*(1), 4667. https://doi.org/10.1038/s41467-021-25026-3

Herold, M., & Roberts, D. (2005). Spectral characteristics of asphalt road aging and deterioration: implications for remote-sensing applications. *Applied Optics*, *44*(20), 4327. https://doi.org/10.1364/AO.44.004327

Hoehne, C. G., Chester, M. V., Fraser, A. M., & King, D. A. (2019). Valley of the sun-drenched parking space: The growth, extent, and implications of parking infrastructure in Phoenix. *Cities*, *89*, 186–198. https://doi.org/10.1016/j.cities.2019.02.007

Hoehne, C. G., Chester, M. V., Sailor, D. J., & King, D. A. (2022). Urban Heat Implications from Parking, Roads, and Cars: a Case Study of Metro Phoenix. *Sustainable and Resilient Infrastructure*, *7*(4), 272–290. https://doi.org/10.1080/23789689.2020.1773013

Hoffman, J. S., Shandas, V., & Pendleton, N. (2020). The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. *Climate*, *8*(1), 12. https://doi.org/10.3390/cli8010012

Hölscher, K., & Frantzeskaki, N. (2021). Perspectives on urban transformation research: transformations in, of, and by cities. *Urban Transformations*, *3*(1), 2. https://doi.org/10.1186/s42854-021-00019-z

Hondula, D. M., Balling, R. C., Vanos, J. K., & Georgescu, M. (2015). Rising Temperatures, Human Health, and the Role of Adaptation. *Current Climate Change Reports*, *1*(3), 144–154. https://doi.org/10.1007/s40641-015-0016-4

Howe, P. D., Marlon, J. R., Wang, X., & Leiserowitz, A. (2019). Public perceptions of the health risks of extreme heat across US states, counties, and neighborhoods. *Proceedings of the National Academy of Sciences*, *116*(14), 6743–6748. https://doi.org/10.1073/pnas.1813145116

Hsu, A., Sheriff, G., Chakraborty, T., & Manya, D. (2021). Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, *12*(1), 2721. https://doi.org/10.1038/s41467-021-22799-5

Hughes, S., Giest, S., & Tozer, L. (2020). Accountability and data-driven urban climate governance. *Nature Climate Change*, *10*(12), 1085–1090. https://doi.org/10.1038/s41558-020-00953-z

Johansson, E., Thorsson, S., Emmanuel, R., & Krüger, E. (2014). Instruments and methods in outdoor thermal comfort studies – The need for standardization. *Urban Climate*, *10*, 346–366. https://doi.org/10.1016/j.uclim.2013.12.002

Kaloustian, N., Bitar, H., & Diab, Y. (2016). Urban Heat Island and Urban Planning in Beirut. *Procedia Engineering*, *169*, 72–79. https://doi.org/10.1016/j.proeng.2016.10.009

Kántor, N., & Unger, J. (2011). The most problematic variable in the course of human-biometeorological comfort assessment - The mean radiant temperature. *Central European Journal of Geosciences*, *3*(1), 90–100. https://doi.org/10.2478/s13533-011-0010-x

Keith, L., Meerow, S., Hondula, D. M., Turner, V. K., & Arnott, J. C. (2021). Deploy heat officers, policies and metrics. *Nature*, *598*(7879), 29–31. https://doi.org/10.1038/d41586-021-02677-2

Keith, L., Meerow, S., & Wagner, T. (2019). Planning for Extreme Heat: A Review. *Journal of Extreme Events*, *06*(03n04), 2050003. https://doi.org/10.1142/S2345737620500037

Kenski, K. (2017). Overcoming confirmation and blind spot biases when communicating science. In K. H. Jamieson, D. Kahan, & D. A. Scheufele (Eds.), *The Oxford Handbook of the Science of Science Communication* (Vol. 1, pp. 369–375). Oxford University Press.

Kingsborough, A., Jenkins, K., & Hall, J. W. (2017). Development and appraisal of long-term adaptation pathways for managing heat-risk in London. *Climate Risk Management*, *16*, 73–92. https://doi.org/10.1016/j.crm.2017.01.001

Ko, J., Schlaerth, H., Bruce, A., Sanders, K., & Ban-Weiss, G. (2022). Measuring the impacts of a real-world neighborhood-scale cool pavement deployment on albedo and temperatures in Los Angeles. *Environmental Research Letters*, *17*(4), 044027. https://doi.org/10.1088/1748-9326/ac58a8

Koop, S. H. A., Koetsier, L., Doornhof, A., Reinstra, O., Van Leeuwen, C. J., Brouwer, S., Dieperink, C., & Driessen, P. P. J. (2017). Assessing the Governance Capacity of Cities to Address Challenges of Water, Waste, and Climate Change. *Water Resources Management*, *31*(11), 3427–3443. https://doi.org/10.1007/s11269-017-1677-7

Krayenhoff, E. S., Broadbent, A. M., Zhao, L., Georgescu, M., Middel, A., Voogt, J. A., Martilli, A., Sailor, D. J., & Erell, E. (2021). Cooling hot cities: a systematic and critical review of the numerical modelling literature. *Environmental Research Letters*, *16*(5), 053007. https://doi.org/10.1088/1748-9326/abdcf1

Krayenhoff, E. S., Moustaoui, M., Broadbent, A. M., Gupta, V., & Georgescu, M. (2018). Diurnal interaction between urban expansion, climate change and adaptation in US cities. *Nature Climate Change*, *8*(12), 1097–1103. https://doi.org/10.1038/s41558-018-0320-9

Krayenhoff, E. S., & Voogt, J. A. (2010). Impacts of Urban Albedo Increase on Local Air Temperature at Daily–Annual Time Scales: Model Results and Synthesis of Previous Work. *Journal of Applied Meteorology and Climatology*, *49*(8), 1634–1648. https://doi.org/10.1175/2010JAMC2356.1

Kulkarni, K. K., Schneider, F. A., Gowda, T., Jayasuriya, S., & Middel, A. (2022). MaRTiny—A Low-Cost Biometeorological Sensing Device With Embedded Computer Vision for Urban Climate Research. *Frontiers in Environmental Science*, *10*, 550. https://doi.org/10.3389/fenvs.2022.866240

Lai, D., Liu, W., Gan, T., Liu, K., & Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Science of The Total Environment*, *661*, 337–353. https://doi.org/10.1016/j.scitotenv.2019.01.062

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., & Thomas, C. J. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science*, *7*(S1), 25–43. https://doi.org/10.1007/s11625-011-0149-x

Larsen, L. (2015). Urban climate and adaptation strategies. *Frontiers in Ecology and the Environment*, *13*(9), 486–492. https://doi.org/10.1890/150103

Leal Filho, W., Wolf, F., Castro-Díaz, R., Li, C., Ojeh, V. N., Gutiérrez, N., Nagy, G. J., Savić, S., Natenzon, C. E., Quasem Al-Amin, A., Maruna, M., & Bönecke, J. (2021). Addressing the Urban Heat Islands Effect: A Cross-Country Assessment of the Role of Green Infrastructure. *Sustainability*, *13*(2), 753. https://doi.org/10.3390/su13020753

Lemos, M. C., & Morehouse, B. J. (2005). The co-production of science and policy in integrated climate assessments. *Global Environmental Change*, *15*(1), 57–68. https://doi.org/10.1016/j.gloenvcha.2004.09.004

Livesley, S. J., McPherson, E. G., & Calfapietra, C. (2016). The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *Journal of Environmental Quality*, *45*(1), 119–124. https://doi.org/10.2134/jeq2015.11.0567

Long, J., & Rice, J. L. (2019). From sustainable urbanism to climate urbanism. *Urban Studies*, *56*(5), 992–1008. https://doi.org/10.1177/0042098018770846

Maes, M. J. A., Jones, K. E., Toledano, M. B., & Milligan, B. (2019). Mapping synergies and trade-offs between urban ecosystems and the sustainable development goals. *Environmental Science & Policy*, *93*, 181–188. https://doi.org/10.1016/j.envsci.2018.12.010

Mancebo, F., & Certomà, C. (2019). Urban Planning for Sustainability and Justice. In C. Certomà, H. Bulkeley, & J. van der Heijden (Eds.), *Urban Climate Politics* (pp. 135–151). Cambridge University Press. https://doi.org/10.1017/9781108632157.008

Marchetti, M., Muzet, V., Pitre, R., Datcu, S., Ibos, L., & Livet, J. (2004). Emissivity measurements of road materials. *Proceedings of the 2004 International Conference on Quantitative InfraRed Thermography*, *1*(1). https://doi.org/10.21611/qirt.2004.012

Marek, L. I., Brock, D.-J. P., & Savla, J. (2015). Evaluating Collaboration for Effectiveness. *American Journal of Evaluation*, *36*(1), 67–85. https://doi.org/10.1177/1098214014531068

Martilli, A., Krayenhoff, E. S., & Nazarian, N. (2020). Is the Urban Heat Island intensity relevant for heat mitigation studies? *Urban Climate*, *31*, 100541. https://doi.org/10.1016/j.uclim.2019.100541

McDonald, R. I., Biswas, T., Sachar, C., Housman, I., Boucher, T. M., Balk, D., Nowak, D., Spotswood, E., Stanley, C. K., & Leyk, S. (2021). The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLoS ONE*, *16*(4), e0249715. https://doi.org/10.1371/journal.pone.0249715

McNie, E. C., Parris, A., & Sarewitz, D. (2016). Improving the public value of science: A typology to inform discussion, design and implementation of research. *Research Policy*, *45*(4), 884–895. https://doi.org/10.1016/j.respol.2016.01.004

Meerow, S., & Keith, L. (2022). Planning for Extreme Heat: A National Survey of U.S. Planners. *Journal of the American Planning Association*, *88*(3), 319–334. https://doi.org/10.1080/01944363.2021.1977682

Meerow, S., & Newell, J. P. (2019). Urban resilience for whom, what, when, where, and why? *Urban Geography*, *40*(3), 309–329. https://doi.org/10.1080/02723638.2016.1206395

Meerow, S., Pajouhesh, P., & Miller, T. R. (2019). Social equity in urban resilience planning. *Local Environment*, *24*(9), 793–808. https://doi.org/10.1080/13549839.2019.1645103

Meili, N., Manoli, G., Burlando, P., Carmeliet, J., Chow, W. T. L., Coutts, A. M., Roth, M., Velasco, E., Vivoni, E. R., & Fatichi, S. (2021). Tree effects on urban microclimate: Diurnal, seasonal, and climatic temperature differences explained by separating radiation, evapotranspiration, and roughness effects. *Urban Forestry & Urban Greening*, *58*, 126970. https://doi.org/10.1016/j.ufug.2020.126970

Merchant, C., Meggers, F., Hou, M., Aviv, D., Schneider, F. A., & Middel, A. (2022). Resolving Radiant: Combining Spatially Resolved Longwave and Shortwave Measurements to Improve the Understanding of Radiant Heat Flux Reflections and Heterogeneity. *Frontiers in Sustainable Cities*, *4*, 82. https://doi.org/10.3389/frsc.2022.869743

Meyer, R. (2011). The Public Values Failures of Climate Science in the US. *Minerva*, *49*(1), 47–70. https://doi.org/10.1007/s11024-011-9164-4

Middel, A., AlKhaled, S., Schneider, F. A., Hagen, B., & Coseo, P. (2021). 50 Grades of Shade. *Bulletin of the American Meteorological Society*, *102*(9), E1805–E1820. https://doi.org/10.1175/BAMS-D-20-0193.1

Middel, A., Chhetri, N., & Quay, R. (2015). Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry and Urban Greening*, *14*(1), 178–186. https://doi.org/10.1016/j.ufug.2014.09.010

Middel, A., Huff, M., Krayenhoff, E. S., Udupa, A., & Schneider, F. A. (2023). PanoMRT: Panoramic infrared thermography to model human thermal exposure and comfort. *Science of The Total Environment*, *859*, 160301. https://doi.org/10.1016/j.scitotenv.2022.160301

Middel, A., & Krayenhoff, E. S. (2019). Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: Introducing the MaRTy observational platform. *Science of The Total Environment*, *687*, 137–151. https://doi.org/10.1016/j.scitotenv.2019.06.085

Middel, A., Turner, V. K., Schneider, F. A., Zhang, Y., & Stiller, M. (2020). Solar reflective pavements—A policy panacea to heat mitigation? *Environmental Research Letters*, *15*(6), 064016. https://doi.org/10.1088/1748-9326/ab87d4

Millstein, D., & Levinson, R. (2018). Preparatory meteorological modeling and theoretical analysis for a neighborhood-scale cool roof demonstration. *Urban Climate*, *24*, 616–632. https://doi.org/10.1016/j.uclim.2017.02.005

Mohegh, A., Rosado, P., Jin, L., Millstein, D., Levinson, R., & Ban-Weiss, G. (2017). Modeling the climate impacts of deploying solar reflective cool pavements in California cities. *Journal of Geophysical Research: Atmospheres*, *122*(13), 6798–6817. https://doi.org/10.1002/2017JD026845

Muñoz-Erickson, T. A. (2014). Co-production of knowledge–action systems in urban sustainable governance: The KASA approach. *Environmental Science & Policy*, *37*(2007), 182–191. https://doi.org/10.1016/j.envsci.2013.09.014

Muñoz-Erickson, T., Miller, C., & Miller, T. (2017). How Cities Think: Knowledge Co-Production for Urban Sustainability and Resilience. *Forests*, *8*(6), 203. https://doi.org/10.3390/f8060203

Nasir, D. S., Pantua, C. A. J., Zhou, B., Vital, B., Calautit, J., & Hughes, B. (2021). Numerical analysis of an urban road pavement solar collector (U-RPSC) for heat island mitigation: Impact on the urban environment. *Renewable Energy*, *164*, 618–641. https://doi.org/10.1016/j.renene.2020.07.107

Nazarian, N., Krayenhoff, E. S., Bechtel, B., Hondula, D. M., Paolini, R., Vanos, J., Cheung, T., Chow, W. T. L., de Dear, R., Jay, O., Lee, J. K. W., Martilli, A., Middel, A., Norford, L. K., Sadeghi, M., Schiavon, S., & Santamouris, M. (2022). Integrated Assessment of Urban Overheating Impacts on Human Life. *Earth's Future*, *10*(8), e2022EF002682. https://doi.org/10.1029/2022EF002682

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

Oke, T. R., Johnson, G. T., Steyn, D. G., & Watson, I. D. (1991). Simulation of surface urban heat islands under "ideal" conditions at night part 2: Diagnosis of causation. *Boundary-Layer Meteorology*, *56*(4), 339–358. https://doi.org/10.1007/BF00119211

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

Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., Pouyat, R. V., Whitlow, T. H., & Zipperer, W. C. (2011). Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, *9*(1), 27–36. https://doi.org/10.1890/090220

Patterson, J. J., & van der Grijp, N. (2019). Empowerment and Disempowerment of Urban Climate Governance Initiatives. In C. Certomà, H. Bulkeley, & J. van der Heijden (Eds.), *Urban Climate Politics* (pp. 39–58). Cambridge University Press. https://doi.org/10.1017/9781108632157.003

Patton, M. Q. (2023). Evaluating Transformation Means Transforming Evaluation. In B. Edmondson (Ed.), *Sustainability Transformations, Social Transitions and Environmental Accountabilities* (pp. 15–38). Springer International Publishing. https://doi.org/10.1007/978-3-031-18268-6_2

Pielke Jr, R. A. (2007). *The honest broker: making sense of science in policy and politics*. Cambridge University Press.

Plummer, R., & Armitage, D. (2007). A resilience-based framework for evaluating adaptive co-management: Linking ecology, economics and society in a complex world. *Ecological Economics*, *61*(1), 62–74. https://doi.org/10.1016/j.ecolecon.2006.09.025

Pomerantz, M. (2018). Are cooler surfaces a cost-effect mitigation of urban heat islands? *Urban Climate*, *24*, 393–397. https://doi.org/10.1016/j.uclim.2017.04.009

Pouyat, R. V, Weathers, K. C., Hauber, R., Lovett, G. M., Bartuska, A., Christenson, L., Davis, J. L., Findlay, S. E., Menninger, H., Rosi-Marshall, E., Stine, P., & Lymn, N. (2010). The role of federal agencies in the application of scientific knowledge. *Frontiers in Ecology and the Environment*, *8*(6), 322–328. https://doi.org/10.1890/090180

Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and Sustainable Energy Reviews*, *52*, 445–459. https://doi.org/10.1016/J.RSER.2015.07.177

Qin, Y., He, Y., Hiller, J. E., & Mei, G. (2018). A new water-retaining paver block for reducing runoff and cooling pavement. *Journal of Cleaner Production*, *199*, 948–956. https://doi.org/10.1016/j.jclepro.2018.07.250

Rickards, L. (2019). Making Climates through the City. In C. Certomà, H. Bulkeley, & J. van der Heijden (Eds.), *Urban Climate Politics* (pp. 80–97). Cambridge University Press. https://doi.org/10.1017/9781108632157.005

Roman, L. A., Conway, T. M., Eisenman, T. S., Koeser, A. K., Ordóñez Barona, C., Locke, D. H., Jenerette, G. D., Östberg, J., & Vogt, J. (2021). Beyond 'trees are good': Disservices, management costs, and tradeoffs in urban forestry. *Ambio*, *50*(3), 615–630. https://doi.org/10.1007/s13280-020-01396-8

Sailor, D., Shepherd, M., Sheridan, S., Stone, B., Kalkstein, L., Russell, A., Vargo, J., & Andersen, T. (2016). Improving Heat-Related Health Outcomes in an Urban Environment with Science-Based Policy. *Sustainability*, *8*(10), 1015. https://doi.org/10.3390/su8101015

Sallis, J. F., Bull, F., Burdett, R., Frank, L. D., Griffiths, P., Giles-Corti, B., & Stevenson, M. (2016). Use of science to guide city planning policy and practice: how to achieve healthy and sustainable future cities. *The Lancet*, *388*(10062), 2936–2947. https://doi.org/10.1016/S0140-6736(16)30068-X

Sankar Cheela, V. R., John, M., Biswas, W., & Sarker, P. (2021). Combating Urban Heat Island Effect—A Review of Reflective Pavements and Tree Shading Strategies. *Buildings*, *11*(3), 93. https://doi.org/10.3390/buildings11030093

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments. *Renewable and Sustainable Energy Reviews*, *26*, 224–240. https://doi.org/10.1016/j.rser.2013.05.047

Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., & Synnefa, A. (2017). Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy*, *154*, 14–33. https://doi.org/10.1016/j.solener.2016.12.006

Santamouris, Mat, Ban-Weiss, G., Osmond, P., Paolini, R., Synnefa, A., Cartalis, C., Muscio, A., Zinzi, M., Morakinyo, T. E., Ng, E., Tan, Z., Takebayashi, H., Sailor, D., Crank, P., Taha, H., Pisello, A. L., Rossi, F., Zhang, J., & Kolokotsa, D. (2018). Progress in urban greenery mitigation science - assessment methodologies advanced technologies and impact on cities. *Journal of Civil Engineering and Management*, *24*(8), 638–671. https://doi.org/10.3846/jcem.2018.6604

Sarewitz, D., & Pielke, R. A. (2007). The neglected heart of science policy: reconciling supply of and demand for science. *Environmental Science & Policy*, *10*(1), 5–16. https://doi.org/10.1016/j.envsci.2006.10.001

Schell, C. J., Dyson, K., Fuentes, T. L., Des Roches, S., Harris, N. C., Miller, D. S., Woelfle-Erskine, C. A., & Lambert, M. R. (2020). The ecological and evolutionary consequences of systemic racism in urban environments. *Science*, *369*(6510). https://doi.org/10.1126/science.aay4497

Schnebele, E., Tanyu, B. F., Cervone, G., & Waters, N. (2015). Review of remote sensing methodologies for pavement management and assessment. *European Transport Research Review*, *7*(2), 7. https://doi.org/10.1007/s12544-015-0156-6

Schneider, F. A., Cordova Ortiz, J., Vanos, J. K., Sailor, D. J., & Middel, A. (2023). Evidence-based guidance on reflective pavement for urban heat mitigation in Arizona. *Nature Communications*, *14*, 1467. https://doi.org/10.1038/s41467-023-36972-5

Schrijvers, P. J. C., Jonker, H. J. J., de Roode, S. R., & Kenjereš, S. (2016). The effect of using a high-albedo material on the Universal Temperature Climate Index within a street canyon. *Urban Climate*, *17*, 284–303. https://doi.org/10.1016/j.uclim.2016.02.005

Sen, S., & Khazanovich, L. (2021). Limited application of reflective surfaces can mitigate urban heat pollution. *Nature Communications*, *12*(1), 3491. https://doi.org/10.1038/s41467-021-23634-7

Sen, S., Roesler, J., Ruddell, B., & Middel, A. (2019). Cool Pavement Strategies for Urban Heat Island Mitigation in Suburban Phoenix, Arizona. *Sustainability*, *11*(16), 4452. https://doi.org/10.3390/su11164452

Shackleton, C. M., Ruwanza, S., Sinasson Sanni, G. K., Bennett, S., De Lacy, P., Modipa, R., Mtati, N., Sachikonye, M., & Thondhlana, G. (2016). Unpacking Pandora's Box: Understanding and Categorising Ecosystem Disservices for Environmental Management and Human Wellbeing. *Ecosystems*, *19*(4), 587–600. https://doi.org/10.1007/s10021-015-9952-z

Sinha, P., Coville, R. C., Hirabayashi, S., Lim, B., Endreny, T. A., & Nowak, D. J. (2021). Modeling lives saved from extreme heat by urban tree cover. *Ecological Modelling*, *449*, 109553. https://doi.org/10.1016/j.ecolmodel.2021.109553

Sippel, M., & Jenssen, T. (2009). What About Local Climate Governance? A Review of Promise and Problems. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1514334

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

Synnefa, A., Santamouris, M., & Apostolakis, K. (2007). On the development, optical properties and thermal performance of cool colored coatings for the urban environment. *Solar Energy*, *81*(4), 488–497. https://doi.org/10.1016/j.solener.2006.08.005

Taha, H. (1997). Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, *25*(2), 99–103. https://doi.org/10.1016/S0378-7788(96)00999-1

Taha, H., Akbari, H., Rosenfeld, A., & Huang, J. (1988). Residential cooling loads and the urban heat island-the effects of albedo. *Building and Environment*, *23*(4), 271–283. https://doi.org/10.1016/0360-1323(88)90033-9

Taleghani, M. (2018). Outdoor thermal comfort by different heat mitigation strategies- A review. *Renewable and Sustainable Energy Reviews*, *81*, 2011–2018. https://doi.org/10.1016/j.rser.2017.06.010

Teskey, R., Wertin, T., Bauweraerts, I., Ameye, M., Mcguire, M. A., & Steppe, K. (2015). Responses of tree species to heat waves and extreme heat events. *Plant, Cell & Environment*, *38*(9), 1699–1712. https://doi.org/10.1111/pce.12417

Turner, V. K., Rogers, M. L., Zhang, Y., Middel, A., Schneider, F. A., Ocón, J. P., Seeley, M., & Dialesandro, J. (2022). More than surface temperature: mitigating thermal exposure in hyper-local land system. *Journal of Land Use Science*, *17*(1), 79–99. https://doi.org/10.1080/1747423X.2021.2015003

Uittenbroek, C. J., Mees, H. L. P., Hegger, D. L. T., & Driessen, P. P. J. (2019). From Public to Citizen Responsibilities in Urban Climate Adaptation. In C. Certomà, H. Bulkeley, & J. van der Heijden (Eds.), *Urban Climate Politics* (pp. 171–189). Cambridge University Press. https://doi.org/10.1017/9781108632157.010

UN General Assembly. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. https://www.refworld.org/docid/57b6e3e44.html

United Nations. (2018). *World Urbanization Prospects: The 2018 Revision*. https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf

Vahmani, P., & Jones, A. D. (2017). Water conservation benefits of urban heat mitigation. *Nature Communications*, *8*(1), 1072. https://doi.org/10.1038/s41467-017-01346-1

van der Heijden, J., Bulkeley, H., & Certomà, C. (2019). Promises and Concerns of the Urban Century. In C. Certomà, H. Bulkeley, & J. van der Heijden (Eds.), *Urban Climate Politics* (pp. 1–20). Cambridge University Press. https://doi.org/10.1017/9781108632157.001

van der Heijden, J., Certomà, C., & Bulkeley, H. (2019). The Politics of Urban Climate Futures. In C. Certomà, H. Bulkeley, & J. van der Heijden (Eds.), *Urban Climate Politics* (pp. 231–242). Cambridge University Press. https://doi.org/10.1017/9781108632157.013

Vanos, J. K., Wright, M. K., Kaiser, A., Middel, A., Ambrose, H., & Hondula, D. M. (2022). Evaporative misters for urban cooling and comfort: effectiveness and motivations for use. *International Journal of Biometeorology*, *66*(2), 357–369. https://doi.org/10.1007/s00484-020-02056-y

Vedeld, T., Hofstad, H., Solli, H., & Hanssen, G. S. (2021). Polycentric urban climate governance: Creating synergies between integrative and interactive governance in Oslo. *Environmental Policy and Governance*, *31*(4), 347–360. https://doi.org/10.1002/eet.1935

Verweij, M., & Thompson, M. (2006). *Clumsy Solutions for a Complex World: Governance, Politics and Plural Perceptions* (M. Verweij & M. Thompson (eds.)). Palgrave Macmillan.

Wall, T. U., McNie, E., & Garfin, G. M. (2017). Use-inspired science: making science usable by and useful to decision makers. *Frontiers in Ecology and the Environment*, *15*(10), 551–559. https://doi.org/10.1002/fee.1735

Wang, C., Middel, A., Myint, S. W., Kaplan, S., Brazel, A. J., & Lukasczyk, J. (2018). Assessing local climate zones in arid cities: The case of Phoenix, Arizona and Las Vegas, Nevada. *ISPRS Journal of Photogrammetry and Remote Sensing*, *141*, 59–71. https://doi.org/10.1016/j.isprsjprs.2018.04.009

Wickham, H., Francois, R., Henry, L., & Müller, K. (2018). *dplyr: A Grammar of Data Manipulation* (p. R package version 0.7.6). https://cran.r-project.org/package=dplyr

Withycombe Keeler, L., Beaudoin, F., Lerner, A., John, B., Beecroft, R., Tamm, K., Wiek, A., & Lang, D. (2018). Transferring Sustainability Solutions across Contexts through City–University Partnerships. *Sustainability*, *10*(9), 2966. https://doi.org/10.3390/su10092966

Xu, W., Jimenez-Bescos, C., Pantua, C. A. J., Calautit, J., & Wu, Y. (2021). A Coupled Modelling Method for the Evaluation of the Impact of Pavement Solar Collector on Urban Air Temperature and Thermal Collection. *Future Cities and Environment*, *7*(1), 2. https://doi.org/10.5334/fce.109

Yang, F., Lau, S. S. Y., & Qian, F. (2015). Cooling performance of residential greenery in localised urban climates: A case study in Shanghai China. *International Journal of Environmental Technology and Management*, *18*(5–6), 478–503. https://doi.org/10.1504/IJETM.2015.073098

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A. M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S.-C., … Li, S. (2021). Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *The Lancet Planetary Health*, *5*(7), e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4

Zheng, N., Lei, J., Wang, S., Li, Z., & Chen, X. (2020). Influence of Heat Reflective Coating on the Cooling and Pavement Performance of Large Void Asphalt Pavement. *Coatings*, *10*(11), 1065. https://doi.org/10.3390/coatings10111065

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

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3

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