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A disconnect in science and practitioner perspectives on heat mitigation

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Researchers and city practitioners are paramount stakeholders in creating urban resilience but have diverse and potentially competing views. To understand varying stakeholder perspectives, we conducted a systematic literature content analysis on green infrastructure (GI) and reflective pavement (RP). The analysis shows a United States (US)-based science-practice disconnect in written communication, potentially hindering holistic decision-making. We identified 191 GI and 93 RP impacts, categorized into co-benefits, trade-offs, disservices, or neutral. Impacts were further classified as environmental, social, or economic. The analysis demonstrates that US city practitioners emphasize social and economic co-benefits that may not be fully represented in the scientific discourse. Scientists communicate a broader range of impacts, including trade-offs and disservices, highlighting a nuanced understanding of the potential consequences. Identifying contrasting perspectives and integrating knowledge from various agents is critical in urban climate governance. Our findings facilitate bridging the science-policy disconnect in the US heat mitigation literature.

Urban heat mitigation strategies aim to cool the built environment and reduce heat-related morbidity and mortality, which are increasing globally[1], especially in developing countries[2]. Green infrastructure (GI) is the most commonly used strategy to cool cities with demonstrated co-benefits related to air quality, water, food, physical activity, mental health, and social capital[3–6]. However, current urban expansion tends to deplete green spaces rather than sustain them, and GI loss may be exacerbated in rapidly urbanizing developing countries[5]. Asking "for whom, what, where, when, and why?" is essential for sustainable and equitable heat mitigation[7]. Reflective pavement (RP) is an alternative heat mitigation strategy recently explored in real-world applications[8]. RP is a type of cool pavement with higher surface reflectance (albedo) to reduce solar radiation absorption, lowering surface temperature[9–12]. RP reduces the surface temperature, increases solar radiation exposure, and has limited air temperature impacts[13], demonstrating that a holistic assessment of the overall thermal conditions is required to minimize urban overheating[14,15].

Heat mitigation requires transformative thinking[1,16] and involves a diverse range of non-academic actors and agencies (users) crossing traditional research boundaries[17] to integrate the best available knowledge into policy[18]. As two relevant stakeholders who create usable science, scientists and practitioners have diverse and potentially competing views on urban climate governance. Depending on the stakeholder, the primary interest may not be to reduce heat but to cut implementation costs[17]. People tend to search for and selectively choose the information that confirms their beliefs and attitudes based on confirmation bias or motivated reasoning, which prevents contradicting and potentially diverse information from being considered in their evaluations[19]. Even if unintentional, missing communication could lead to consequences that outweigh the intentional heat mitigation impact when considering cost, population health[20–24], or climate justice and affect minority groups and poorer populations disproportionally[25]. Limited and biased communication may create an inequitable and unsustainable implementation of actions[26,27].

This disconnect between the knowledge producers (science; basic) and the knowledge users (practice; applied) is considered the basic-applied paradigm[28]. The basic-applied paradigm, 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 conventional 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 supports stealth issue advocates pursuing a hidden agenda[29] due to different levels of agency that contest empowerment in this transformation[17]. Science policy lacks a formal conception of research that fully integrates users in knowledge

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production and their perspectives[18], which challenges the production of transformative, usable science[17,30].

It is paramount to consider and expand the holistic knowledge on the consequences of implementing GI and RP as heat mitigation strategies in research and practice to find geographically appropriate solutions[31] and unintended effects that will be valuable to decision-making[32]. Impacts defined here are categorized as neutral, trade-off, disservice, or co-benefit:

- A neutral impact is an impact that has no interpretable positive or adverse effects.
- A co-benefit is a positive impact that benefits the environment, society, economy, or all.
- A disservice is a negative impact, harming the environment, society, economy, or all.
- An impact is considered a trade-off if it has co-benefits and disservices.

Co-benefits, trade-offs, disservices, and neutral impacts of these strategies should be researched using diverse methods and communicated between science and practice to result in a fair and sustainable implementation via practitioner plans and actions, currently in high demand[33–35].

This study focuses on GI and RP because GI is a well-researched heat mitigation strategy with various real-world implementations, while RP is well-researched but lacks widespread implementation, although pilot studies have emerged[8,13]. While many heat mitigation strategy reviews have been published[36,37], no prior research has analyzed the United States (US) stakeholder communication perspectives of heat mitigation strategy impacts. It is critical to collect more evidence about the nature of implementation and how this affects the intended services[32]. Following the need to overcome the science-practice disconnect to address urban issues comprehensively and allow usable science to cross traditional boundaries, it is essential to understand how the written communication perspectives of the individuals (science and practice) differ. We hypothesize that a science-practice disconnect exists for heat mitigation strategies in written communication, preventing holistic decision-making, including the involvement of the urban environment, society, and economy when increasing urban heat resilience. We conducted a systematic literature review to test this hypothesis using a text content analysis that addresses three research questions:

- What is communicated (un-)intended co-benefits, trade-offs, and disservices of GI and RP as heat mitigation strategies?
- How does the written perspective of co-benefits, trade-offs, and disservices of the same heat mitigation strategy differ between the science and US practice literature universes? Where is an agreement, and where is a disconnect?
- What co-benefits, trade-offs, or disservices are mostly neglected in either or both literature universes?

Results

Literature metadata

Using the systematic literature search and filters shown in Fig. 1, we identified 129 GI and 30 RP scientific peer-reviewed documents, of which 10 discuss both heat mitigation strategies. In addition to the 149 peer-reviewed publications, we identified 76 US practitioner documents for the text content analysis. The GI scientific literature is from Asia ($n = 61$), Europe ($n = 39$), North America ($n = 17$), Australia ($n = 10$), and North Africa ($n = 2$). The RP scientific literature is from Asia ($n = 12$), Europe ($n = 12$), and North America ($n = 6$). The American Council of Energy Efficient Economy (ACEEE) State and Local Policy Database for UHI Mitigation Goals focuses the practitioner literature on the US, i.e., 60 cities from 31 US States, including Hawaii and one US District. The number of GI and RP publications increased between 2010 and 2021, though more literature was generally published on GI than RP (Supplementary Fig. 1). The practitioner works (city plans) relevant to heat mitigation were published between 2010 and 2022 without a particular emphasis on more recent works.

Green infrastructure communication in the scientific and US city practitioner literature

191 GI impacts were identified and grouped into social, economic, and environmental (Level 1) co-benefits, trade-offs, disservices, and neutral impacts (Supplementary Table 1). For GI, we summarized the 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 (Supplementary Table 1). Figure 2 shows a Venn diagram for Level-2 GI impacts and depicts the overlap of impacts found between the written communication in the science and city practitioner literature. The diagram shows if an effect was present in either literature universe but not how often. It has three sections from top to bottom, representing the economic, social, and environmental impacts. An impact on the left (right) side means that the impact is only communicated in the science (US practice) literature. The impact in the center of the Venn diagram is discussed in both science and US practice literature. Neutral or unclear impacts (white), except "Modification of thermal environment," were only found in scientific literature. The US practice literature communicates more economical (+5) and social (+4) GI co-benefits (blue). Trade-offs (green) are discussed in both literature universes. Both kinds of literature discuss some disservices (4, yellow) but also communicate disservices (6 each) unique to each perspective.

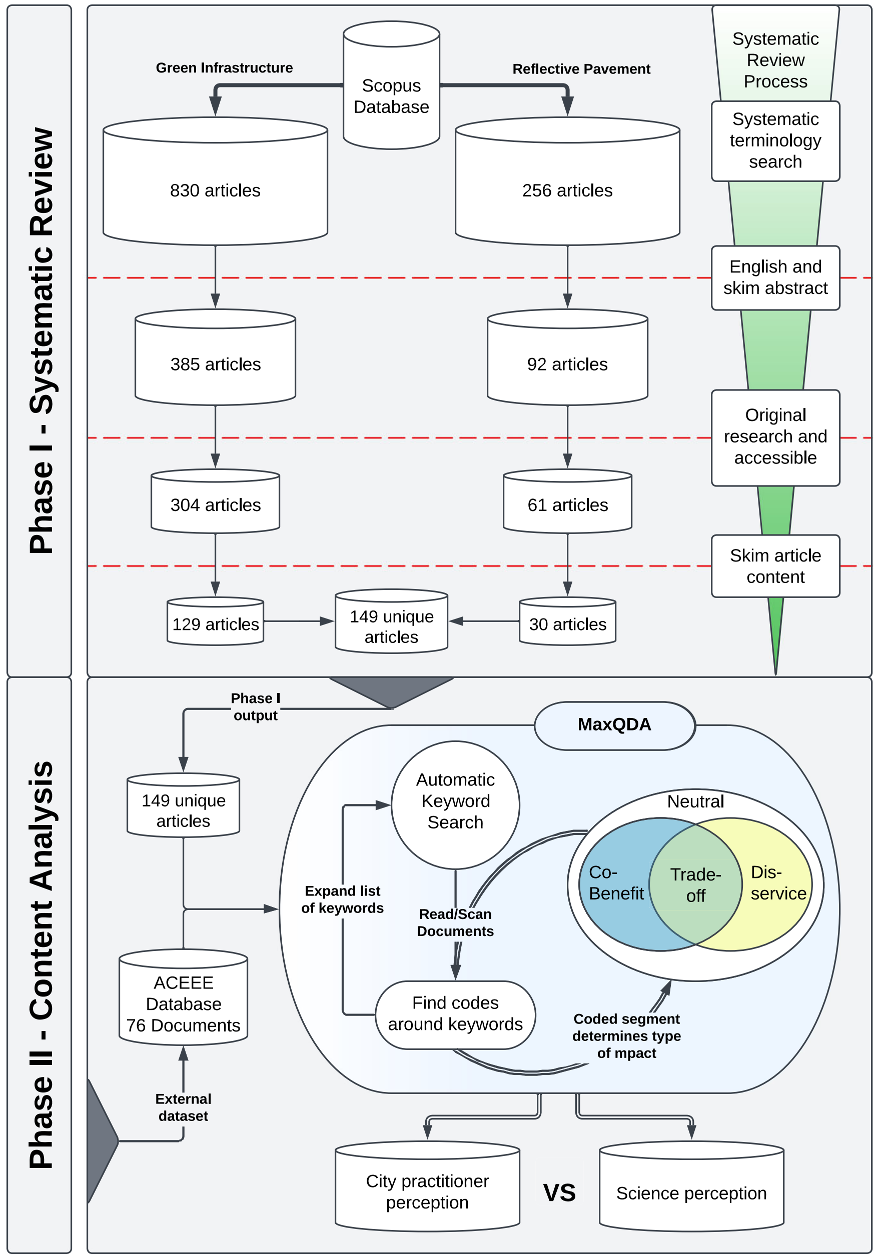
Scientists and US city practitioners communicate GI positively using various co-benefits even though those differ between the literature groups, as shown in Fig. 2. All science and US practice GI documents include co-benefits, while disservices are included in 47% and 30%, and trade-offs are included in 69% and 67% of the literature, respectively (Table 1). US city practitioners almost always included 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.

The scientific GI literature that discusses trade-offs does not mention social trade-offs (n/a). 30% of the articles communicate economic trade-offs, and 93% communicate environmental trade-offs. The opposite is the case for the US 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. Of those documents, 20%, 8%, and 88% mention social, economic, and environmental disservices. For the US 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 neutral economic impacts were found in either of the literature groups.

For both literature universes across all groups (co-benefits, trade-offs, disservices, and neutral impacts), environmental impact representation is dominant, except for trade-offs in the US city practice literature where economic trade-offs stand out (Table 1).

The scientific literature mentions the level 2 impact group "Modifications of thermal environment" as co-benefit, trade-off, neutral impact, and disservice within the same document. This group includes the largest cluster of sub-codes related to thermal environment changes such as air, surface, or mean radiant temperature or thermal comfort changes. In addition, the general "Cooling effect" and other impacts such as "Save energy," "Urban design solution," or "Improve health/well-being" are discussed as co-benefits within the same document (Supplementary Fig. 2). "Cooling effect" includes impacts concerning "UHI mitigation," "Heat mitigation," or the type of cooling such as "Cooling shade." The most common trade-offs apart from the thermal modification discussed in the research literature are "Costs vs. intended benefits," "Intended benefits vs. water use," and "Space vs. intended benefits." Some vague statements, such as "Affect urban environment," are considered neutral impacts. Disservices are

Fig. 1 | Methodology overview. Methodology Phases I (Systematic Review) and II (Content Analysis). Phase I is the data collection phase in which the Scopus database is systematically searched using keywords. The found articles are filtered using three filters: English and abstract of relevance; original research and accessible; and articles of relevance that do 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. That includes an automatic keyword search (deductive) to identify words/paragraphs of interest concerning 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.



isolated from other impact groups in scientific literature. Some documents discuss individual disservices, such as "Damage public/private property," "Replace native vegetation," and "Safety hazard."

A network analysis of the US city practitioner literature revealed that co-benefits are often mentioned together. 30+ level 2 co-benefits are mentioned within the same document, most across many documents. Disservices and trade-offs are less discussed but appear combined with many different impacts across the US 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/well-being," 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 uncovered that the social and economic impacts of GI are more often discussed with environmental impacts in the practitioner literature than in scientific publications.

Reflective pavement communication in the scientific and US City Practitioner literature

93 RP impacts were identified and grouped into social, economic, and environmental (Level 1) co-benefits, trade-offs, disservices, and neutral impacts (Supplementary Table 2). We summarized the impacts into 30 Level-2 RP impact groups, incorporating Level-3 and Level-4 impacts due to similar impact areas (Supplementary Table 2). Figure 3 shows a Venn diagram for all Level-2 RP impacts and depicts overlaps between the written communication in the science and US practitioner literature. No impacts are uniquely found in the US practitioner literature. Neutral or unclear impacts (4), trade-offs (5), and disservices (7) were only found in scientific literature. The scientific literature communicates more economic (+2), social (+2), and environmental (+3) co-benefits of GI.

Scientists and US city practitioners communicate RP positively using various co-benefits even though the scientific literature is more comprehensive (Fig. 3). All science documents and 30% of all US practice documents include co-benefits (Table 1). Trade-offs, disservices, and neutral impacts are communicated in 37%, 60%, and 47% of the scientific literature,

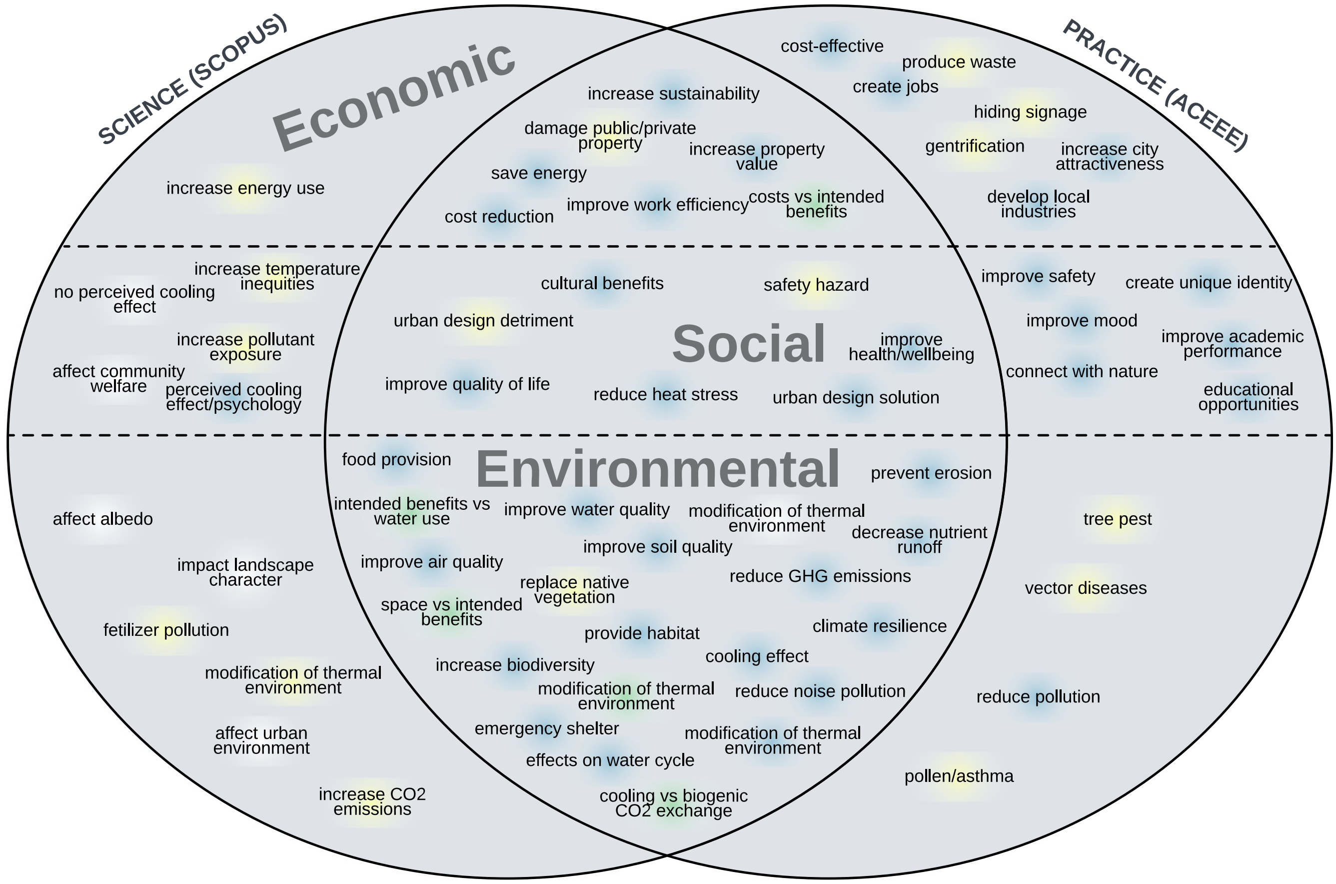


Fig. 2 | Green infrastructure impacts overview. Venn diagram for green infrastructure (GI) that depicts the overlap of found impacts between the written communication of science (Scopus literature) and practice (ACEEE archive). Impacts in the diagram are sorted by their economic, social, and environmental influence. The color code is: blue is a co-benefit; green is a trade-off; yellow is a disservice; white is a neutral impact.

Table 1 | Impact representation in analyzed documents

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

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.).

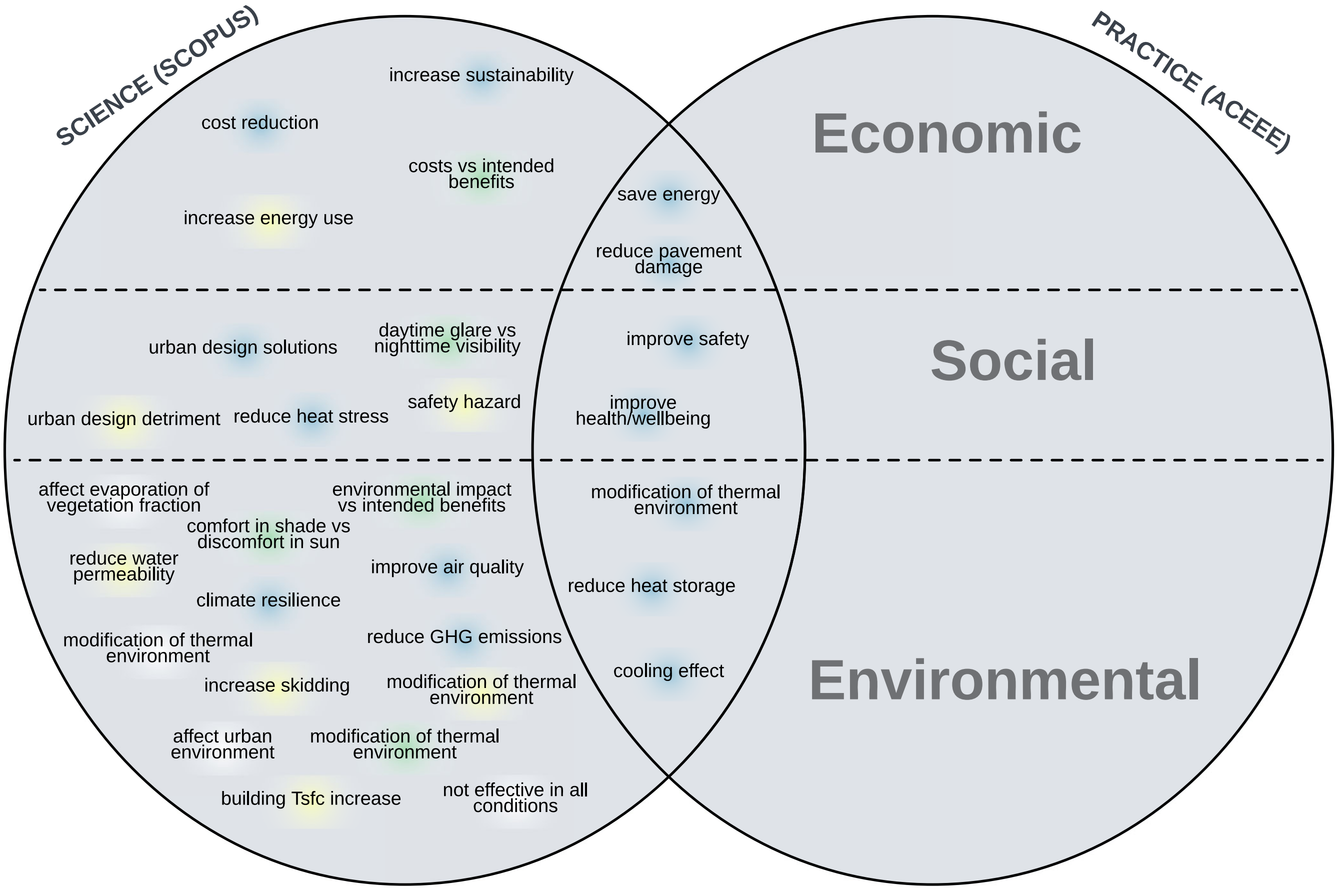


Fig. 3 | Reflective pavement impacts overview. Venn diagram for reflective pavement (RP) that depicts the overlap of found impacts between the written communication of science (Scopus literature) and practice (ACEEE archive). Impacts in the diagram are sorted by their economic, social, and environmental influence. The color code is: blue is a co-benefit; green is a trade-off; yellow is a disservice; white is a neutral impact.

respectively, but not mentioned in the US practitioner literature. 3% of the US practitioner literature included social and economic co-benefits, and 16% included environmental co-benefits. 37% of the scientific literature included social co-benefits, 53% included economic benefits, and all articles included environmental co-benefits. Environmental impact representation is dominant for both literature universes across all groups (co-benefits, trade-offs, disservices, and neutral impacts) (Table 1).

A network analysis 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, 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" (for a visualization of the network analysis, please see Supplementary Fig. 2). The most discussed economic trade-off is "Costs vs. intended benefits." The scientific literature communicates neutral impacts such as "Not effective in all conditions" and "Affect urban environment." Some disservices (e.g., "Reduce water permeability," "Increase skidding," and "Safety hazard") and co-benefits (e.g., "Reduce heat stress" and "Urban design solutions") are rarely mentioned.

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

In general, all but one social ("Daytime glare vs. nighttime visibility") and economic ("Reduce pavement damage") RP impact group were found for GI as well. However, 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 RP environmental impacts are also communicated for GI, except for RP technology-specific impacts such as "Increase skidding" or "Reduce water permeability." In general, GI literature discusses 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 to identify other potential consequences.

Discussion

To date, more original research on GI than RP has been published (Supplementary Fig. 2), which suggests that more impacts of social, economic, and environmental dimensions should be discussed across the literature for GI (191) than for RP (93) in urban spaces. However, both the GI and RP scientific literature focus their communication on all types (co-benefits, trade-offs, and disservices) of environmental impacts, with social and economic impacts mainly discussed as co-benefits alone. A comparison between the practice communication of RP and GI is impossible 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[8,11,13,38–40]. Expanding RP research and practice based on the identified impacts from the GI literature could be of interest for a more holistic and better evidence-based RP research and practice, leading to improved and informed decision-making and, thus, urban climate governance.

The discussion focuses on GI only because more GI impacts are communicated in the practitioner literature (Table 1 and Fig. 2), confirming the broader perspective that US practice has to apply to their work when writing plans to consider co-benefits[17,41]. In addition, US practice emphasizes social and economic co-beneficial impacts that have not been found in the research literature, including impacts on "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 US city practitioners aligns with the highly political[42] and fiscal nature of urban climate governance[41,43]. Impacts that are solely represented in the US practitioner literature may be carefully considered. The methodology used to filter eligible literature in this study may have excluded works that would have made more extensive 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-benefits (Table 1). This finding aligns with the applied confirmation bias[19] and the general narrative that research and practice want to achieve some good with their actions[42]. Notably, scientific literature communicates about neutral or unclear GI impacts, indicating that scientific literature communicates potential impacts without weighing them positively or negatively, while US practitioners do not mention neutral impacts. This observation may benefit US practice by preventing unintended consequences based on potential misconceptions.

On the other hand, science provides suggestions, a future research agenda, and impacts that have not been evaluated yet, while US practice provides evidence-based recommendations and learns from other real-world practice implementations[44]. Due to different social, economic, and environmental backgrounds, the latter should be carefully generalized for other focus areas beyond the US or other fields of interest beyond heat mitigation.

The large variety of economic, social, and environmental impacts in the GI literature raises the question of whether it is reasonable to expect either literature type to communicate beyond the science-practice disconnect about the co-benefits, trade-offs, disservices, and potential neutral impacts. Here, a disconnect exists between science and US practice in how consequences are communicated, yet closing this gap may not be beneficial due to the different purposes of the scientific and US practice literature. US city practitioners communicate GI from a co-beneficial social, economic, and environmental perspective, which is more holistic than the science perspective, but they do not communicate the trade-offs and disservices comprehensively. The fewer disservices and trade-offs confirm former findings by Shackleton et al. [45], who states that researchers and practitioners often fail to acknowledge the diversity and validity of people's opinions, experiences[45], and the urban system complexity. Including more trade-offs and disservice communication into US practice could be beneficial by incorporating users, mediators, and honest brokers, who can provide an alternative pathway to solve a problem by involving new perspectives[29].

McNie et al. [18] stated that the basic-applied paradigm, or the found science-practice disconnect, limits recognition of processes that address knowledge creation (science) and participation (applied; practice). Such processes involve users who are not recognized in the decision-making[18]. Incorporating a holistic communication perspective in the scientific and US practice literature may not be beneficial. It may lead to an overload of information that cannot transfer critical messages to the audience, which often is a user of the provided knowledge or action. Users such as vulnerable groups already underestimate their heat risk in the US[46], and awareness is critical for their heat resilience[47]. Overcoming the science-practice disconnect in the traditional sense by providing more information may backfire. Developing a transformative approach to generate usable science that is co-created between users, science, and practice is suggested as a next step, building on this research.

Transformational thinking is required to address urban issues[16,30]. We observed that the science-practice disconnect exists in written communication and that science and, in our case, US practice need to find an alternative pathway around said science-practice disconnect. What could such a bridge look like? Are there approaches and perspectives already being discussed? Research has introduced transformational approaches such as usable science and co-production over the last decade[26,46,48]. However, the approaches have either not been applied or led to a change in written communication by GI heat mitigation science or the US city practitioner literature. The existing communication disconnect and the primarily observed disregard of disservices and trade-offs suggest that the literature of both stakeholders still needs to adapt to the transformative approaches by involving users, mediators, and/or honest brokers.

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 a balance between potentially conflicting goals[49]. Partnerships co-create an agenda while not ignoring individual needs. Additionally, city–university–community partnerships would embrace the basic-applied paradigm and instead co-create usable, policy-relevant science that can be readily applied[18,33], thus overcoming the communication disconnect from the source.

In conclusion, this case study sheds light on the science-practice disconnect in the context of urban heat mitigation strategies, mainly focusing on Green Infrastructure (GI) and Reflective Pavement (RP) in the US. The findings reveal that while scientists and US city practitioners communicate positively about these strategies, a disparity exists in the emphasis on co-benefits, trade-offs, and disservices. The comprehensive literature analysis demonstrates that US city practitioners, driven by political and fiscal considerations, emphasize social and economic co-benefits that may not be fully represented in the scientific discourse. On the other hand, scientists tend to communicate a broader range of impacts, including trade-offs and disservices, highlighting a nuanced understanding of the potential consequences of heat mitigation strategies.

Research on urban sustainability issues such as heat should produce usable, policy-relevant, transferable knowledge. The identified science-practice disconnect poses challenges to the holistic decision-making needed for effective urban climate governance. The study underscores the importance of bridging this gap to ensure that both the scientific and practitioner perspectives are considered in implementing heat mitigation actions. While acknowledging the limitations of simply increasing information exchange between the two realms, the study suggests that a transformative approach, such as city–university–community partnerships, is crucial. These partnerships have the potential to co-create usable, policy-relevant science that considers the diverse perspectives of users, practitioners, and researchers, thereby overcoming the existing communication challenges and fostering sustainable and equitable urban heat resilience. Moving forward, adopting transformational thinking and alternative pathways is recommended to address urban issues comprehensively and promote the co-creation of knowledge for effective urban climate governance.

Methods

This study was conducted in two phases (Fig. 1): In phase I, the scientific GI and RP literature of the SCOPUS database was systematically reviewed to identify relevant work for phase II. The US 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[50]. In phase II, an inductive and deductive text content analysis in MaxQDA was performed to identify the impacts of heat mitigation strategies (co-benefit, trade-off, disservice, and neutral effects) as outlined in the selected literature. Our 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 decade.

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 completed 12 years (2010 to 2021). The systematic search yielded 830 articles related to GI and 256 articles related to RP. All publications went through a 3-tier filter process (Fig. 1). The first filter excluded all articles not written in English or not focusing 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 the cool but not RP (e.g., permeable pavement) was also removed. After filtering, 129 GI and 30 RP articles between 2010 and 2021 remained. Ten articles covered both GI and RP, resulting in 149 unique articles.

For the metadata analysis, we 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 origins and whether those are similar between GI and RP research and city practice. To visualize the differences, we mapped those origins, which can be found in the supplementary material (Supplementary Fig. 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. Sixty cities have eligible documents. For the given 60 US cities, we also searched Google for practitioner literature such as climate action plans, sustainability plans, or similar ones, which the ACEEE does not include. Of the provided database, only central policy and plan documents such as climate action plans, comprehensive plans, heat mitigation plans, resiliency plans, stormwater management plans, sustainability plans, urban forest management plans, 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.

Impact identification—deductive/inductive content analysis using MaxQDA

Phase II used deductive and inductive coding to identify GI and RP communicated impacts 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, explicitly focusing on GI and RP. The code list was expanded and amended during the content analysis process due to new knowledge of terminology and the distance between impacts and the mentioned strategy. A single statement could include multiple codes. The initial definition of deductive codes was adapted throughout the coding process as new terminology was identified and was expanded for the autocoding of GI and RP. After autocoding, each identified area of interest +/− three sentences were read for potential impacts and relationships. If one was found, either an updated 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 (Fig. 2) and were identified based on the context around the autocoded section.

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

Limitations

The identified scientific literature does not cover the breadth of all science for GI and RP due to the exclusion of remote sensing work. This literature reduction was necessary for this study to be manageable. Similarly, we did not include other terminology that is used instead of "mitigation" in other areas of the world, such as "adaptation" in Europe, because our case study focuses on the US. Lastly, we have not considered science, policy, and practice dialogs from nationally or internationally operating agencies for feasibility reasons since the study already included 1000+ documents. A future step in this research could be using AI, which may make this process more inclusive[51]; however, the authors did not code inductively, which would be a challenge to overcome.

The city practitioner literature is limited to the US collection of plans provided in the ACEEE database, thus creating a bias based on the database. An additional search for plans based on their focus on RP would allow a more inclusive comparison between the impacts of GI and RP. Additionally, many additional plans or policy documents may exist outside cities in non-governmental organizations, non-profits, or other institutions that can inform heat mitigation strategies, which would allow insights into operations that foster collaboration between science and practice. This assessment focused on US city practitioner plans only and thus has a unique perspective. It is worth noting that practice includes a set of different plans that combine to create a comprehensive communication tool focusing on individual challenges and actions[35].

As shown in Supplementary Fig. 2, not all countries and languages are represented in the scientific peer review dataset. This shortcoming is likely due to the language and accessibility filter. Including other languages in the database and purchasing research literature would create a more inclusive database. Again, there is an opportunity for AI to analyze literature content across languages. Similarly, including city practitioner works from other countries, languages, and cultures, despite making the effort much more complex, may increase the understanding of nuances and how some collaborations or partnerships are at different stages in terms of communication.

Original research, by default, is meant to be specific and has historically been siloed research rather than inter- or transdisciplinary. Literature reviews were excluded from the content analysis due to their different nature from original research but provide an opportunity to bridge different fields, include other 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.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated during and/or analyzed during the current study can be found using the systematic methodology provided in the manuscript and are available upon request. US city practitioner documents were derived from the website of the American Council for an Energy-Efficient Economy.

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Author contributions
F.A.S. conceptualized the study. A.M. supervised the project. Data collection was led and supervised by F.A.S. Data was collected by F.A.S. and E.E. The analysis was conducted by F.A.S. and E.E. Figures were produced by F.A.S. Results were critically assessed and interpreted by F.A.S., E.E., and A.M. The manuscript draft was written by F.A.S. All authors edited and approved the manuscript.

Competing interests
The authors declare no competing interests.

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