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# Designing urban green spaces for climate adaptation: A critical review of research outputs

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ABSTRACT

Urban green spaces provide important contributions to enhance climate adaptation, and therefore research in this area has increased exponentially in the last decades. While several studies showed that the morphology and type of living and built elements of urban green spaces greatly affect their performance, a persistent gap between theory and practice continues to pervade the design of green spaces. This study conducts a semi-systematic review of research published in the last decade to investigate to what extent recent research has produced evidence-based outputs relevant to practitioners concerning the design of outdoor urban green spaces in the context of climate adaptation. An innovative design-oriented approach is subsequently applied to critically review evidence-based research outputs considering a comprehensive spectrum of climate impacts and adaptation measures. Our specific objectives are to: *i*) identify evidence-based research outputs of relevance to practitioners according to type of climatic impact; *ii*) assess the level of relevance and geographical transferability of such outputs to support the design of urban green spaces; and *iii*) identify key challenges that might hinder the implementation of evidence-based guidelines. Our results support a call to align research to confront the 'wicked' gap between scientific research and implementation in design practice.

## 1. Introduction

Cities worldwide are increasingly exposed to intensified climate impacts that require an urgent need to advance urban climate adaptation. In the last decade, a mounting body of scientific studies on evidence-based approaches to foster climate adaptation in cities has emerged, and continues to expand (Lai et al., 2019; Runhaar et al., 2018). A prolific branch of climate adaptation research has focussed specifically on analysing the role of greening strategies to improve the urban environment, e.g. by increasing human thermal comfort and reducing negative impacts from heatwaves and flooding (Demuzere et al., 2014; Koc et al., 2018), and the growing body of

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evidence contributed to recognize green infrastructure (GI) as an indisputable requirement for resilient cities (Chatzimentor et al., 2020). While different concepts related to urban green spaces have emerged in the last 15 years, such as nature-based solutions (NBS), GI or urban ecosystem services (UES) (Escobedo et al., 2018), the term urban green space is here understood in the broad sense of an overarching concept of nature in cities, encompassing "*bodies of water or areas of vegetation in a landscape, such as forests and wilderness areas, street trees and parks, gardens and backyards, geological formations, farmland, coastal areas and food crops*" (Taylor and Hochuli, 2017). In this review, we focus specifically on the subset of urban green spaces that are designed by landscape architects, urban designers and other professionals (henceforth referred to as "practitioners") to attain specific goals, thus excluding elements such as geological formations, natural bodies of water or wild areas, but including in our scope designed water features and inert built elements existing within urban green spaces.

Noteworthy advances have undoubtedly been made to develop research outcomes useful for practitioners in tackling climate adaptation at the urban scale, yet a persistent gap between theory and practice seems to pervade the design of green spaces (Klemm et al., 2017a; Lenzholzer et al., 2020; Matthews et al., 2015). 'Designing' is conceptualized as "*the process of giving form to objects or space on diverse levels of scale*", while 'design' refers to *"the results of a design process"* (Lenzholzer et al., 2013). Given the proliferation of scientific research aiming to inform the design of urban green spaces, the question emerges of what the notion of 'design' implies for researchers generating evidence-based guidelines focussed on climate adaptation. Addressing the underlying idea of design is of relevance as it influences the framing of research questions, the selection of research methods and the application potential of outputs for practitioners. Solís et al. (2017) argue that a spatial incongruence exists between the decision-making / accountability level and the research linking environmental science and policy, and highlighted how problems arise when there is a mismatch between the research scale and the heat mitigation strategies or health consequences that occur at higher spatial resolutions. Adding to this issue, using green spaces to support urban ecosystem services such as microclimate regulation requires that those ecosystem services are related to mensurable ecosystem processes and properties that affect the desired outcomes (Pataki et al., 2011), which need to be accounted for in the design process to attain positive changes in the urban environment. As Taylor and Hochuli (2017) note, the simple allusion to types of green spaces (e.g. urban forest) does not convey how properties such as their shape, size and tree cover are critical to influence urban temperatures.

Urban green spaces provide a range of regulating ecosystem services, such as urban temperature regulation, water flow regulation and runoff mitigation, and moderation of environmental extremes (Gomez-Baggethun and Barton, 2013) that contribute to climate adaptation in cities. These ecosystem services are dependent on the abundance and structure of the urban vegetation, as variables such as the size, shape, density and condition of plants affect e.g. the capacity of vegetation to influence microclimate through evapotranspiration and shading, intercept rainfall, modify air movements and heat exchanges with the surrounding environment (Graça et al., 2018; Nowak and Dwyer, 2007) . Plant composition and diversity may also influence the provision of relevant ecosystem services for climate adaptation, e.g. by determining the type of photosynthetic metabolism that influences the cooling potential of vegetation (Gunawardena et al., 2017), key canopy and leaf characteristics that affect the ability of street trees to modify local microclimate (Sanusi et al., 2017), summer roof temperatures and stormwater capture in green roofs (Lundholm et al., 2010). In line with this, previous research has confirmed that the composition and configuration of urban green spaces can significantly affect their performance in terms of delivering regulating ecosystem services (Graça et al., 2018; Koc et al., 2018; Lundholm et al., 2010), while specific traits of plants impact their cooling potential (Rahman et al., 2020b), rainfall interception and retention (Blanusa and Hadley, 2019). Other studies have demonstrated that the planting design adopted in urban spaces may generate different outcomes in terms of climate adaptation (Zölch et al., 2019), as the location and structure of vegetation influence climatic conditions (Mathey et al., 2011). Klemm et al. (2017b) showed that different tree configurations are able to create a variety of solar exposure conditions in parks, and point to the need of climate-responsive design to facilitate adaptation of users according to various thermal conditions that are expected to increase in the future.

Water bodies also impact the performance of urban green spaces in regulating surrounding temperatures, by converting sensible heat to latent heat via evaporative cooling and acting as thermal buffers (Gunawardena et al., 2017). Besides natural elements, urban green spaces also include inert built elements that affect their local climate. For example, pergolas and other shading devices intercept direct radiation from the sun and reduce surface and air temperatures, while pavements using light coloured, permeable materials with low thermal resistance and high porosity can reduce surface temperature and modify the nearby thermal environment (Shooshtarian et al., 2018). Therefore, features such as the arrangement of elements in a specific pattern or configuration, which is also determined by the size and shape of these elements (henceforth "morphology"), and the type of living and built elements (composition) of urban green spaces greatly influence their performance in the urban matrix, and should be accounted for in their design to accomplish the full potential for climate adaptation. Consequently, it is critical that practitioners involved in the design of green spaces are equipped with accurate evidence of the effect of different design variables in terms of urban climate adaptation. However, the Intergovernmental Panel on Climate Change (2014) reported that the assessment of adaptation has so far focussed mostly on impacts, vulnerability and planning, while the effects of specific adaptation measures are still little explored. Yet, recent research has highlighted that current evidence concerning urban green spaces points to their higher efficacy as climate adaptation than mitigation strategies, stressing that their environmental and ecological impact is particularly achieved through careful management and design at site to municipal scale (Baró and Gómez-Baggethun, 2017; Pataki et al., 2021). More research and evidence is needed on which elements and variables can be targeted, and how, by urban green space design to support climate adaptation (Kabisch et al., 2016). Furthermore, practitioners demand more research in the fields of sustainable design, water management, construction techniques and ecology (Chen, 2013) and report difficulties in adopting ecological design strategies due to limited information on the economic, environmental and functional performance of such strategies (Calkins, 2005).

This study aims to assess to what extent recent research has produced evidence-based information relevant to practitioners and easily transferable to different contexts, by reviewing peer-reviewed research published between 2010 and 2020 concerning the design of outdoor urban green spaces targeting climate adaptation, and critically assessing the research outputs to support practice. This timespan was considered representative of relevant advances in research since the publication of the review by Bowler et al. (2010), which concluded that in 2010 the existing evidence was insufficient to deliver specific recommendations on how to guide the design and planning of urban green spaces on the use of urban greening to cool cities. The specific objectives of this review are to: *i*) identify evidence-based research outputs of relevance to practitioners according to type of climatic impact; *ii*) assess the level of relevance and geographical transferability of such outputs to support the design of urban green spaces; and *iii*) identify key challenges that might hinder the implementation of evidence-based guidelines. We collected information on journal and year of publication of articles to understand how research has evolved in the last decade, geographical location of case studies, type of climate impact analysed, spatial scale, type of methodology used, and type of outputs delivered for practitioners. We also assessed to what extent the application of research outputs into the design practice is feasible, by developing and applying a qualitative scale to evaluate the potential for implementation in different types of green spaces and urban contexts. An effort has been made to include a wide scope of climate impacts to provide insights on which topics have been more explored in the realm of climate adaptation design-oriented research, and what future directions should be prioritized to strengthen evidence-based practice. Due to the diversity of disciplines, research scopes, spatial scales, methods and types of outputs for practitioners delivered by studies addressing the design of outdoor urban green spaces in the context of climate adaptation, we adopted a semi-systematic review to identify broad trends concerning each of our three specific research objectives, thus facilitating a compilation and analysis of all potentially relevant research with implications for the professional practice (Snyder, 2019).

Other reviews have been published within our review timeframe in related topics to systematize evidence on the cooling effects of green spaces (Koc et al., 2018) or concerning issues such as thermal comfort, focussing on thresholds for public space design (Santos Nouri et al., 2018) and mitigating strategies in urban outdoor spaces (Lai et al., 2019). Yet, to our knowledge, this is the first review adopting a design-oriented approach to assess the relevance and degree of transferability of evidence-based research outputs and to consider a comprehensive spectrum of climate impacts and adaptation measures. Our results support a call to align research with practitioners needs to address the 'wicked' gap between scientific research and implementation in design practice (Brown and Corry, 2011; Calkins, 2005).

## 2. Materials and methods

To address our research question, a literature search was conducted in ISI Web of Science (WoS) and Scopus between July and October of 2020. Following Bilotta et al. (2014), we developed a search string based in the Population-Intervention-Comparison-Outcome (PICO) framework to identify dimensions of relevant keywords concerning green spaces in the urban context (*population*), design (*intervention*) and climate adaptation (*outcome*), which were useful to filter research potentially useful for practitioners. Within each dimension, a selection of keywords was obtained through discussion involving team researchers specialized in urban planning, design of green spaces and climate adaptation. Care was taken to select keywords common across a wide range of disciplines, to include all relevant studies in our review even if the keywords fall outside the scope of design disciplines. Hence, we deliberately avoided discipline-specific keywords concerning e.g. specific conceptualizations of green spaces, which could have significantly biased our literature selection and omitted relevant contributions of other disciplines involved in climate adaptation research. The final selection of keywords was complemented with additional keywords obtained from reference papers (Table 1). The literature search combined the three dimensions of keywords using the Boolean operator AND, to retrieve a list of articles and reviews published in English between January 2010 and October 2020. We limited the search to peer-reviewed articles to ensure a high standard of quality. Only articles featuring case studies were selected for review, making sure that all relevant primary research was fully analysed and comparable using the same set of review variables. After combining records retrieved by Scopus ($n = 350$) and WoS ($n = 269$) and removing duplicates, 422 unique records were listed for analysis. Excluding unavailable, non-English, not peer-reviewed publications and other types of articles outside our scope (e.g. reviews), 381 documents were screened (title, abstract and keywords) to assess agreement with a set of predetermined selection criteria for full review. The selection criteria were developed by the research team as a list of yes/no questions to retain only evidence-based articles concerning urban green spaces in the context of climate adaptation and related to design (Table 2). Each criterion was applied in order, and non-compliance led to exclusion. Papers were considered evidence-based (criterion 4) if they presented a case study with a replicable methodology to support research conclusions, and therefore all conceptual articles were excluded. We limited our scope to outdoor green spaces, thus excluding green roofs and courtyards, as their impact in climate adaptation is highly dependent on building characteristics that we could not feasibly assess within this review. However, all types of outdoor green spaces with a design component and detached from buildings, whether public or private, were

**Table 1**
Keywords used for the literature search in Scopus and WoS, organized in three dimensions following PICO guidelines.

| PICO | Search keywords |
|---|---|
| *Population*: green spaces in the urban context | ("city" OR "cities" OR "urban") AND ("green*" OR "veget*" OR "plant*") |
| *Intervention*: design | "planting design" OR "ecological design" OR "evidence-based design" OR "urban design" OR "spatial configuration" OR "spatial design" |
| *Outcome*: climate adaptation impact | "climate adaptation" OR "flood*" OR "heat*" OR "thermal*" OR "cool*" |

**Table 2**
List of criteria used to select documents for further review. Each criterion was applied by order, and documents not complying with one criterion were excluded.

| Selection criteria by application order |
|---|
| 1 - The paper focusses on climate adaptation? (yes/no) |
| 2 – Addresses explicitly the urban context? (yes/no) |
| 3 – Addresses design issues? (yes/no) |
| 4 – Is the paper evidence-based? (yes/no) |
| 5 – Addresses explicitly outdoor green spaces or vegetation? (yes/n) |

potentially eligible for review, and in this regard, we did not consider specific categories; instead, we used general search keywords that are common across different disciplines and research scopes, to define the *population* in the study.

A total of 93 documents complied with the set of selection criteria (Fig. 1) and were fully reviewed to retrieve the list of variables in Table 3. During this thorough analysis, 17 additional papers were excluded as their content did not comply with the selection criteria (Table 2), resulting in a final set of 76 articles.

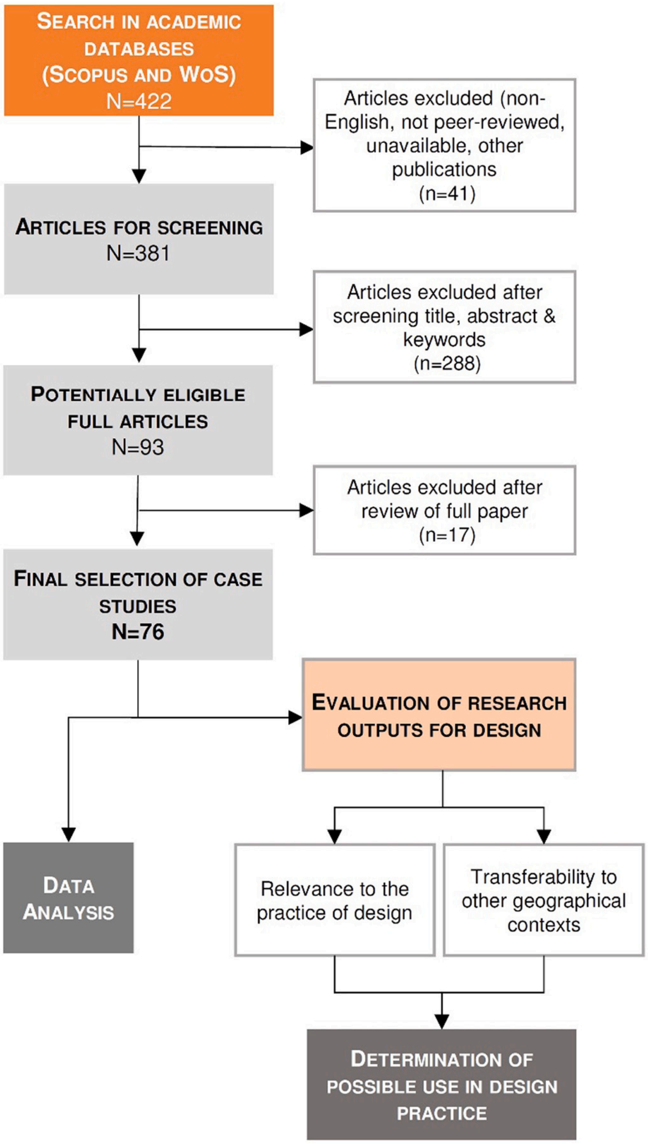


**Fig. 1.** Methodological workflow adopted to select and assess studies concerning evidence-based design of urban green spaces targeting climate adaptation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 3**
List of variables for analysing case study papers, and possible categories.

| Variable (question) | Possible categories |
|---|---|
| 1 – Where is the case study located? | Identify city and country. |
| 2 – Which climate impact is being considered? | Flooding, heatwaves, thermal comfort, cold waves, wind distress. |
| 3 – What is the research scale? | City region, city, neighbourhood, site. |
| 4 – What kind of research methodology is applied? | Observational (field data), experimental, remote sensing, modelling & simulation. |
| 6 – Which types of outputs potentially useful for practitioners are provided? | Design guidelines, software, model, … |

Research outputs for practitioners collected in question 5 of Table 3 were subsequently subjected to a qualitative evaluation (detailed below) to determine their feasibility for application in the design of green spaces with the purpose of climate adaptation (Fig. 1). From a practitioner perspective, we considered that the goal of useful research is to provide evidence-based information that can be easily implemented in the design of new green spaces. Accordingly, to confirm such usefulness, we developed a methodology to assess the potential implementation of research outputs in professional practice. Two criteria for evaluation were established, one referring to the relevance of the research outputs to the practice of design, and the other concerning their transferability to other geographical contexts. The first criterion, 'relevance to the design practice', was considered met if research outputs provided clear orientations on how to shape the morphology or determine the composition of green spaces to achieve desired performance in climate adaptation. Contrarily, vague insights that could not easily be translated into a specific 'form' of green spaces were considered not relevant for design purposes. The second criterion, 'transferability to other geographical contexts', aimed to assess the potential application of research outputs in other areas besides the one considered in the case study. We defined three possible grades to qualitatively evaluate the potential for implementation outside the study area: (A) low potential; (B) medium potential; and (C) high potential. Grade A was given to studies in which the research outputs are highly site-specific and were assessed not to be applicable elsewhere. This is usually the case for highly technical studies based in remote sensing or modelling which aim to provide innovative methods to generate site-specific evidence, but due to their technical complexity such methods can seldom be adopted by practitioners. In these cases, we considered that the research outputs useful for practitioners are the design guidelines that emerge from cases illustrating the use of evidence-generating methods, instead of evaluating the method itself. Grade B refers to research outputs that can be applied elsewhere, but only to a certain extent (e.g. same type of green space or urban context). Grade C concerns those outputs that provide a higher level of transferability to other geographical settings, including to different types of green spaces and urban contexts.

## 3. Results

This section is organized in 3 subsections. Subsection 3.1 provides a contextual background of the literature analysed in this review, and explores research evolution across the last decade considering the geographical location of case studies, journal and year of publication of articles. Subsection 3.2 tackles our objective *i*), by discriminating the case studies analysed in terms of: climate adaptation impacts, research scale, research methods and type of output delivered. Lastly, subsection 3.3 focusses on objective *ii*), by analysing the relevance and transferability of outputs for practitioners.

### 3.1. Contextual background

The final set of 76 articles (see Appendix A) featured predominantly case studies located in a single country, with only two articles featuring research conducted in two countries or more: Brown et al. (2015) analysed cities in Malaysia, Pakistan, Australia, Japan and Canada; Suleiman et al. (2020) focussed on projects in Sweden and Spain (Fig. 2). More than a third of the case studies were in Europe (36%), although the country with by far most case studies was China (26%). Our analysis highlights that few studies were conducted in the Global South, particularly in Latin America and Africa. The articles were published in 39 different journals, but four journals

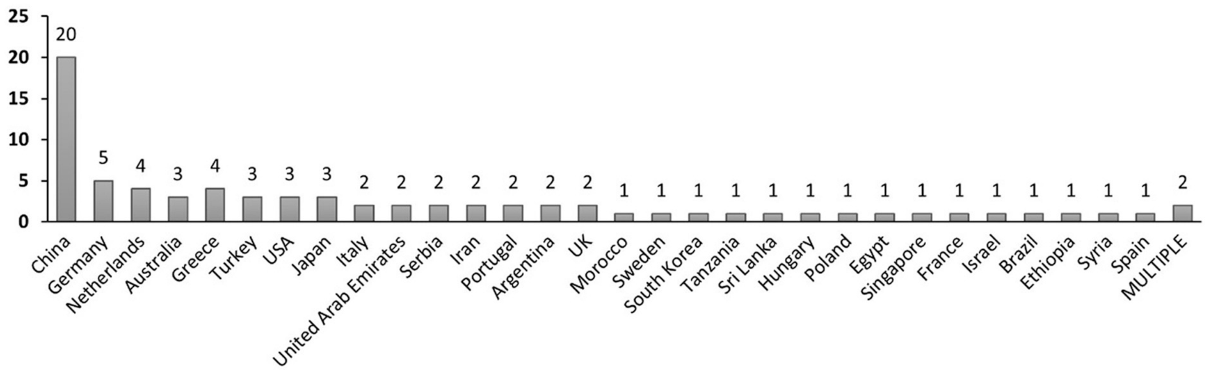


**Fig. 2.** Distribution of research case studies by country (articles published between January 2010 and October 2020).

comprised almost 45% of all papers: *Landscape and Urban Planning, Building and Environment, Urban Forestry & Urban Greening* and *Sustainable Cities and Society* (Fig. 3). A clear upward trend is visible in the number of publications per year, which rose from only 1 article in 2010 to 12 or more per year between 2017 and 2019 (and 11 till the end of October of 2020) (Fig. 4).

### 3.2. Identifying evidence-based research outputs of relevance to practitioners

*a) Climate adaptation impacts*

While the articles used different expressions to frame climate adaptation, it was possible to group these into three main categories: measures to address thermal comfort, UHI mitigation and stormwater management.

The main category of 'Thermal Comfort' included 64% of all articles (Fig. 5). The studies under this category addressed 'bioclimatic comfort' (Yucekaya and Uslu, 2020) and 'microclimate' (Gebert et al., 2019; Rantzoudi and Georgi, 2017; Yahia et al., 2018), but the vast majority (94% of all papers in this main class) concerned 'thermal comfort' (e.g. Cortesão et al., 2016; Stocco et al., 2015). While most studies in the later subcategory addressed aspects related to heat periods, two exceptions should be noted: Afshar et al. (2018) explored the influence of planting design on winter thermal comfort in an urban park in Iran, and Johansson and Yahia (2020) assessed wind comfort and solar access in a coastal development in Malmö, Sweden.

'UHI Mitigation' comprised 29% of all papers (Fig. 5), and included studies not specifically linked with human comfort distributed in four subcategories: 'heat mitigation' (Bajsanski et al., 2016), 'land surface temperature' (Shi et al., 2019; Vanos et al., 2016), 'UHI mitigation' (e.g. Chen et al., 2020; Feyisa et al., 2014) and 'urban cooling' (e.g. Broadbent et al., 2018; Wu and Chen, 2017).

'Stormwater Management' included 7% of the articles, which explored 'urban rain harvesting' (Suleiman et al., 2020), 'surface water flooding' (Lee et al., 2018) and 'stormwater management' (e.g. Ishimatsu et al., 2017; Kazak et al., 2018).

*b) Research scale*

The case studies were developed at distinct scales which could not be aggregated into main categories due to contextual differences that we could not reliably assess within this review. For example, Makido et al. (2019) focussed on city blocks with maximum area of approximately 180 × 180 m (3.24 ha) in Portland, while a similar spatial area was framed as city neighbourhood in a study conducted in Poland by Kazak et al. (2018), and in another in Tanzania by Yahia et al. (2018). However, an area four times larger (around 12 ha) was considered a city neighbourhood in Chen et al. (2020) in a study located in Beijing, similarly to an area many times larger (720 × 372 × 60 m; >26 ha) in a study by Kleerekoper et al. (2015) in Amsterdam. Therefore, to analyse the research scale of all articles we established eight categories using the authors' own designations to avoid misinterpretations due to geographic and cultural particularities: city, city region, residential district, residential quarter, city neighbourhood, city block, street and site. An additional category included multiscale studies. Using this approach, the site scale was by large the most adopted in case studies (43%), and 13% of the articles addressed more than one spatial scale (e.g. Kleerekoper et al., 2015; Morakinyo et al., 2020) (Fig. 6). Noteworthy was also the number of case studies in city regions (16%) and streets (12%).

*c) Research methods*

Considering the research methods, the articles could be grouped into five categories: biophysical models, observational studies, remote sensing, experimental studies and multi-method research. Most case studies (70%) used only one research method. The biophysical models category included studies based in simulations of complex biophysical systems using mathematical models of the properties of that system to analyse or predict the influence of biological or physical factors on the system. In this class, we included all research centred primarily in simulations using modelling software such as ENVI-met (e.g. Sodoudi et al., 2018) or in equations that simulate biophysical systems (e.g. Vanos et al., 2019). In case studies where field measurements were conducted merely to obtain variables to feed or calibrate the models (e.g. to calibrate ENVI-met models with local data before conducting simulations), the main

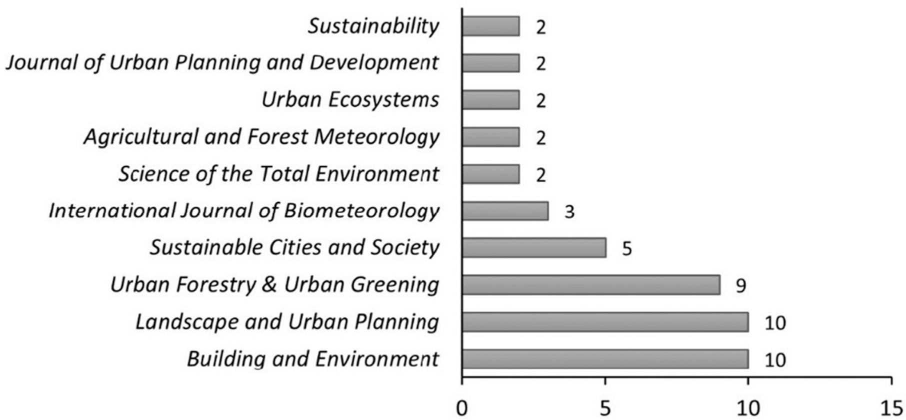


**Fig. 3.** Number of articles ranked per top 10 journals.

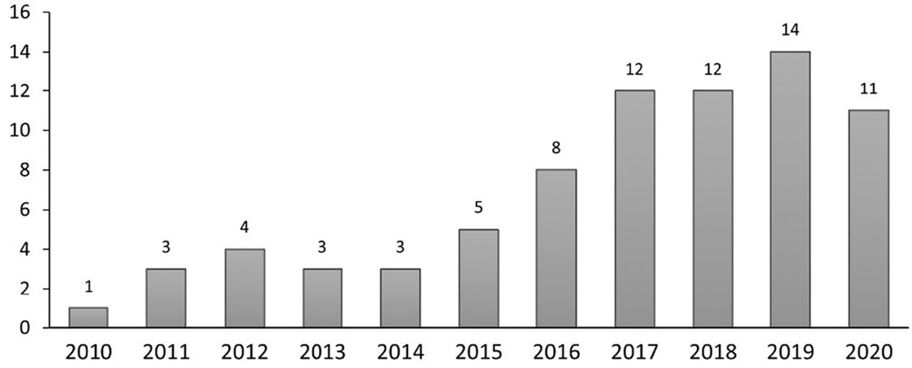


**Fig. 4.** Articles included in the review according to the year of publication (between January 2010 and October 2020).

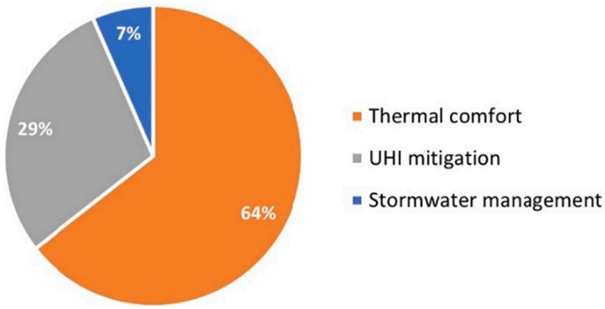


**Fig. 5.** Share of case studies per climatic impact addressed.

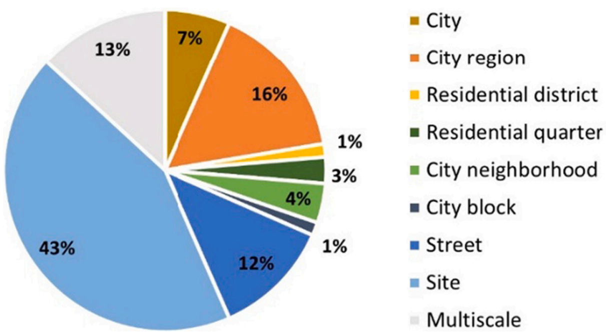


**Fig. 6.** Share of case studies per research scale.

research method was still considered in this class. Biophysical models accounted for 64% of articles using only one research method, and 45% of the total number of articles in this review (Fig. 7).

Observational methods refer to research based on the observation of phenomena or systems in which no independent variable can be isolated or controlled. This category contained all case studies collecting observational data in real urban systems, independent of whether special equipment was used or not. Correlative studies were also categorized as observational research, as only observed data is used. Observational methods comprised 23% of articles using only one research method, and 16% of all articles analysed (Fig. 7).

The remote sensing category included research based on data obtained through remote sensing technologies and was used in 9% of single method studies and only in 4 of the 23 multi-method studies. Interestingly, 5 of the 9 case studies using remote sensing were located in China.

The experimental method was the one least used in the reviewed articles, with only 4% of single-method studies and one multi-method study. This category refers to research involving an experiment to control specific variables in a given biophysical system, and assessing results before and after manipulating those variables.

Only one multimethod study ($n = 23$) used more than two methods (Feyisa et al., 2014); the remainder used mostly a combination of biophysical models and observational methods ($n = 18$).

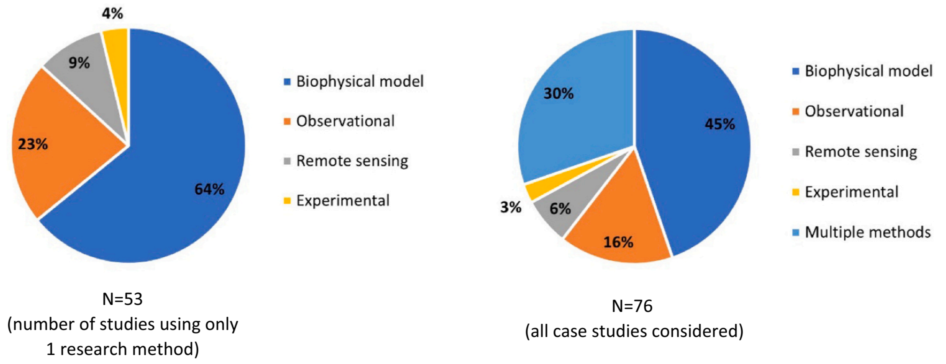


**Fig. 7.** Share of case studies per research method. The results are shown considering only case studies using one method (left) and considering all case studies regardless of using one or more methods (right).

*d) Type of output*

In terms of research outputs potentially useful for practitioners, the case studies could be organized in five categories: recommendations, guidelines, design proposal, insights, and other. The first category comprised all articles including a specific section or at least an explicit reference to recommendations for practitioners (e.g. Vanos et al., 2019; Zölch et al., 2019); the second category included articles featuring design guidelines (e.g. Klemm et al., 2017a; Nouri and Costa, 2017), usually more detailed and comprehensive than recommendations; the design proposal category concerned all case studies in which new designs for the study area were proposed and their performance was assessed (Cortesão et al., 2016; Gaitani et al., 2011; Kleerekoper et al., 2015). The insights category indicated relevant information for practitioners emerging from the articles, but less structured than recommendations, guidelines and design proposals (e.g. Kántor et al., 2018; Vukmirovic et al., 2019); insights frequently require an additional interpretation from the reader to translate the research results to the design practice, and therefore complicate an objective appraisal by practitioners. The category referring to other types of outputs included a diversity of end products potentially useful for practitioners, such as databases (Lin and Tsai, 2017), methodological frameworks (Rantzoudi and Georgi, 2017) or prediction models (Shi et al., 2019).

Four case studies (5%) did not provide any type of research output suitable for design practitioners, and only 11 articles (14%) featured more than one type of output. More than half of the case studies (57%) produced insights, and only around a quarter (24%) featured explicit recommendations to practitioners (Fig. 8). Design proposals were presented in just 3% of the articles, while design guidelines ranked slightly better (5%). Other types of outputs were developed in 11% of the case studies.

### 3.3. *Assessing relevance and geographical transferability of outputs*

The 72 articles that provided research outputs suitable for design practitioners were subsequently assessed according to the two evaluation criteria set for this review: relevance of research outputs to the practice of design, and transferability to other geographical

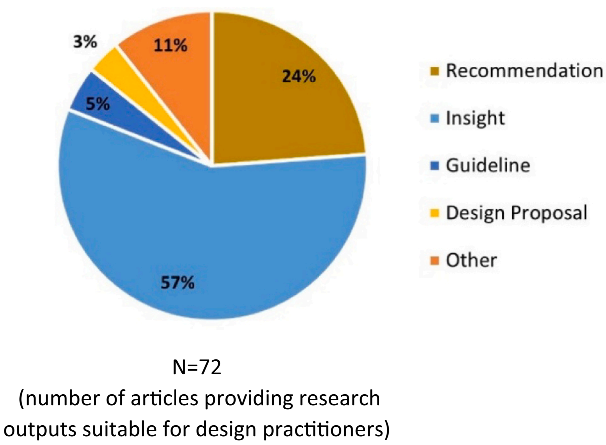


**Fig. 8.** Research outputs for design practitioners per type. Articles delivering multiple outputs ($n = 11$) were considered in all appropriate categories, and therefore were counted more than once.

contexts (see details in section 2). We found that 64 (89%) of the articles delivered relevant outputs for the design practice under analysis. Considering the type of output delivered by case studies, 15% of articles featured in the insights category failed to comply with our relevance subcriterion (Fig. 9); the same applied to one article providing an output framed in the 'other' category, and with one study delivering more than one output. The remainder of the articles fulfilled the relevance for practitioners through at least one type of output.

In terms of transferability to other contexts, of the 64 articles with relevant outputs for design practice, 47% were classified as delivering outputs with medium potential (class B), 42% with high potential (class C) and only 11% with low potential (class A). When considering the results per type of output, the two design proposals and one output in the 'other' category featured in single-output articles were grouped in class A due to their highly site-specific nature (Fig. 10). All the articles featured in the remaining categories delivered mostly outputs in class B or C, but only in the insights category were there more outputs in class C than in class B.

## 4. Discussion

Results addressing objective *i*), concerning the identification of research outputs according to climate impact, prompt two important questions: a) *How is climate adaptation framed in a design-oriented perspective?*, and b) *What type of outputs is evidence-based research providing to design practitioners?* We discuss the implications of our findings accordingly, in subsections 4.1 and 4.2. Subsequently, subsection 4.3 critically addresses the relevance and geographical transferability of outputs (objective *ii)*), and subsection 4.4 synthesizes key challenges that might hinder the implementation of evidence-based guidelines (objective *iii)*).

### *4.1. How is climate adaptation framed in a design-oriented perspective?*

Several of the reviewed articles focussed on disciplines such as climatology (e.g. Lee et al., 2016; Yahia and Johansson, 2014), remote sensing (Chen et al., 2020; Shi et al., 2019), landscape ecology (Xu et al., 2017) and arboriculture (e.g. Rahman et al., 2013; Rahman et al., 2020a), and many did not focus specifically on the design of green spaces, hence resulting in research outputs that were not categorized as relevant for the design practice in the scope of our review (e.g. Yahia and Johansson, 2014). Although some articles stated that they addressed the design of outdoor green spaces or related elements, their contribution was rather on the strategic level of urban planning since they did not provide clear recommendations on how to shape morphology and/or composition of outdoor green spaces to support climate adaptation (e.g. Xue et al., 2019). These results suggest that a significant amount of evidence-based research informing the design of green spaces for climate adaptation is developed by researchers outside design-oriented disciplines, which could explain the conflation between design and planning purposes found in some articles. Such conflation is further corroborated by our findings in the selection phase of articles for this review, in which most of the 422 articles initially obtained (Fig. 1) were excluded due to addressing urban planning instead of design, despite using keywords related to the design practice.

Our review indicates a dominance of research concerning thermal comfort and UHI mitigation. While it has been recognized that one of the most important contributions of GI for climate adaptation is in reducing urban stormwater runoff (Matthews et al., 2015), which is particularly important in cities increasingly exposed to recurrent flooding, only 5 of the 76 reviewed articles focussed on stormwater management, which may suggest that this important research area is currently overlooked. However, a recent review analysing NBS for hydro-meteorological risk reduction highlighted several studies addressing the role of GI or its individual elements (Ruangpan et al., 2020), even though the authors focussed on the performance of NBS without adopting a design-oriented perspective that may assist practitioners in implementing these solutions. The lack of studies of stormwater management in our review might be due to the selection of keywords, in which only the term "flood*" focussed directly on water issues. However, it might likewise suggest the lack of a design-oriented approach in studies that could, consequently, have fallen out of our research scope. Although our search keywords aimed to be comprehensive and common across diverse disciplines, we acknowledge that a large share of recent research has adopted more specific concepts that might have fallen out of our scope, such as UES, NBS, "ecosystem-based approach" and "urban forests". Still, the concept of GI was well represented in our review (e.g. Kazak et al., 2018; Klemm et al., 2017a). While these concepts

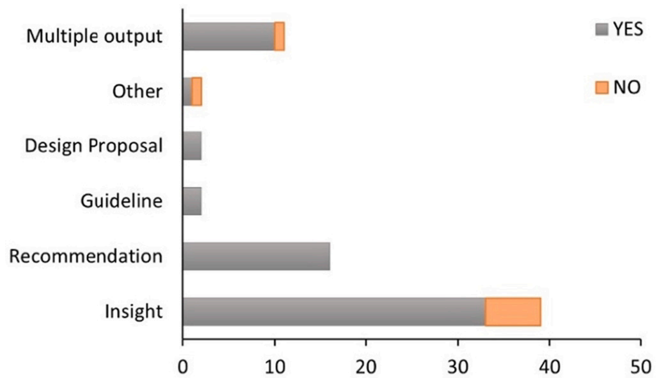


**Fig. 9.** Relevance of outputs for design practitioners, according to type of output ($n = 72$).

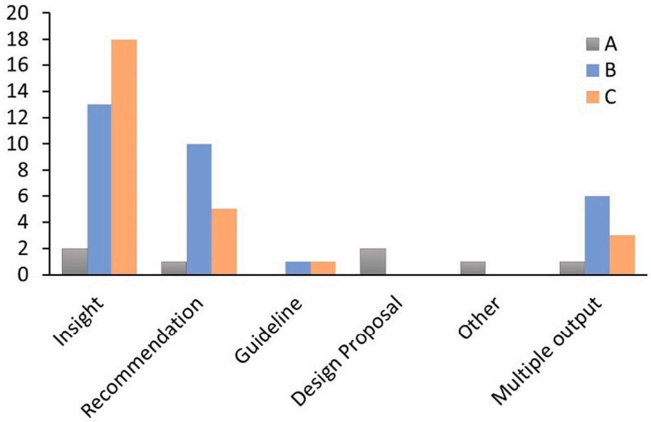


**Fig. 10.** Transferability potential of relevant research outputs, according to type of output ($n = 64$).

are valuable to disentangle different meanings, values and objectives in research, given their novelty it has been argued that they are evolving metaphors which bear less relevance for their differences than for their shared focus in nurturing interdisciplinary knowledge on urban ecosystems to enhance human wellbeing (Escobedo et al., 2018). We add that while research is rapidly expanding on the clarification of these similar concepts (Escobedo et al., 2018; Taylor and Hochuli, 2017), practitioners are lost in an increasingly complex web of interrelated ideas that further complicates the translation of research into practice. This is especially the case when considering a design-oriented perspective in climate adaptation, in which the scale of the design practice should matter more for the operationalization of research and performance of green spaces, than the specific conceptual metaphor under which such action is framed. The difficulty in tracking down and synthesizing existing information was precisely one of the obstacles highlighted by practitioners in a survey on the use of green strategies in their design practice (Calkins, 2005).

Only two studies considered the impact of green spaces in winter and in relation to wind flows and solar access. Even though the critical role of urban greening to cool cities has been widely acknowledged (Bowler et al., 2010; Koc et al., 2018), the design practice should also incorporate the full range of vegetation potential for climate adaptation and human comfort in different seasons, while addressing trade-offs concerning e.g. the positive and negative aspects of specific species. For example, evergreen trees may reduce stormwater in rainy seasons, but potentially increase thermal discomfort and energy use for heating in cold seasons through shading and evapotranspiration (Dimoudi and Nikolopoulou, 2003). Moreover, differences in climate zones and geographic settings may also require different greening solutions (Brown et al., 2015).

Our results underline a lack of consensual scale categories translating similar spatial extents in research, particularly in intermediate scales between the city and the site levels, which may hamper the comparison across case studies and the systematization of evidence. Nevertheless, more than half of the articles focussed on the site and street levels, which are undoubtedly within the realm of the design practice.

We observed a low prevalence of case studies adopting experimental methods. Experimental methods make it possible to isolate and control specific variables, and therefore they provide detailed information on the performance of these variables under diverse conditions, thus facilitating translation of research into practice. This capacity of experimental methods for evidence-based design was explored in just three case studies in our review: Ishimatsu et al. (2017) conducted an experiment in Japan to analyse the function of rain gardens, which revealed that the performance of this solution is dependent on rainwater volumes, soil properties and catchment area, and requires connection to sewage systems and maintenance; a study by Rahman et al. (2013) assessed the growth and physiology of a common tree species in the city of Manchester in different types of pits, and concluded that trees in open pits performed better in cooling compared with trees in small and large covered pits; and Snir et al. (2016) analysed the cooling effect of surface cover using succulent plants, compared to other plants such as grass that require substantially more irrigation. These three experimental studies generated detailed information for the design of specific greening solutions, while also providing evidence on the impact of design in the performance of green spaces in climate adaptation, in line with information demanded by design practitioners (Calkins, 2005). Another interesting approach was adopted by Lenzholzer (2012) in a case study in the Netherlands, involving 'research for design' and 'research by design' phases: 'research for design' aimed to provide guidelines for thermally comfortable urban squares and survey people's microclimate perceptions to inform new design hypotheses, which were applied in a 'research by design' proposal and tested through microclimate simulations (using ENVI-met). This methodological approach integrated the design perspective in framing both the research questions and methods, and delivered recommendations useful to practitioners. Lastly, it is noteworthy that in our review only one case study (Martins et al., 2016) stated explicitly that it was developed to inform the design and planning process of a real intervention (in a new district of Toulouse, France), which suggests that design-oriented research is rarely linked to ongoing design processes.

### 4.2. What type of outputs is evidence-based research providing to design practitioners?

Grose (2014) noted the lack of interdisciplinary engagement with designers in academic research, which is corroborated in our review by the absence of collaborative research focussing on real design interventions. Our analysis underlined other obstacles to bridging the gap between theory and practice. For example, we found that more than half of all case studies provided only insights for practitioners, thus requiring an added effort from the reader to assess the potential to inform the design practice. Still, 84% of the articles in the review delivered research outputs relevant to the design practice as they addressed tangible aspects of morphology or composition of green spaces that could be manipulated by design. Furthermore, only a small percentage of case studies (7%) produced outputs with low potential of transferability to other contexts (ranked in class A). Of the eight articles that did not deliver outputs directly applicable to the design of green spaces, Suleiman et al. (2020) had a different focus (governance related with urban rain-harvesting schemes); Ouali et al. (2020) explored the approach of Open Urban Design to improve thermal comfort but did not present insights related to green space design; Xue et al. (2019) presented strategic recommendations in the scope of urban planning, concerning the cooling effects of urban and peri-urban wetlands; Bajsanski et al. (2016) developed an algorithm to increase shadowing through tree location in parking lots, but although the method provided useful information it was complex and not easily accessible for practitioners. Considering the articles delivering outputs classified as not relevant for design, some used a scale of analysis too coarse to address the design of green spaces, although they provided important information to urban planning (Chen et al., 2020; Shi et al., 2019). Others did not provide enough information to support or clarify the performance of specific variables in the design of green spaces (Lee et al., 2018; Yilmaz et al., 2018), therefore making it difficult for practitioners to apply the research results. Some studies analysed aspects such as the performance of tree patch size in urban cooling (Jiao et al., 2017) or the impact of trees in thermal comfort compared to grass (Yang et al., 2016), but did not provide enough information on how the research results could be applied in the design of green spaces. One study provided evidence on the impact of landscape configuration and composition in land surface temperature inside parks (Xu et al., 2017), yet no orientations on how to shape the structure of parks to improve their performance were given. Lastly, Yahia and Johansson (2014) assessed the performance of vegetation and landscape elements focussing on urban design variables outside the scope of this review (urban morphology, street orientation).

### 4.3. Relevance and geographical transferability of outputs

Considering the transferability potential, we found that most of the 64 articles providing relevant outputs for design were classified in class B (medium potential) or A (high potential). However, in some cases the outputs with high transferability potential presented a considerable level of abstraction that could affect their translation to the design practice. For example, Chatzidimitriou and Yannas (2016) ranked urban design effects on pedestrian thermal comfort in summer, considering proportions of e.g. vegetation types or water in two types of typical urban spaces, a square and a courtyard; this information is useful for practitioners, but it does not address variables that are necessarily decided in green space design, such as the species or location of vegetation. Moreover, several studies have demonstrated that the structure, composition, and location of vegetation affect its cooling potential (Morakinyo et al., 2020; Rahman et al., 2020b). Nevertheless, a decade after the review by Bowler et al. (2010), the scientific evidence about the optimal types, amounts and distribution of vegetation required to mitigate heat more efficiently at the local scale is still limited (Koc et al., 2018). Lee et al. (2016) provided evidence of the heat stress mitigation of tree canopies compared to grasslands, but no specific recommendations for practitioners. Similarly, Li et al. (2020) assessed the optimal design of green, blue and grey infrastructures in improving microclimate regulation by exploring different coverage ratios of each type of infrastructure, but did not take into account the site-specific infrastructure design. Another case study used the sky view factor (SVF) to analyse the effect of the location of roadside trees on thermal comfort (Tan et al., 2017), using a model representing only one tree species. A similar study was conducted by Ahmadi Venhari et al. (2019). Herath et al. (2018) assessed the impact of urban GI elements to mitigate UHI, considering only cover percentages. Hamdan and de Oliveira (2019) analysed the impact of the location of vegetation in microclimate considering solely the shading factor of one species. Yet, other variables of vegetation such as evapotranspiration potential have been shown to significantly affect their microclimate impact (Rahman et al., 2019), while tree transpiration is strongly affected by the ground cover under trees (Rahman et al., 2020b). Another caveat in the reviewed literature relates to the high complexity of some outputs for practitioners. For example, the methodological framework developed by Kazak et al. (2018) to guide the location of GI for stormwater management involves complex hydrological modelling and requires a large variety of information (e.g. soil types, land use at the cadastral level, tree coverage etc.) which might not always be available for practitioners, who must nevertheless develop their practice with limited information and deal with uncertainty. Another example is the study by Bajsanski et al. (2016), which developed an algorithm to optimize the location of trees in parking lots to provide maximum shade. While these case studies show difficulties in translating research outputs to green space design, several studies in the review provided relevant information that can be easily applied in the design practice. For example, Morakinyo et al. (2020) proposed a methodological framework to select the right species for the right place to mitigate urban heat in street canyons, a ranking of the best tree forms for different urban morphologies, and tree selection recommendations according to different SVF. Vanos et al. (2019) presented an extensive list of recommendations and actions to promote adaptive design and coping strategies for thermal comfort improvement during the Tokyo 2020 Olympic marathons, which can be adapted to other large sub-tropical cities. Nouri and Costa (2017) provided guidelines to inform bioclimatic design of public spaces, particularly detailed for water and misting systems to reduce temperatures. Rantzoudi and Georgi (2017) developed a method to account for the complex interactions between trees, sun, building shade and energy savings in a simplified and practical way, while synthesizing relevant information in visual sections of streets and summarizing key relationships useful as rule of thumb to inform design in street canyons. Klemm et al. (2017a) developed a participatory approach in which several climate-responsive design guidelines were refined and improved with the input of practitioners, to increase the applicability potential in real designs. Some studies provided several recommendations targeting vegetation to enhance shade in warm climates (Yahia et al., 2018) or to increase thermal comfort (Kong et al., 2017). Lenzholzer (2012) developed a climate-responsive design that can be easily introduced into the layout of Dutch squares. Yang et al. (2011) proposed several landscape design recommendations to mitigate UHI. Shashua-Bar et al. (2012) explored passive cooling design solutions to increase thermal comfort in urban streets and delivered several recommendations for practitioners. Brown et al. (2015) analysed the effect of urban park characteristics on thermal comfort in five climate zones and provided accordingly differentiated recommendations for practitioners to enhance cooling capacity in this type of green space. Vanos et al. (2016) conducted a multiscale analysis of playground surface temperatures in Arizona, USA, and provided crucial insights concerning hot-hazard mitigation techniques aiming to enhance environmental and public health, which can also contribute to set new design standards. Another study (Feyisa et al., 2014) provided information concerning relationships between park characteristics and cooling effects, and proposed some recommendations for choosing species to achieve best results. Interestingly, the study by Cortesão et al. (2016) was the only one considering the life cycle environmental impact of a design proposal, which resulted in selecting an alternative solution for paving material to achieve the best design performance in terms of sustainability and thermal comfort. Considering that practitioners need to make a multitude of decisions concerning sustainability when developing a design proposal for urban spaces, this study opens an innovative systemic approach to research addressing performance in climate adaptation.

Although a significant number of case studies in our review seemed to support green space design, our results suggest that to close the gap between theory and practice, scientific research must progress toward the scale of inquiry of practitioners, and provide more specific guidelines and recommendations.

### 4.4. *Key challenges hindering the implementation of evidence-based guidelines*

The results of our review indicate that despite the large amount of studies that have been published on outdoor urban green spaces and climate adaptation since Bowler et al. (2010), evidence-based guidelines to inform the design of green spaces are still limited. Based on our findings, we highlight several gaps and obstacles that prevent the transferability and operationalization of evidence-based research into practice, and provide a roadmap for future research addressing five key challenges:

1. *Ambiguity in key definitions and orientations for the design practice:* Our results evidence some vagueness in research concerning what is the purpose of design in the context of urban green spaces, even though many of the reviewed articles state the relevance of their findings for the design practice. Such ambiguity potentially explains why in many case studies the spatial resolution of research outputs collided with the specificity and detail of the information involved in design processes. Difficulties for design practitioners arise also from studies claiming to inform design but providing only strategic-level information useful for urban planning, lacking the spatial resolution and purpose of design. These results suggest a somewhat misaligned view of design and planning from academic vis-à-vis practice perspectives. Other studies have also found mismatches between academic research and practitioner needs, even when solely considering research in practice-oriented disciplines such as landscape architecture (Milburn and Brown, 2016), and differences in the cultures of designers and researchers in ecological science (Grose, 2014). Although practitioners have adopted general strategies to promote green space connectivity, resilience and biodiversity, design inevitably entails a site-specific approach that requires fine-resolution information about how to achieve desired goals, which cannot be attained through vague recommendations or general frameworks (Grose, 2014). Furthermore, we frequently observed that similar spatial scales were defined differently across studies, thus complicating comparisons, and some studies did not provide enough information on the spatial extent considered in the research.

   In the scope of our investigation, we suggest that future research should consider the operative level of the design practice at the site scale and identify explicitly which, and how, morphological characteristics and/or composition of green spaces can be manipulated at which spatial extent, thus narrowing down the design possibilities in relation to climate adaptation goals. For example, studies analysing the effect of vegetation on thermal comfort could identify specific structural aspects of plants (size, shape, density, location, condition) or composition elements (species, functional traits, diversity) that influence the microclimate in a 1-100 m range, and provide recommendations on how to shape those characteristics of urban green spaces to achieve better performance;

2. *Identifying key mechanisms linking specific types or elements of design to climate adaptation outcomes*: Much of the research informing practitioners has focussed on aggregated predictor variables that cast light on general trends or signals in urban systems, which has contributed to advance basic science and generated new hypotheses, but has failed to address practitioners' needs for information (McDonnell and Hahs, 2013). Due to the specificity and individuality of design research questions, aggregated predictor variables that rely on statistical associations rarely provide insights that can be translated to a design output, because a cause-effect relationship is not clearly established. Moreover, urban green spaces are dynamic ecosystems that respond to changes in the morphology and composition of ecological elements, interact with social and economic systems, and evolve across time. Thus, a more mechanistic approach in research, that clarifies the mechanisms and drivers triggering specific performances at the site scale, would facilitate the operationalization of scientific outputs in the design practice across diverse sites and contexts, while allowing more flexibility in how green spaces are shaped to achieve a desired goal (McDonnell and Hahs, 2013). Examples of causal mechanisms that need to be better understood concern e.g. how mensurable ecological properties and processes occurring in urban green spaces drive the site-level performance of ecosystem services such as wind protection, microclimate regulation and runoff

mitigation, how these in turn generate mensurable human health, social or economic benefits, and how such linkages change across different time scales (seasons, after short or long-term implementation) and climate zones (Kabisch et al., 2016; Pataki et al., 2011);

3. *Identifying trade-offs and synergies between the morphology and composition of urban green spaces impacting climate adaptation outcomes:* While many case studies have analysed isolated characteristics of green spaces (e.g. coverage by different proportions of vegetation, shading coefficients, sky view factors, specific species), it is not clear what trade-offs and synergies exist between different elements of design that need to be simultaneously considered when shaping green spaces. For example, to what extent do soil type, ground cover or irrigation influence the role of vegetation in microclimate regulation across time (e.g. night/day, seasons) and climate zones? How does the condition and size of vegetation affect the cooling effect or wind reduction in relation to specific arrangements of vegetation and types of species? Which species or types of vegetation perform better under different climate zones, and how can their performance be optimized in specific types of green spaces (e.g. street trees, parks, squares)? To what extent is the performance of similar types of vegetation altered by density, location, arrangement and ground cover? How is the heat exchange of pavements or water bodies with the surrounding atmosphere affected by different types of nearby vegetation or built structures, and what is the impact in terms of thermal comfort? These are examples of questions that go beyond analysing solely the effect of the size of green spaces or the proportion of cover types in climate adaptation and seek to understand how multiple qualities of green spaces (which are shaped by designers) interact with each other and modulate their response to the local environment, generating potential synergies or trade-offs. While it is neither possible nor desirable to seek one-size-fits-all responses that may suit different climate zones and urban contexts, there is a clear lack of research addressing the underlying mechanisms and processes that are inevitably shaped simultaneously by the morphology and composition of urban green spaces, which could assist practitioners in designing and implementing more efficient solutions targeting climate adaptation;

4. *Developing indicators and frameworks to monitor the performance of types or elements of designs across temporal and spatial scales:* While monitoring is a prerequisite of experimental methods in science, it is not common in the design practice (Ahern et al., 2014) and therefore, design outcomes are usually not assessed in terms of their performance to achieve a desired goal. In climate adaptation, the scarcity of evidence-based knowledge of measures that can be easily implemented is further aggravated by the lack of a monitoring culture that would contribute to advance both scientific knowledge and design practice. We identified an absence of studies assessing the performance of real urban green spaces by comparing pre- and post-design outcomes relevant to climate adaptation. Furthermore, our review did not retrieve any monitoring frameworks that could facilitate assessing pre- and post-design performance in relation to design variables. Developing standards for monitoring frameworks and indicators could promote an evidence-based culture that is currently missing in design-oriented disciplines such as landscape architecture (Brown and Corry, 2011), and could generate comprehensive datasets relating environmental variables to design interventions in diverse geographical, temporal, and climatic contexts that may open new avenues for scientific research in the realm of climate adaptation. While scenario-based modelling approaches area also useful to assess the impact of different design options in e.g. land surface temperature, our results suggest that these may fail to capture the interplay between the full spectrum of morphological and compositional aspects of real green spaces. We acknowledge that long-term monitoring of real pre- and post-design sites might prove challenging for e.g. local authorities due to variable environmental conditions and resource constraints, and also within research projects, given their limited timeframe. However, comparative monitoring of different types of existing green spaces (e.g. squares, parks, street trees) with diverse composition, surface cover or vegetation arrangement may provide useful insights on the performance of different design options;

5. *Co-designing research grounded in science-practice interactions:* Our research highlights that the resolution of biophysical variables of green spaces addressed in research questions and methods needs to be refined to match the design variables that can be manipulated by practitioners to improve performance in climate adaptation (McDonnell and Hahs, 2013). Expanding interdisciplinary approaches linking research to real design processes could potentially facilitate a realignment of research questions, methods, and outputs to better address the spatial resolution of professional practice. The analysed case studies reveal that stakeholder involvement in climate adaptation research concerning green space design is rare, although some exceptions should be noted (e.g. Makido et al., 2019). We suggest that involving design practitioners in framing research questions and in providing inputs for the research process can help to align research outputs with practitioners' needs, and to implement scientific research advances into the design of urban green spaces. While real design processes are always an unrepeatable experiment at a specific site, they provide unique opportunities to test and advance knowledge on the cause-effect relationships and underlying mechanisms involving environmental variables. Although it has been argued that small, safe-to-fail design experiments support innovation and the integration of science and professional practice to advance knowledge on performance of “constructed ecologies” (Ahern et al., 2014; Grose, 2014), our results suggest that researchers have barely started to explore the possibilities of this approach in bridging different cultures. Additionally, some difficulties in how research results are commonly communicated to practitioners were particularly obvious in our review, which might partially explain why evidence-based knowledge has not yet made its way into the design practice. One of the main obstacles was evident in the large share of articles providing only insights that leave to practitioners the job of analysing, selecting, synthesizing, and ascertaining how to translate the research outputs to site-specific contexts. Furthermore, as Klemm et al. (2017a) state, design practitioners often have a limited understanding of scientific knowledge of complex issues such as microclimate, which further complicates how they interpret research results. Yet, in our review very few articles addressed explicitly the need to present research outputs in a format more comprehensible to practitioners. Design guidelines supported by visual examples facilitate the understanding of scientific information by practitioners (e.g. Klemm et al.,

2017a; Rantzoudi and Georgi, 2017) but are not always feasible. Our review underlines that research results informing the design practice for climate adaptation need to be translated into very specific and comprehensible orientations, well framed under a specific scope (e.g., designing specific types of green spaces, selecting species etc.) that direct design actions toward tangible configurations and compositions of green spaces. Our review also showed that the methods delivered by some studies as outputs to inform the design practice are sometimes overly technical and difficult for practitioners to use, therefore requiring an additional step to create an accessible interface or structure that allows their use in the design practice. To overcome all these difficulties and set forth a new research agenda for urban green space design targeting climate adaptation, we argue that it is critical to develop collaborative research involving practitioners to identify their perceptions on the most pressing knowledge needs, and on how to best communicate research findings in a way that might effectively support the transfer of scientific knowledge to the design of urban green spaces (e.g. Klemm et al., 2017a; Ugolini et al., 2015).

### 4.5. Limitations

Several limitations need to be acknowledged in our review. While this study focussed only on peer-reviewed research, we are aware that practitioners face many constraints in accessing scientific literature such as costly subscriptions and the lack of a common language (Ugolini et al., 2015), and thus rely more on grey literature to access information, which we did not have the means to review in the present work. Nevertheless, grey literature aims to translate scientific information into guidance for practitioners, and therefore relies on available evidence that remains scarce in relation to the complex interplays between morphology and composition of urban green spaces that affect their performance in terms of climate adaptation.

Due to the wide spectrum of disciplines and perspectives captured in our semi-systematic analysis, we were unable to collect comparable information across studies on the type of designed green space that was analysed, as the different conceptualizations were frequently not translatable into categories such as parks, squares or street trees (e.g. Makido et al., 2019). Yet, future research addressing specific types of design could provide more detailed insights on knowledge gaps to better support the practice.

Lastly, we underline that urban green space design requires dealing with a multitude of ecological, social and economic objectives, and thus future research should take into account how multifunctional designs weight different criteria (including, but not limited to climate adaptation) in order to achieve the best results to address the many challenges of modern cities. Likewise, future research should also consider the interplay between green, blue and grey infrastructures to achieve the best design outcomes in terms of climate adaptation, as these three dimensions are strongly interlinked and complementary in urban areas.

## 5. Conclusion

We analysed peer-reviewed studies published in the last decade concerning the design of outdoor urban green spaces in the context of climate adaptation, and developed an innovative design-oriented approach to critically assess what type of outputs recent research has produced to support the design practice. Our results show that the vast majority of studies addressed Thermal Comfort or UHI mitigation, and more than half provided only general insights for practitioners that are difficult to translate into the design practice. Yet, most research outputs addressed tangible aspects of morphology or composition of green spaces that could be manipulated by design, thus providing relevant information. Nonetheless, despite a clear increase in the number of publications per year, several constraints in research outputs hinder the implementation in practice, including an ambiguity in key definitions and orientations for the design practice, and a mismatch between the scale of research and the site-level operational scale of design. Our analysis has contributed to advance future research by highlighting key challenges to better translate theory into practice, including identifying key mechanisms linking specific types or elements of design to climate adaptation outcomes, addressing trade-offs and synergies between the morphology and composition of urban green spaces impacting climate adaptation outcomes, developing indicators and frameworks to monitor the performance of types or elements of designs across temporal and spatial scales, and co-designing research grounded in science-practice interactions. We conclude with a call for a collective effort in the academic community, to align research in order to better support the professional practice with the evidence-based foundation that is required to successfully assist cities in the global challenge of climate adaptation.

## CRediT authorship contribution statement

**Marisa Graça:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Sara Cruz:** Methodology, Writing – review & editing, Funding acquisition. **Ana Monteiro:** Methodology. **Tina-Simone Neset:** Methodology, Writing – review & editing, Funding acquisition.

## Declaration of Competing Interest

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

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## Appendix A. Supplementary data

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