Landscape Architecture Solutions to Extreme Heat

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OJB Landscape Architecture reimagined a 9-acre brownfield site to reflect its New England context. The site addresses urban heat, incorporates many natural features, details stormwater on site, and adapts to sea-level rise.

ASLA 2022 Professional General Design Honor Award. From Brownfield to Green Anchor in the Assembly Square District, Somerville, Massachusetts. OJB Landscape Architecture / Kyle Caldwell

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ASLA Fund

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1. Introduction

Extreme heat is the deadliest of all weather-related disasters (Hondula et al., 2015) and encompasses both acute and chronic risks. Climate change and urban heat island (UHI) — a phenomenon in which temperature tends to be higher in urban zones than surrounding non-urban areas — both contribute to extreme heat. Vulnerable populations, including children, the elderly, and low-income households, are especially at risk for heat-related health concerns (Chow et al., 2012; Kovats & Hajat, 2008). In 2017, an estimated 153 billion hours of labor was lost globally due to extreme heat (Watts et al., 2018) and heat increases are projected to decrease global economic productivity by 20 percent during hot months by 2050 (Zander et al., 2015). In addition to the quality of life and economic impacts, extreme heat can also raise energy demands (Santamouris et al., 2015), increase water use (Guhathakurta & Gober, 2007), impact the functionality of urban infrastructure (Golden, 2004), cause additional stress to urban ecosystems (Grimm et al., 2013), and in cases, may threaten the viability of some cities (Pal & Eltahir, 2016). Heat severity is also disproportionately experienced by lower-income, minority, and marginalized community members (Jesdale et al., 2013; Keith & Meerow, 2022). Recent research in the Southwest U.S. found that low-income communities in urban areas were 4°F (2.2°C) hotter than their wealthier counterparts (Dialesandro et al., 2021).

Nature-based solutions (NbS) can mediate the impacts from extreme heat caused by climate change and urbanization (Keith & Meerow, 2022). The Federal Emergency Management Agency (FEMA) defines NbS as "sustainable planning, design, environmental management and engineering practices that weave natural features or processes into the built environment to promote adaptation and resilience." In contrast, the term "green infrastructure" is sometimes limited to urban areas or is defined as simply "an interconnected network of green space" (Tzoulas et al., 2007). NbS more accurately describes the types of physical projects that can transform built environments to address extreme heat.

For landscape architects and allied professionals, there remains uncertainty about precisely which site design and community-wide planning strategies provide the greatest reductions in temperature. To address this gap, we conducted a review of peer reviewed literature. We identified and analyzed 107 articles published between 2007 and 2022. We assessed the articles in terms of their geographic distribution, the climate context of the site, the scale and nature of NbS used, the researcher's methods, and the insights the researchers gained from their work.

2. Methods

To assess the current state of knowledge on NbS and their potential to mitigate extreme heat, we conducted a literature review following procedures common in social sciences (Berrang-Ford et al., 2021; Petticrew, 2001).

We searched Scopus, the largest citation database of peer-reviewed literature, for all English language articles published after 1900 through the end of 2022.

We searched for articles that met three criteria:

1. They were related to NbS
2. They related heat
3. They were related to design and planning of the built environment.

We used the following search string to identify these articles: (TITLE-ABS-KEY("nature-based solution*") OR TITLE-ABS-KEY("green infrastructure") OR TITLE-ABS-KEY("green spaces")) AND (TITLE-ABS-KEY("urban heat") OR TITLE-ABS-KEY("extreme heat")) AND (TITLE-ABS-KEY("Design") OR TITLE-ABS-KEY("plan") OR TITLE-ABS-KEY("Landscape") OR TITLE-ABS-KEY("Architecture")) AND PUBYEAR > 1900 AND PUBYEAR < 2023 AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"re")) AND (LIMIT-TO (LANGUAGE,"English")). These search criteria resulted in a dataset of 348 articles (Fig 1).

We then carefully read the title and abstract of each paper in the dataset, and categorized them based on their relevance to our research focus.

Two researchers independently read through the titles, abstracts, and in some cases the full article, to determine whether the papers were focused on assessing the impact of NbS on extreme heat, and therefore should be reviewed in depth.

After abstract review, we found 10 articles where there were discrepancies in the decision to include the article for full review. We discussed these articles with our lab group to make final determinations.

Articles were excluded for ten different reasons (see Fig 1). The most common reasons for exclusions were they did not measure heat, they did not include NbS, and the article was the wrong type (e.g., review articles).

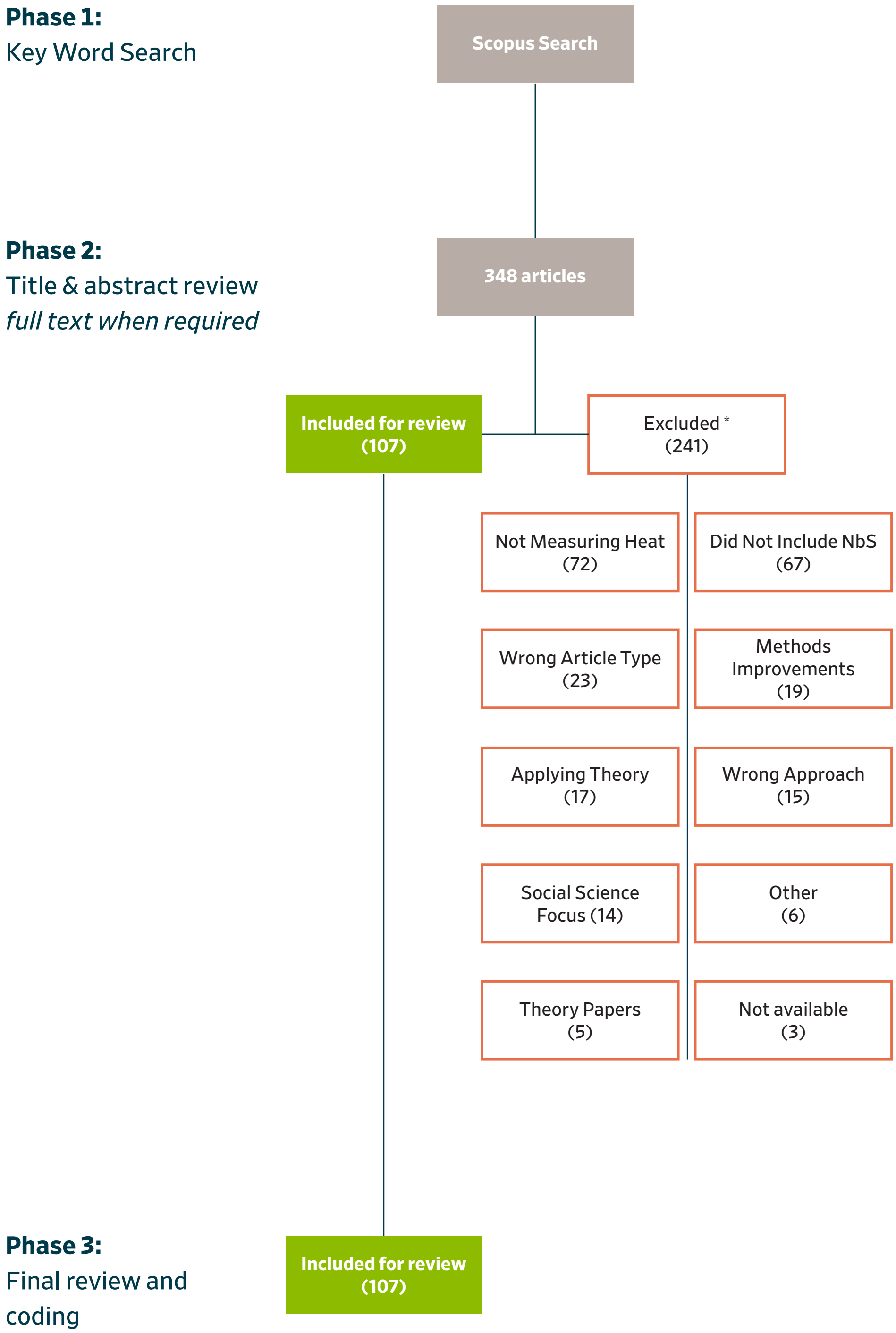

Fig. 1. Summary of document selection process

* Many documents can be classified with multiple categories. These represent the dominant reason for exclusion

Ultimately, 107 of the original 348 articles were included in the in-depth review. The earliest published article came out in 2007 with an upward trend from that point (Fig 2). The greatest number of articles (21) in our sample were published in 2022 and the second greatest number (20) were published in 2021.

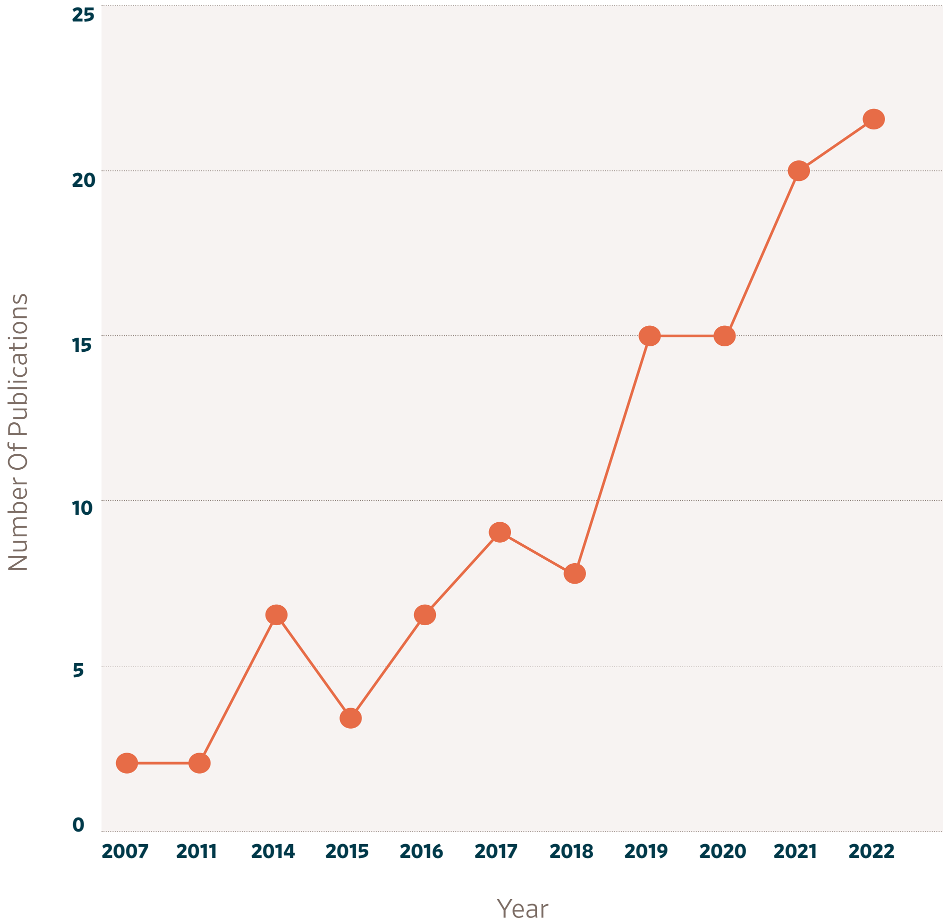

Fig. 2. Number of publications in our sample by year

Our sample represents a very diverse set of journals. We found relevant articles in 50 different journals. Journals include those in the building sciences (e.g., Journal of Building Engineering), those in the spatial sciences (e.g., Remote Sensing of Environment), those in the natural sciences (e.g. Ecosystem Services), and those in the Urban Sciences (e.g., Urban Ecosystems).

Figure 3 shows the eight most common journals (those with 3 or more articles in them) and the percent of articles in each of those journals. We found that Urban Forestry and Urban Greening was the most common journal with 14 articles published. Sustainability (Switzerland) was the second most common journal with 10 articles published.

We analyzed each of the articles with a focus on the following themes:

1. **Geographic distribution**
   Specifically we looked at the location that the research was about. We looked at the city, the United Nations M49 standardized region, and continent.

2. **Climate context**
   Based on the location, we used the standardized Köppen-Geiger climate classification system to analyze this.

3. **Scale and nature of NbS**
   We explored the scale of the research conducted, which ranged from small parklets, to entire megacity regions. Within each scale we looked at the type of NbS the researchers stated they were focusing on.

4. **Methods**
   Here we centered our research into the approach the researchers took for measuring heat.

5. **Insights gained**
   We investigated the types of new information that the researchers found through their work.

We then synthesized our findings through iterative coding methods. We discuss these findings in the results section below.

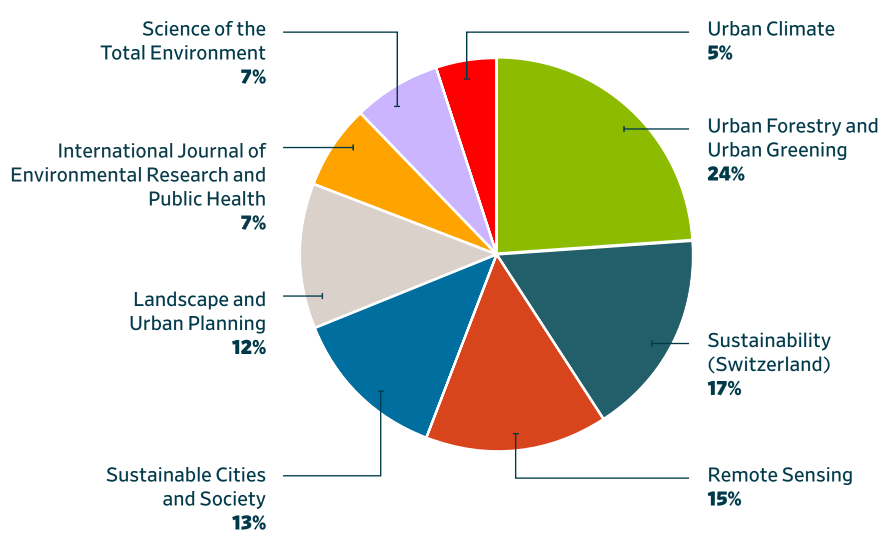

Fig. 3. The top eight journals where articles in our sample were published. For each journal we show the percentage of articles published

3. Results

Here we present our findings related to the geographic distribution of current research. We also provide our findings about the types of data used in the research conducted. We then focus our attention on the different design and planning insights gained through current research.

The articles in our database are diverse in terms of their geographic focus (Fig. 4 and Fig. 5). However, we find some continents (Fig. 4) and some countries (Fig. 5) are overrepresented. Asia and Europe represent the greatest number of studies. In fact, these two continents together represent over 80 percent of the dataset. This is surprising since North America often represents one of the two largest producers of scientific articles (Tollefson, 2018).

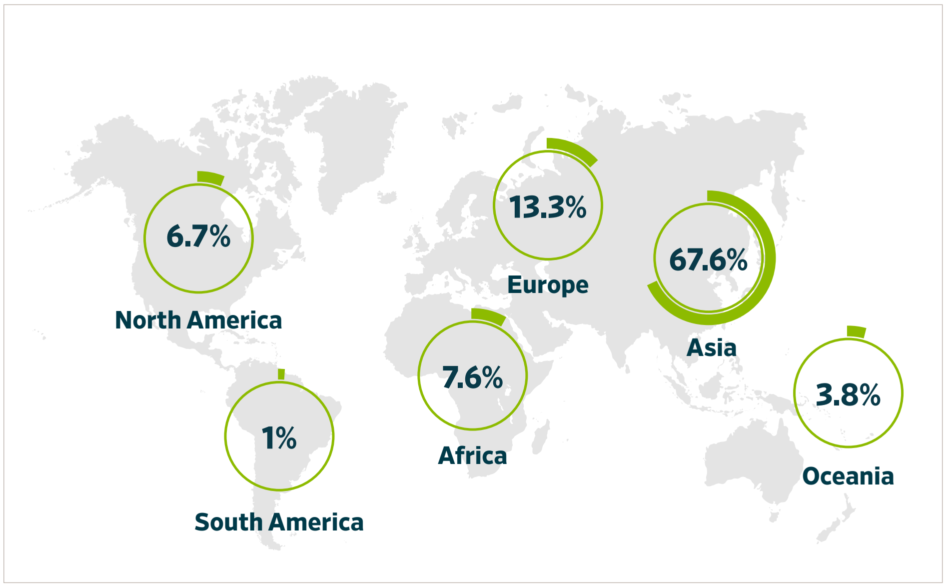

Fig. 4. Map showing the percent of publications by each continent

Looking at the United Nations M49 standard for designating regions (United Nations - Statistics Division, 2024), the most common study sites are in Eastern Asia with 55 publications. North America, Western Europe, Southern Asia, Eastern Africa, and South-eastern Asia are far below, though they are the next most common regions with 7, 7, 6, 5, and 5 publications respectively (Fig. 5).

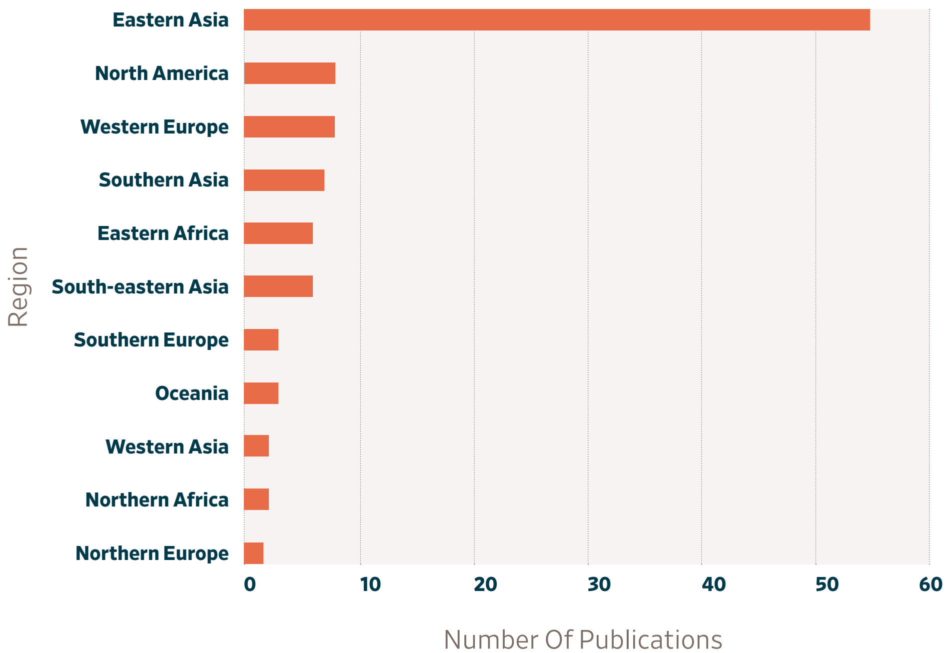

Fig. 5. The number of publications with the subject of the research set in the eleven most common regions based on the United Nations' M49 standard

Urban heat and the potential for NbS to reduce this threat varies across climates. The average weather found in places is measured in 30 year intervals.

The Köppen-Geiger climate classification system consists of six major categories:

a. Tropical Climates
b. Dry Climates
c. Moist Subtropical Mid-Latitude Climates
d. Moist Continental Mid-Latitude Climates
e. Polar Climates
f. Highlands

These are further subdivided by precipitation patterns (second letter) and seasonal variations (third letter) to create 31 subcategories (National Oceanic and Atmospheric Administration, 2023). We categorized the publications into the 31 subcategories within the Köppen-Geiger climate classification system (Fig. 6. and Appendix).

We find that most of the research – with 65 publications accounting for 62% – is set in the major group of C - Moist Subtropical Mid-Latitude Climates. This includes three of the four most common subcategories - Cwa, Cfa, & Cfb. Publications in the Cwa subcategory were the most common group with 26 publications (25%). This includes many cities in China and India and captures places that are considered mild with dry winters and hot summers.

The second most common subcategory is CFA with 19 publications (18%). These places are mild with no dry season and hot summers. Many of the North American cities fit into this category as do parts of China including Shanghai. There were also 13 publications (12%) in subcategory Cfb, which are places that are mild with no dry season and a warm summer. This includes the publications looking at places in Europe and Australia.

Publications in the Dwa subcategory were the third most common group with 16 publications (15%). This subcategory captures the work done in Beijing, China and is characterized by humidity with severe, dry winters and hot summer.

Full descriptions of each subcategories and the number of publications can be found in Appendix 1)

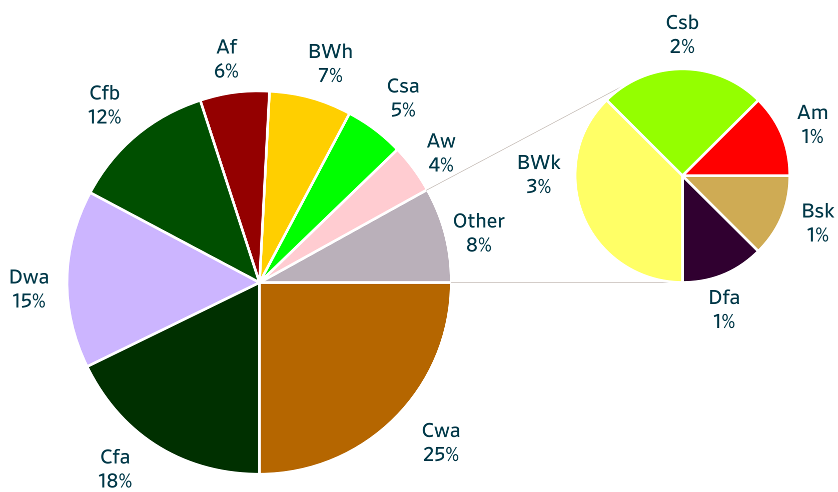

Fig. 6. The percent of publications with the subject of the research set in the Köppen-Geiger climate classification system.

Af	Equatorial rainforest
Am	Equatorial monsoon
Aw	Equatorial savanna
BSk	Mid-latitude steppe
BWh	Subtropical desert
BWk	Mid-latitude desert
Cfa	Humid subtropical
Cfb	Marine west coast
Csa	Mediterranean
Csb	Mediterranean
Cwa	Humid subtropical
Dfa	Humid continental
Dwa	Humid continental

We characterized the publications based on the scale of analysis conducted into four groups – site scale, neighborhood scale, city scale, and regional scale (Fig. 7). We found that nearly 50% of the research is at the site scale, with city scale, neighborhood scale, and regional scale constituting 26.2%, 21.5% and 7.5% respectively.

When it comes to the types of NbS, much of the work is focused on integrated green systems rather than site-scale specific designs. Under this umbrella, the authors use more vague and interchangeable terms such as "greenspaces," "green infrastructure," and "green corridors."

Using the language of the authors, we coded the articles by both scale and the authors' types of NbS. We found that green spaces were the most commonly used term and accounted for 43% of the research conducted. Parks was the second most common with 16% of the publications. Some authors used a combination of terms and were categorized as multiple and accounted for 9% of the publications we reviewed. We found that 8% of the published literature was specifically about trees. Green infrastructure, green roofs, green corridors, and green walls were also less used in our collection of publications with 7%, 4% 3%, and 2% of the publications respectively.

We observe some interesting patterns when we look at NbS by scale of the research. For example, green walls are only studied at the smaller scales – neighborhood and site. We also see a much greater focus on parks at the site scale. Green corridors on the other hand are only studied at larger scales. At the regional scale they make up 13% of the NbS types. On the other hand, green corridors are not studied at the site scale.

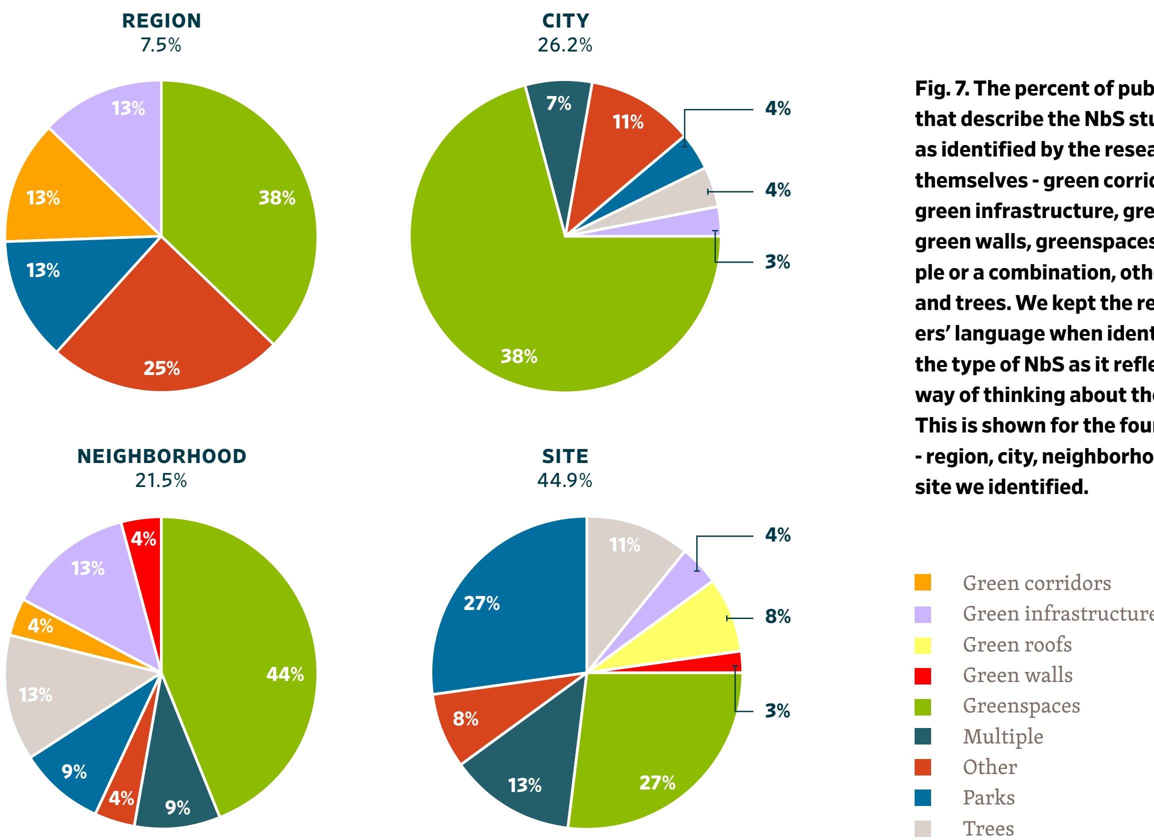

Fig. 7. The percent of publications that describe the NbS studied as identified by the researchers themselves - green corridors, green infrastructure, green roofs, green walls, greenspaces, multiple or a combination, other, parks, and trees. We kept the researchers' language when identifying the type of NbS as it reflects their way of thinking about the topic. This is shown for the four scales - region, city, neighborhood, and site we identified.

We also explored the number of articles that include water as part of the NbS solution set. In this context we find that 25% of the articles in our database include water and the cooling functions it provides. These papers include a broad range of water-related topics.

This includes articles that looked at irrigation, such as one called "Effects of urban parks on the local urban thermal environment," which explored the impacts of night time irrigation on neighboring communities from 60 parks in Taipei City, Taiwan (Chang & Li, 2014). It also includes a paper that investigates the extent to which Suzhou Bay in Jiangsu, China, is capable of lowering daytime temperatures (Z. Wu & Zhang, 2019).

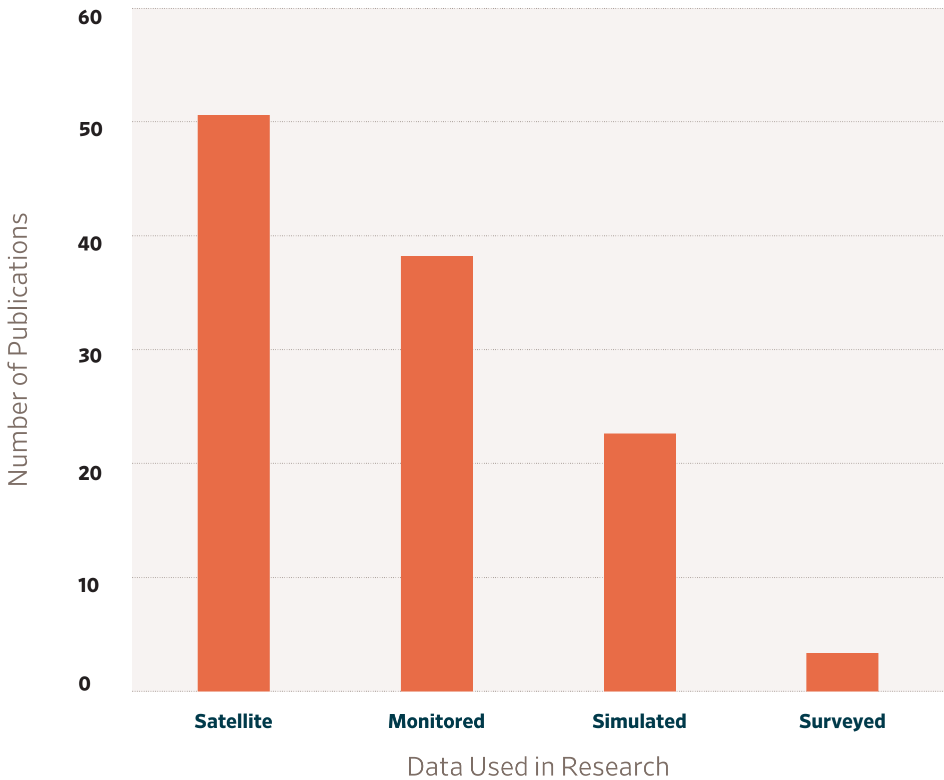

Fig. 8. The number of publications that used each of four different types of data to capture heat, the dependent variable, in their research. We looked at research that used satellite data, monitored or in-situ data, simulated data, and surveyed data. Note these categories are not mutually exclusive and ten publications used multiple types of data.

We were particularly interested in the methods used by the researchers to study heat. We identified four categories of data gathered by the publications we looked at (Fig. 8).

The first category is satellite data with 51 publications using this information. In this context, most researchers used Landsat data to generate land surface temperatures (NASA, 2021).

A second category is monitored data, where researchers gathered temperature data from a range of different instrumentation methods.

The third category is simulated data, with 23 publications relying on this information. Simulated data relies on fundamental physics principles to generate statistically significant potential futures. We found that of the 23 articles that relied on simulated data 17 used a software called ENVI-met, while the others each used a unique software.

The fourth category is surveyed data, and we found 4 publications that used this data. In this context researchers asked participants about their perceptions of heat. In all four of these cases, the surveyed data was compared with another data type.

These categories are not mutually exclusive and we found 10 articles that relied on a combination of methods.

Understanding the type of knowledge and insights gained from prior research is a key part of our work. We first categorized the research by the type of insights the research provides (Table 1).

Knowledge Type	Number	Percent
Planning	62	58%
Design	42	39%
Both	3	3%

Table 1
Number and percent of publications providing specific types of insights

We found that 58% of the articles in our database provide specific planning insights. These include new knowledge about the ideal size of parks to reduce extreme heat, the adjacent land use types that are most impacted by NbS, and the configuration of green corridors across the city (Fig. 9). We also found that 39% of publications offer specific design findings. These insights highlight the materials (e.g., grass versus trees) that provide the greatest impact, the size of trees that should be planted, and the combination of plants that could be used (Fig. 10). There are also 3% of the articles that provide a mixture of planning and design specific insights.

Through our coding process, we identified the following seven planning strategies that could impact the heating or cooling potential of NbS (Fig. 9).

1. **Land use**
   The ways land is used. It could be about the residential nature versus the commercial nature of the area.

2. **Size**
   The physical size of the NbS.

3. **Tree canopy**
   How much tree canopy exists either inside of a patch or across a city.

4. **Configuration**
   Spatial arrangement of urban elements, including streets, buildings, public and green spaces, and other infrastructure.

5. **Connectivity**
   Degree to which landscape features (e.g. NbS) are proximate or next to each other. This connection facilitates the movement of organisms, energy, and materials from one location to another.

6. **Edge**
   Relationship between the patch (e.g. NbS) and its surroundings (e.g. the buildings).

7. **Shape**
   Complexity of the shape of NbS patches. Patches that are linear are less complex in contrast to patches that have irregular edges.

This list is not exhaustive, but rather are the dominant themes we observed in three or more publications. These categories can be loosely grouped under the landscape ecology concepts of composition and configuration.

Composition is about the types of land uses that are present and the relative prevalence. Our categories of land use, size, and tree canopy all fit into this broader category.

Configuration captures how land use is distributed across the study area. Connectivity, edge, shape, and the more general category of configuration fit into this overarching category. Also note that these categories are not mutually exclusive.

Most researchers explored two or more strategies (Table 2), with only 31% exploring a singular topic. We find a relatively even distribution between the different strategies with most of them being studied by at least 18 publications. Connectivity is the exception – it was only the focus of 9 publications. We see that size and tree canopy are the most studied strategies, with 28 and 26 publications pursuing this line of work respectively.

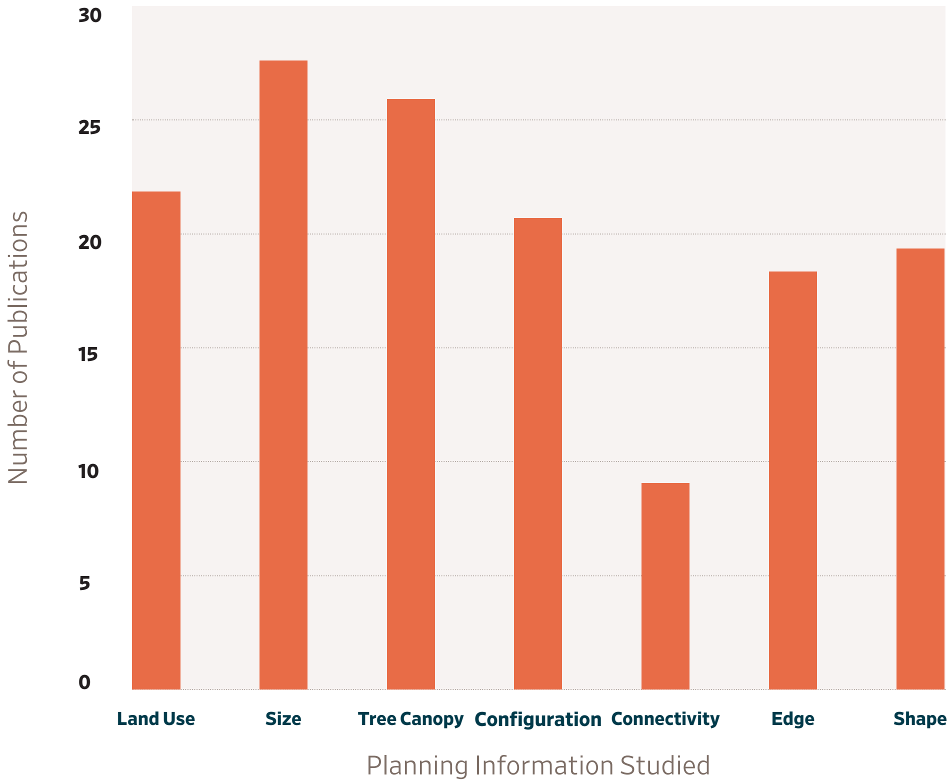

Fig. 9. The number of publications that studied specific planning changes that could impact the heating or cooling potential of NbS. Note these categories are not mutually exclusive.

Table 2
Number of planning or design strategies and the number and percent of publications that investigated that number of strategies

Number of Strategies	Planning Count	Planning Percent	Design Count	Design Percent
Four	11	17%	3	7%
Three	11	17%	6	15%
Two	23	35%	14	34%
One	20	31%	18	44%

We similarly identified seven design interventions (Fig, 10) through our coding process that researchers noted could impact the heating or cooling potential of NbS (Fig. 11).

1. **Ground cover**
   Specific materials on the ground, including pavements and grasses.

2. **Materials**
   Used in other settings, such as on walls or in planters.

3. **Plant types**
   Plants used in the NbS, including species of trees as well as the mix of different heights of plants.

4. **Solar radiation**
   Extent to which sunlight is able to penetrate into the space being designed. For example, if there are tall buildings surrounding the area, there is less solar radiation.

5. **Tree percentage**
   Amount of trees within a given NbS

6. **Tree arrangement**
   The way trees are laid out on the site. For example, are the trees clustered together or are they in a straight line?

7. **Tree spacing**
   How far apart the trees are in the design.

As with planning, this list of design strategies is not exhaustive, but rather it represents the dominant themes that we observed in three or more publications. These categories are also not mutually exclusive and many researchers explored two or more strategies (Table 2).

We find that tree percentage and materials are the dominant themes explored by researchers. Ground cover, plant types, and solar radiation are the middle three strategies. Tree arrangement and tree spacing are only considered by three research projects.

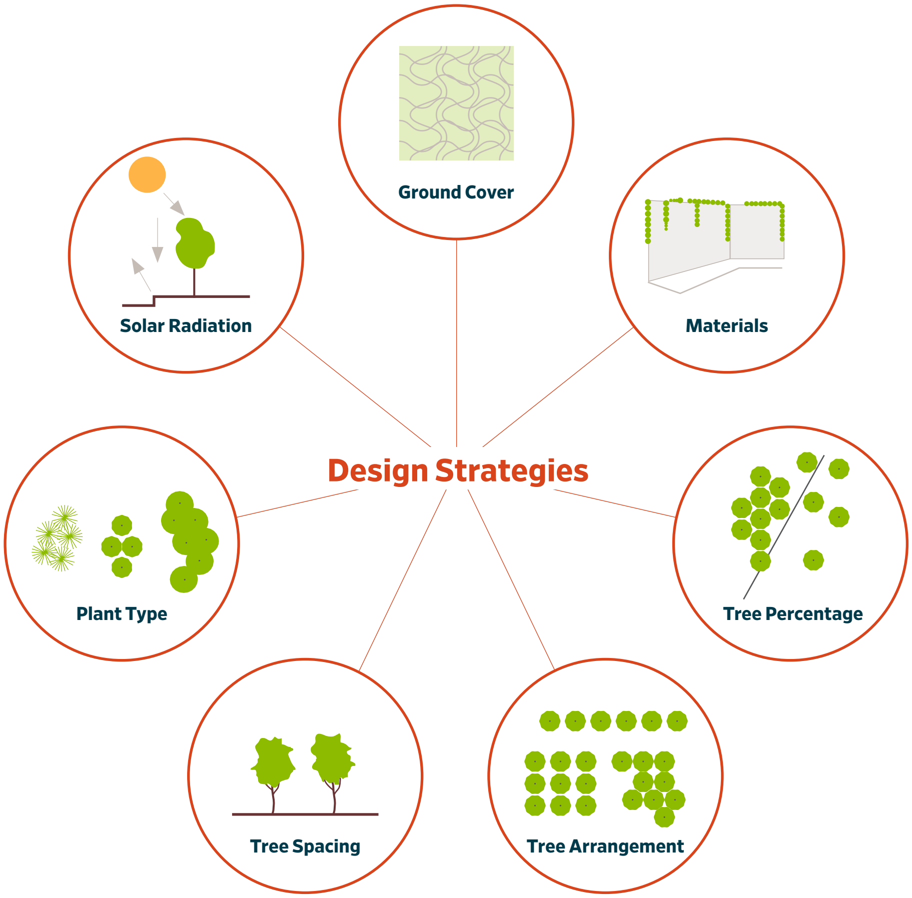

Fig. 10. Diagrams depicting the seven design interventions we identified

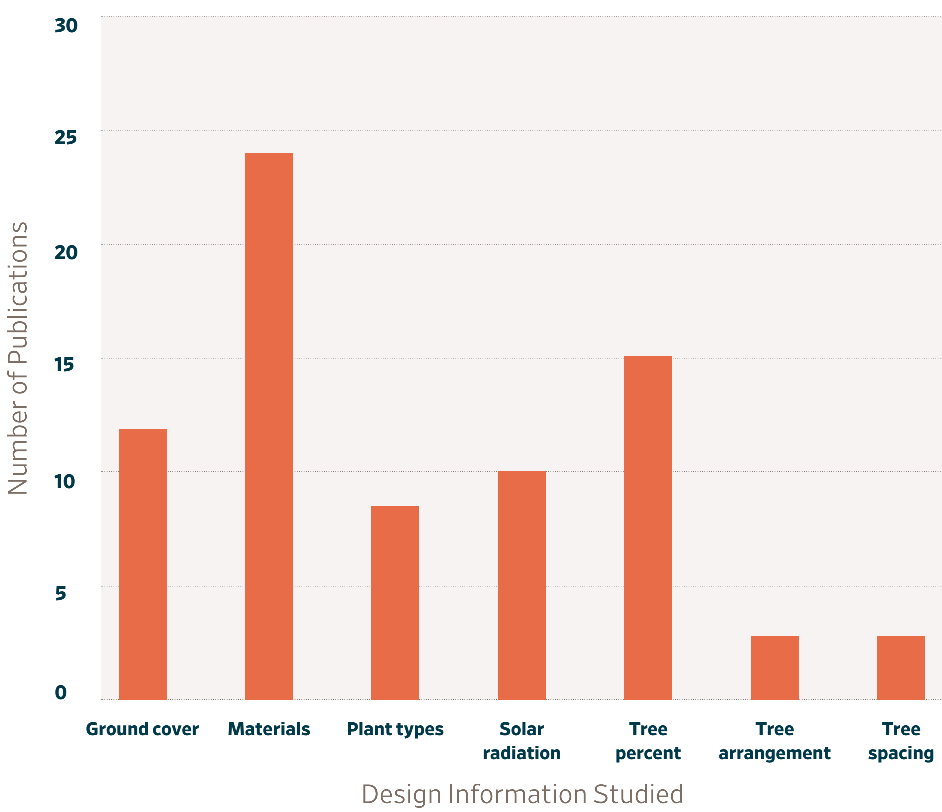

Fig. 11. The number of publications that studied design changes that could impact the heating or cooling potential of a NbS. Note these categories are not mutually exclusive.

4. Summary of Insights

4.1 Landscape Architecture: Planning

We observe a complex relationship between NbS and urban heat reduction. Generally, from the studies we looked at there are a few factors that contribute to heat reduction.

First, the overall amount of green and blue spaces contributes to changes in urban heat. For example, in a study looking at Bangkok,Thailand; Jakarta, Indonesia; and Manila, Philippines researchers found that the green spaces are on average 5.4°F (3°C) cooler than impervious surfaces (Estoque et al., 2017). Another study revealed that the two landscape changes that reduce temperatures are: the enhancement of blue spaces and the enhancement of green spaces (Shi & Zhao, 2022).

Similarly, several studies present these findings by focusing on the impervious surface land use and find that increased impervious surface has a positive correlation with greater urban heat (Lu et al., 2020; Simwanda et al., 2019). However, not all green spaces are created equal. Studies show that urban forests perform better than parks at reducing heat (Jaganmohan et al., 2016) and rivers provide greater cooling than wetlands (Xue et al., 2014). Another study notes that the number and quality of green spaces are not sufficient for understanding their potential to reduce the urban heat island (R. Sun & Chen, 2017).

Additionally, we notice the amount of greenness – also categorized as tree canopy – within green spaces, parks, green corridors, and others contributes to the reduction of urban heat islands. For example, the ratio of green and blue space within a park contributes to its ability to provide cooling services (M. Chen et al., 2022).

On a larger spatial scale, the cooling effect of parks on their surroundings (Park Cooling Intensity [PCI]) was positively related to the greenness (Feyisa et al., 2014). In this case, greenness was measured by the normalized difference vegetation index (NDVI), which is based on remote sensing data (USGS, 2024). Green spaces with a higher density of trees were more efficient in delivering the cooling effect (Grilo et al., 2020). One study suggests that maintaining the forest canopy density above 0.4% is an effective measure to regulate the regional thermal environment (Huang & Wang, 2022).

The size of green spaces also has a positive effect on reductions in the urban heat island. For example, several studies note that larger parks cool further distances into the city and have higher park cooling intensities (M. Chen et al., 2022; Feyisa et al., 2014). Another recognizes that the average size of the green patch is very important to reduce the UHI (Pramanik & Punia, 2019). Authors of another study state: "The efficient methods to decrease land surface temperatures of green spaces include increasing green space area" (Du et al., 2017). In a study in Leipzig, Germany they highlight this relationship is not simple. They find that increasing size is different for forests and parks (Jaganmohan et al., 2016).

Though more green spaces, greater tree canopy, and larger-sized green spaces contribute to cooling urban regions, the relationship is not linear (Park & Cho, 2016; Vaz Monteiro et al., 2016). In one study of pocket green spaces, researchers found the relationship between park size and cooling of the surrounding to be logarithmic (C. Wu et al., 2021). In another study of 3,970 samples of observed vegetation leaf area index they found non-linear relationships that were more specific to climate zones (Su et al., 2022). Based on data collected in and around eight London green spaces, researchers learned that tree canopy had the strongest link with cooling distance, but grass coverage has the strongest relationship with the amount of cooling provided (Vaz Monteiro et al., 2016).

Since composition alone cannot explain the positive impacts of trees and green spaces on urban environments, configuration is understood to play an important role.

One key strategy we observe is the interconnectivity of green spaces. Though only 9 studies explicitly looked at connectivity, 8 of the 9 found a strong connection between the degree to which green spaces are connected and reductions in urban heat (An et al., 2022; A. Chen et al., 2014; Estoque et al., 2017; Kim et al., 2016; Masoudi et al., 2021; Pramanik & Punia, 2019; Razzaghmanesh et al., 2021; Zhang et al., 2022).

For example, one study that looked at the neighborhood environments of 15,862 single-family houses in Austin, Texas, found larger and better-connected landscape spatial patterns were positively correlated with lower land surface temperatures (Kim et al., 2016). Similarly, in a study set in Bangkok, Thailand; Jakarta Indonesia; and Manila, Philippines researchers found that aggregation of green spaces had the most consistent strong correlation (Estoque et al., 2017).

Shape also plays an important role in the NbS providing urban heat benefits. However, the data is inconclusive in terms of exactly what role shape plays.

In a number of studies, the researchers found that more complex green spaces provide greater cooling benefits (Du et al., 2017; Feyisa et al., 2014; Park & Cho, 2016). On the other hand, a number of studies suggest that simpler shapes lead to greater cooling effects (An et al., 2022; Masoudi et al., 2019; Terfa et al., 2020). One study conducted in Delhi, India found that green space with a complex shape could increase the land surface temperature (Pramanik & Punia, 2019). This conflicting finding indicates that further research is needed to understand the exact relationship between shape and cooling benefits.

4.2 Landscape Architecture: Site Design

Below we provide further insights related to the seven design strategies researchers explored.

- **Ground cover**
  Among the eleven studies that looked at ground cover there was consensus that it matters what is on the ground, and places can be designed to address thermal comfort. For example, one study found that hardened grounds had a negative impact on thermal comfort (R. Sun & Chen, 2017). Another study found that parks with a combination of trees, shrubs, and grasses had the highest cooling efficiency (C. Wu et al., 2021). Similarly, another study found urban parks that cluster trees with short ground vegetation generated a higher cooling effect than single trees. In this same study, they note that proper irrigation regimes are needed to enhance the cooling effect of grasses (Amani-Beni et al., 2018).

- **Materials**
  This category captures a wide array of studies that compare plant materials with the built environment. In most of these studies, the researchers find that plant materials reduce heat relative to built infrastructure.

  For example, this includes a study where green facades were compared to shade sails. In this study, the results show that the external wall temperatures behind the green façade were up to 12.6°F (7°C) cooler than those behind the shade sail during hot sunny days (Bakhshoodeh et al., 2022). One study looked in depth at mosses in gardens across Kyoto, Japan and found that gardens covered by moss had the lowest temperatures, whereas gardens with only small patches of moss had the highest temperatures (Oishi, 2019). Another study found that multi-layer vegetation-cover is the most effective at reducing the urban heat island (H. Li et al., 2020).

- **Plant types**

  Research into the impacts on urban heat from the types of plants varied, with studies having different focus areas and methods.

  Some studies focused on more general factors about trees. For example, one study found that the most significant influential factor on the moderation of thermal comfort is the height of trees, with taller trees providing greater benefits (S. Sun et al., 2017). Another study found that trunk circumference is a very valuable indicator of the tree's potential to provide benefits for urban heat (Helletsgruber et al., 2020).

  Other studies looked at plants from the perspective of their provision of evapotranspiration, which is the evaporation from plants of water. Higher evapotranspiration provides greater emiloration of heat according to some studies (Gößner et al., 2021; Jim, 2015).

  We observed another difference based on the methods used. We found that a study using on-site measurements observed that deciduous trees provide greater heat reduction benefits, while evergreen trees did not provide any heat reduction benefits (Y. Li et al., 2021). In contrast, a study that simulated tree benefits found evergreen trees were more effective at regulating temperatures than deciduous trees. These conflicting results suggest that further research is needed to clarify the relationship between the types of trees and their specific local cooling benefits (Choi et al., 2021). Practitioners can use tools such as i-Tree or ENVI-met to help them understand the best trees for their particular site.

- **Solar radiation**

  Findings were consistent across the ten papers that looked at the solar radiation – the places with greater shade were found to be cool. For example, in one study that looked at specific design features in a long belt-shaped park (around 5.5 mi or 9 km) in Beijing, China, they found that solar radiation can reduce the thermal comfort benefits of parks (R. Sun & Chen, 2017). In another study that simulated different placement of trees, they found that trees provide greater benefits when located in places of high solar radiation than trees located in already shady locations (Z. Wu & Chen, 2017). Another study found that plants and reflective materials can achieve the same effect as other methods (e.g., shade structures) of reducing solar radiation (Tan et al., 2021). Interestingly, when surveyed, people perceived shaded locations to be cooler and more comfortable than sunlit locations (Klok et al., 2019).

- **Tree percentage**

  Articles consistently reported that the percentage of trees in park and green spaces was positively correlated with reductions in temperature and / or thermal comfort. For example, one paper states "green spaces with a higher density of trees were more efficient in delivering the cooling effect" (Grilo et al., 2020). Some authors went as far as to recommend specific design interventions. They suggested that at least 30% of the surfaces should be trees and shrubs (Chang & Li, 2014).

- **Tree arrangement & tree spacing**

  All three studies looking at tree arrangements found that this can impact the benefits trees provide to a site. To study this, they used the simulation software ENVI-met. These studies explored exactly how trees could be placed on a site to produce the greatest amount of heat reduction benefits.

  One study found that tree clustering in general produced greater benefits than evenly distributed trees (Elbardisy et al., 2021). In another study, they found that a rectangular shape was more effective than a triangular shape of evergreen trees (Abdi et al., 2020).

  These insights could be applied to different sites and should be studied in greater depth to determine how transferable they are.

5. Future Research

Based on our literature review and findings, we propose future research in the realm of NbS and urban heat should prioritize the following five key directions.

Improvements in these areas will allow landscape architects planning and designing communities and sites to more effectively apply these solutions to mitigating the urban heat island effect and promote sustainable urban development:

1. **Better Geographic and Climate Zone Distribution:**
   NbS and the urban heat island benefits they provide can vary by geography. Future research should be conducted in a broader range of locations. Different climate zones present challenges and opportunities for NbS implementation. Researchers should investigate how these solutions perform across various climatic conditions, ensuring they are not only effective but also adaptable to diverse environments. This understanding is vital for developing context-specific strategies that can be applied globally but still consider variability in climate and environmental conditions.

2. **Assessments that Cross Scale from Site Design to Neighborhood or City:**
   Future research should emphasize assessments that transcend individual site designs and extend to broader scales, encompassing neighborhoods or entire cities. While site design is valuable, understanding how these solutions operate and interact at larger scales is essential for holistic urban planning. Researchers should explore methodologies and frameworks that facilitate the scaling up of successful NbS from sites to broader urban contexts. This involves considering the cumulative impact of multiple designs and their synergies when implemented across diverse urban landscapes. By conducting assessments that span various scales, researchers can provide valuable insights into the scalability and replicability of NbS, supporting the development of comprehensive strategies for urban heat mitigation and sustainable urban development.

3. **Shifting Measurements Approaches:**
   To enhance the reliability of research findings, future studies should prioritize improved long-term instrumentation and an increased reliance on on-site measurements rather than the current reliance on satellite data. Long-term monitoring allows for a comprehensive assessment of NbS performance over time, offering insights into their sustained effectiveness.

Additionally, relying on on-site measurements provides more accurate and context-specific data, enabling researchers to evaluate the real-time impact of NbS on urban heat dynamics. This empirical approach ensures a more robust foundation for policy recommendations and urban planning decisions.

4. **Increased Work on the Co-Benefits of Design:**
   Beyond temperature reduction, future research should delve into the multifaceted co-benefits associated with NbS. These co-benefits may include: improvements in air and water quality, enhanced biodiversity, and positive socio-economic impacts. Investigating and quantifying these additional advantages will contribute to a more holistic understanding of NbS, making a compelling case for their adoption. By highlighting the multiple positive outcomes, researchers can provide decision-makers with a broader perspective on the value of integrating NbS into urban planning.

5. **Exploration of Equitable Distribution of NbS:**
   Recognizing the importance of equitable urban development, future research should focus on exploring ways to ensure the fair distribution of nature-based solutions. Investigating how NbS can be strategically implemented to address environmental justice concerns, particularly in vulnerable and marginalized communities, is crucial. This involves assessing the socio-economic implications of NbS implementation and developing strategies to prevent potential disparities in access and benefits.

In conclusion, the future research directions outlined above aim to advance our understanding and application of NbS in mitigating urban heat.

By considering geographical nuances, climate zone variability, long-term effectiveness, co-benefits, and equitable distribution, researchers can contribute valuable insights that support the development of sustainable, inclusive, and effective urban planning strategies.

These efforts are essential for creating resilient cities that prioritize environmental well-being and social equity in the face of ongoing urbanization and climate change.

6. Appendix

The table below provides detailed descriptions of the 31 subcategories of the Köppen-Geiger climate classification system. We also provide the percent of publications we reviewed in each of the 31 subcategories.

Köppen-Geiger Classification	Percent of Publications	Description of Climate
Af Equatorial rainforest	7%	No dry season. The driest month has at least 2.36" (60 mm) of rain. Rainfall is generally evenly distributed throughout the year. All average monthly temperatures are greater than 64°F (18°C).
Am Equatorial monsoon	1%	Pronounced wet season. Short dry season. There are one or more months with less than 2.36" (60 mm). All average monthly temperatures are greater than 64°F (18°C). Highest annual temperature occurs just prior to the rainy season.
As Equatorial savanna	0%	Summer dry season. There are more than two months with less than 2.36" (60 mm) in summer. All average monthly temperatures are greater than 64°F (18°C).
Aw Equatorial savanna	4%	Winter dry season. There are more than two months with less than 2.36" (60 mm) in winter. All average monthly temperatures are greater than 64°F (18°C).
BWk Mid-latitude desert	3%	Mid-latitude desert. Evaporation exceeds precipitation on average but is less than half potential evaporation. Average temperature is less than 64°F (18°C). Winter has below freezing temperatures.
BWh Subtropical desert	7%	Low-latitude desert. Evaporation exceeds precipitation on average but is less than half potential evaporation. Average temperature is more than 64°F (18°C). Frost is absent or infrequent.

Köppen-Geiger Classification	Percent of Publications	Description of Climate
BSk Mid-latitude steppe	1%	Mid-latitude dry. Evaporation exceeds precipitation on average but is less than potential evaporation. Average temperature is less than 64°F (18°C).
BSh Subtropical steppe	0%	Low-latitude dry. Evaporation exceeds precipitation on average but is less than potential evaporation. Average temperature is more than 64°F (18°C).
Cfa Humid subtropical	18%	Mild with no dry season, hot summer. Average temperature of warmest months are over 72°F (22°C). Average temperature of coldest months are under 64°F (18°C). Year-round rainfall but highly variable.
Cfb Marine west coast	12%	Mild with no dry season, warm summer. Average temperature of all months is lower than 72°F (22°C). At least four months with average temperatures over 50°F (10°C). Year-round equally spread rainfall.
Cfc Marine west coast	0%	Mild with no dry season, cool summer. Average temperature of all months is lower than 72°F (22°C). There are one to three months with average temperatures over 50°F (10°C). Year-round equally spread rainfall.
Csa Mediterranean	5%	Mild with dry, hot summer. Warmest month has average temperature more than 72°F (22°C). At least four months with average temperatures over 50°F (10°C). Frost danger in winter. At least three times as much precipitation during wettest winter months as in the driest summer month.
Csb Mediterranean	2%	Mild with cool, dry summer. No month with average temperature over 72°F (22°C). At least four months with average temperatures over 50°F (10°C). Frost danger in winter. At least three times as much precipitation during wettest winter months as in the driest summer month.
Cwa Humid subtropical	25%	Mild with dry winter, hot summer

Köppen-Geiger Classification	Percent of Publications	Description of Climate
Dfa Humid continental	1%	Humid with hot summer
Dfb Humid continental	0%	Humid with severe winter, no dry season, warm summer
Dfc Subarctic	0%	Severe winter, no dry season, cool summer
Dfd Subarctic	0%	Severe, very cold winter, no dry season, cool summer
Dwa Humid continental	15%	Humid with severe, dry winter, hot summer
Dwb Humid continental	0%	Humid with severe, dry winter, warm summer
Dwc Subarctic	0%	Severe, dry winter, cool summer
Dwd Subarctic	0%	Severe, very cold and dry winter, cool summer

Köppen-Geiger Classification	Percent of Publications	Description of Climate
ET Tundra	0%	Polar tundra, no true summer
EF Ice Cap	0%	Perennial ice
H Complex zone	0%	Can encompass any of the above classifications due to the mountainous terrain.

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The authors would like to thank the Extreme Heat Research Grant Selection and Review Panel

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Recommended Citation
Hirschfeld, D., & Guenther, A., Landscape Architecture Solutions to Extreme Heat: Research Study. American Society of Landscape Architects Fund (ASLA Fund). March 2024. https://www.asla.org/evidence

This research was funded by the American Society of Landscape Architects Fund (ASLA Fund).

American Society of Landscape Architects

ASLA Fund

UtahState University