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# Contextual conditions for the application of urban heat mitigation measures: A review of reviews

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Climate change and urban heat islands are contributing to the warming of urban areas worldwide. Previous research has made it clear that the implementation and success of urban heat mitigation measures are dependent on context, but which contextual conditions matter is less clear. This study addresses the state of knowledge regarding contextual conditions for the application of physical urban heat mitigation measures, and gauges the transferability of measures to Nordic cities. A scoping review of literature reviews was done. Results show that contextual conditions are not systematically reported in literature, and are often mentioned implicitly rather than explicitly. Relevant contextual conditions for physical mitigation measures include: climate and prominent wind patterns; water availability; soil perviousness; the population´s thermal comfort and tolerance; site geometry; surrounding surfaces; space availability and site adaptability; budget; maintenance; information availability; proximity to the sea; site function; and sun path; risks or co-occurring societal challenges; social norms, cultural values and aesthetics. Contextual conditions for which commonalities were found between Nordic cities allowed for the creation of an overview of considerations for transferability of measures to this region, which should inform design criteria for future planning. Knowing what contextual conditions are relevant to heat mitigation measures can guide the analysis of transferability of measures in the future, and clusters of cities with similar contexts can be made, between which the transferability of solutions would be high.

*Keywords*: Heat mitigation, Urban climate, Thermal comfort, Urban heat island, Climate change adaptation, Transferability of solutions

## 1. Introduction

Climate change and urban heat islands are contributing to the warming of urban areas worldwide (IPCC 2022; Phelan et al. 2015; Koppe et al. 2004). Extreme heat exposure can result in a range of health problems, from heat stress to mortality (IPCC 2022). As exposure to heat continues to increase due to climate change and urbanization (IPCC 2022), heat mitigation is crucial.

Heat is identified as the greatest threat to public health from climate change in Sweden (Folkhälsomyndigheten 2021). Nordic populations and cities may be insufficiently adapted to heat, as they have historically experienced little heat exposure (Koppe et al. 2004). Since the application of mitigation measures has been found to depend on context (Lai et al. 2019), it is concerning that heat adaptation strategies have been under researched in Sweden (Jonsson & Lundgren 2015). It is clear that conflicting requirements between summer and winter pose a challenge (Koppe et al. 2004), but literature does not clearly delineate whether there are further transferability obstacles for Nordic cities.

To analyze transferability, Hintz et al. (2018) propose differentiating urban settings by geography, demography, and architecture. However, these suggested factors, referred to as contextual conditions in this article, are based on research by Macário and Viegas (2006) on local mobility solutions, not heat mitigation. Lai et al. (2019) suggest that future research should focus on the conditions and measures needed to select feasible, effective measures. To my knowledge, an overview of contextual conditions relevant to the transferability of heat mitigation measures is still lacking. Based on relevant contextual conditions, cities and urban areas could be formed into clusters with similar contextual settings (Hintz et al. 2018). Within these clusters transferability of solutions would be high, simplifying decision making. Therefore, it is valuable for decision making to identify which contextual conditions are relevant for the transferability of heat mitigation measures.

Transferability refers to the ability to adopt measures that were previously successfully applied in one context and achieve comparable results in another context (Hintz et al. 2018). Context, or setting, is the constellation of factors distinguishing one place from another. Contextual conditions are those factors arising from the context which influence if and how a measure can be applied, and how effective it is.

This study aims to identify (1) how contextual conditions and transferability have been discussed in literature, (2) which contextual conditions are relevant for heat mitigation measures, focusing on blue, green and grey infrastructures, and (3) discuss findings relevant to transferability of heat mitigation measures to Nordic cities.

## 2. Methodology

A scoping review of literature reviews was conducted to to address the aims of the study. Given the high saturation of original and review articles on urban heat mitigation, this was deemed most appropriate. Papers were selected from the Scopus database, chosen for its broad scope and rigorous quality criteria. Keywords were identified based on the study focus, guided by previously identified relevant articles found through Google Scholar. To capture all literature reviews, two search strings were used: search string A filtered by document type "review", and search string B by inclusion of the word "review*" in titles, abstracts, or keywords. Performed on March 6, 2024, the searches yielded 127 papers from search string A and 179 from search string B. The search was limited to English, Swedish, Norwegian, and Danish, but only English articles were found. After removing duplicates and conference papers, 173 articles remained. Titles and abstracts were screened using inclusion and exclusion criteria (table 1), followed by full-text scanning using the same criteria. 16 articles were selected for analysis.

Table 1. Overview of inclusion and exclusion criteria

| |
|---|
| Include: |
| • The article relates to implementation or outcomes of physical heat mitigation measures in outdoor urban spaces.<br>• The article presents a literature review.<br>• The article covers multiple types of heat mitigation measures (and is thus not, for example, specifically about green infrastructure, reflective pavements, etcetera). |
| Exclude: |
| • The article primarily relates to (a) topic(s) outside of the topic of urban heat mitigation, such as saving energy, pollution, or the mental health benefits of green infrastructure.<br>• The article presents recommendations which lack evidence.<br>• The review relates to a specific region, which does not include Nordic countries. |

Data was coded by measure, with subcodes on description, benefits, contextual conditions, and context related knowledge gaps for each measure. Another code was created for comments on contextual conditions and transferability independent of specific measures. Mentions of transferability to Nordic cities or heating dominated climates were coded too. A spreadsheet was used to organize codes and corresponding text.

Contextual conditions were viewed broadly, encompassing the inputs required to implement a measure, its impact on the context, and conditions that influence its effectiveness (Hintz et al. 2018). Contextual conditions were compiled per category of mitigation measure and per specific mitigation measure. For mitigation measures for which more detail was known on contextual conditions, categories of contextual conditions were identified inductively. Following the identification of relevant contextual conditions, common characteristics of Nordic cities were considered to discuss the implications of the found contextual conditions for the Nordic context.

While some of the papers discussed secondary risks like power outages, air quality, and wildfires, this was outside the scope of this paper. Similarly, indoor spaces were not considered. The review focused on blue, green and grey infrastructures, excluding measures within early warning, healthcare, individual behaviors, etcetera.

## 3. Results

Following the aims of this study, the results are structured as follows: 3.1 outlines how transferability and contextuality are discussed in literature. Then, contextual conditions related to green-blue infrastructure (3.2) and grey infrastructure (3.3) are presented.

### 3.1 *Literature on transferability and contextuality*

Three of the included articles specifically focus on transferability or contextuality for the application of heat mitigation measures: Hintz et al. (2018), Li et al. (2023), and Turek-Hankins et al. (2021). Hintz et al. (2018) did an exploratory literature review on the transferability of heat adaptation and mitigation measures, considering geographical distribution, characteristics and pivotal actors. As noted in the introduction, they propose that transferability could be analyzed using contextual conditions, which could be clustered into similar settings, using contextual conditions.

Li et al. (2023) studied thermal perceptions and the effects of strategies, in Tropical, Arid, Temperate, and Snow climates. Their findings highlight the differences in cooling effects of green roofs, green spaces, and irrigation in different climate zones, and the importance of understanding thermal comfort needs in different climates. They discuss that in high-latitude cold regions, the choice of deciduous tree species can achieve the effect of shading in summer without reducing the solar radiation in winter, and that both plants and buildings are effective solutions for breaking cold winter winds. They further mention the benefits of mobile, dynamic shading in heating-dominated climates.

Turek-Hankins et al. (2021) studied global heat adaptation strategies, finding that their implementation varies by country development level, highlighting financial feasibility as a contextual condition. Other articles also point to cost-efficiency as a key condition (Lam et al. 2021).

Most articles did not systematically report contextual conditions. Some explicitly mentioned the importance of context, while many did so implicitly. For example, Kiarsi et al. (2023) explicitly sum up contextual conditions that may be relevant to the application of heat mitigation measures. They write “Due to differences in climate patterns, cultural contexts, and degree of public relations in each country, some adaptive strategies may differ due to complex social factors” (p.2), although it should be noted that they are not only referring to physical measures in this passage. A common way that articles report on contextual conditions, without explicitly stating the importance of context, is by stating proven benefits of a measure, and what the effects depend on. However, these descriptions are often unexhaustive or lack detail. For example, Liu et al. (2023) report: “Bartfelder and Köhler found that the cooling effect of green walls depended on the outdoor temperature. On cold days and hot days, the cooling effects of green walls were 0.4 ◦C and 5.8 ◦C respectively” (p.18). In similar fashion, Antoniadis et al. (2020) write: “The cooling potential of urban trees is also affected by the characteristics of the surrounding urban environment that include surface materials, geometry, height and density of buildings, traffic intensity, and street orientation” (p.11). The first details how a contextual condition impacts a measure´s effect, but does not touch on other contextual conditions or knowledge gaps on the matter. The later explores a broad range of contextual conditions, but does not go into detail by, for example, describing which street orientation results in the greatest cooling effect for trees, despite findings on this matter existing (Lai et al. 2019).

One contextual condition that multiple articles discussed, regardless of the specific measures considered, is data availability. To map heat health risk, contextual information is needed on topography profiles, building densities, vegetation bodies, transport networks, night temperatures and socio-demographic data (Fernandez Milan & Creutzig 2015; Kiarsi et al. 2023). This kind of spatial mapping is done to enable the spatial prioritization of heat mitigation measures, or to create models for estimating the cooling effects of interventions (He et al. 2023). Heaviside et al. (2017) point out that spatial mapping may also highlight variation in effectiveness related to demographic and socio-economic factors. Data on the thermal comfort limits of populations, using thermal comfort indices that are adapted to the local population (Lai et al. 2019), allows for design in accordance with heat and cold tolerance of the population, rather than maximizing temperature reduction (Ren et al. 2023). Thus, to be able to estimate whether a measure is needed or fitting in a specific context, data is needed on the context at hand. The need for this information both highlights the importance of context, and that information availability may be considered a contextual condition in itself.

### 3.2 *Green-blue infrastructure*

Green infrastructure includes vegetation at street level, rooftops, or building facades (Jay et al. 2021). Vegetation includes different types of trees, shrubs, and/or grassland (Antoniadis et al. 2020). Blue infrastructure includes waterbodies fountains, the improvement of public water supply (Hintz et al. 2018). When referring to both, the term ´green-blue infrastructure´ is used.

#### 3.2.1 *Benefits of green-blue infrastructure*

Green infrastructure reduces temperatures through shade casting, transpiration from leaves, evaporation of soil moisture (Jay et al. 2021), and wind speed modification (Lai et al. 2019). Green infrastructure can reduce air temperature on-site and up to several kilometers away, depending on size (Kiarsi et al. 2023).

Blue infrastructures have a cooling effect as they absorb and store heat, reducing long wave radiation and temperature at the water surface (Liu et al. 2023). Energy is released through evaporation, increasing relative air humidity (Liu et al. 2023). Depending on a context´s humidity saturation and air temperature, this may or may not improve thermal comfort (Li et al. 2023; Ren et al. 2023).

#### 3.2.2 *Contextual conditions of green-blue infrastructure*

Implementing green-blue infrastructure is not equally feasible or effective in all settings. Contextual conditions related to input required for implementation include: water availability (Liu et al. 2023; Hintz et al. 2018; Lam et al. 2021); maintenance (with personnel, technical infrastructure, energy demand and budget) (Antoniadis et al. 2020; Heaviside et al. 2017); budget for implementation (Jay et al. 2021; Antoniadis et al. 2020); soil perviousness (Hintz et al. 2018; Antoniadis et al. 2020); and space for root systems (Antoniadis et al. 2020).

Contextual conditions influencing the effectiveness of green-blue infrastructures include: climate (Ren et al. 2023; Liu et al. 2023), prominent wind direction (Lam et al. 2021; Liu et al. 2023), building height (Ren et al. 2023; Lam et al. 2021; Lai et al. 2019), street orientation (Lam et al. 2021; Liu et al. 2023), building density (Lam et al. 2021; Antoniadis et al. 2020), and surrounding surfaces (Hintz et al. 2018).

Impact on the context goes beyond the cooling effect. Green-blue infrastructure has several co-benefits including carbon sequestration, noise reduction, dust retention, encouragement of walking and cycling (Kiarsi et al. 2023), increased biodiversity, reduced stormwater runoff, reduced air pollution, energy savings (Ren et al. 2023), improved mental health and wellbeing (Heaviside et al. 2017) and aesthetic value (Lai et al. 2019). On the other hand, green-blue infrastructure can come with risks, including allergies drowning, injury, and increased urban vectors (Heaviside et al. 2017), which may need to be mitigated in their design.

In addition to the types of conditions outlined by Hintz et al. (2018), a fourth type of contextual condition was found. The ultimate form of an intervention does not only depend on input, effectiveness and co-benefits and risks but may also be influenced by social norms (Hintz et al. 2018), cultural values (Hintz et al. 2018; Antoniadis et al. 2020), and aesthetics (Antoniadis et al. 2020). The sun path, site function, and the time-of-day site attendance is highest must also be considered (Antoniadis et al. 2020).

The contextual conditions on which more detail is known on a measure level are expanded upon in table 2. Co-benefits and risks are not included in the table. When considering what categories of contextual conditions are expanded upon in the table, it becomes clear that little is known about the impact of social, cultural and aesthetic conditions, as well as sun path and site usage, compared to those that are detailed in the table.

### 3.3 *Grey infrastructure*

Grey infrastructure includes all urban design elements that are non-natural or non-living (Hintz et al. 2018). Grey infrastructure is the majority of the physical structures that make up the outdoor cityscape.

#### 3.3.1 *Benefits of grey infrastructure*

Grey infrastructure can mitigate urban heat by manipulating shading, ventilation, heat storage, and reflexivity. One aspect of grey infrastructure is the notion of urban geometry: the arrangement of buildings (Lam et al. 2021). Street orientation, street canyon and sky view factor impact the absorption of solar radiation by buildings (Ren et al. 2023), as well as long-wave radiation (Liu et al. 2023). Street orientation and canyons further impact ventilation (Lam et al. 2021). Street orientation refers to the angle of a street viewed from above, expressed in cardinal directions: a North-South (N-S) oriented street is a linear street with one end in the north and its other in the south, to which an East-West (E-W) street is perpendicular. A street canyon refers to the heights of buildings on either side of the street and the width of the gap in between, measured in height-to-width ratio (H/W) (Liu et al. 2023). A high H/W value represents a deep, dense canyon (Lai et al. 2019). Sky view factor (SVF) quantifies the amount of unobstructed sky from a given point, wherein a low SVF indicates high obstruction from, for example, trees and buildings (Lai et al. 2019).

Surface materials are another aspect of grey infrastructure. Different surfaces have different albedos, meaning different degrees of reflexivity. Surfaces with higher albedo have significantly lower surface temperatures under the same microclimatic conditions compared to low albedo surfaces, since they absorb less solar radiation than low albedo materials (Ren et al. 2023). High city-wide albedo can reduce peak temperatures by up to 18°C (Fernandez Milan & Creutzig 2015).

#### 3.3.2 *Contextual conditions of grey infrastructure*

Changing urban geometry requires a lot of input related to space availability or the ability to significantly change existing urban geometry (Liu et al. 2023), and such a large undertaking which would require a large budget. Reflective surfaces, on the other hand, require less in terms of space adaptability, and are cheaper and low maintenance (Heaviside et al. 2017). Maintenance remains important however, as the effectiveness of reflective surfaces reduces with aging and dirt (Lam et al. 2019).

Contextual conditions influencing the effectiveness of grey infrastructures include: local climate (Liu et al. 2023; Ren et al. 2023; Lai et al. 2019); wind direction (Lai et al. 2019); wind speed (Kiarsi et al. 2023); building type (Ren et al. 2023; Liu et al. 2023: Lam et al. 2021; Lai et al. 2019); and proximity to the sea (Ren et al. 2023).

The influence of grey infrastructure on its context is not limited to cooling. Several risks and co-benefits should be weighed. Co-benefits of reflective roofs include saving energy on cooling and extending the lifetime of the roofing material (Liu et al. 2023). When urban geometry is geared towards promoting increased wind speeds, air pollution can be reduced (Ren et al. 2023). Reflexive surfaces on street level are highly debated as they can result in increased thermal and visual discomfort due to increased reflected solar radiation (Liu et al. 2023; Lam et al. 2019; Antoniadis et al. 2020; Lai et al. 2019; Jay et al. 2021). The level of increased thermal stress depends on street orientation (Jay et al. 2021; Lam et al. 2021). Reflective pavements have also been linked to increased surface level ozone (Heaviside et al. 2017).

The contextual conditions for which more detail is known on a measure level are expanded upon in table 3. Co-benefits and risks are not included in the table. While not discussed in the considered literature, it should be considered that, as for green-blue infrastructures, social norms, cultural values, aesthetics, sun path and site usage may play a role in the desirability and ultimate form of grey infrastructure.

Table 2. Green-blue heat mitigation measures and their contextual conditions.

| Measure | Contextual conditions |
|---|---|
| Parks | In hot dry places, large-scale use of vegetation can be expensive or impractical (Liu et al. 2023)[1,3]. |
| | Cooling effect increases the hotter and drier the climate (Liu et al. 2023)[1]. |
| | Cooling effect depends on park size, but available space, maintenance and cost of implementation are more demanding for large parks compared to smaller parks (Ren et al. 2023; Liu et al. 2023; Jay et al. 2021; Kiarsi et al. 2023)[6,7]. |
| | Cooling effect of large-scale vegetation may compromise thermal comfort in winter in heating-dominated climates (Ren et al. 2023). Deciduous plants bring cooling in the summer without compromising winter comfort (Antoniadis et al. 2020) [1]. |
| | Cooling effect is increased by irrigating vegetated surfaces (Antoniadis et al. 2020). Green space irrigation systems have the greatest cooling effect in an arid climate, followed by a temperate climate, and the smallest cooling effect in a snow climate (Li et al. 2023)[1,3]. |
| (Street) trees | Cooling effect depends on street orientation and prominent wind direction (Lam et al. 2021). The effect is positive in East-West oriented streets. North-South streets were already found to be thermally comfortable in the summer (Lai et al. 2019)[3,4]. |
| | Cooling effect depends on the species (which is dependent on the climate), maintenance and age (Antoniadis et al., 2016)[1,7]. |
| | Cooling effect depends on building height. The effect is positive in a street with low buildings (up to 20 meters). Because shade is already present between high buildings, and trees reduce wind speed, trees might make these sites warmer (Lam et al. 2021; Lai et al. 2019)[4]. |
| | The effectiveness of tree shade depends on water availability (Lam et al. 2021)[3,7]. |
| | Cooling effect depends on wind availability (Lam et al. 2021)[2]. |
| | Cooling effect is affected by surrounding surface materials (Antoniadis et al. 2020), particularly the degree of hard surfaces (Hintz et al. 2018)[4]. |
| | Cooling effect is affected building density (Antoniadis et al. 2020)[4]. |
| | Cooling effect is affected by traffic intensity (Antoniadis et al. 2020)[8]. |
| | Cooling effect increases the hotter and drier the climate (Liu et al. 2023)[1]. |
| | In heating-dominated climates, trees should be selected with attention to the point that deciduous plants bring cooling in the summer without compromising winter comfort (Antoniadis et al. 2020). |
| Green facades | Cooling effect is not influenced by facade orientation (Lam et al. 2021)[3]. |
| | Cooling effect is dependent on outdoor temperature (Liu et al, 2023)[1]. |
| | Cooling effect is likely limited on a pedestrian level, as it has only been observed very close to the façade (Liu et al. 2023)[9]. |
| | Cooling effect increases the hotter and drier the climate (Liu et al. 2023)[1]. |
| Vegetated pergolas | Cooling effect is does not compromise thermal comfort in winter in heating-dominated climates if deciduous plants are used (Antoniadis et al. 2020)[1]. |
| Green roofs | Cooling effect depends on the albedo of the original roofing material, in the case of retrofitting (Heaviside et al. 2017)[9]. |
| | Cooling effect depends on the climate (Heaviside et al. 2017). It was found to be higher in arid climate zones compared to tropical zones and snow climate zones (Li et al. 2023)[1]. Effect increases the hotter and drier the climate (Liu et al. 2023)[1]. |
| | Cooling effect depends on irrigation and maintenance (Heaviside et al. 2017)[3,7]. |
| | Cooling effect on the pedestrian level depends on the height of the building. On buildings higher than 10 m the effect on the pedestrian level may be negligible (Lai et al. 2019; Liu et al. 2023)[4]. |
| Water bodies | Large-scale use of water bodies can be expensive or impractical, depending on water availability (Liu et al. 2023; Jay et al. 2021)[3,7]. |
| | Cooling effect depends on water body size and shading. A larger water body leads to a greater decrease in air temperature compared to a smaller water body if they are exposed to solar radiation. Shaded water bodies show no difference in cooling between large and small water bodies (Lai et al. 2019)[4,6]. |
| | Cooling effect is increased with drier air (Jay et al. 2021). In hot-humid climate zones, the increased humidity caused by a water body may reduce thermal comfort. Ren et al. (2023); Li et al. (2023)[1]. |
| | Cooling effect may be increased by surrounding vegetation (Kiarsi et al. 2023)[5]. |
| | Cooling effect may be decreased by physical barriers (Kiarsi et al. 2023)[4,6]. |
| | Cooling effect may be decreased by dark surrounding surfaces (Kiarsi et al. 2023)[5]. |
| | Cooling effect is increased with higher wind speeds, drier air (Jay et al. 2021)[1,2]. |
| | Cooling effect is greatest on the leeward side (Lai et al. 2019)[2,4]. |
| | Cooling effect of a water body depends on the surrounding environment of the water body (Liu et al. 2023)[4,5]. |
| Fountains | Cooling effect may be increased by surrounding vegetation (Kiarsi et al. 2023)[5]. |
| | Cooling effect may be decreased by physical barriers (Kiarsi et al. 2023)[4,6]. |
| | Cooling effect may be decreased by dark surrounding surfaces (Kiarsi et al. 2023)[5]. |
| | Cooling effect depends on wind availability (Liu et al. 2023)[3]. |
| | In hot-humid climate zones, increased humidity may reduce thermal comfort (Li et al. 2023)[1]. |
| Categories of contextual conditions | [1] Climate<br>[2] Prominent wind patterns<br>3 Water availability<br>[4] Site geometry<br>[5] Surrounding surfaces<br>[6] Space availability/adaptability<br>[7] Budget for implementation and maintenance<br>[8] Site function<br>[9] Other |

Table 3: Grey adaptive measures and their contextual conditions.

| Measure | Contextual conditions |
|---|---|
| Urban geometry | There is often a limit to the extent to which the geometry of cities can be changed (Liu et al. 2023)[6]. |
| | Streets with high H/W provide the most shade, and the lack of solar radiation has a cooling effect, while positive in the summer this could be detrimental for thermal comfort in winter (Lai et al. 2019). Shallow and medium canyons (0.5 < H/W < 1.5) are favorable in cold climates, where deeper canyons (H/W > 1.5) are not recommended due to low solar access (Ren et al. 2023)[1]. |
| | Sites with high SVF are uncomfortable in summer, but sites with low SVF are uncomfortable in winter, a median shading level (SVF = 0.129) was found to achieve the longest period of thermal comfort throughout the year in the case of Taiwan (Liu et al. 2023)[1]. |
| | Several Northern Hemisphere studies found that streets with E-W orientation have higher heat stress than streets with N-S orientations; NE-SW and NW-SE orientations might provide a good compromise if both winter and summer time scenarios are considered important (Lai et al. 2019; Lam et al. 2021)[1]. |
| | In climate zones with hot summers and mild winters, people are less tolerant of the cold, and thus, outdoor spaces should not incorporate too many shaded areas. Meanwhile, in predominantly cold climates people are less heat-tolerant, and so more shading may be desired for summer time comfort (Ren et al. 2023)[1]. |
| | For low-rise buildings, a north–south orientation is recommended, but for mid-rise (H = 12 m) and high-rise (H = 36 m) buildings, the orientation has virtually no impact on cooling (Ren et al. 2023; Liu et al. 2023)[5]. |
| | For places with low wind speeds, optimizing airflow through the intersection streets, creating wind corridors, and the use of porous building materials are recommended (Kiarsi et al. 2023)[2]. |
| | In coastal areas, maximizing sea breeze significantly increases relative humidity, which could have a cooling effect depending on the context´s humidity saturation and air temperature (Ren et al. 2023)[1]. |
| | For detached buildings, street orientation and aspect ratio are found to have a weak influence on outdoor thermal comfort (Lam et al. 2021)[5]. |
| Reflective surfaces | Cooling effect of increased albedo is higher for places with high population density (Kiarsi et al. 2023)[8]. |
| | Cooling effect is low in shaded areas compared to open areas. Between high rise buildings reflective pavements have minimal effect due to short time of exposure; medium-rise buildings yield a greater cooling effect (Lai et al. 2019)[4]. |
| | Reflective pavements in compact urban canyons will cause a large part of the radiation to be absorbed in building walls; they should only be used if an urban canyon has a 1.0 H/W ratio (Lai et al. 2019)[4]. |
| | Reflective roofs are of particular importance from a cost-efficiency perspective at the household level; they are particularly recommended in housing for middle and low-income occupants (Fernandez Milan & Creutzig 2015). Reflective roofs are relatively cheap and easier to maintain compared to green roofs, although green roofs and walls come with additional health benefits (Heaviside et al. 2017)[7]. |
| | In mid-latitudes, reflective roofs do not modify the urban heat island effect during winter (Heaviside et al. 2017)[3]. |
| | Cooling effect of reflective roofs on pedestrian level decreases as building height increases (Lai et al. 2019: Lam et al. 2021)[4]. |
| Shade sails / pergolas | Flexibility is particularly beneficial for contexts with large seasonal differences (Antoniadis et al. 2020; Li et al. 2021). |
| Categories of contextual conditions | [1] Climate<br>[2] Prominent wind patterns<br>3 Latitude<br>[4] Site geometry<br>[5] Building type<br>[6] Space availability/adaptability<br>[7] Budget for implementation and maintenance<br>[8] Population density |

## 4. Discussion

The discussion addresses the third and final aim on the study, as 4.1 relates the results of the literature review to transferability to Nordic cities. While 4.1 presents research gaps as they were found to relate to the Nordic context, 4.2 takes up the discussion of future research on transferability at large. This study´s was not without limitations, which are discussed in 4.3

### 4.1 *Transferability to Nordic cities*

This literature study was partially prompted by the question whether all contextual conditions relevant for the transfer of heat mitigation measures to Nordic cities had been mapped. Following the contextual conditions found to be relevant to heat mitigation measures, this section touches on those contextual conditions for which commonalities are found between Nordic cities. Considerations for transferability of measures to this region are discussed, as are research gaps on the matter.

#### 4.1.1 *Climate and prominent wind patterns*

The Nordic context encompasses multiple climate types, but the entire region can be classified as heating-dominated. With that, the issue of conflicting requirements between heat measures and winter preparedness is central (Koppe et al. 2004). Increasing year-round comfort may require reducing solar access in the summer while allowing for more solar radiation in winter (Liu et al. 2023). Because of this, deciduous trees are recommended (Wallenberg et al. 2023). As suggested by Antoniadis et al. (2020), a categorization and ranking of tree species and their effect on microclimates should be done, also for the different Nordic climates. Lam et al. (2021) assert that plants suitable for green facades, should also be categorized and ranked, focusing on their impact on pedestrian thermal comfort.

Solar access can also be manipulated using grey infrastructure. Streets with high H/W provide the most shade; while positive in the summer, this could reduce thermal comfort in winter (Liu et al. 2023). Shallow and medium canyons (0.5 < H/W < 1.5) were found to be more favorable in cold climates (Ren et al. 2023), but this finding may not consider a transition toward hotter summers. The impact of asymmetrical street canyons on outdoor thermal comfort is furthermore understudied (Lam et al. 2021). Shade sails and pergolas are particularly good contenders for heat mitigation in Nordic cities due to their flexible nature (Li et al. 2023; Antoniadis et al. 2020). Using temporary measures means that there is no risk of increased thermal discomfort in the winter. However, it is important that they are put up and taken down at the right times, which requires knowledge of the population´s heat and cold tolerance, as well as maintenance personnel.

Beyond altering solar access, ventilation can effectively alter thermal comfort. In Nordic cities, cold northern winds should be blocked in winter (Vanos et al. 2017). Vegetation and buildings are effective at doing so, but intensive blockage may obstruct needed ventilation in the summer (Li et al. 2023). Mobile windbreaks, combined with green and blue infrastructures are among flexible solutions (Li et al. 2023).

#### 4.1.2 *Latitude*

Reflective roofs are also effective at reducing summer temperatures. It was found that they do not modify the urban heat island effect during winter in mid-latitudes regions (Heaviside et al. 2017). It should be researched if the same is true for high-latitudes.

#### 4.1.3 *Space adaptability, cultural values and aesthetics*

Another contextual condition which may impact what is possible in terms of heat mitigation in Nordic cities is the adaptability of the site. This condition likely interacts with cultural values and aesthetics. The majority of Nordic cities have historical centers. Cultural heritage may be an obstacle for the implementation of heat mitigation measures in Nordic cites, per aesthetic and cultural values, as it is for other types of climate change mitigation and adaptation measures (Granberg et al. 2022). Compared to green infrastructures, and especially compared to urban morphology, temporary measures can be more easily installed where restrictions in the adaptability of the site apply (Liu et al. 2023). Even then, conflicts may arise between heat mitigation and aesthetically and historically valuable objects, as was the case for temporary shade sails in Cairo, discussed by Elnabawi and Hamza (2020).

#### 4.1.4 *Budget for implementation and maintenance*

Lack of finance may not be a large issue compared to countries with lower degrees of economic development (Turek- Hankins et al. 2021), but political-financial obstacles may still be present in Nordic countries. Because heat has historically not been a large risk in the Nordics, there may be challenges with convincing stakeholders to invest in its mitigation. Maximizing a measure´s co-benefits and therewith tackling societal challenges beyond heat would improve the cost-effectiveness of these measures, and make them more attractive to policy makers. The roles of politics, policies and regulations in the adoption of heat mitigation measures did not receive attention in the literature.

### 4.2 *Future research on transferability*

Future research should further focus on year-round studies to ensure that mitigation measures indeed balance the needs for different seasons (Liu et al. 2023; Lai et al. 2019; Hintz et al. 2018). Not only actual temperatures, but also behavior and thermal requirement may vary in different seasons (Lam et al. 2021).

It is important that the effects of mitigation measures on year-round temperatures are looked at through a lens of heat and cold tolerance (Ren et al. 2023). According to Liu et al. (2023) and Lai et al. (2019) international thermal comfort indices have low accuracy. Using thermal comfort indices that are adapted to the local population helps to determine the thermal requirements of a place (Lai et al. 2019). Context specific and more accurate universal indices should be developed, so that they are suitable for the different areas and climates, taking into account various factors such as the physiology, psychology, behavior, and culture of local populations (Lai et al. 2019). Lai et al. (2019) highlights that within these indices, behavior is particularly poorly understood. Studies should look into the ability to include behavior such as changing clothes and moving across the street into simulations of thermal conditions, which will require more observational data on behavior (Lam et al. 2021). Studies on the individual adaptive behaviors of local populations are valuable in this pursuit. Such studies can also directly inform the design of heat mitigation measures, through providing knowledge on site usage, so that spatial prioritization can be done effectively (Lam et al. 2021).

Research on of heat mitigation measures would greatly benefit from cross-regional research (He et al. 2023). This will further improve knowledge of transferability, and increase understanding of geographical differences. Because it is not feasible that all cities in the world are included in one study, a common format for the presentation of context in case study descriptions is crucial, so that the effects and prerequisites of measures can be compared more effectively and systematically (Hintz et al. 2018).

### 4.3 *Limitations*

It should be emphasized that this is not a review on the comparative effectiveness of different heat mitigation measures, but rather on the contextual conditions that influence the transferability of these measures. In addition to contextual conditions, the form of the mitigation measure itself greatly impacts its cooling effect, and ultimately, the intrinsic characteristics and contextual conditions coproduce a measure´s effectiveness.

While the study following a review of reviews design enabled the execution of this study. Additional contextual conditions may have been discussed in original articles, while remaining unreported by the literature reviews. It has further been considered that using more than one data base would have strengthened the basis of this study, but time limits did not permit this. A more in-depth study should include several data bases, including ones specialized in Nordic scientific literature.

## 5. Conclusion

The implementation of physical heat mitigation measures is not confined to geographical boundaries. These measures are transferable across borders and oceans, but the importance of context in their application and effectiveness should not be overlooked.

This study set out to do a scoping review of literature reviews to identity how contextual conditions and transferability have been discussed in literature, what contextual conditions exist for blue, green and grey infrastructures, and discuss what these conditions entail for the of heat mitigation measures to Nordic cities.

The importance of context is outlined by the finding that all reviewed articles mention some type of contextual condition relevant to input, effectiveness or output of physical heat mitigation measures. Contextual conditions that were found to be relevant relate to: climate and prominent wind patterns; water availability; soil; the population´s thermal comfort and tolerance; site geometry; surrounding surfaces; space availability and site adaptability; budget; maintenance; and information availability. Financing and co-occurring societal challenges further highlight the importance of a measure´s co-benefits and risks. Additionally, the ultimate form of an intervention may be influenced by social norms, cultural values, aesthetics, sun path, site function, and the time-of-day site attendance is highest.

It was found that literature often implicitly rather than explicitly expressed the importance of context. Contextual conditions were not systematically reported for discussed measures. To reduce maladaptation and enable decision makers and implementers to get a good overview of which measures would fit their respective contexts, research on heat mitigation measures should explicitly and systematically report contextual conditions. Literature on heat mitigation measures should have transferability in mind.

The identified contextual conditions were used to create a profile, synthesizing commonalities between Nordic cities. This resulted on a discussion on design considerations for: heating dominant climates, high latitude regions, limited space adaptability in historical centers, and political-financial obstacles. It has become clear that transferability obstacles to Nordic cities are not limited to conflicting summer and winter requirements. However, many research gaps remain.

This study has identified what contextual conditions are relevant to transferability of heat mitigation measures. Identified relevant contextual conditions should guide the analysis of transferability in future research. The identified contextual conditions could guide the creation of clusters of cities with similar contexts between which the transferability of solutions is high. This will simplify decision making processes.

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**Data availability**
Coding spreadsheets and search strings will be made available upon request.

**Declaration of competing interest**
The author declares that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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