Mitigating Urban Heat Islands through sustainable development

Author: Vaughan van Inge

17-02-2023

Student number: S3486591

Course: Bachelor Project Spatial Planning & Design

Supervisor: Charnè Theron

Course Coordinator: Stefan Verweij

Abstract

The Urban Heat Island (UHI) effect is largely to blame for cities becoming increasingly unsustainable. Sustainable development is frequently cited as the panacea to this unsustainable problem. However, the relationship between sustainable development and the UHI effect has not been covered in depth in literature. The subject of how the UHI effect relates to sustainable development and what it entails for particular mitigation strategies and government policy is raised. The broad term of sustainable development is reduced to three specific land development principles related to the UHI effect. (i) higher-density development, (ii) energy and resource-efficient urban design, and (iii) protection of natural and biological functions and processes. From these principles, case studies are identified where an effect on the UHI effect is measured. An impact on the UHI is measured as a change in local air temperatures. The first principle, densification, is seen to primarily increase the UHI effect in ranges from 1 °C and 2°C both during the day and night. In contrast, the other two development principles are seen to decrease air temperatures up to 1 °C during the day but only show minor effects during the night. Across the different case studies examined, the magnitude of the effect is roughly the same. This implies that sustainable development can negatively and positively impact the UHI effect. However, combating nighttime UHIs through sustainable development is challenging. Policies looking to combat the UHI effects must focus on compensating urban densification with the other development principles or look beyond sustainable development. The articles analysed did not combine multiple land development principles. The combination of different land development principles and their effect on the UHI effect has to be further studied.

Contents

1. Introduction

Cities are getting increasingly unsustainable as a result of a plethora of factors. Some argue that cities and other urban agglomerations are inherently unsustainable (Berger et al., 2014). While this might be true, there are strategies to counter it. This paper will focus on one of the most significant contributors to the unsustainability of urban agglomerations today, the urban heat island (UHI) effect. The UHI effect is a mechanism where heat increases air and surface temperatures disproportionally in urban areas compared to surrounding rural areas (Piracha et al., 2022). Due to this effect, the difference in air temperature between cities and their rural areas can measure up to 10°C in some cities (Peng et al., 2012). The magnitude of this difference is referred to as the UHI intensity. The cause of this disproportionate increase in temperature are characteristics of the urban environment and human activity. Urban environments are built with mainly dark and heat-absorbent materials and often lack vegetation, increasing ambient air temperatures (Mohajerani et al., 2017). Activities such as air-conditioning and construction all add additional heat to the urban atmosphere (Piracha et al., 2022).

Heat, especially heatwaves, is a significant cause of excess mortality and has resulted in approximately 150.000 more fatalities since 1900, and this will be further exacerbated by the UHI effect (Rustemeyer et al., 2021; Vaidyanathan et al., 2020). The detrimental impacts of UHI are even more prevalent among vulnerable individuals and communities, which get hit the hardest by extreme weather events (Vaidyanathan et al., 2020). It is, therefore, of great concern that due to climate change, extreme heat wave events are becoming more common and more severe (Lhotka, *et al*., 2018). Since 2007, most of the world's population has lived in cities, increasing rapidly by almost 100 million yearly (Ritchie et al., 2018). The combination of the ever-growing urban population and the increasing threats of climate change makes the UHI effect a top priority in today's agenda of sustainable development for cities.

In addition, the heat island effect has more far-reaching indirect impacts. A short, non-exhaustive list of implications is: ecosystems are put under pressure, energy and water consumption increase substantially, economic consequences because of decreased productivity of workers, and healthcare systems experience extreme stress (Singh et al., 2019).

Sustainable development is often superficially mentioned as an approach to making cities more sustainable and countering the UHI effect (O'Malley et al., 2014; Bai et al., 2016; Yang et al., 2016). However, the literature does not specify how sustainable development relates to the UHI effect and how it translates into concrete measures and policy. A reason for the lack of specificity is the broad definition of sustainable development. What exactly this concept tackles and the conflicts of values within it make it challenging to see how it solves specific problems (Godschalk, 2007; Holden et al., 2014). This lack of a definition makes it difficult to use it as a guide towards actual policy implementations (Holden et al., 2014). The concept, however, is not to be discarded as it has been on the global political agenda and a major topic during multiple world climate summits (Sachs, 2015). The International Insitute for Sustainable Development (IISD) defines sustainable development as "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs" ("IISD," n.d.). The before-mentioned definition is still too extensive but can already be somewhat related to the UHI effect. 'Current' development only exacerbates the UHI effect, thus impeding future generations' livelihood. The definition of sustainable development will be narrowed down according to Edwards, (2010), which derives fourteen land development principles from their definition of sustainable human system development. These fourteen land development principles are a starting point to narrow down the definition of sustainable development and which part relates to the UHI effect. Three of these principles are identified as being the most relevant to this study. These are; (i) higher-density development, (ii) energy and resource-efficient urban design (in short, efficient urban design), and (iii) protection of natural and biological functions and processes. These three principles are not an exhaustive list, and more land development principles could be related to the UHI effect. However, this study will focus on these three sustainable development concepts.

The reason for using this definition is because it translates sustainable development into specific land development principles that can be related to the UHI effect. Therefore, partly bridging the gap between a broad definition to actual policy implementation. The theory section will further dissect and explain these land development principles and how they are related to the UHI effect. This paper aims to answer the question, "Does sustainable development contribute to changes in the UHI effect?”. This main research question gives way to several sub-questions to answer the main research question. First, “What is the UHI effect and what are indicators of the UHI effect?” This lays the basis for how the development principles can be related to the UHI effect and how they may affect it. Next, “how do these land development principles bring about changes in this indicator?” This question tries to identify how the land development principles are related to the UHI effect. Lastly, this paper tries the answer the question, “Are these sustainable land development principles effective in mitigating the UHI effect?”. This question will be answered based on changes in the UHI indicator caused by the development principles.

2. Theoretical framework

First, defining the UHI effect and its indicators is crucial in establishing whether the sustainable land development principles affect it. Tzavali et al., (2015, p. 1) put it simply “Air temperatures in built urban areas are higher than those of the surrounding rural country”. Thus, a positive change is that a land development principle brings the urban air temperature closer to that of the surrounding rural areas. This can be further simplified to a net negative change in air temperatures after the implementation of the land development. However, local air temperatures fluctuate throughout the day and night. The UHI effect is, therefore, often measured with diurnal air temperature variations and can be averaged for its day and night time UHI effect (Phelan et al., 2015). While ambient air and surface temperatures are involved in the

UHI effect, some case studies only measure either. While both measures would be ideal in substantiating the effectiveness of a land development principle, only air temperatures will be examined. Air temperature change reflects the local climate changes and their effect on inhabitants more accurately (Lemonsu et al., 2015).

Secondly, the land development principles need to be further dissected to be related to the UHI effect and how they bring about temperature changes. The land development principles will be related to the UHI effect based on some examples. Densification can be defined by limiting the increase of urban surface area while a city still grows in other aspects (Næss et al., 2020). The way this principle is related to the UHI effect can be seen in an example of fighting urban sprawl. Limiting urban sprawl is often mentioned as a part of sustainable development (Edwards, 2010). A case study by Deilami et al., (2017) shows that urban sprawl can increase the UHI effect, but dense urban development can also increase the UHI effect through a multitude of mechanisms. In this way, the aim to increase urban density and limit sprawl is ineffective in mitigating the UHI effect. Sprawl increases a city's metropolitan area, increasing the grey area that absorbs heat. However, urban sprawl has more negative effects rather than positive when it comes to the overall sustainability of a city (Johnson, 2001). This back-and-forth highlights the caveats within the land development principle of densification. The second and third principles will be considered together, as there is a significant overlap between them and their mechanisms. Trees, among other vegetation, have a vital function in a city's natural and biological processes (Karuppannan et al., 2013; Threlfall et al., 2016, 2017). An example of how planting trees influence the UHI effect is the reduction in energy use within a city due to decreasing surface temperatures (Akbari et al., 2001; Akbari, 2002; Zhang et al., 2017). This can result in reduced air conditioning use, contributing to the UHI effect (Akbari, 2002). Next, efficient urban design does not have to include urban vegetation and can also take other forms. An example is 'cool pavement and roofs', specifically developed to reduce urban heat islands (Yang et al., 2018;

Moretti et al., 2021). These roofs also reduce buildings' energy use and can therefore reduce the UHI effect.

An important thing to consider is that it cannot be assumed that a mitigation strategy is sustainable when selecting case studies. This means that a measure could reduce the UHI effect but will not improve the overall sustainability of a city. A framework proposed by Bathaei and Abdel-Raheem, (2022) can assess the sustainability and resilience of UHI mitigation strategies. While determining the sustainability and resilience of each case study is outside the scope of this comparative analysis. A brief consideration of the sustainability of a measure within a case study is still made with their framework. Bathaei and Abdel-Raheem, (2022) propose three criteria for the sustainability of a mitigation strategy. These are economic, environmental and social sustainability. The first criterion dictates that a strategy does not have high maintenance costs that are unsustainable in the future. This cannot be inferred from the selected sustainable development principles. The second principle relates to environmental considerations and assumes that a UHI mitigation strategy restores natural resources and ecosystem services. This is in line with the third sustainable land development principle. It also mentions the environmental burden of the production of said UHI mitigation strategy in the form of greenhouse gasses emitted during the process. The former can be considered; however the latter falls outside the scope of this study. Finally, they consider social sustainability through the impact a UHI mitigation strategy has on the quality of life, but this again falls outside of the scope of this study.

2.1. Conceptual model

Figure 1 shows the conceptual model, highlighting the steps this paper makes to reach a satisfactory conclusion. It starts from the three identified land development principles and will conclude their effect on diurnal air temperatures. The diurnal air temperature variation will be averaged for their day and night sections for easier comparison between different land development principles. An overall analysis of the effect of the three land development principles can be derived from this comparison. This will bridge the gap between the cumbersome definition of sustainable development and how it is related to the UHI effect.

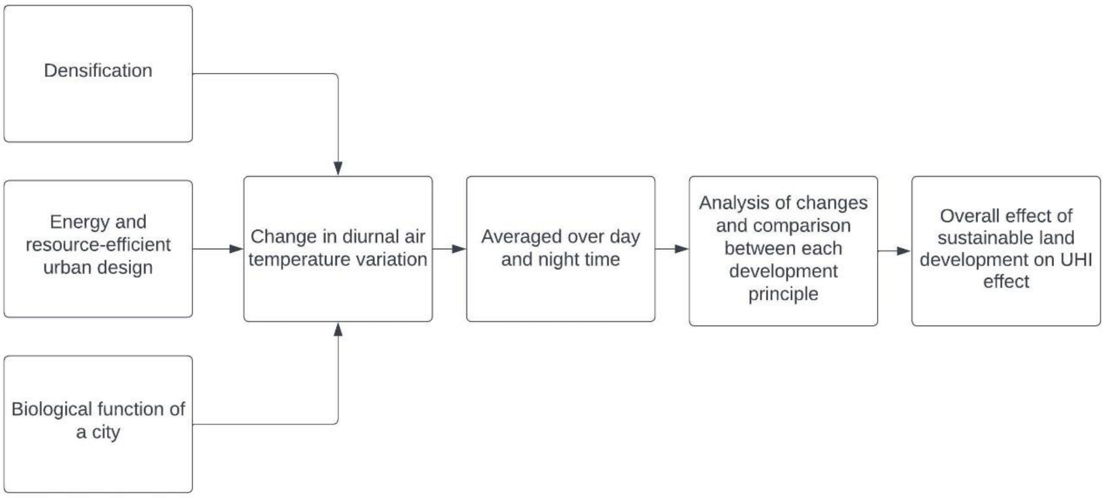

Figure 1: Conceptual Model

2.2. Expectations

It is expected that higher density development will increase the UHI effect due to increasing factors such as human activity within the same surface area of a city. Next, it is expected that efficient urban design and increasing biological functions of a city can decrease the UHI effect. This decrease is expected as this land development helps reduce energy usage in cities and, therefore, can lower temperatures. However, the magnitude of the effect of the different land development principles is yet to be seen. Magnitudes between the land development principles might overshadow the other. The increase or decrease of one of the principles might be substantially more significant than the others. It might only come down to one of the development principles to make a real difference in the UHI effect. A thing to note is that the selection of UHI mitigation strategies depends on a city's geographical context (Zhang et al., 2022). While different factors contribute towards UHI, no factor stands out globally in developing UHIs and depends on the context mentioned before (Zhang et al., 2022). This implies that the three land development principles will have varying results depending on the context.

3. Methodology

To answer the research question, a literature review will be conducted. Secondary data will be gathered from case studies where diurnal temperature changes are measured before and after implementing one of the development principles. After this, a conclusion will be drawn from the overall effectiveness across the different case studies. The implementation of UHI mitigation strategies is, to an extent, context-specific. Thus, results between the case studies might vary greatly depending on different parameters (Bathaei et al., 2022). However, a comparative analysis between cases that have similar parameters can still be done. Similar parameters in this context mean case studies with measurements during a period of high temperatures, for example, during summer or a heat wave. During such a period, the UHI effect shows the highest temperature differences in cities compared to their rural surroundings (Tzavali et al., 2015). A conclusion can be made based on a holistic view of the overall effect of all case studies if the results are similar in magnitude. If results are completely different per case studies selected, it will be much harder, if not impossible, to generalise outcomes based on a literature review alone. *Figure 2* shows the process of analysing the data gathered from the literature review.

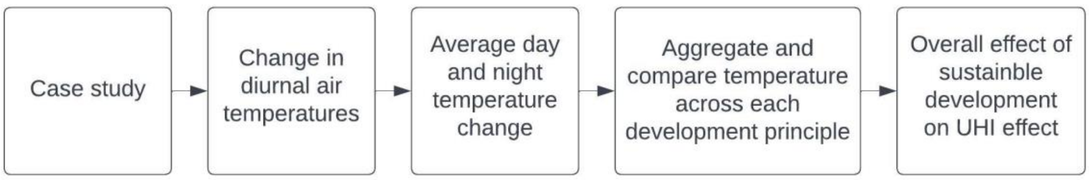

Figure 2: Data analysis scheme

The use of secondary data implies that no ethical concerns will be encountered. The reporting on the UHI effect concerning sustainable development concepts is assumed to not cause harm to any individual or organisation as it is solely to broaden knowledge on the subject.

3.1 Data collection

A selection of cases will be made where the diurnal air temperature variation is measured before and after the implementation of one or more sustainable development principles. Next to this, other literature reviews of case studies on a specific development principle can also be included if they include a similar selection criterion. The selection scheme is shown in *figure 3,* which guides the literature selection process. While the primary objective of this study is to compare case studies where measures have been implemented, these are often only on a smaller scale (Moretti et al., 2021). Several case studies used modelling techniques to establish whether a mitigation strategy would affect the UHI effect on much larger scales (Lemonsu et al., 2015; Bosch Padros, 2021).

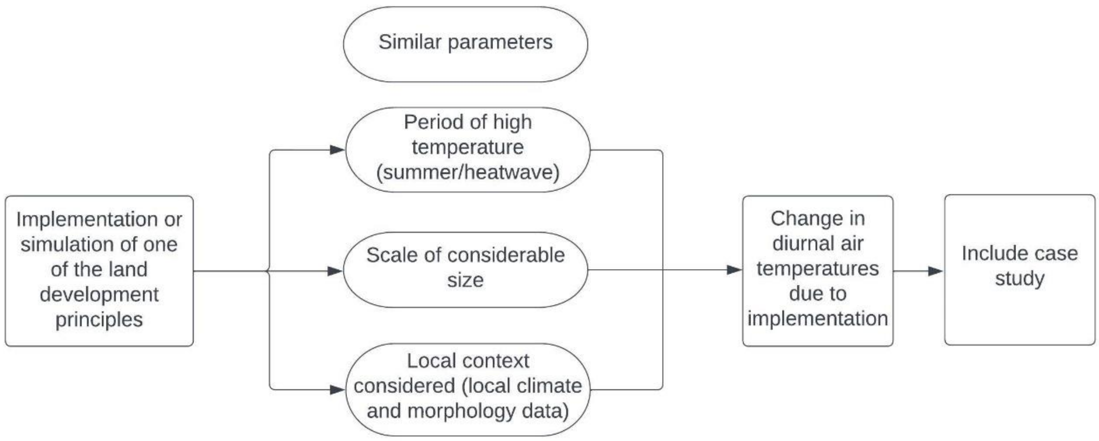

Figure 3: Case study selection scheme

The cases to be analysed exist of a multitude of scales, locations and development principles. Below is a summary of a diverse set of studies where different types of UHI mitigation strategies are deployed under one of the three development principles. Below in *Table 1,* a summary of the selected case studies is listed in no particular order. For simplification, the scale is indicated at either city or neighbourhood level. All cases use a period where temperatures are relatively high during summer or a heat wave also during summer. Next to this, most case studies are of considerable size of at least multiple building blocks up to simulations, including entire cities' metropolitan areas.

Table 1: Summary of cases studies identified according to the methodology

Author	**Implemented measure**	**Development principle**	**Negative or positive effect on UHI**	**Scale**	**Location**
(Lemonsu et al., 2015)	Limiting urban sprawl (model)	Densification	Negative	City	Paris, France
(Barbosa et al., 2019)	Densification	Densification	Negative	Neighbourhood	Copacabana, Brazil
(Mughal et al., 2020)	Densification	Densification	Negative	City	Singapore, Asia
(Solcerova et al., 2017)	Green roofs	Natural and biological function	Positive	Building	Utrecht, Netherlands
(Cortes et al., 2022)	Green roof and vegetation	Natural and biological functions	Positive	Neighbourhood	Mandaue City, Philippines
(AboElata, 2017)	Urban vegetation	Natural and biological functions	Positive	City	Cairo, Egypt
(Bowler et al., 2010)	Parks and tree clusters	Natural and biological function	Positive	Neighbourhood	Various
(Loughner et al., 2012)	Urban tree canopy	Natural and biological function	Positive day, negative night	City	Three cities within the USA
(Santamouris, 2014)	Cool and green roofs	Energy and resource-efficient urban design	Varying	Various scales	Multiple cities
(Zhang et al., 2017)	Optimising green space locations	Energy and resource-efficient urban design	Positive	City	Arizona, USA
(Kong et al., 2014)	Spatial pattern of green space	Efficient urban design	Positive effect.	City	Nanjing, China

4. Results

The next section will extract the diurnal temperature variations from each case study in *table 1.* Depending on the study, some data is only available in diurnal temperature variation and will be averaged for their day and night section. While other studies already provide the average day and night time temperature changes.

4.1 Densification

First, the higher-density development case studies will be analysed. The studies that will be examined use one of two different scales. The first two studies are models simulating two large metropolitan areas. The third model is based on a smaller-scale simulation of a part of a city but is valuable nonetheless. All case studies include diurnal temperature variations as described in the case selection diagram.

The first case study is a model of two future expansion scenarios in Paris, France (Lemonsu et al., 2015). A reference case of future growth based on past expansion data and current zoning regulations compared to a future scenario based on significantly stricter urban containment policies. The first indicator of UHI intensity they look at is the temperature difference between the rural surrounding and the historic city centre in both scenarios. *Figure 4* shows the temperature changes within the city of Paris between their control and densification scenarios. These changes are +0.13°C and -0.16°C for daytime and nighttime, respectively.

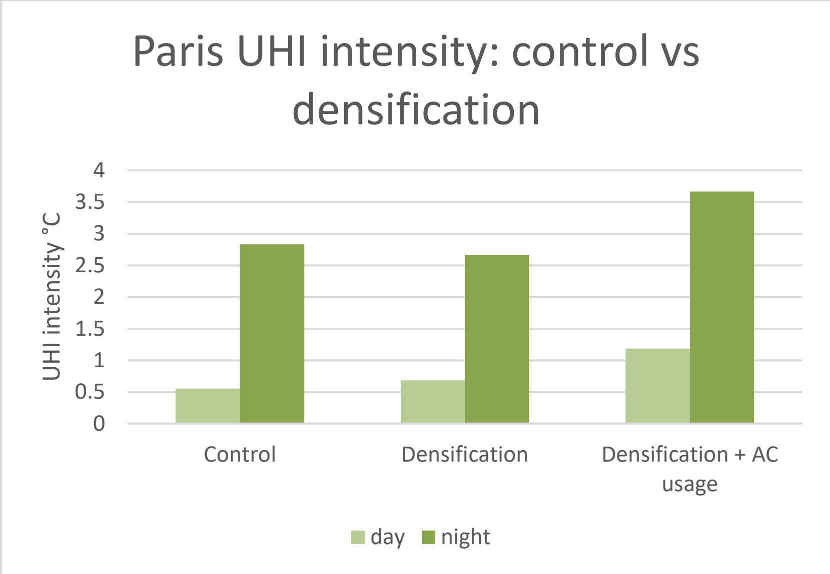

Figure 4: Difference in day and night UHI intensity of the densification vs control scenario Paris case study (Lemonsu et al., 2015).

The small changes are due to the minimal morphology changes applied within the model, as the historical city centre of France is unlikely to change morphologically. In this model, it is assumed that no buildings are equipped with air-conditioning (AC). However, across mid to northern Europe, AC usage is not as common closer to the equator but is expected to increase massively (Jakubcionis, et al., 2017). A case study on Paris shows that ambient air temperatures could increase by 0.5°C and 1°C day and night, respectively, when air conditioning use keeps growing (de Munck et al., 2013). This holds for cities where AC usage is likely to increase simply due to the UHI effect alone without densification considered (Salamanca et al., 2014). Combining the Paris model and the addition of AC usage, a rough estimate of an increase of 0.6°C and 0.8°C for day and night time UHI intensity. AC usage increase attributed specifically to densification might result in different air temperature changes.

Mughal et al., (2020) have done a similar study in Singapore, Indonesia. They consider a future densification scenario based on Singapore's 2014 master plan. They define 10 different classes of morphology called local climate zones (LCZ). LCZ 1, compact high-rise, increases its percentage coverage of the city from 2% to almost 40%. This is at the cost of decreasing 'open mid- and low-rise buildings' from 35% and 20% to 0% and 5%. *Figure 5* shows the diurnal air temperature fluctuations between the control and densification case. Measurements were based on April, which separates daytime to about 07:00 – 19:00 local time and nighttime the other half (Mughal et al., 2020).

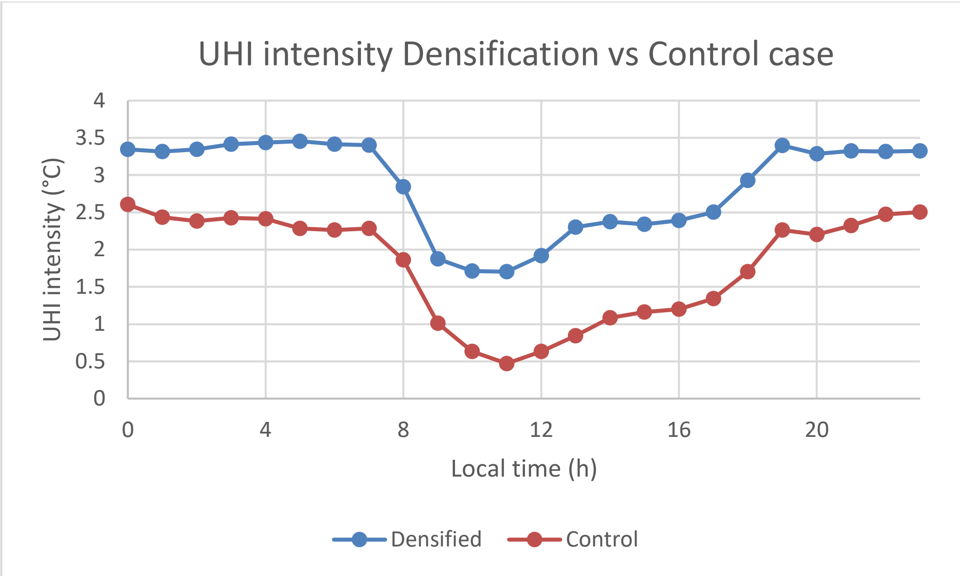

Figure 5: Difference in UHI intensity of the densification vs control scenario 24h Singapore case study (Mughal et al., 2020).

The average daytime and nighttime UHI intensity changes are +1.2 °C and +1.0 °C, respectively, as seen in *figure 6*.

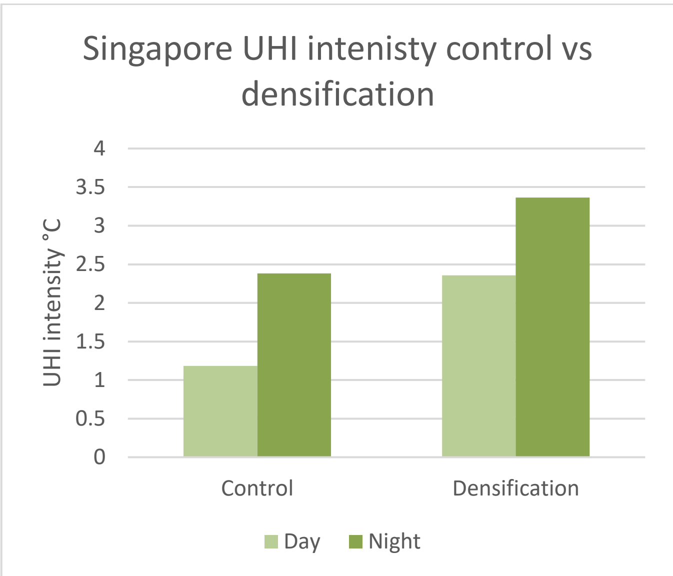

Figure 6: Difference in day and night UHI intensity in Singapore control vs densification case (Mughal et al., 2020)

This model includes heat released from AC systems, significantly impacting ambient air temperatures. The scenario involves mainly an increase in compact high rises and heavy industry while decreasing lower-density buildings. The temperature changes were predominantly caused by the blocking of wind and higher AC usage, both due to higher building density. However, morphological changes in the form of increased building height increased shading, reducing buildings' cooling loads, but this effect was insignificant against the temperature increase. These results align with the Paris case study, showing similar increases in day and night temperatures (Lemonsu et al., 2015; Mughal et al., 2020).

Barbosa et al., (2019) conducted a study with similar results to the previous two studies. They modelled the densification for 1930, 1950 and 2018 of Copacabana, Brazil and their respective day and night time air temperatures. To control for factors outside morphological changes, all three scenarios use 2018 climate data. In *figure 7*, the morphological differences can be seen. Where the difference between the 1950 and 2018 scenarios more closely resembles the control and densification case, similar to previous studies. The 1930 scenario will be excluded here as this study tries to analyse cities increasing in density.

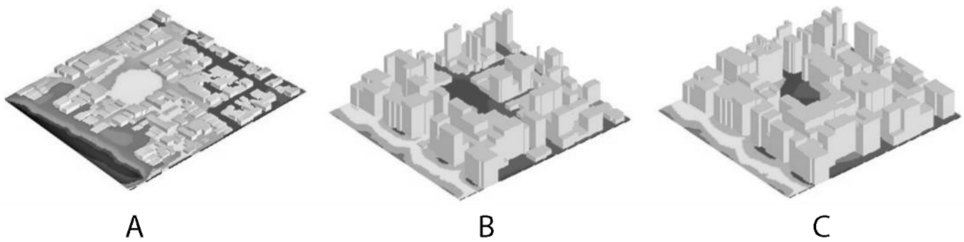

Figure 7: Morphology Copacabana, Brazil. (A): 1930, (B): 1950, (C): 2018 (Barbosa et al., 2019)

Figure 8 shows the temperature increases between the 1950 and 2018 scenarios. Results show actual temperatures instead of UHI intensity. This study did not include UHI intensity but only reported air temperature differences between scenarios. The increases from 1950 to 2018 are 0.5°C and 0.4°C for day and night, respectively. The 1930 data can be used as a reference similar to rural surroundings to estimate UHI intensity and calculate intensity increases. The day and night temperatures between 1930 and 1950 increased by 2.9°C and 3.2°C as seen in *figure 8*. This can be done because climate data and parameters are the same across all scenarios.

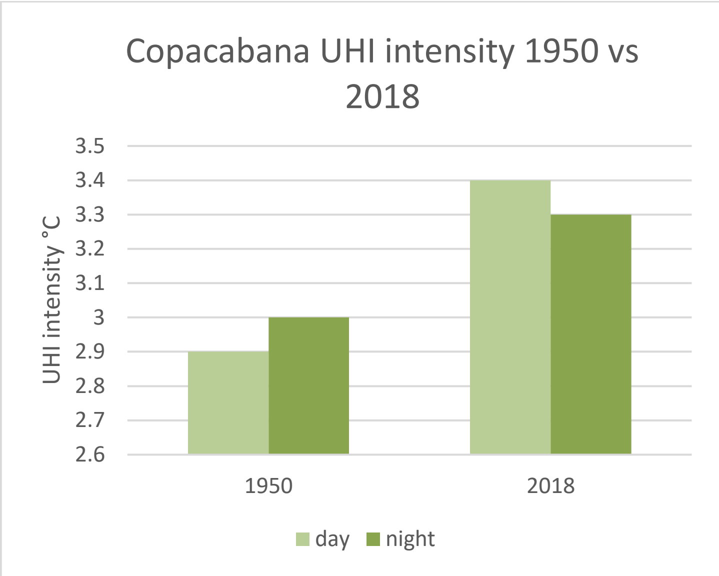

Figure 8: Difference in day and night UHI intensity in Copacabana 1950 vs 2018(Barbosa et al., 2019)

From the previous case studies, morphology and anthropogenic heat from AC usage seem to be the deciding factor in increasing the UHI effect regarding urban densification. However, Lemonsu et al., (2015) excluded waste heat released from AC systems, which in the case of Singapore is an essential factor (Mughal et al., 2020). Next, the climate of both these case studies is vastly different. Mughal et al., (2020) concluded that their results match up with other cities in warm climates, namely Tokyo, Japan and Hong Kong, China. However, compared to the increases in temperature derived from the Paris and Copacabana study, temperature increases are still in the same ballpark.

4.2 The biological function of a city & efficient urban design

Next, the effect of increasing urban green space on the UHI effect in cities is analysed from the selected case studies. Urban green space comes in many forms, but the most researched types for mitigating urban heat islands are urban vegetation in the form of trees and green roofs.

Only minor changes in air temperatures are directly attributed to implementing green roofs. Only a slight decrease in 2m ambient air temperatures can be seen from 0 °C to 0.8 °C across multiple studies in different climates (Pompeii II and Hawkins, 2011; Santamouris, 2014; Solcerova et al., 2017; Cortes et al., 2022). This effect is more pronounced within dryer climates and decreases in higher humidity climates (Alexandri et al., 2008).

However, green roofs also reduce the internal air temperature of buildings through their increased insulation and decrease in surface temperature, which reduces air-conditioning needs by up to 30% (Razzaghmanesh et al., 2016). Air conditioning increases outside air temperatures by more than 1°C to 2°C (de Munck et al., 2013; Salamanca et al., 2014). Green roofs could then be more effective in cases where air-conditioning is abundantly used. Green roofs could indirectly have a bigger positive effect on the UHI effect by decreasing AC usage within cities. However, literature on air temperature decrease contributed directly to less AC usage caused by green roofs is still lacking.

Through different physical mechanisms, cool roofs have similar results to green roofs when mitigating the UHI effect (Santamouris, 2014). Due to their higher albedo, they reflect more sunlight than traditional roofing and reduce the cooling loads of buildings. The main difference between cool and green roofs is that on peak sunlight days, cool roofs are more effective (Santamouris, 2014).

The effect of trees and their cooling on surrounding air and surfaces is more thoroughly studied in the literature. A meta-analysis from 2010 suggests that, on average urban parks and tree clusters and their nearby surroundings are 1 °C cooler during the day than other non-green sites in the same areas but saw only minor differences in nighttime temperatures (Bowler et al., 2010). A comparable study in Madison, USA, showed that daytime temperature decreased with increasing canopy cover (Cheela et al., 2021). Depending on the surface cover type, tree clusters were on decreases in air temperature ranging from 1 to 2.5 °C. However, they measured only slight changes in nighttime average air temperatures with a reduction of 0.3 to 0.7 °C. Another study modelled the effect of an increase in tree cover on air temperatures and yielded similar results (Loughner et al., 2012). They found daytime air temperatures decrease up to 4 °C and only slight decreases in nighttime air temperatures of 0.5 °C. All three studies also show a high reduction in building and road surface temperatures due to the tree shading effect (Bowler et al., 2010; Loughner et al., 2012; Cheela et al., 2021). This can just as green roofs reduce buildings' cooling loads and air temperatures in this pathway. Another case study in Cairo, Egypt, showed similar results but a high increase in air temperature at night following the implementation of trees within building blocks (AboElata, 2017). This significant difference was due to the location of the measurements, which was directly under the trees, which is logical for the daytime decrease. However, this study's high differences at night are an anomaly compared to the other case studies.

Continuing the story of urban green space, another interesting way of looking at it is how it is distributed. Two case studies have examined green space distribution optimisation to combat urban heat islands (Kong et al., 2014; Zhang et al., 2017). The model done by Kong et al., (2014) on the spatial distribution of a fixed amount of forest cover shows that optimal distribution can decrease by 0.8 °C air temperatures compared to their base case. Zhang et al., (2017), demonstrated similar results in a 1°C to 2 °C reduction in land surface temperatures. While they only indicate surface temperatures, this is still interesting as this is only the location of trees without increasing total tree coverage.

4.3 Comparison

Green roofs and cool roofs provide only a small direct reduction in ambient air temperatures but could have a significant impact on reducing AC-conditioning needs. This, in turn, will significantly impact reducing air temperatures within cities. Next, vegetation that creates sufficient shading due to its canopy can cause a significant decrease in daytime temperatures. Next, shading from trees can massively reduce cooling loads, but not to the same spatial extent as green roofs, unless trees are planted on top of buildings, which is not as expected. Trees are bound to grow mainly on the ground, and shading will have a limited effect in cities with a higher share of high-rise buildings. *Figure 9* shows an overview of all identified studies and their impact on UHI intensity.

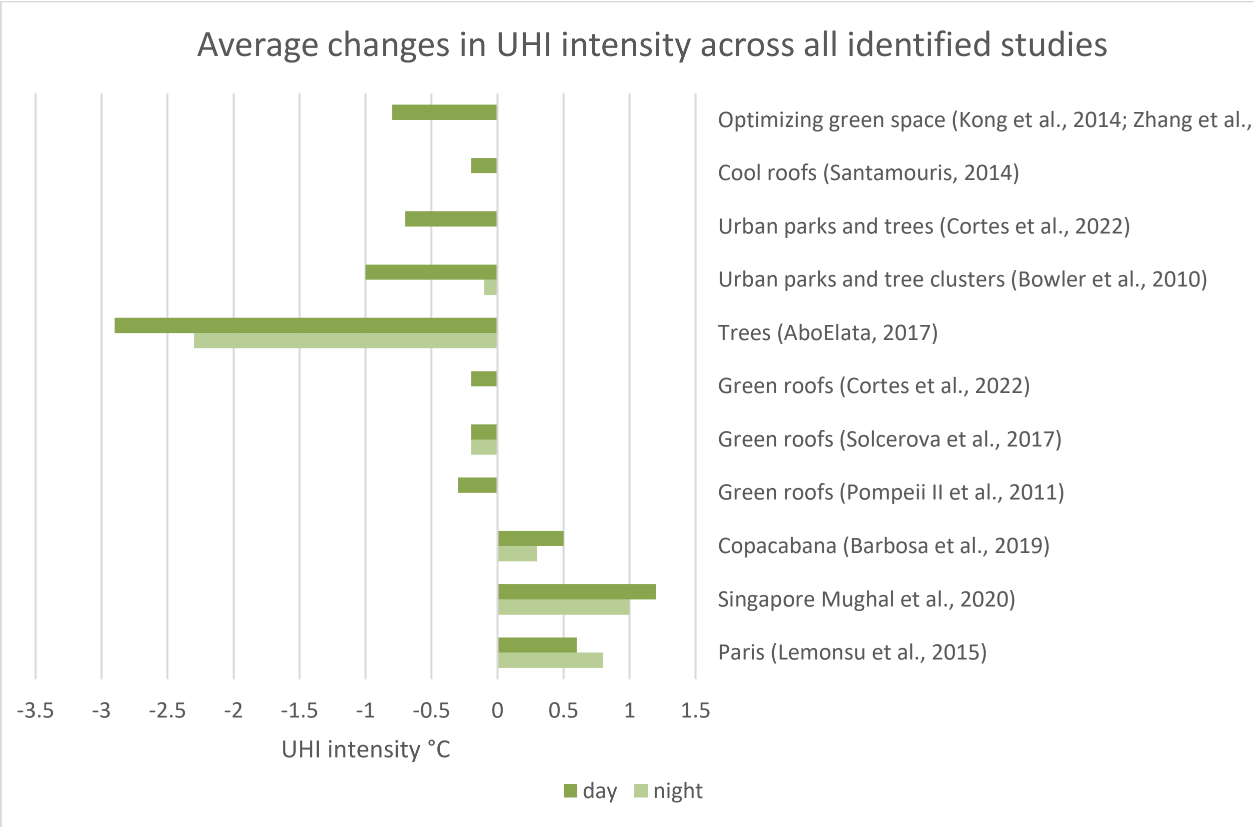

Figure 9: Overview of UHI intensity changes across all identified studies. (Note: Bars missing indicate no measurements or insignificant difference)

The most interesting part is that, except for one case study, most effect sizes are roughly in the same ballpark. However, the nighttime reduction of UHI intensity through efficient urban design and the biological function of a city is most effective during the day when urban densification has similar increases for both day and night time.

5. Conclusion

The UHI effect is determinantal to the global thermal comfort of the cities. Extreme heat has a severe and far-reaching impact on cities' inhabitants, functioning, economy and ecology. This is one of the most pressing problems that cause cities to become increasingly unsustainable. Sustainable urban design and development are often coined as the solution for this ever-growing unsustainability of cities and every urban agglomeration. However, the effect of these development practices on the UHI effect is not yet thoroughly studied. This study investigates how sustainable development changes the UHI effect and whether there is a positive mitigation effect. This is done through an extensive literature review of three sustainable development and design principles. These were densification, energy and resource-efficient urban design and protection of natural and biological functions and processes.

The overall effect of densification leans towards increasing the UHI effect. This is due to decreased wind speeds and increased human activity that generate heat per unit area (for example, AC). While some decreases in surface temperatures can be seen through shading from higher urban canyons, this is not effective against prolonged periods of heat. Across the different studies analysed, increases in ambient air temperatures within a range of densification scenarios will be seen. These increases can range from minimal numbers of up to 2 °C. Depending on the context, densification will either not affect the already increasing UHI effect or worsen it.

To mitigate the UHI effect, vegetation and green/cool roofs seem like the best option, as these seem to have the highest impact on reducing daytime air temperatures. However, they do not influence nighttime temperatures to the same extent.

Looking at sustainable development as the magic bullet for increasing the sustainability of cities is not as straightforward as it seems. Careful considerations should be taken as to what parts of sustainable development are used in cities' development. This literature review reveals some discrepancies within the definition of sustainable development and its effect on the UHI effect.

5.1. Limitations

Most of the analysed literature was on simulation and models based on historical and forecasted data, which means that the results cannot be translated entirely into the real-life implementation of the mitigation strategies. Additionally, this research only considered separate instances of each development principle and, in some cases, a slight overlap. Simulations on the combination of all three land development principles and their combined effect on the UHI effect should be studied. Their combined effect could have different outcomes than the sum of each part.

Furthermore, SVF is often stated to reduce temperatures within a city. Vuckovic et al., (2019) looked at the impacts of urban densification in the form of increased building heights within a neighbourhood in Vienna, Austria. They concluded that higher buildings reduce mean radiant temperature up to 14.5 °C at ground level during the day, which is contradictory compared to the larger scale models. Their model also shows that the reduced sky view factor (SVF) from the higher buildings increases the nighttime heat island effect caused by trapped heat in deep urban canyons, which is in line with the other findings. However, the increased nighttime UHI effect was a significantly lesser degree than the decrease in the daytime UHI. This suggests that deeper urban canyons are beneficial in mitigating the UHI effect. This is supported by a larger-scale model in Seoul, Korea (Kim et al., 2019). Higher-density urban areas showed a statistically significant decrease in land surface temperatures (LST) compared to lower-density development and rural areas. However, these studies only included LST and did not consider ambient air or canopy layer temperatures.

5.2 Policy implications for future development for mitigation of UHIs

While the UHI effect is set to increase over time due to climate change, a specific mix of policy and urban design needs to be catered to local conditions. However, a generalisation on densification can be made where densification will mainly increase the UHI effect. Policymakers should be careful in which way these policies should be implemented. Policymakers should be looking to compensate for the UHI effect that is set to happen due to climate change and densification combined through the other two sustainable development principles. These principles combined would significantly impact the air temperatures within a city to make a difference against the high UHI intensities that can be seen across the globe. However, densification will happen on a large scale throughout cities; thus, other mitigation strategies should be implemented wherever densification occurs.

An example can be seen in the densification policy in the Netherlands. Densification was on hold from 2002 to 2008 within this country. However, densification has been rising since 2008 (Nabielek, 2012). In the government report by Nabielek, (2012), no reference is made towards the negative effect of densification on the UHI effect. This disconnect is of great concern because its effects on sustainable development policy are not as straightforward as they seem and should be more closely linked to the UHI effect.

References

AboElata, A.A.A., 2017. Study the Vegetation as Urban Strategy to Mitigate Urban Heat Island in Mega City Cairo. Procedia Environ. Sci. 37, 386–395. https://doi.org/10.1016/j.proenv.2017.03.004

Akbari, H., 2002. Shade trees reduce building energy use and CO2 emissions from power plants. Environ. Pollut. 116, S119–S126. https://doi.org/10.1016/S0269-7491(01)00264-0

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

Alexandri, E., Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Build. Environ. 43, 480–493. https://doi.org/10.1016/j.buildenv.2006.10.055

Bai, X., Surveyer, A., Elmqvist, T., Gatzweiler, F.W., Güneralp, B., Parnell, S., Prieur-Richard, A.-H., Shrivastava, P., Siri, J.G., Stafford-Smith, M., Toussaint, J.-P., Webb, R., 2016. Defining and advancing a systems approach for sustainable cities. Curr. Opin. Environ. Sustain. 23, 69–78. https://doi.org/10.1016/j.cosust.2016.11.010

Barbosa, G.S., Drach, P.R.C., Corbella, O.D., 2019. Intraurban Temperature Variations: Urban Morphologies of the Densification Process of Copacabana Neighborhood, Brazil. Climate 7, 65. https://doi.org/10.3390/cli7050065

Bathaei, B., Abdel-Raheem, M., 2022. Parameters Affecting Selection of the Mitigation Strategies of Heat Island Effect, in: Walbridge, S., Nik-Bakht, M., Ng, K.T.W., Shome, M., el Damatty, A., Lovegrove, G. (Eds.), Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021, Lecture Notes in Civil Engineering. Springer Nature Singapore, Singapore, pp. 465–477. https://doi.org/10.1007/978-981-19-0503-2_38

Berger, M., 2014. The Unsustainable City. Sustainability 6, 365–374. https://doi.org/10.3390/su6010365
Bosch Padros, M., 2021. Spatiotemporal patterns of urbanization during the last four decades in Switzerland and their impacts on urban heat islands. https://doi.org/10.5075/EPFL-THESIS-8141
Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landsc. Urban Plan. 97, 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006
Cheela, V.R.S., John, M., Biswas, W., Sarker, P., 2021. Combating Urban Heat Island Effect—A Review of Reflective Pavements and Tree Shading Strategies. Buildings 11, 93. https://doi.org/10.3390/buildings11030093
Cortes, A., Rejuso, A.J., Santos, J.A., Blanco, A., 2022. Evaluating mitigation strategies for urban heat island in Mandaue City using ENVI-met. J. Urban Manag. 11, 97–106. https://doi.org/10.1016/j.jum.2022.01.002
de Munck, C., Pigeon, G., Masson, V., Meunier, F., Bousquet, P., Tréméac, B., Merchat, M., Poeuf, P., Marchadier, C., 2013. How much can air conditioning increase air temperatures for a city like Paris, France? Int. J. Climatol. 33, 210–227. https://doi.org/10.1002/joc.3415
Deilami, K., Kamruzzaman, Md., 2017. Modelling the urban heat island effect of smart growth policy scenarios in Brisbane. Land Use Policy 64, 38–55. https://doi.org/10.1016/j.landusepol.2017.02.027
Edwards, M.M., 2010. How Possible is Sustainable Urban Development? An Analysis of Planners' Perceptions about New Urbanism, Smart Growth and the Ecological City. Plan. Pract. Res. 25, 417–437. https://doi.org/10.1080/02697459.2010.511016
Godschalk, D.R., 2007. Land Use Planning Challenges: Coping with Conflicts in Visions of Sustainable Development and Livable Communities. J. Am. Plann. Assoc. 70, 5–13. https://doi.org/10.1080/01944360408976334
Holden, E., Linnerud, K., Banister, D., 2014. Sustainable development: Our Common Future revisited. Glob. Environ. Change 26, 130–139. https://doi.org/10.1016/j.gloenvcha.2014.04.006
IISD [WWW Document], n.d. . Sustain. Dev. URL https://www.iisd.org/mission-and-goals/sustainable-development (accessed 2.14.23).
Jakubcionis, M., Carlsson, J., 2017. Estimation of European Union residential sector space cooling potential. Energy Policy 101, 225–235. https://doi.org/10.1016/j.enpol.2016.11.047
Johnson, M.P., 2001. Environmental Impacts of Urban Sprawl: A Survey of the Literature and Proposed Research Agenda. Environ. Plan. Econ. Space 33, 717–735. https://doi.org/10.1068/a3327
Karuppannan, S., Baharuddin, Z.M., Sivam, A., Daniels, C.B., 2013. Urban Green Space and Urban Biodiversity: Kuala Lumpur, Malaysia. J. Sustain. Dev. 7, p1. https://doi.org/10.5539/jsd.v7n1p1
Kim, J.-I., Jun, M.-J., Yeo, C.-H., Kwon, K.-H., Hyun, J.Y., 2019. The Effects of Land Use Zoning and Densification on Changes in Land Surface Temperature in Seoul. Sustainability 11, 7056. https://doi.org/10.3390/su11247056
Kong, F., Yin, H., James, P., Hutyra, L.R., He, H.S., 2014. Effects of spatial pattern of greenspace on urban cooling in a large metropolitan area of eastern China. Landsc. Urban Plan. 128, 35–47. https://doi.org/10.1016/j.landurbplan.2014.04.018
Lemonsu, A., Viguié, V., Daniel, M., Masson, V., 2015. Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). Urban Clim. 14, 586–605. https://doi.org/10.1016/j.uclim.2015.10.007
Lhotka, O., Kyselý, J., Farda, A., 2018. Climate change scenarios of heat waves in Central Europe and their uncertainties. Theor. Appl. Climatol. 131, 1043–1054. https://doi.org/10.1007/s00704-016-2031-3

Loughner, C.P., Allen, D.J., Zhang, D.-L., Pickering, K.E., Dickerson, R.R., Landry, L., 2012. Roles of Urban Tree Canopy and Buildings in Urban Heat Island Effects: Parameterization and Preliminary Results. J. Appl. Meteorol. Climatol. 51, 1775–1793. https://doi.org/10.1175/JAMC-D-11-0228.1
Mohajerani, A., Bakaric, J., Jeffrey-Bailey, T., 2017. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. J. Environ. Manage. 197, 522–538. https://doi.org/10.1016/j.jenvman.2017.03.095
Moretti, L., Cantisani, G., Carpiceci, M., D'Andrea, A., Del Serrone, G., Di Mascio, P., Loprencipe, G., 2021. Effect of Sampietrini Pavers on Urban Heat Islands. Int. J. Environ. Res. Public. Health 18, 13108. https://doi.org/10.3390/ijerph182413108
Mughal, M.O., Li, X.-X., Norford, L.K., 2020. Urban heat island mitigation in Singapore: Evaluation using WRF/multilayer urban canopy model and local climate zones. Urban Clim. 34, 100714. https://doi.org/10.1016/j.uclim.2020.100714
Nabielek, K., 2012. Stedelijke verdichting: een ruimtelijke verkenning van binnenstedelijk wonen en werken. Planbureau voor de Leefomgeving, Den Haag.
Næss, P., Saglie, I.-L., Richardson, T., 2020. Urban sustainability: is densification sufficient? Eur. Plan. Stud. 28, 146–165. https://doi.org/10.1080/09654313.2019.1604633
O'Malley, C., Piroozfarb, P.A.E., Farr, E.R.P., Gates, J., 2014. An Investigation into Minimizing Urban Heat Island (UHI) Effects: A UK Perspective. Energy Procedia 62, 72–80. https://doi.org/10.1016/j.egypro.2014.12.368
Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Bréon, F.-M., Nan, H., Zhou, L., Myneni, R.B., 2012. Surface Urban Heat Island Across 419 Global Big Cities. Environ. Sci. Technol. 46, 696–703. https://doi.org/10.1021/es2030438
Phelan, P.E., Kaloush, K., Miner, M., Golden, J., Phelan, B., Silva, H., Taylor, R.A., 2015. Urban Heat Island: Mechanisms, Implications, and Possible Remedies. Annu. Rev. Environ. Resour. 40, 285–307. https://doi.org/10.1146/annurev-environ-102014-021155
Piracha, A., Chaudhary, M.T., 2022. Urban Air Pollution, Urban Heat Island and Human Health: A Review of the Literature. Sustainability 14, 9234. https://doi.org/10.3390/su14159234
Pompeii II, W.C., Hawkins, T.W., 2011. Assessing the impact of green roofs on urban heat island mitigation: A hardware scale modeling approach. Geogr. Bull. - Gamma Theta Upsilon 52, 52–61.
Razzaghmanesh, M., Beecham, S., Salemi, T., 2016. The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. Urban For. Urban Green. 15, 89–102. https://doi.org/10.1016/j.ufug.2015.11.013
Ritchie, H., Roser, M., 2018. Urbanization [WWW Document]. OurWorldInData.org. URL https://ourworldindata.org/urbanization (accessed 9.30.22).
Rustemeyer, N., Howells, M., 2021. Excess Mortality in England during the 2019 Summer Heatwaves. Climate 9, 14. https://doi.org/10.3390/cli9010014
Sachs, J.D., 2015. Achieving the sustainable development goals. J. Int. Bus. Ethics 8, 53–62.
Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., Wang, M., 2014. Anthropogenic heating of the urban environment due to air conditioning: Anthropogenic Heating due to AC. J. Geophys. Res. Atmospheres 119, 5949–5965. https://doi.org/10.1002/2013JD021225
Santamouris, M., 2014. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol. Energy 103, 682–703. https://doi.org/10.1016/j.solener.2012.07.003
Singh, R., Arrighi, J., Jjemba, E., Strachan, K., Spires, M., Kadihasanoglu, M., 2019. Heatwave Guide for Cities.
Solcerova, A., van de Ven, F., Wang, M., Rijsdijk, M., van de Giesen, N., 2017. Do green roofs cool the air? Build. Environ. 111, 249–255. https://doi.org/10.1016/j.buildenv.2016.10.021

Threlfall, C.G., Mata, L., Mackie, J.A., Hahs, A.K., Stork, N.E., Williams, N.S.G., Livesley, S.J., 2017. Increasing biodiversity in urban green spaces through simple vegetation interventions. J. Appl. Ecol. 54, 1874–1883. https://doi.org/10.1111/1365-2664.12876
Threlfall, C.G., Williams, N.S.G., Hahs, A.K., Livesley, S.J., 2016. Approaches to urban vegetation management and the impacts on urban bird and bat assemblages. Landsc. Urban Plan. 153, 28–39. https://doi.org/10.1016/j.landurbplan.2016.04.011
Tzavali, A., Paravantis, J., Mihalakakou, G., Fotiadi, A., Stigka, E., 2015. Urban heat island intensity: A literature review 24.
Vaidyanathan, A., Malilay, J., Schramm, P., Saha, S., 2020. Heat-Related Deaths — United States, 2004–2018. MMWR Morb. Mortal. Wkly. Rep. 69, 729–734. https://doi.org/10.15585/mmwr.mm6924a1
Vuckovic, Loibl, Tötzer, Stollnberger, 2019. Potential of Urban Densification to Mitigate the Effects of Heat Island in Vienna, Austria. Environments 6, 82. https://doi.org/10.3390/environments6070082
Yang, J., Mohan Kumar, D. llamathy, Pyrgou, A., Chong, A., Santamouris, M., Kolokotsa, D., Lee, S.E., 2018. Green and cool roofs' urban heat island mitigation potential in tropical climate. Sol. Energy 173, 597–609. https://doi.org/10.1016/j.solener.2018.08.006
Yang, L., Qian, F., Song, D.-X., Zheng, K.-J., 2016. Research on Urban Heat-Island Effect. Procedia Eng. 169, 11–18. https://doi.org/10.1016/j.proeng.2016.10.002
Zhang, Y., Murray, A.T., Turner, B.L., 2017. Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona. Landsc. Urban Plan. 165, 162–171. https://doi.org/10.1016/j.landurbplan.2017.04.009
Zhang, Z., Paschalis, A., Mijic, A., Meili, N., Manoli, G., van Reeuwijk, M., Fatichi, S., 2022. A mechanistic assessment of urban heat island intensities and drivers across climates. Urban Clim. 44, 101215. https://doi.org/10.1016/j.uclim.2022.101215