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ACCESS TO URBAN COOL AND GREEN SPACES FOR OLD ADULTS IN GOTHENBURG – A GIS-BASED ANALYSIS OF RADIANT HEAT

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But not only does this work mark the end of a scientific chapter, but it is also the conclusion to a chapter in life – the decision to move abroad in the midst of a global pandemic. It was a time with many challenges and way more benefits. This would not have been possible without amazing people entering into my life and making me want to stay. I want to deeply thank all the people I met here and who have become friends – hopefully lasting beyond this period. Our shared moments of both struggle and joy have been the essence of my time here and they have contributed a lot to my personal growth.

Front cover: Urban vegetation in Kungsparken, Gothenburg; © Per Pixel Petersson/imagebank.sweden.se

Abstract

Old adults are particularly vulnerable against heat stress. Considering the ageing society and the projected increase of heat events, planning for heat-resilient urban environments for old adults will become increasingly important. As the city of Gothenburg aims to provide access to cool islands to its citizens, the thermal conditions for old adults in the city have been analyzed and the access of old adults to cool and green spaces has been assessed in this study. The QGIS tool SOLWEIG has been used to model mean radiant temperature distribution in the city, which is a suitable indicator for human heat stress. A district-wise analysis of these outputs as well as vegetation and building characteristics has been conducted. The results demonstrate that there is no considerable variation in average thermal risk conditions for different district-wise densities of old adults. The average distance to urban cool and green spaces is slightly higher in districts with very high densities of old adults than in districts with low density of old adults. Five hotspot areas have been identified where many old adults are living and the distance to cool and green spaces is particularly high. The availability of tree cover and canopy volume has been found to have direct influence on risk-minimizing conditions for old adults. Changing the canopy cover in an area has a stronger effect on thermal conditions compared to changing canopy volume. An influence of urban geometry is observable as well, especially in dense areas with little vegetation around the city centre. Derived recommendations for urban planners include reaching a higher tree cover in districts with little vegetation. However, in a nordic setting, this must be carefully elaborated due to pronounced cool stress conditions in the winter.

Keywords: urban climate, heat stress, mean radiant temperature, SOLWEIG, urban vegetation, urban planning

Popular Science Summary

In Gothenburg, areas with a lot of old adults are not more protected against heat stress than other areas. This study demonstrates that the distance to cool and green spaces is slightly longer in areas where a lot of old adults are living.

Old adults are more vulnerable to heat than other age groups. Cities, where a lot of old adults are living in a small area, must thus prepare for heat events in a future climate to protect their citizens. The most important indicator for heat stress is not air temperature, but exposure to solar radiation. At an air temperature of 20°C, it can feel very warm in the sun, but also a little chilly in the shade. Shading from trees can thus help to reduce heat stress in cities.

In this study, I looked for places in Gothenburg where the risk for heat stress for old adults is especially high. I also analyzed how the distribution of buildings and vegetation is influencing the risk for heat stress. For this reason, I modeled heat stress for the whole city of Gothenburg for a hot summer day. With these results, I calculated the distance to cool and green spaces and related it to vegetation and building characteristics for different districts in Gothenburg.

The results show that heat conditions are quite evenly distributed, no matter how many old adults are living in the districts. The distance to cool and green spaces increases a bit for districts where a lot of old adults are living. In dense areas around the city centre, there is little vegetation to provide shading, but the shading from buildings also contributes to avoiding heat stress. However, the calculations make clear that tree cover is a good measure to reduce heat stress risk in the city. Additionally, vegetation has many benefits for human health, so planners should try to increase the share of vegetation in dense urban areas. But there are some trade-offs with trees, as they block the sun also in the cold seasons. Planners must keep this in mind and be careful when planning vegetation in dense districts!

I identified five districts where a lot of old adults are living and the distance to cool and green spaces is especially far. These districts are all very dense and have a very low tree cover. These are districts that planners can address first if they want to introduce measures to improve the protection of old adults against outdoor heat stress. However, it has to be carefully discussed whether adaptive measures for thermal conditions in these districts are practical and justified.

Contents

1 Introduction

1.1 Background

Worldwide urban population is increasing. In 2020, 4.4 billion people were living in urban areas, corresponding to 56.2 per cent of the global population. Projections for 2035 show an urban population of 5.6 billion (62.5 per cent) (UN-Habitat, 2020). Hence, urban areas are crucial to consider for assessing human wellbeing. At the same time, many societies - particularly in Europe and North America - are ageing (UN-DESA, 2019), resulting in an increasing number of old adults living in cities. Their needs and vulnerabilities thus will play an increasing role in planning cities as a livable place for all parts of society.

The United Nations 2030 Agenda for Sustainable Development dedicates SDG11 to sustainable cities and communities. Subgoal 11.5 aims to reduce the number of people affected by disasters, with focus on vulnerable groups (United Nations, 2015). Events of excessive heat have caused high numbers of deaths in cities especially among the older population, for example the 2003 heatwave in Europe with more than 2000 excess deaths in Paris alone (Le Tertre et al., 2006). With ongoing climate change, extreme heat events are expected to increase in both frequency and intensity (IPCC, 2021), resulting in heat stress and mortality as a growing problem. This applies especially to old adults, as they are particularly vulnerable to thermal stress (Stapleton et al., 2014). Additionally, urban areas tend to show higher temperatures compared to their surroundings, as a result of the urban built environment and human activity (Rizwan et al., 2008). These factors together demonstrate that urban heat stress and its implications especially for old adults will become an increasingly important issue in the coming decades. Urban vegetation can, among many other benefits for human health and environmental resilience, contribute to mitigating urban heat. Therefore, recommendations regarding vegetation for a healthy urban environment have been forwarded and numerous strategic documents from international cities are already aiming for introducing more vegetation in their urban structure (van den Bosch, 2021).

Previous research suggests that although heat-related risks are expected to be more serious in other parts of Europe (Thorsson et al., 2017), the issue should be considered serious also in Scandinavian cities, considering the projected increase in future summer temperatures (Rocklöv & Forsberg, 2008). In their *miljö- och klimatprogram 2021–2030* the city of Gothenburg aims to provide its citizens access to “cool islands” as a measure of climate change adaptation (Göteborgs stad, 2020). However, the same report states that the status quo has not yet been assessed at a city scale. Therefore, this study is going to assess the availability of cool and green spaces in Gothenburg with a focus on old adults, since they are particularly vulnerable to heat-related risks.

1.2 Aim and research questions

While a previous thesis assessed the access to cool islands around elderly care institutions in Gothenburg (Kalori & Lind, 2021), this study aims to extend this objective to a city-scale. The access of urban cool and green spaces for old adults in Gothenburg will be assessed through modelling of thermal conditions and district-level analysis of the modelling outputs. This aim will be fulfilled by addressing the following research questions:

- Are areas with varying densities of old adults showing varying thermal conditions?
- What are influential factors for the thermal conditions?
- How far is the distance to cool and green spaces in Gothenburg?
- Where are hotspot areas of concern for urban planning regarding heat-related risks for old adults?

2 Theoretical Background

2.1 Urban Climate

The urban environment consists of numerous different structures with varying characteristics such as buildings, paved surfaces or trees and bushes. The distribution of these elements and the resulting complex interaction of energy fluxes determines the formation of various microclimates within a city (Bourbia & Boucheriba, 2010; Lindberg et al., 2016; Shashua-Bar et al., 2009). Buildings are blocking incoming solar radiation but also represent a thermal mass that can store and release heat together with paved surfaces. This great thermal mass causes the formation of a macroclimate within the urban boundary layer (Coutts et al., 2007).

In general, urban areas show higher mean air temperatures compared to their surroundings, as a result of the dense urban built environment with a greater thermal mass and human activity (Coutts et al., 2007; Rizwan et al. 2008). The formation of this Urban Heat Island (UHI) is mainly a nocturnal phenomenon due to the emission of sensible heat stored in buildings and surfaces at nighttime. The lack of vegetation to provide evaporative cooling further contributes to the UHI formation (Erell & Williamson, 2007). During the day, however, a dense urban geometry can lead to the formation of an Intra-Urban Cool Island with slightly lower temperatures in the city centre compared to suburban districts (Erell & Williamson, 2007). This effect is however minimal and not always observable.

Microclimatic thermal conditions are dominated by sunlight exposure and shading from both built structures and vegetation (Ali-Toudert & Mayer, 2007; Chen et al., 2016; Lindberg et al., 2016). It is thus the radiation influx that has the biggest influence on thermal comfort. This influx is composed of various parameters such as direct shortwave radiation from the sun, scattered radiation from the sky and reflected shortwave or emitted longwave radiation from walls and surfaces. Especially on warm and clear days, very distinct thermal microclimates can be observed. The influence of shading from urban geometry and trees can be particularly big in these conditions (Ali-Toudert & Mayer, 2007). Emission of stored heat from surfaces is also playing a role but is less important (Lindberg et al., 2016).

A commonly used concept for investigating urban microclimates is the sky view factor (SVF) (Oke et al., 2017). It describes the visibility of the sky as a rate from 0 to 1. While 0 means that the sky is completely obstructed by e.g. buildings or vegetation, a SVF of 1 describes a totally open setting with no obstacles to block the view of the sky from a specific point of view (Lindberg et al., 2018). This makes SVF a useful tool to quantify incoming radiation and solar access, thus it is widely applied for assessing the thermal conditions in urban microclimates (e.g. Oliveira et al., 2011; Thorsson et al., 2011).

2.2 Mean Radiant Temperature as an indicator of heat stress and mortality

Air temperature is quite evenly spread among different urban environments during daytime and does therefore not well represent the great thermal variability of urban microclimates. A parameter that can however measure the spatial variations in thermal comfort conditions is the mean radiant temperature (T_{mrt}). Previous studies present large local differences (>30°C) in T_{mrt} between sunlit and shaded spots, while air temperature remains rather stable (Ali-Toudert &

Mayer, 2007; Oliveira et al., 2011). A commonly used definition of T_{mrt} in literature is "the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space" (ASHRAE, 2004). In easier words, it is a temperature index that sums up the effects of all radiation fluxes (long- and shortwave; direct, reflected and emitted) the human body is exposed to (Kántor & Unger, 2011).

The most accurate method to determine T_{mrt} is to use incoming and outgoing radiation fluxes from all six directions: north, east, south, west, up and down (Thorsson et al., 2007). Detailed descriptions how to calculate and measure T_{mrt} are explained by Kántor & Unger (2011) and by Thorsson et al. (2007) and will be briefly presented here:

The mean radiant flux density (S_{str}) of the human body is required to calculate T_{mrt}:

$$S_{str} = \alpha_k \sum_{i=1}^{6} K_i F_i + \varepsilon_\rho \sum_{i=1}^{6} L_i F_i$$

K_i	=	shortwave radiation fluxes
L_i	=	longwave radiation fluxes
F_i	=	angular factors between a person and the surrounding surfaces (for a standing person: 0.22 for radiation fluxes from the cardinal points (N, E, S, W); 0.06 for fluxes from above and below)
α_k	=	absorption coefficient for shortwave radiation (standard value 0.7)
ε_ρ	=	emissivity of the human body (standard value 0.97)

T_{mrt} in °C can then be calculated using the Stefan-Boltzmann law:

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{\varepsilon_\rho \sigma}} - 273.15$$

σ	=	Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$)

Since in clear and calm conditions the radiant environment is dominating thermal conditions in outdoor settings, T_{mrt} is a better indicator of human thermal comfort and thus heat stress than air temperature (Kántor & Unger, 2011; Mayer & Höppe, 1987). T_{mrt} is used to calculate other thermal comfort indexes such as the physiological equivalent temperature (PET) (Mazarakis et al., 1999). Thorsson et al. (2014) also describe T_{mrt} as a much better predictor of heat-related mortality than air temperature.

2.3 Urban vegetation and its role for heat mitigation and human health

Since sunlight exposure is the dominant cause of excessive heat and steering T_{mrt}, shading through vegetation, especially trees, is an effective way to mitigate heat and lower T_{mrt}. Several field studies demonstrate this effect (Ali-Toudert & Mayer, 2007; Lee et al., 2013; Oliveira et al., 2011). Vegetation also contributes to heat mitigation to some extent through evaporative cooling (Gromke et al., 2015; Konarska et al., 2016). Shashua-Bar et al. (2009) conclude that vegetation (particularly a combination of grass surface with tree canopy cover) is a superior heat mitigator in comparison to other measures available in urban environments.

Other than heat mitigation, urban vegetation provides more benefits for human health and wellbeing. Previous studies have found positive effects on mental health, particularly the value of vegetation for recreation, stress release and decreased levels of depression (Wolf et al., 2020). Several benefits for physical health have been postulated, such as increased physical activity or reduced stroke mortality. These effects are however often hardly quantified or vulnerable to bias (Lee & Maheswaran, 2011). Furthermore, urban vegetation can reduce noise and levels of air pollution in larger green areas (Klingberg et al., 2017a). Other ecosystem services of urban vegetation include increased biodiversity in cities (Threlfall et al., 2017) and regulation of stormwater runoff (Berland et al., 2017). Benefits from urban vegetation are reaching from single street trees (Mullaney et al., 2015) to bigger green spaces and parks (Lee & Maheswaran, 2011).

Considering its numerous benefits, guidelines regarding urban vegetation have been suggested that aim for a healthy urban environment. A suggestion that has recently raised attention is the *3-30-300 rule* (von den Bosch, 2021). The author recommends the following subgoals:

- A minimum of three mature trees should be visible from every home.
- Tree canopy cover should be at least 30%. This goal has been adapted by several cities such as Barcelona (Ajuntament de Barcelona, 2017) and Seattle (City of Seattle, 2013).
- The distance to the closest green space should not exceed 300m.

2.4 The effect of heat stress on old adults

The issue of heat stress affects all parts of the population, but not everyone to the same extent. Groups like people with chronic diseases and old adults are particularly vulnerable to heat-related risks (Kenny et al., 2010). Ageing bodies are not able to adapt their cardiovascular activity to thermal stress as good as younger bodies. Additionally, the different skin properties of old adults further weaken the response to thermal stress (Kenney et al., 2014; Kenny et al., 2010). This leads to a higher rate of heat gain and hence to greater thermal discomfort for old adults compared to young adults (Stapleton et al., 2014).

Consequences of these compromised responses of old adults to thermal stress are an increased occurrence of pneumonia, dehydration, cardiovascular diseases, hypo-/hyperthermia or heat stroke (Kenny et al., 2010; van Hoof et al., 2017). The result is an increased morbidity and mortality risk for old adults under heat stress. It is notable that few of the excess heat deaths are directly caused by the mentioned effects of heat stress, these effects rather serve as a contributing factor to mortality (Kenney et al., 2014).

Thorsson et al. (2014) demonstrate that maximum daily T_{mrt} is the best predictor for mortality among adults aged 80 years and older. Their conclusion is that this age group is thus more vulnerable to daytime heat stress than nighttime stress. According to Rocklöv et al. (2011), the 80+ age group shows a significant increase in mortality risk for daily hot temperatures, while the risk for younger groups increased only after an extended heat period. Accordingly, conditions of increasing risk for old adults occur more easily and thus more frequently than for younger age groups. This further increases the vulnerability of old adults against excessive heat.

3 Study Area

The city of Gothenburg (57.70° N, 11.94° E) is located in the Västra Götaland county on the Swedish west coast surrounding the Göta Älv estuary (figure 1). With its 588 000 inhabitants, it is the country's second biggest city (Göteborgs stad, 2022a). Gothenburg's population is growing and the same is expected for the number of old adults (80 years and older) in the city, from 23100 in 2021 to 36100 in 2035 (Göteborgs stad, 2022a). Hence, currently the share of old adults in Gothenburg is 3.9%. As of 2022, the Gothenburg municipality is divided into 1014 small-scale districts (Basområden) of varying size and population. The division into these districts is based on the goal that the building structure in each district is as homogenous as possible (Göteborgs stad, 2022b).

Gothenburg's coastal location at a fairly high northern latitude determines its climate with cool winters, mild summers and a moderately high precipitation. Despite the projected increase in air temperature, T_{mrt} in Gothenburg is not expected to increase as much as elsewhere in Europe (Thorsson et al., 2017).

The city centre of Gothenburg is characterized by a typical European dense mid-rise building structure with little vegetation. The city is very spread out with many suburban districts that have been built as part of the Swedish 'Million Homes Program' in the in the 1960s and 70s (Hall & Vidén, 2005). These districts typically show a rather open mid-rise building structure with a lot of parks and vegetation. Göteborgs Skärgard, the archipelago southwest of the city that is part of the municipality, is not included in the used datasets and is hence not part of the study area.

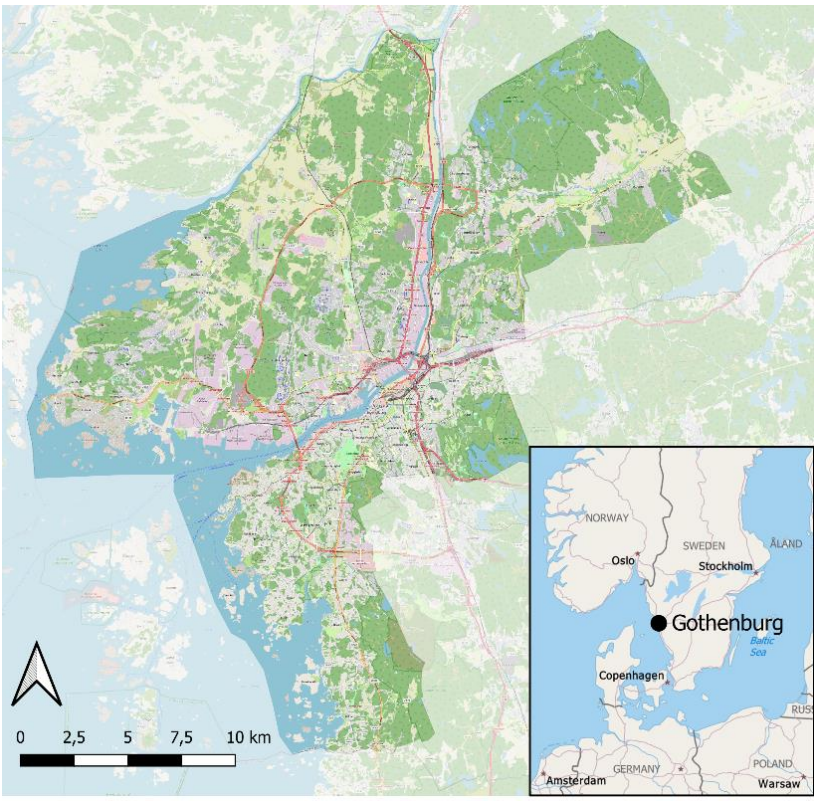

Figure 1: Overview map of Gothenburg. Basemap: OpenStreetMap

4 Material and Methods

4.1 Study design

The study is designed as a GIS-based quantitative analysis of T_{mrt} at a city scale, using the program QGIS (v3.18). The QGIS plugin Urban Multi-Scale Environmental Predictor (UMEP) includes the Solar and LongWave Environmental Irradiance Geometry model (SOLWEIG) and SOLWEIG Analyzer. These tools have been used to model and analyze T_{mrt} distribution throughout the city during a warm and clear summer day. Before the model run, available input data has been updated manually. The output from SOLWEIG has been processed in QGIS and prepared for further analysis.

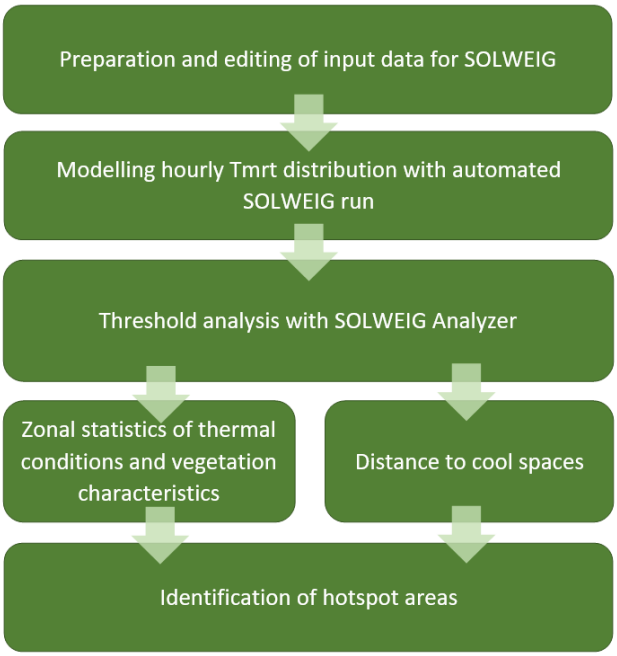

Figure 2: Overview over the study design

Population data have been gathered to identify the areas of residence of old adults in the city. This data has been used to analyze thermal conditions and vegetation characteristics on a district level and assess the access of old adults to cool and green spaces in Gothenburg. Since the used research is based on adults aged 80 years and older, the term 'old adults' refers to this age group in this study. Figure 2 gives an overview over the study design.

4.2 The Solar and LongWave Environmental Irradiance Geometry model (SOLWEIG)

SOLWEIG (v2019a) is a 2.5-dimensional model that can simulate spatial variations of radiation fluxes and T_{mrt} in urban environments (Lindberg et al., 2008). It derives T_{mrt} using radiation fluxes from six directions, as presented in chapter 2.2 and in Thorsson et al. (2007). The input data required for SOLWEIG are:

- Three digital surface models including (1) urban morphology and buildings, (2) vegetation and (3) terrain
- A meteorological time series including air temperature, relative humidity, and global radiation

A land cover dataset as well as time series for direct and diffuse radiation are optional inputs that have been used in this study to improve the accuracy of the simulations. The used version of SOLWEIG (v2019a) uses an anisotropic sky model to estimate diffuse radiation, which leads more accurate T_{mrt} estimates in front of north and south facing walls (Wallenberg et al., 2018).

SOLWEIG has been evaluated and applied numerous times, both in Gothenburg (Lindberg et al. 2008; Thorsson et al., 2011) and internationally (Chen et al., 2016; Thom et al., 2016). It has been deemed more accurate for assessing heat stress than comparable models (Gál & Kántor,

2020). Jähnicke et al. (2016) demonstrate that SOLWEIG is suitable for modelling T_{mrt} at a city-scale with only point measurements of meteorological inputs. SOLWEIG has been found to produce very accurate T_{mrt} values around mid day (10:00-16:00) (Thom et al., 2016), when the highest heat load is expected. This makes it a very applicable model for this study. A detailed description of SOLWEIG and its underlying processes can be found in Lindberg et al. (2008).

4.3 Description and editing of data

4.3.1 Input data for SOLWEIG

The geodata data used for mapping T_{mrt} with SOLWEIG consists of the following grids with the extent of the Gothenburg municipality (without the archipelago):

- a Digital Elevation Model (DEM) in m.a.s.l. with 1m x 1m resolution.
- a Digital Surface Model (DSM) including ground and building elevation in m.a.s.l. with 1m x 1m resolution
- a Canopy Digital Surface Model (CDSM) including canopy heights in m above ground level with 1m x 1m resolution
- a land cover grid with 4m x 4m resolution, containing 7 classes: paved, buildings, evergreen trees, deciduous trees, grass, bare soil and water

The grids are derived from LiDAR data from 2010 (Lindberg et al., 2013). In areas with a lot of recent construction development the DSM and CDSM have been manually updated using a DSM including vegetation with data from 2019 retrieved from Lantmäteriet (2020). Newly built buildings have been added to the grids, removed buildings have been taken away. For the CDSM, only areas where vegetation has been removed have been updated. Newly planted vegetation and vegetation growth since 2010 could not be considered. The land cover grid has been reclassified according to the SOLWEIG input format, so that only ground cover is accounted for. The ground cover classes are paved, building, grass, bare soil and water. The ground cover beneath high vegetation (classified as deciduous trees and conifer trees in the initial grid) has been reclassified as bare soil, using the *Land Cover Reclassifier* included in UMEP. All grids have been resampled to a 2m x 2m resolution in order to limit computation to a reasonable amount.

Additionally, a meteorological dataset including air temperature, relative humidity, direct radiation, diffuse radiation and global radiation in hourly resolution is required for modelling T_{mrt} distribution throughout a day with SOLWEIG. Since no recent continuous measurements of all these parameters together are available for Gothenburg, the meteorological dataset has been derived from the ERA5 reanalysis dataset (Hersbach et al., 2018), retrieved from Rokka (2021). SOLWEIG provides the possibility to calculate direct and diffuse radiation fluxes from global radiation, but Jähnicke et al. (2016) demonstrate that this leads to a loss of accuracy. Therefore, the ERA5 estimates have been chosen instead of stationary measurements of global radiation. To represent a future warmer climate, an exceptionally warm, calm and clear summer day (3 June 2016) has been selected as meteorological forcing, so that the thermal conditions are determined by T_{mrt} (Kántor & Unger, 2011). The meteorological data is presented in Appendix 1.

4.3.2 Population data

Population and age distribution data have been used for zonal statistics to assess the thermal environment in residence areas of old adults. Population data from 2021 for 5-year age classes at small-scale district level (Basområden) has been retrieved from Göteborgs stad (2022a), layers with the spatial extents of the districts are available at Göteborgs stad (2022c). A map of the districts classified by the density of old adults is displayed in Appendix 2.

4.4 Mapping of T_{mrt}

To model T_{mrt} with SOLWEIG, it is required to calculate wall heights and aspects for buildings, as well as the sky view factor for each pixel of the input data. However, the size of the input datasets (15000 x 15000 pixels) was too big to be processed with SOLWEIG in one run. Therefore, the datasets have been tiled into rasters of 700 x 700 pixels (1400m x 1400m), with an overlap of 50 pixels (100m) to avoid the neglection of shading originating from neighboring tiles. The detailed settings used for running SOLWEIG are presented in table 1.

Table 1: Settings used in SOLWEIG

Parameter	Value
Spatial resolution	2m
Temporal resolution	1h
Albedo building walls	0.20
Albedo building roofs	0.18
Emissivity building walls	0.90
Radiation transmissivity through vegetation	0.03
Body longwave absorption	0.97
Body shortwave absorption	0.70
Body as cylinder	Yes
Posture	Standing

The mentioned processes have been automated in the QGIS Graphical Model Builder. The created model (figure 3) selects a desired tile (counter) from a grid, clips the input datasets to this size, and calculates hourly T_{mrt} distribution for the selected tile. The model has been run as a batch process, counting through the different tiles, to obtain T_{mrt} distribution for the whole input dataset extent. This was made possible by slightly adapting the SOLWEIG algorithm. To be able to save the output T_{mrt} maps for the different tiles without overwriting them with every run, SOLWEIG needs permission to create a specified output folder in the given directory in case this folder is not existing. Therefore, the lines below have been inserted into the SOLWEIG algorithm document after line 360 before running the model:

```
# To make it possible to run with spec. output dir
if not (os.path.isdir(outputDir)):
        os.mkdir(outputDir)
```

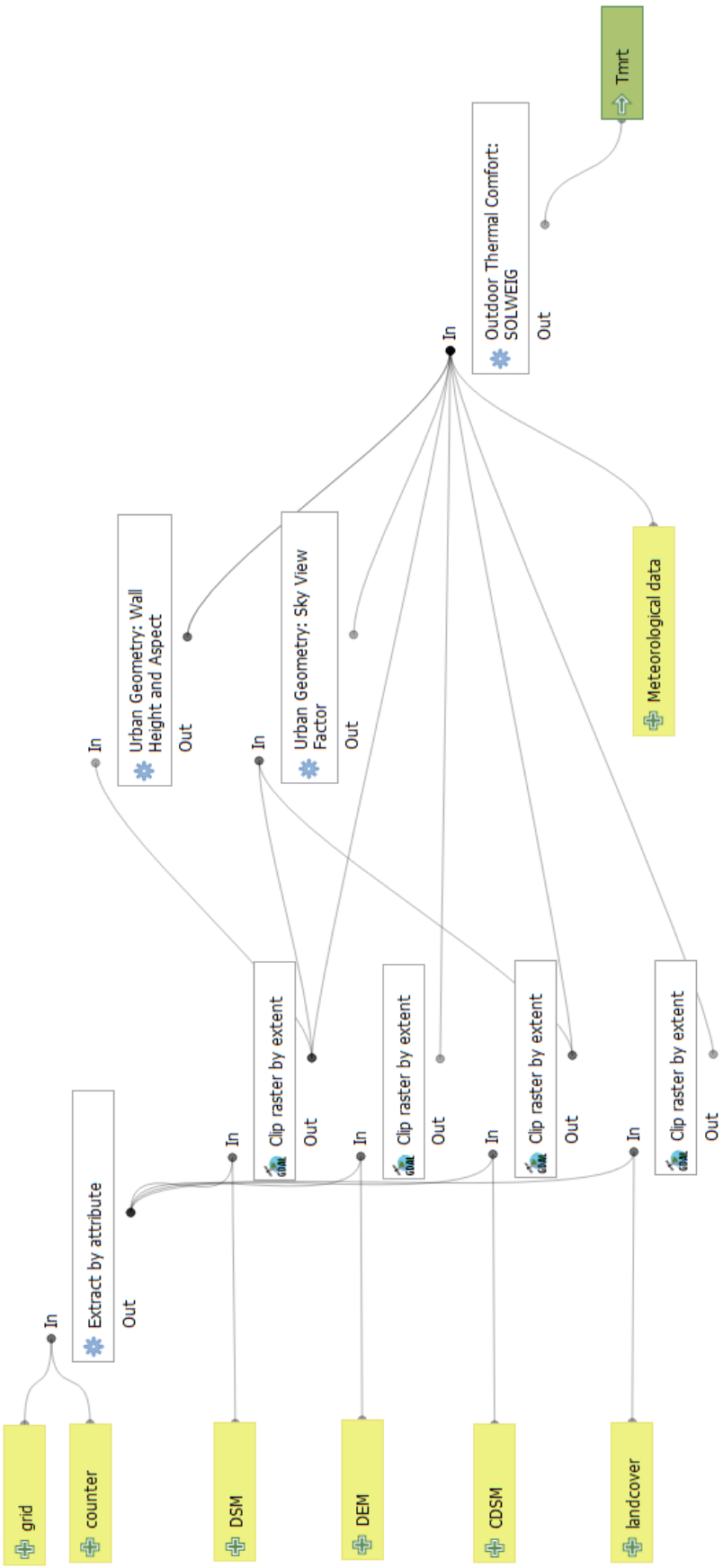

Figure 3: Automated modelling process in the QGIS model builder: yellow boxes are input variables, white boxes are tools in QGIS, the green box represents the output map of T_{mrt}.

4.5 Classification of T_{mrt} distribution into risk levels

The tiles with T_{mrt} distribution have further been investigated using SOLWEIG Analyzer in another batch process. A threshold analysis has been carried out in order to obtain rasters with the share of time that every pixel has exceeded a given T_{mrt} value. The used thresholds to identify risk classes for old adults are presented in Thorsson et al. (2014) and displayed in (table 2).

Table 2: Risk levels with thresholds

Risk level	Risk increase	T_{mrt} (°C) thresholds for ages 80+
0	---	
1	≥ 0	47.6
2	≥ 5	55.5
3	≥ 10	59.4

The analyzed tiles have then been mosaicked to obtain three maps of how many hours the risk thresholds have been exceeded for the whole city of Gothenburg. This was carried out using the *Mosaicking* tool in the SAGA (v. 2.3.2) QGIS plugin. (Conrad et al., 2015). The values in the overlapping areas have been calculated using a blend boundary of 50 pixels, which equals the grid overlap from tiling the datasets. The outputs have been merged into two risk class maps indicating areas (1) where the threshold values are not exceeded and (2) where the threshold values are exceeded for not more than two hours during a hot summer day. The vast majority of hours with increased mortality risk occur at 1 and 2 pm (Thorsson et al., 2014). Furthermore, old adults show behavioral adaptations to heat, which includes staying inside during the hottest hours of the day (van Hoof et al., 2017). Thus, it can be assumed that these hours can be avoided, and it is sufficient to be classified as a cool space if heat-related risk is increased (T_{mrt} > 47.6°C) for not more than two hours during a hot summer day. If not explicitly specified otherwise, the term *risk level* generally refers to scenario (2), an exceedance of the threshold for not more than two hours.

In the maps, inaccessible areas such as highways or railways (derived from Urban Atlas (European Union et al., 2020)) as well as buildings and water surfaces (derived from land cover dataset) have been masked out.

4.6 Distance to cool and green spaces

The distance to cool and green spaces has been calculated using a cost raster. The tool used for this is *r.cost* from the GRASS (v. 7.8.7) QGIS plugin (Neteler et al., 2012). Cool and green spaces have been defined as *canopy-covered areas of at least 400m^2 where T_{mrt} exceeds 47.6°C for not more than two hours*. These criteria have been set because:

- Vegetated shading is preferred over building shading due to the numerous additional benefits of vegetation for human health and wellbeing and other ecosystem services (see chapter 2.3)
- It is assumed that an area of 400m2 (20m x 20m) is not covered by one tree, but it requires several trees to create a shaded area of this size. The proximity of multiple trees

is beneficial for health and wellbeing (van den Bosch, 2021) and other ecosystem services (Mullaney et al., 2015)

- T_{mrt} = 47.6°C is the threshold of increased mortality risk for old adults (Thorsson et al., 2014)
- It can be assumed that the two hours of highest heat stress can be avoided (see chapter 4.5)

By removing inaccessible areas from the raster (see chapter 4.5) and setting the cost for each pixel to two (2m resolution), the obtained distance values are providing some information on the access to green spaces, rather than just the euclidian distance. This makes a cost raster superior to a simple distance raster for the analysis in this study. Before the cost calculation, minor fixes have been made regarding the removed inaccessible spaces. The land cover dataset often ignores bridges where a water stream can be crossed. The same applies to the Urban Atlas dataset for highways and railways, where opportunities to cross these safely are often not represented. This could have remarkable consequences for the calculated distance to the next cool and green space in the surrounding districts. Therefore, these crossings have been added manually for both water streams as well as highways and railways before the distance calculation.

4.7 Zonal statistics

For zonal statistics regarding thermal conditions and vegetation, only districts with a density of more than 100 old adults per km^2 have been investigated. This means exactly half (n=507) of the districts in the Gothenburg municipality have been analyzed, representing 81.6% of the total population of old adults in Gothenburg. This threshold has been set for making the analyzed districts somehow comparable. Accordingly, very rural districts in the outskirts, purely industrial or commercial districts and districts being covered with only park or forest, with only little or no population, have been excluded from the analysis.

The considered districts have then been divided into five density bins according to table 3 in order to assess the availability of cool and green spaces throughout different densities of old adults.

Table 3: Overview over the bins for density of old adults

	density of old adults	**number of districts**	**share of old adults in Gothenburg represented**
Bin 1	>100/km²	202	21.4%
Bin 2	>250/km²	157	22.9%
Bin 3	>500/km²	64	14.1%
Bin 4	>750/km²	29	7.2%
Bin 5	>1000/km²	55	16.0%

4.8 Identification of hotspot areas

The district-wise statistics on population data and distance to cool and green spaces have been used to identify hotspot areas. Two ways of identifying these have been used, filtering the following districts.

- (1) districts that show a very high density of old adults (>1000/km²) and exceed an average distance of 100m to the next cool and green space.
- (2) districts that show a very high share of old adults (>8%, more than twice the share of old adults over the whole city) and exceed an average distance of 100m to the next cool and green space.

Districts under (1) are particularly relevant for urban planning measures regarding thermal conditions for old adults since a high absolute number of old adults in a relatively small area are affected. Districts under (2) however show an especially high share of old adults. Accordingly, it is easier to justify an adaptation of these districts to the needs of old adults.

5 Results

This section will present and analyze different outputs of the modelling and resulting maps by presenting zoom-in examples, as well as zonal statistics on a city scale. Examples from map outputs are presented separately as they can be highly interesting for urban planning authorities. Therefore, it will briefly be described what kind of information can be drawn from the maps produced in this study. Then, the output will be analyzed regarding relevant parameters using zonal statistics. The complete datasets are stored at the Department of Earth Sciences for further usage beyond this study.

5.1 Map outputs

5.1.1 T_{mrt} distribution outputs from SOLWEIG

As output from SOLWEIG, 24 maps have been obtained for every tile, showing T_{mrt} distribution for every hour of the day. Figure 4 shows an example from the city centre at 3pm. The map demonstrates the high dependance of T_{mrt} distribution on solar direction and altitude, as well as the latitude of the location. The shadow patterns in the aerial map are clearly observable in the T_{mrt} distribution. Maximum values occur next to sunlit, southwest-facing walls. In these settings (1) parts of the incoming solar radiation get reflected by the walls and (2) surfaces such as pavements and walls start to emit stored heat in the afternoon (see chapter 2.1). Northeast-facing walls however are shaded and therefore T_{mrt} is low in these areas. Hence, southeast-northwest-oriented canyons that are narrow enough are completely shaded. Bigger tree-covered areas such as parks show consistently low T_{mrt} values. It is notable that in a nordic city like Gothenburg the extension of shaded areas is already remarkable at 3pm, even in summer, due to the relatively low solar altitude. While the T_{mrt} distribution maps clearly demonstrate the influence of urban geometry and vegetation on T_{mrt}, they are only a momentary snapshot of

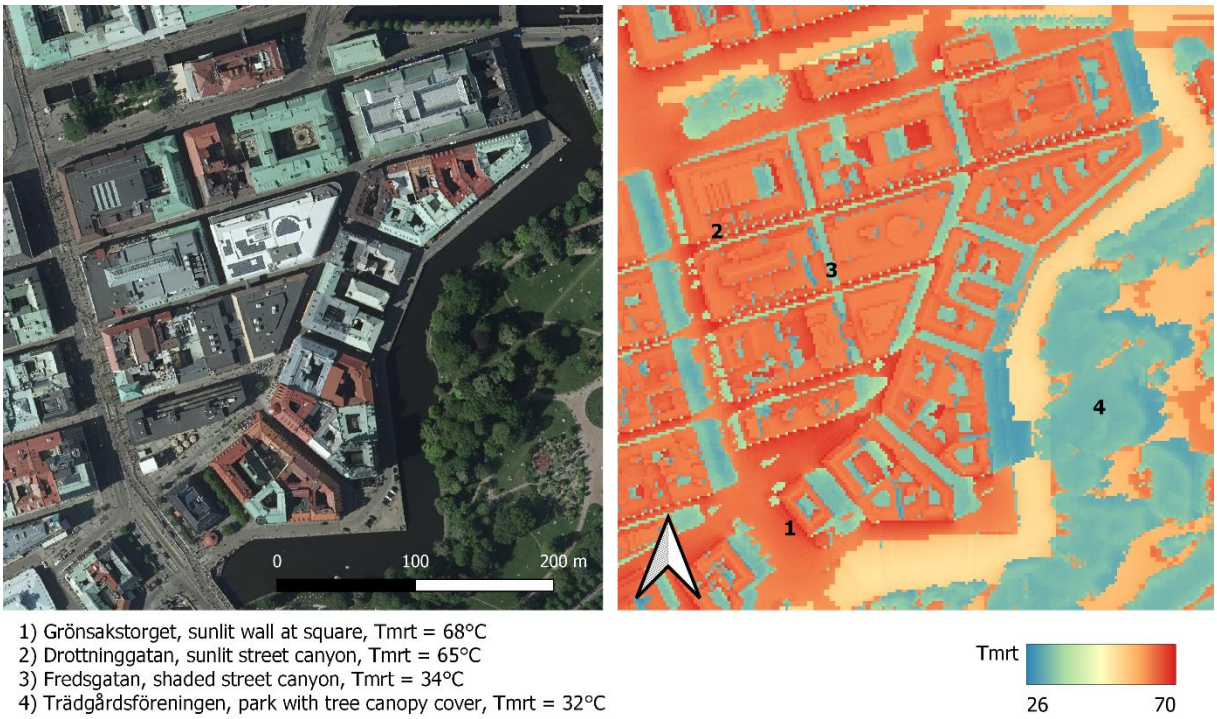

Figure 4: T_{mrt} distribution in central Gothenburg on 3 June 2016 at 3pm. Source aerial map: Läntmäteriet

thermal conditions for one point in time. In order to create spatial information on heat-related risks, the daily course of T_{mrt} distribution has been analyzed and is presented in the following section.

5.1.2 Risk classes

The main output after analyzing the hourly T_{mrt} distribution with SOLWEIG Analyzer are two risk class maps as described in chapter 4.5. Figure 5 shows a comparison of the maps in two exemplary settings:

- (1) Areas where the threshold values are not exceeded and (2) areas where the threshold values are exceeded for not more than two hours
- (a) A compact urban environment in the city centre and (b) a suburban environment in Biskopsgården

The comparison of (1) and (2) shows that areas of no increased risk are remarkably increasing when the two hottest hours are omitted (see also chapter 5.2.2). In the city centre (a), this leads to substantial changes in the thermal environment. In (1a) only areas covered by canopy and very narrow courtyards fall into the 'no risk' class, while most streets are in risk class 4. However, (2a) shows most courtyards and many narrow streets as cool spaces, due to the dense urban geometry which shades the canyons for most of the day. This demonstrates that urban geometry cannot substantially contribute to permanent cooling, but, if dense enough, provides areas of no increased risk when the two hottest hours are omitted.

In the rather open suburban setting (b) these mentioned effects of the urban geometry are not so easily observable. The courtyards are too wide to provide effectful shading throughout the day. On north-facing walls, a slight effect of shading is observable for (2b), but most unvegetated spaces are falling into the highest risk class in both (1b) and (2b).

In both urban environments, larger canopy covered areas are clearly distinguishable by appearing as areas of no increased risk. As mentioned before, the areas of risk class 0 cooled by vegetation are substantially more extensive in (2) than in (1).

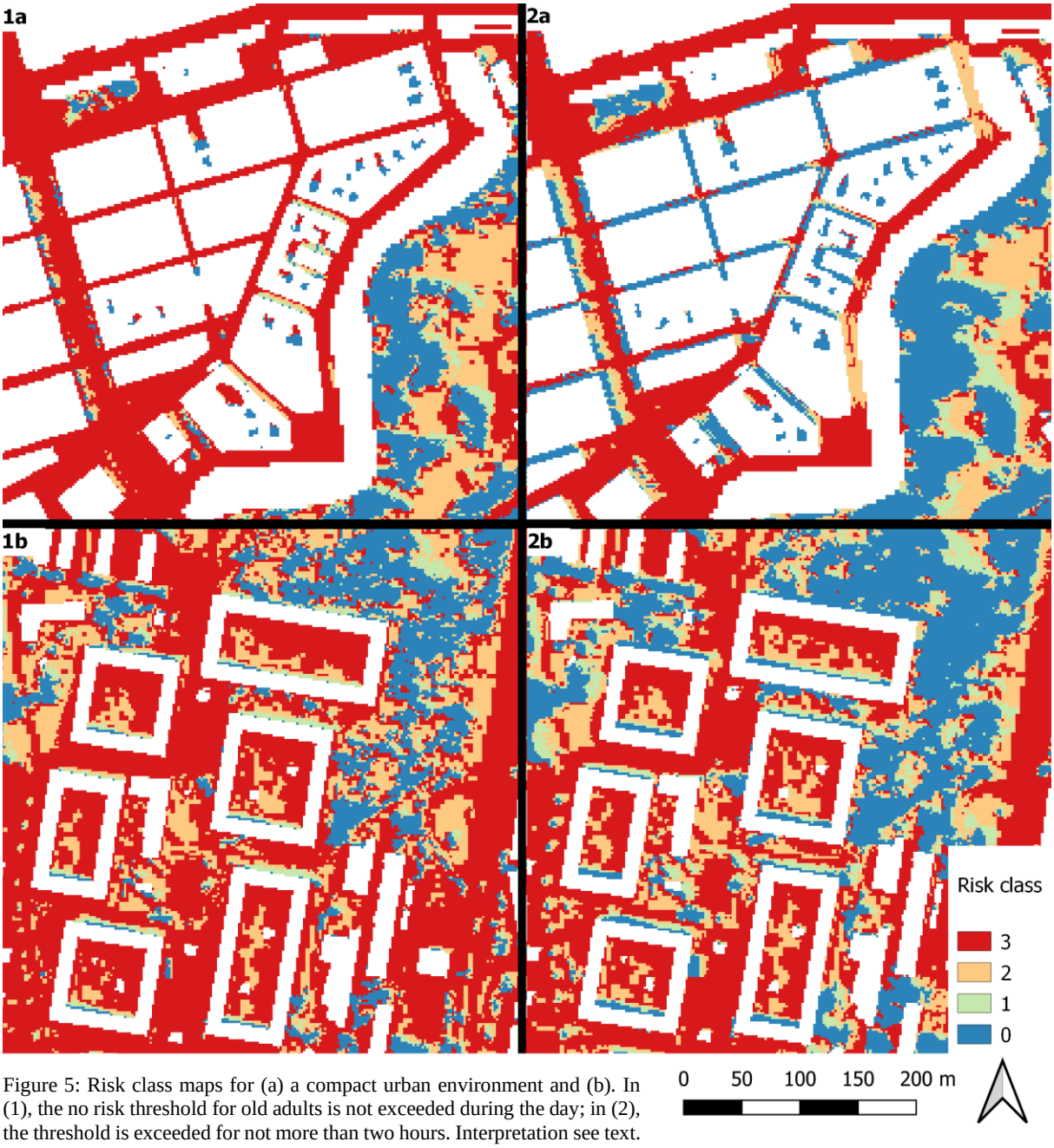

Figure 5: Risk class maps for (a) a compact urban environment and (b). In (1), the no risk threshold for old adults is not exceeded during the day; in (2), the threshold is exceeded for not more than two hours. Interpretation see text.

5.1.3 Distance to cool and green spaces

A cost raster (2m resolution) has been produced presenting the distance from each pixel to the next canopy covered cool space of more than 400m² as described in chapter 4.6. By excluding buildings and inaccessible areas, the values represent the distance to access the next cool and green space rather than euclidian distance. This can lead to situations of concern for urban planning regarding heat on a district level. Two exemplary cases are presented in figure 6. The map shows a part of the city centre with the central station in the north and the park Trädgardsföreningen in the centre. Two remarkable areas with high distances to the next cool and green space are observable, one in the southwest and one in the northeast of the displayed map. In the southwest, the highest distances can be found along the shore of the canal surrounding the old town. The park as a cool and green space is located directly across the canal but can not be accessed directly since there is no opportunity to cross the canal nearby, hence the long distances. The same applies to the situation in the northeast, where the direct way to a cool and green space is blocked by a canal. Additionally, there is a cool and green space in a neighboring courtyard which is however blocked by the surrounding buildings. These cases display well that is essential that cool and green spaces are not only *available* on a neighborhood level but also *accessible* for the residents.

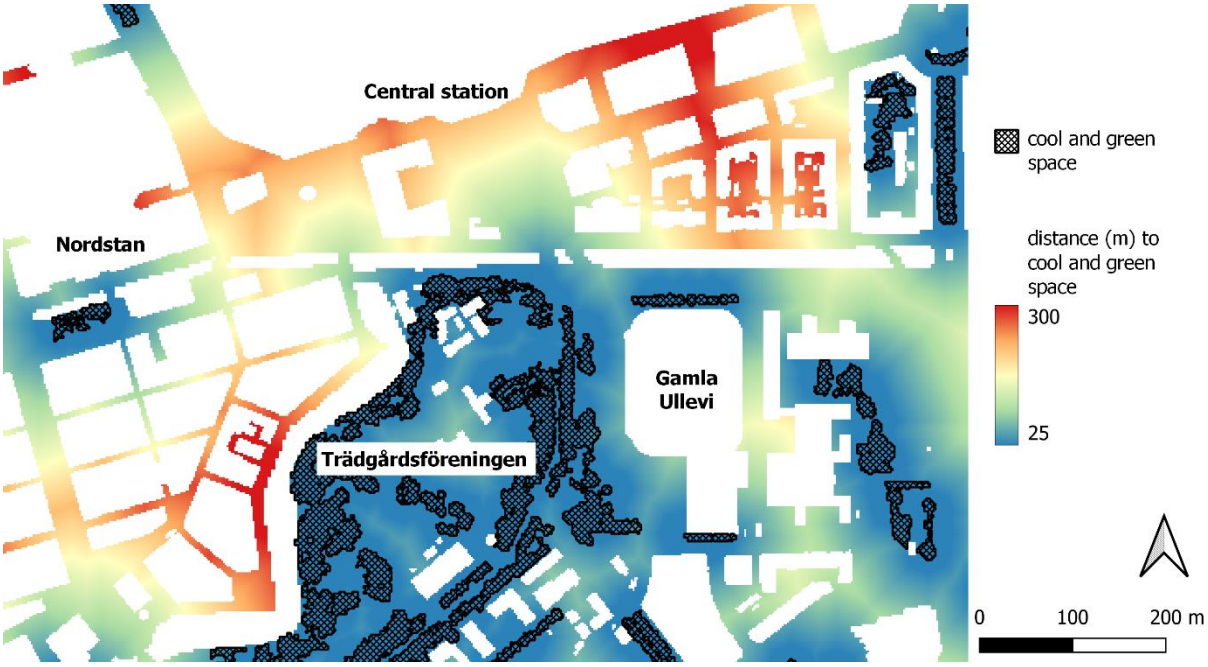

Figure 6: Distance to cool and green spaces in central Gothenburg (interpretation see text).

5.2 Zonal statistics

The risk level maps have been analyzed for the districts where the density of old adults exceeds 100/km². Table 4 gives an overview of the main results from the zonal statistics. It shows averages of relevant parameters by density bin. It is important to note that the share of risk levels is given as share of accessible area (buildings and inaccessible areas masked out; see chapter 4.5), while canopy and building cover are expressed as share of the whole district area. It is notable that the share of risk level 0 with max. 2h exceedance is stable throughout all density bins. The average canopy cover and vegetation volume is decreasing and the average

building cover increasing with increasing density of old adults. The average distance to cool and green spaces is somewhat variable but does not show a remarkable trend throughout the density bins. These findings will be further investigated and discussed in the following chapters.

Table 4: Zonal statistics for the density bins for old adults

Parameter	Bin 1 >100/km²	Bin 2 >250/km²	Bin 3 >500/km²	Bin 4 >750/km²	Bin 5 >1000/km²
Share of old adults over all the districts in the bin (%)	3.2	4.1	5.6	6.7	7.3
Share risk level 0 (no exceedance)	0.22	0.19	0.18	0.19	0.17
Share risk level 0 (max 2h exceedance)	0.36	0.33	0.33	0.35	0.34
Hours of exceedance 47.6°C	4.6	4.8	4.7	4.3	4.3
Canopy cover	0.30	0.25	0.23	0.21	0.19
Vegetation volume (m³/m²)	2.4	2.0	1.8	1.7	1.5
Building cover	0.18	0.21	0.22	0.27	0.26
Distance to canopy-covered cool space >400m²	42m	49m	50m	59m	51m

5.2.1 Zonal histograms for risk levels

The zonal histograms for risk levels (figure 7) show that the share of cool spaces is fairly even across the different density bins. As indicated in the map observation (chapter 5.1.2; figure 5), the share of risk level 0 increases while the share of risk level 3 decreases for (2). The areas classified as risk levels 1 and 2 do not change substantially. An ANOVA has been performed to test the shares of risk level 0 across the density bins for differences. While for (1) the means have been found to be different ($p = 0.009$), this difference does not show when the two hottest hours are avoided ($p = 0.385$). Thus, the share of risk level 0 with max. 2h threshold exceedance can be considered as stable throughout all density bins. This implies that districts with a high density of old adults generally show a similar thermal environment as districts with a low density. Interestingly, this is the case despite the quite high share of old adults in the districts

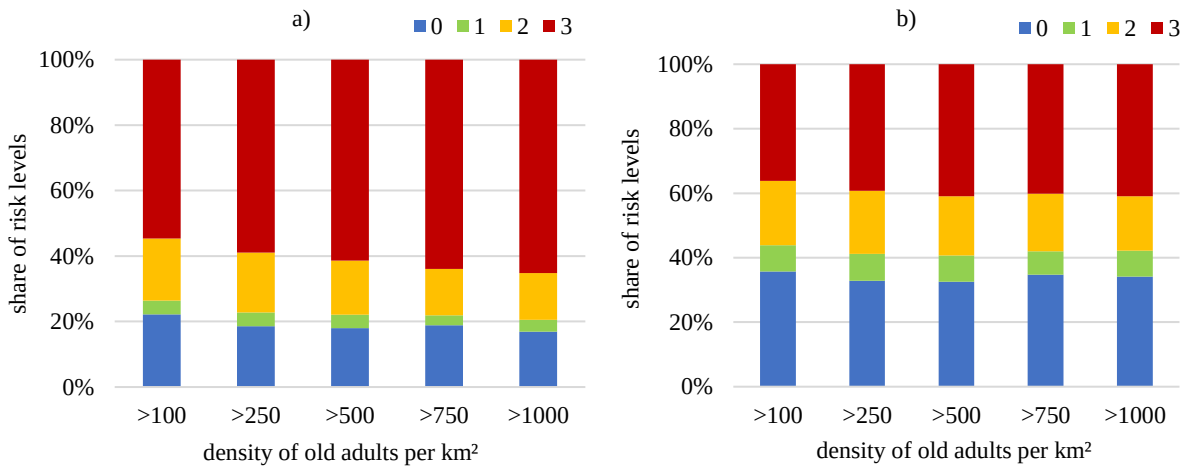

Figure 7: Risk level distribution for no threshold exceedance (a) and threshold exceedance of max. 2h (b). The share of no risk area is relatively stable throughout the density bins. The main difference between a) and b) is the increase of no risk area at the expense of area classified as risk level 3.

with high density of old adults. Accordingly, an adaptation of thermal conditions in these districts according to the needs of old adults would be favorable and justifiable.

5.2.2 Vegetation and urban geometry and their effects on T_{mrt}

Having a CDSM and DSM available, the thermal environment can also be compared against vegetation characteristics and building density in the considered districts in order to draw some more general conclusions independent of age density. The average time that T_{mrt} = 47.6°C has been exceeded (risk level 0) has been plotted against canopy cover (a) and volume (b) in figure 8. The plots show a clear overall correlation between both canopy cover (r^2 = 0.43) and volume (r^2 = 0.46) and the exceedance of the threshold. The plots are further classified by building cover. Through this division, the cooling effect of urban geometry on the thermal environment becomes visible. The trendlines suggest that districts with a dense building cover tend to exceed the threshold for a smaller amount of time with relatively low vegetation cover or volume. This indicates that urban geometry is effectful for cooling below the threshold of increasing risk for old adults. The explained variances throughout the building cover categories are high in general and increasing for lower building density. These findings suggest that vegetation has a slightly bigger influence on the thermal conditions in rather open settings than in dense built environments. The very high explained variances for the series divided by building covers highlights that the effect of canopy cover on thermal conditions is very high. Figure 8 further demonstrates that canopy cover has a stronger effect on thermal conditions than canopy volume. As an example: For the building cover group 20-30%, the amount of hours that exceed the risk threshold shall be reduced from 6h to 4h. This requires a doubling of canopy cover from 13% to 26%, whereas the canopy volume needs to be tripled from 0.7m³/m² to 2.1m³/m². This outcome is also observable throughout other building cover groups.

Considering the mentioned correlations from figure 8 correlations and the observations from the map outputs (chapter 5.1) it can be expected that not only the hours of exceedance, but also the share of risk level 0 per district correlates with vegetation. This is demonstrated in the corresponding plots in figure 9. The plots show a more pronounced overall correlation than the graphs above for both canopy cover (r^2 = 0.67) and volume (r^2 = 0.67). The availability of risk-minimizing areas for old adults thus depends on the presence of vegetation. A cooling influence of urban geometry is still visible – densely built districts tend to show higher shares of risk level 0 despite having relatively little vegetation. However, this influence is smaller than in the graphs above due to the stronger overall correlation with vegetation. Hence, urban geometry is found to have an effect on temporary cooling in denser built areas, which is however decreasing when lowering the number of hours that a threshold can be exceeded. This conclusion is supported by the even higher overall correlation between vegetation and share of risk level 0 (r^2 = 0.83) for permanent cooling (no exceedance of T_{mrt} = 47.6°C; plots not displayed).

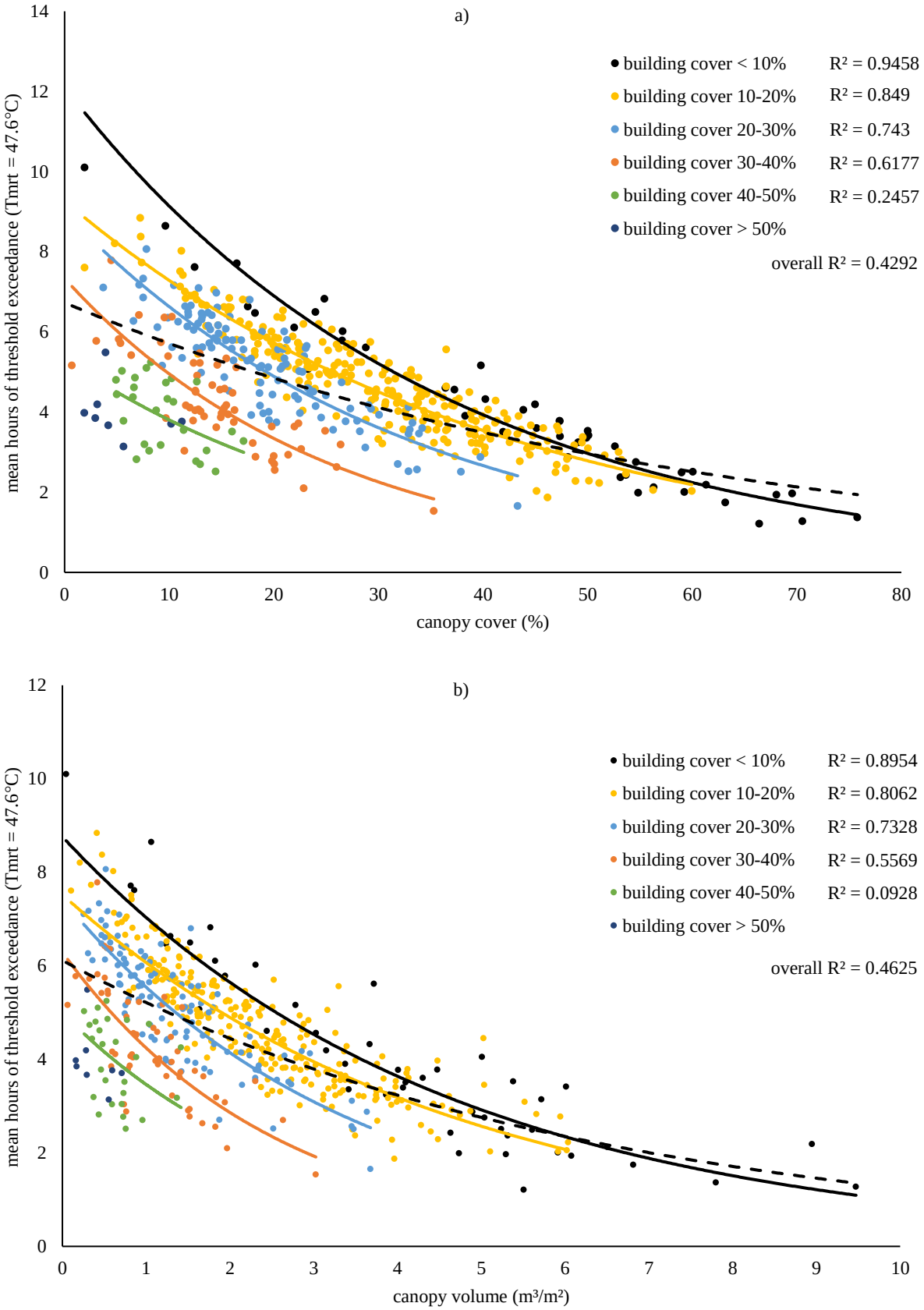

Figure 8: Correlation between canopy cover and average hours of exceedance of Tmrt = 47.6°C (a); correlation between canopy volume and average hours of exceedance of Tmrt = 47.6°C (b). There is a clear influence of vegetation on the thermal conditions. The effect of urban geometry is displayed by the lower trendlines for denser areas, indicating less hours of exceedance for similar vegetation. The dashed lines indicate the overall trendlines for all districts. The trendlines for building cover > 50% are not displayed due to the small number of data points.

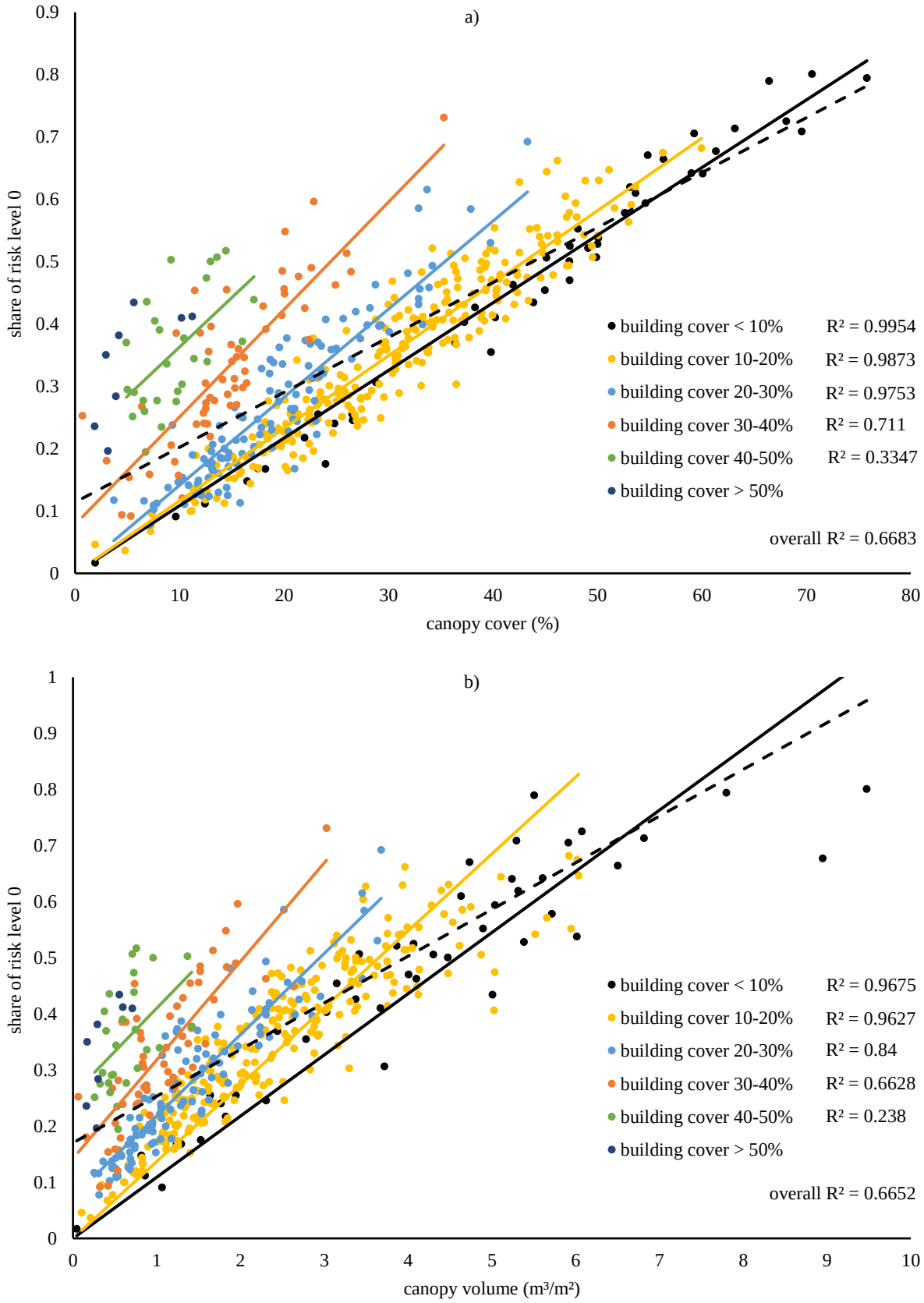

Figure 9: Correlation between canopy cover and share of risk level 0 for a max. exceedance of 2h (a); correlation between canopy volume and share of risk level 0 for a max. exceedance of 2h (b). There is a clear influence of vegetation on the availability of no risk areas for old adults. The effect of urban geometry is displayed by the higher trendlines for denser areas, indicating a comparably higher share of no risk area for similar vegetation. The dashed lines indicate the overall trendlines for all districts. The trendlines for building cover > 50% are not displayed due to the small number of data points.

5.2.3 Availability of vegetation on a neighborhood level

As the previous chapter demonstrates the heat-mitigating effect of vegetation, it is of interest to investigate how vegetation at a neighborhood level is distributed in Gothenburg. Table 4 suggests that average canopy cover is decreasing in higher age density bins, while the building cover is increasing (figure 10). District-wise canopy cover plotted against building cover shows a fairly high correlation (figure 11), with a big variability, however. Hence, densely buildt-up urban neighborhoods in Gothenburg tend to have less canopy cover than more open ones.

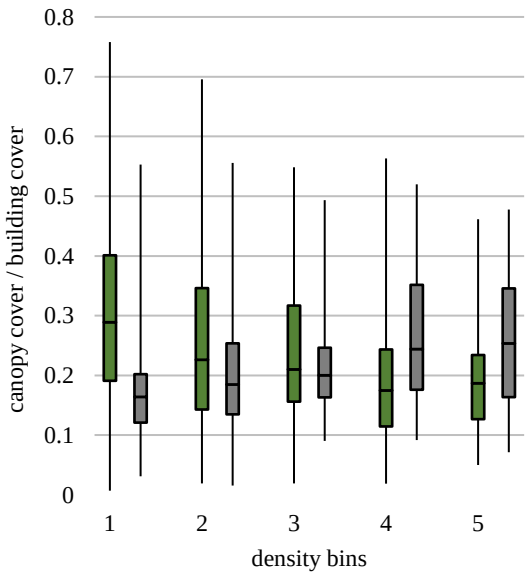

Figure 10: Boxplots for canopy cover (green) and building cover (grey) for the age density bins

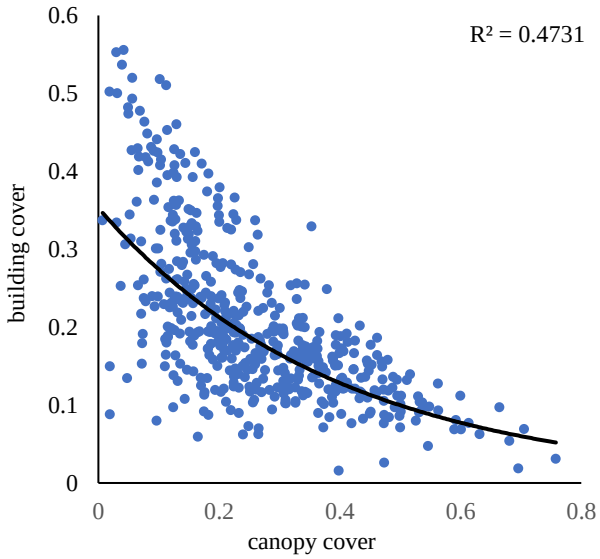

Figure 11: Correlation between canopy cover and building cover

36% (181) of the considered districts show a canopy cover of more than 30%. About 10% (49) of the districts have canopy covers of less than 10%. The spatial distribution of these districts shows that many of them are concentrated in or rather close to the city centre (figure 12). These districts with little vegetation are on average quite dense urban environments with high building cover (35%). It is important to bear in mind that only vegetation within the district borders (neighborhood) is considered here. Potential spacious vegetated areas in neighboring districts are not accounted for. To avoid border effects resulting from this, the distance to urban cool and green spaces is presented in the next chapter.

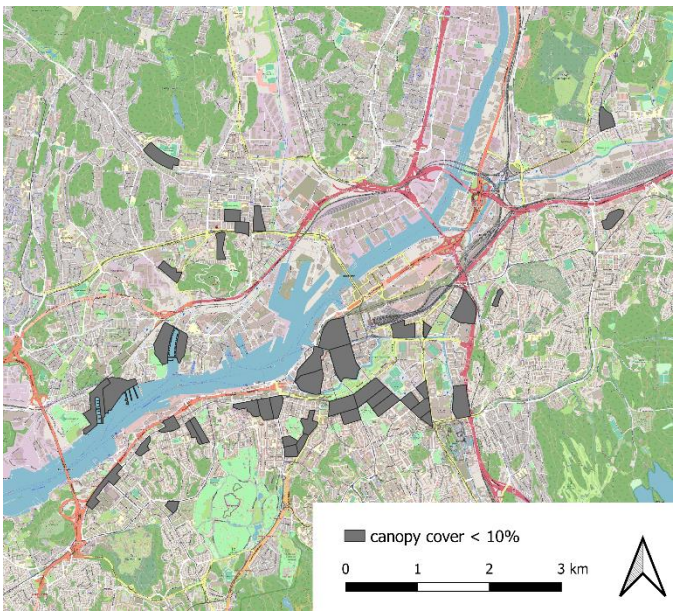

Figure 12: Overview over the districts with less than 10% canopy cover. Most districts are surrounding the city centre. One district in Torslanda is outside the map, but has been restructured the last years, so that the spatial input information and population data are not corresponding and the district is thus not applicable for consideration when drawing conclusions.

5.2.4 Distance to cool and green spaces

As shown in table 4, the average distance to urban cool and green spaces does not vary greatly throughout the age density bins (between 42m and 59m). Hence in areas with a high density of old adults, the access to cool and green spaces is on average slightly worse than in areas with a high density of old adults. Even though the variation is not large, the higher average distance for districts with a high density of old adults (bin 5) compared to those with a low density (bin 1) is statistically significant ($p = 0.02$). This is the case despite the quite high share of old adults in the districts with high density of old adults. Accordingly, an adaptation of thermal conditions in these districts according to the needs of old adults would be favorable and justifiable. The higher average distance for bin 4 could at least be partially due to the relatively low number of districts in this bin ($n = 29$) so that a few outliers will be more influential on the average. The bin-wise boxplots for the distance to cool and green spaces (figure 13) show that variability in the fourth quartiles is very high, so that for every density bin there are districts with very long distances to cool and green spaces. 29 districts have an average distance of more than 100m to the next cool and green space. The spatial distribution (figure 14) shows that most of these are located in rather central areas. Independent of density, high distances can occur particularly in cases such as the ones described in chapter 5.1.3, where cool and green spaces are physically close, but the access is blocked by buildings or inaccessible area. It is thus of high interest to filter the districts that have both a high density of old adults and a poor access to cool and green spaces. This is presented in the following chapter.

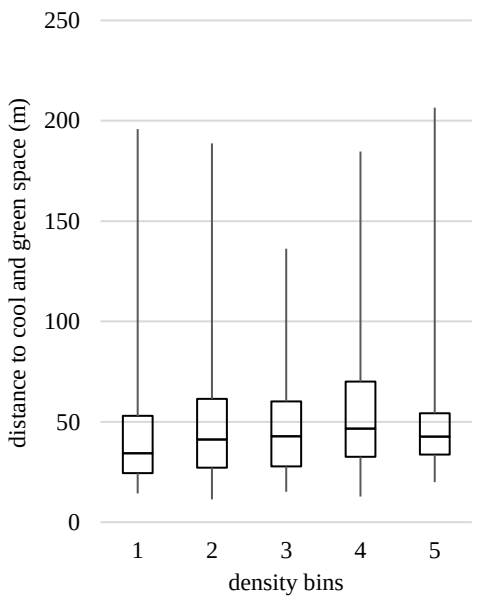

Figure 13: Boxplots for the distance to cool and green spaces for the density bins

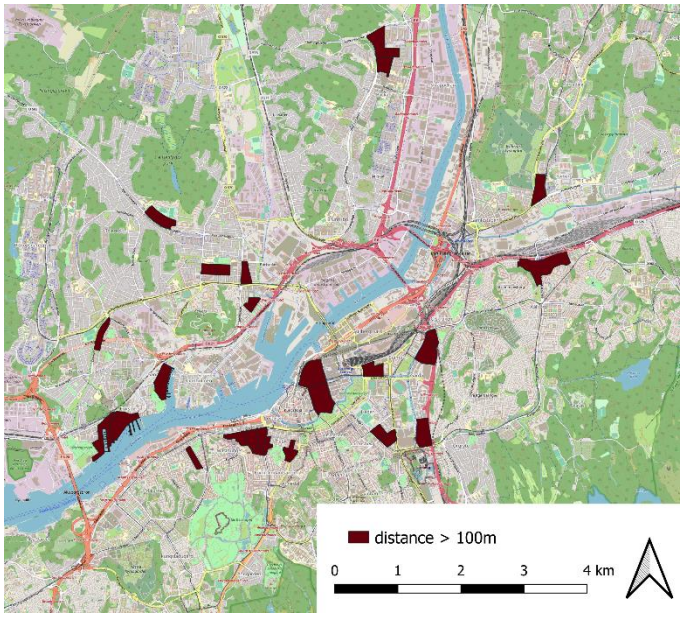

Figure 14: Overview over the districts where average distance to the next cool and green space exceeds 100m. Most districts are located in rather central areas. One district in Fiskebäck is not included in the map. It consists to a major share of the Fiskebäck boat harbour and some islands, where the distances to cool and green spaces are naturally high, but no people are living there. The values for this district are thus not representative.

5.2.5 Hotspot areas

Particularly relevant for planning access of old adults to cool and green spaces are districts with high densities and/or share of old adults and high average distance to cool and green spaces. These areas can serve as priority areas for measures to be taken. Five districts have been identified as such hotspots (figure 15). One additional district that would have been classified as a hotspot has been excluded. This district in Fiskebäck is cosists to a major share the Fiskebäck boat harbour and some islands, where the distances to cool and green spaces are naturally high, but no people are living there. The values for this district are thus not representative. It is notable that all five districts are located close to the city centre. Table 5 shows average values for the identified hotspot districts.

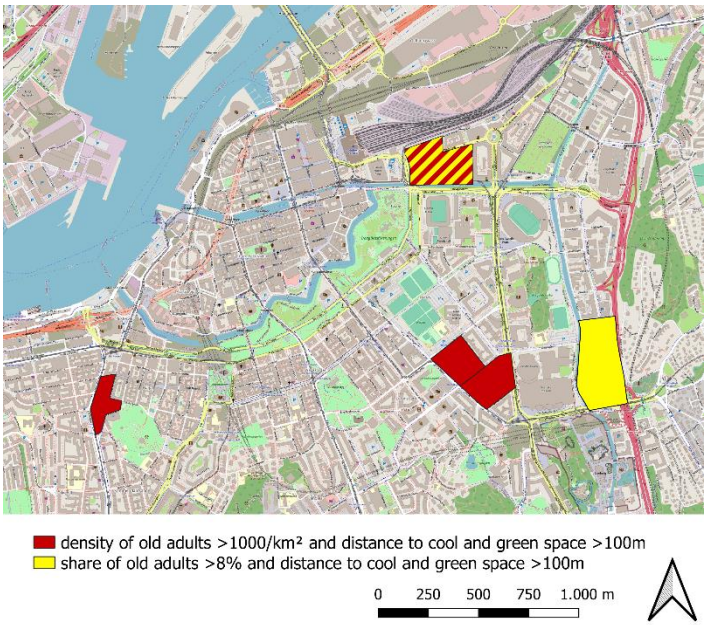

Figure 15: Location of identified hotspot areas. One district in Fiskebäck has been excluded (see text).

Table 5: Zonal statistics for the identified hotspot districts

Parameter	Average for hotspot districts
Share risk level 0 (max 2h exceedance)	0.32
Canopy cover	0.08
Vegetation volume (m^3/m^2)	0.5
Building cover	0.41
Distance to canopy-covered cool space >400m²	131m

These values can be compared with table 4 in chapter 5.2. It is notable that the hotspot districts have very little canopy cover and volume and a much denser building structure. The share of risk-minimizing area is comparable to the average for all districts, however. Thus, the thermal environment is not particularly problematic in these areas. The deciding factor for the classification as hotspot area is the low availability of vegetation, which apparently is insufficient to form adjacent green spaces. Some identified hotspot areas will be discussed in more detail in chapter 6.4.

6 Discussion

6.1 Daytime heat and nighttime heat

This study is using daytime heat as the primary indicator for heat stress of old adults. It is based on previous findings, that mortality of old adults is increasing for daily hot temperatures (Rocklöv et al., 2012). Additionally, Thorsson et al. (2014) conclude that daily maximum Tmrt is the best predictor for mortality in this age group and thus old adults are more vulnerable to daytime heat stress than to nighttime heat stress. However, during extended periods of excessive heat, the nocturnal UHI leads to citizens not being able to cool down anymore during nighttime. This effect is also observable in mortality risks for all age groups (Rocklöv et al., 2012) and is certainly contributing to heat stress. The reason for basing this study on daytime heat stress is that high daily Tmrt values occur quite frequently (Thorsson et al., 2014). Additionally, it can be assumed that extended periods of nighttime heat stress also correlate with high daytime heat, so that a focus on daytime heat is reasonable. One limitation of this is however, that patterns of thermal conditions throughout the city could look different for nighttime heat stress so that there are other districts affected.

6.2 Choice of the no risk threshold

In this study T_{mrt} = 47.6°C has been used as threshold of increased risk. Thorsson et al. (2014) identify this value as the threshold for an increased mortality risk for old adults between 0% and 5% (Ages 80+). However, they use the 5-10% threshold (T_{mrt} = 55.5°C) as threshold for increased risk in their later results. A reason for using the lower threshold here is that Thorsson et al. (2014) consider the mortality risk of old adults. According to their *miljö- och klimatprogram 2021–2030,* the City of Gothenburg aims for minimizing health risks through providing access to cool islands (Göteborgs stad, 2020). Heat stress can cause less severe health risks than mortality (Kenny et al., 2010). It is thus beneficial if cool spaces are not only areas of minimal mortality risk but also areas of reduced heat stress. Lee et al. (2013) present a linear relationship between T_{mrt} and PET. Using this relationship and the PET comfort classification by Matzarakis et al. (1999), the T_{mrt} = 47.6°C threshold almost coincides with the border between moderate heat stress and strong heat stress. T_{mrt} = 55.5°C falls into the upper end of strong heat stress, on the border to extreme heat stress. Hence, it seems reasonable to base this study on the lower threshold value of T_{mrt} = 47.6°C.

Additionally, the comparison of the thresholds on the risk class map (figure 5) and the zonal histograms (figure 7) indicates that the areas that exceed T_{mrt} = 47.6°C but not T_{mrt} = 55.5°C are relatively small. The access to cool areas would not thus change substantially using the higher threshold, but only extended by a bit.

6.3 Effects of vegetation and urban geometry

The positive correlation between vegetation and modelled T_{mrt} with SOLWEIG using zonal statistics across multiple locations has been described previously, both for canopy cover (Bäcklin et al., 2021) and vegetation volume (Lindberg et al., 2018). The results presented here can be seen as an extension to this correlation by a threshold for T_{mrt}. While Lindberg et al.

(2018) present the correlation with momentary T_{mrt} values for one point in time, Bäcklin et al., 2021 correlate with a T_{mrt}-mean over several hours. Even though this study correlates with hours above and share of area beneath a risk threshold, it is practically the same as the previous examples – a correlation between vegetation and T_{mrt}. However, the combination presented here leads straight forward to the conclusion that risk-minimizing thermal conditions for old adults in urban environments are closely related to the presence of vegetation. On a microclimate scale, the beneficial effect of vegetation cover on T_{mrt} and thermal comfort has been extensively studied in field studies (e.g. Ali-Toudert & Mayer, 2007; Oliveira et al., 2011; Shashua-Bar et al., 2009). Accordingly, the clear correlation presented in this study is not surprising. The found influence of canopy volume is supported by Wang & Akbari (2016), who found that tree formations with large crowns provide better radiant heat mitigation than smaller trees due to the large shaded area. Gromke et al. (2015) demonstrate that higher vegetation volume in urban environments leads to increased evaporative cooling. Even if evaporation is not accounted for in SOLWEIG, this provides an additional argument for preferring large trees over smaller ones. In an urban planning perspective, these findings suggest that it is crucial to avoid the removal of large mature trees where possible. Smaller, newly planted trees would require a lot of time until they have the same effect on the thermal environment.

However, the results also demonstrate that increasing the canopy cover has a higher effect on cooling below the risk threshold than canopy volume. The curved shape of the graphs in figure 8 indicates that the effect is particularly high in districts with a low initial canopy cover. Thus, it requires comparably little effort to increase a considerable cooling effect in the most problematic districts with very little vegetation. The stronger effect of canopy cover compared to volume also leads to the conclusion that canopy cover alone is already a good indicator of the thermal conditions of an area. The volume is not necessarily always required for a simplified assessment of thermal conditions. This would ease the process considerably since an input CDSM with canopy heights is rather complicated to produce (Lindberg et al., 2013) whereas only the canopy cover as input is more easily available.

The trendlines in the graphs for the correlation between vegetation and the share of no risk area in figure 9 are steeper for higher building covers. This could lead to the conclusion that increasing canopy cover has a bigger cooling effect in dense environments than in open settings. In this case however, this observation can be attributed to the fact that buildings have been excluded from the considered area for the risk level maps. Hence, the more building cover, the smaller the leftover area that is considered for the calculations. Thus, if the same absolute area is cooled in a dense setting, this will lead to a bigger increase (and thus a steeper trendline) in the share of cool area than in open settings. A result that is however more relevant is that the trendlines divided by building cover are all steeper than the overall trendlines, both in figure 8 and 9. These observations highlight the importance of considering different urban densities separately. When vegetation is introduced into or removed from a district, the building cover stays constant. Thus, the data points would move along the trendline for the corresponding building cover group instead of the overall trendline. Just considering the flatter overall trendlines when assessing the effect of introducing or removing vegetation would hence underestimate the effect of vegetation on thermal conditions.

As a notable result from table 4, the share of area classified as risk level 0 with max. 2h exceedance remains stable throughout the age density bins. Canopy cover however is decreasing with an increasing density of old adults while building cover is increasing. Accordingly, it seems that the cooling effect of urban geometry is increasingly influential with increasing building cover and that the effect of urban geometry can offset the decrease in canopy cover in dense urban environments. It should be mentioned here that this effect can be attributed to a considerable extent to the exclusion of buildings from the risk level map, as described in the previous section. A cooling effect of urban geometry has been found in previous studies. Most works on this issue are focused on very local settings and microclimates. Depending on orientation and width of the street canyon, urban geometry has been found to have considerable effects on local thermal comfort. In a dense urban environment, it can temporarily mitigate heat on pedestrian level through shading (Abreu-Harbich et al., 2014; Thorsson et al., 2011). This is also suggested by the results of this study, considering the lower effect of vegetation on the 2h threshold exceedance compared to no exceedance. However, the districts observed in this study are bigger than just one street canyon, they are more on a neighborhood scale. Jamei et al. (2016) present that, depending on urban layout, the locally observed microclimatic effects of urban geometry can influence thermal conditions also on bigger scales like neighborhoods. This can explain the offset of a decrease in canopy cover by an increasing built-up fraction in denser urban environments observed in this study. One should however also raise attention to winter conditions, where configurations that are beneficial for mitigating heat in the summer could have adverse effects on thermal comfort (Jamei et al., 2016). For Gothenburg, having more yearly hours of cold stress than heat stress (Thorsson et al., 2011), these winter conditions should always be kept in mind.

6.4 Availability of vegetation and access to cool and green spaces

This study has investigated district-wise canopy cover across Gothenburg. In his guidelines for healthy urban environments, van den Bosch (2021) suggests a minimum tree canopy cover of 30%. The results show that most districts where elderly people live do not reach this value. In previous literature, Gothenburg is however described as a relatively green city (Kabisch et al., 2016; Klingberg et al., 2017b). As previously described, this small-scale-district assessment could show considerable border effects. Moreover, districts that consist only of parkland (with high canopy cover) are not considered in the calculations. Therefore, it can be expected that many of the very low values for canopy cover in some districts get evened out when observed on a larger scale. Additionally, it is worth noting that to get a larger scale average, a weighted average would have to be calculated, considering the highly varying size of the districts. As districts with the lowest canopy cover tend to be relatively small, their low values would not influence the overall average to a great extent. But van den Bosch (2021) also explicitly mentions that the neighborhood level is relevant for the 30% canopy cover goal. Accordingly, the district-level assessment presented in this study is relevant for assessing the availability of vegetation in urban environments.

However, the results demonstrate that some dense neighborhoods in and around the city centre are far from reaching the 30% canopy cover goal. It is not surprising that when a big share of the area is covered with buildings, vegetation cover is very limited. Furthermore, the results

show that the average thermal risk conditions are not varying a lot between dense and more open settings, so heat related risks are not necessarily increased in the mentioned districts. Increasing tree canopy cover in these districts would thus not mainly be based on heat mitigation, but on the other benefits for human health and wellbeing. While increasing vegetation might in general be favorable, high vegetation covers have to be carefully weighted against trade-offs that increasing canopy cover in dense urban environments brings. While on heat days a lot of shading is beneficial to avoid heat stress, cold stress in the winter is still a more pronounced issue in Gothenburg (Thorsson et al., 2011). In nordic cities, it is essential to provide solar access for citizens, especially in the colder seasons (Johansson & Yahia, 2020). Due to the very low solar altitude in the winter, shading patterns are very large and spots with solar access are rather rare in dense environments. Introducing more vegetation in these districts would hence decrease access to sunlit spots even further. This raises the question, how applicable the 30% canopy cover goal is for dense cities in a nordic context, or at what scales it is intended to be applied. Regarding solar access in nordic environments, a district-wise canopy cover of 30% in densely built settings at all costs does not seem to be the most practical solution.

The results of this study demonstrate that the average distance to urban cool and green spaces in Gothenburg varies from 42m and 59m throughout the age density bins. There are several outliers towards high values of more than 100m. Van den Bosch (2021) recommends a maximum distance of 300m to the next urban green space. However, his guidelines are based on green spaces of at least 0.5ha (5000m²), whereas in this study, urban cool and green spaces that are bigger than 400m² are identified. It is thus not surprising that the resulting distances are a lot smaller than 300m, since there is a lot more of these small green areas in the urban fabric. Additionally, the 3-30-300 rule does not mention tree cover or thermal conditions as a requirement for green spaces (van den Bosch, 2021). Grasslands with a few scattered trees would qualify for the 3-30-300 rule, whereas in this study closed tree cover and risk-minimizing thermal conditions is required. Therefore, this study cannot deliver an accurate comparison with the 300m value in the 3-30-300 rule. Kabisch et al. (2016) rank Gothenburg as one of the top cities in Europe regarding access to green spaces within 300m radius. In line with that, Kalori & Lind (2021) found that almost all elderly care institutions in Gothenburg have less than 300m walking distance to a cool island.

However, not only bigger green spaces, but also smaller scale vegetation such as green avenues (van den Bosch, 2021) or street trees (Mullaney et al., 2015) contribute to a healthy urban environment. Together with the cooling aspect the findings of this study are therefore useful to assess where in Gothenburg the proximity to urban cool and green spaces contributes to health and wellbeing of old adults and all other citizens. Additionally, the discussed aspects justify the identification of hotspots in this study. The thermal conditions in the hotspot districts have shown to be similar to the average. However, the absence of sufficient canopy cover means they are lacking favorable health and wellbeing benefits which makes them areas of concern. This being said, the above-described trade-offs of higher canopy cover for thermal conditions in the winter should also be kept in mind for the identified hotspot areas.

6.5 Hotspot areas: Case discussion and implications for urban planning

This section will zoom in to some of the hotspot districts and describe and discuss their situation regarding thermal conditions, availability of vegetation and access to cool and green spaces. It includes exemplary considerations that are relevant for urban planners when assessing district-wise thermal conditions and vegetation.

One hotspot district is Basområde 11808, east of Svenska Mässan (figure 16). Its density of old adults is not exceptionally high (678/km²), however the share of old adults is 10%. The average distance to a cool and green space is 112m. Map 1) shows, that within the district borders, there is only very little tree canopy cover (7.1%). The canopy is too sparse to form adjacent covers in order to be classified as a cool and green space. In map 2) it is observable that this translates to very unfavorable thermal conditions for old adults on heat days. Only very few areas fall into risk level 0. Hence, the distances to cool and green spaces are exceptionally high in this district (map 3). It is not beneficial that the access to the next cool and green space is often blocked by the E6 highway in the east and a water stream in the west. Considering the exceptionally high share of old adults in this district, it would be rather easy for urban planners to justify a prioritization of the needs and interests of old adults in planning. This district can thus serve as a key area for implementing adaptive measures counteracting heat risks for old adults.

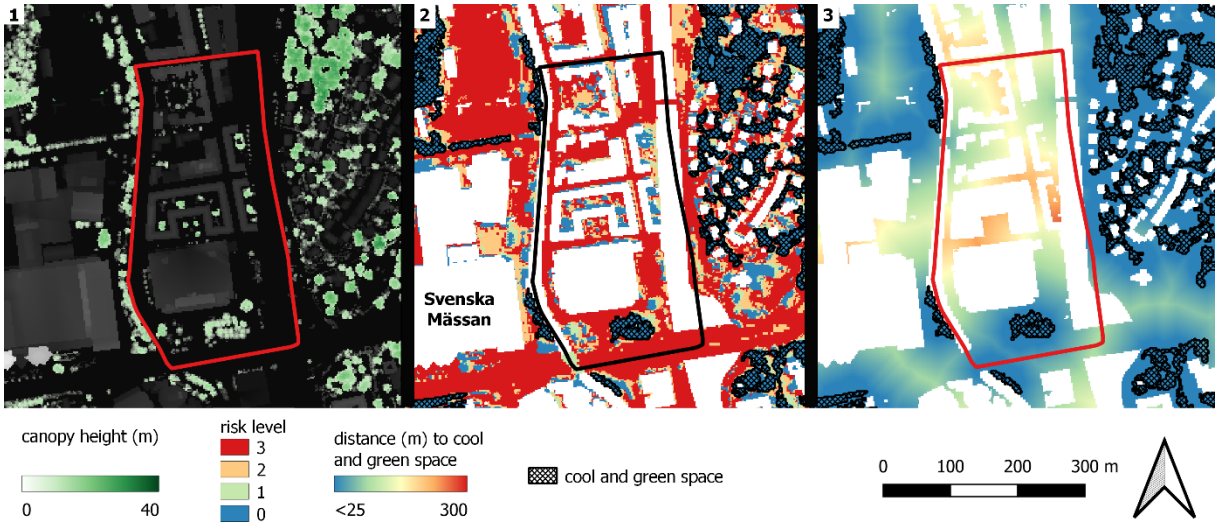

Figure 16: Canopy cover (1), risk levels (2) and distance to cool and green spaces (3) for Basområde 11808. Description see text.

A more complicated case is Basområde 11756, north of the Gamla Ullevi stadium (figure 17). It has a very high density (1417/km²) and share (9,0%) of old adults. Despite the very low canopy cover (map 1), the thermal conditions for old adults are not unfavorable. Many street canyons are classified as risk level 0 due to shading from the rather high buildings (map 2). Increasing vegetation in the district would therefore not substantially improve the thermal conditions for old adults as a priority, but could contribute to other health and wellbeing aspects. However, since it is a very dense district (building cover = 43%) with rather high buildings, it can be assumed that solar access in the winter is relatively low. An increase of vegetation in the district must thus be carefully elaborated. On the other hand, this district is problematic regarding distance to cool and green spaces, with an average distance of 206m (map 3). As previously described in chapter 5.1.3, this area is an extreme case where the access to cool and

green spaces is blocked by a canal in the south and buildings in the west. Regarding the access to green spaces, some measures would hence be particularly beneficial in this district.

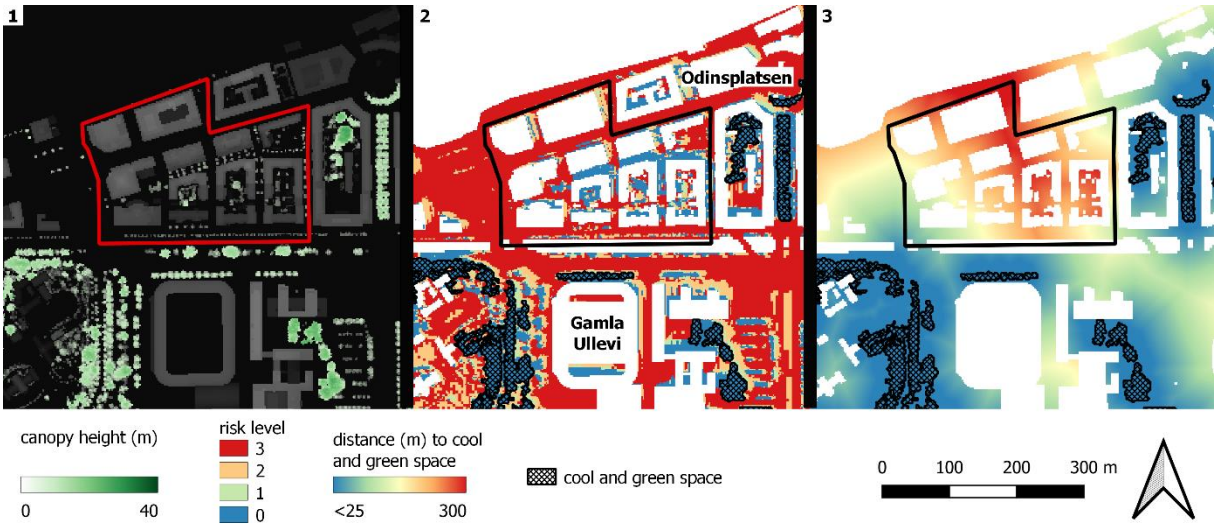

Figure 17: Canopy cover (1), risk levels (2) and distance to cool and green spaces (3) for Basområde 11756. Description see text.

Another hotspot area are Basområden 11804 and 11805, between Götaplatsen and Svenska Mässan (figure 18). Here, the shares of old adults (5.0% and 3.6%) are in range of the overall city average, but the density of old adults are very high (1250/km² and 1167/km²) Despite the very low canopy cover (9.7% and 5.0%; map 1), the overall thermal risk conditions for old adults are not unfavorable (map 2). However, a lot of the area classified as risk level 0 is in shaded courtyards without tree canopy cover. This leads to quite far distances to cool and green spaces, especially in the long streets, where direct access is blocked by buildings (map 3). As visible in map 1, there are street trees available in the street between the districts (Berzeliigatan), they are however not big enough to create an adjacent cool and green space. In this case it remains questionable whether adaptive measures for old adults should be implemented, since the share of old adults is not very high in the considered districts. Even if increasing vegetation

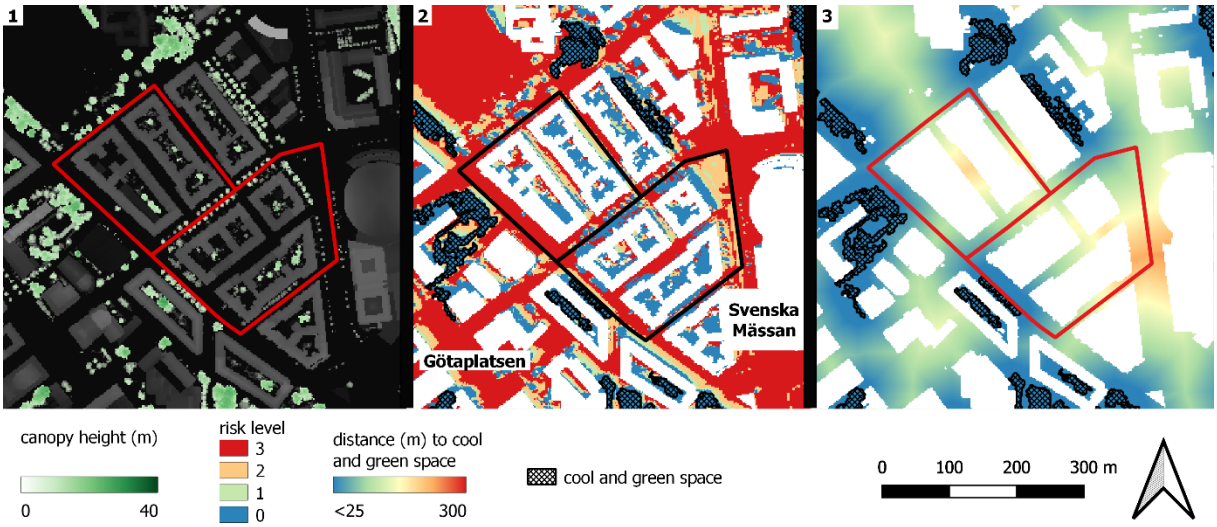

Figure 18: Canopy cover (1), risk levels (2) and distance to cool and green spaces (3) for Basområden 11804 and 11805. Description see text.

could benefit all parts of the population, other age groups are less vulnerable to daily maximum T_{mrt} and might prefer solar access during most of the year.

6.6 Limitations of the study

6.6.1 Modelling approach

As this study is based on modelling, this comes with a limitation in itself. The results only represent one day in a year with specific meteorological conditions. Any deviations from the used parameters will lead to different results in T_{mrt}. Also, since SOLWEIG is based on some assumptions (see chapter 4.4), any variations in these will influence the calculated values. However, the focus of this study is not primarily on the absolute T_{mrt} values (which are subject to change) but rather on the patterns of thermal conditions throughout the city. These patterns of hot and cool spaces remain stable even if input parameters are changing to some extent. Thus, even with a change in absolute T_{mrt} values under different conditions, the major conclusions from this study will still be applicable.

6.6.2 Geospatial input data for SOLWEIG

The available ground data used for modelling T_{mrt} is from 2010, implying that in some parts of the city, the present state is quite different now. It has been manually updated in areas with considerable recent development with information from 2019, but this does not mean that all new buildings, paved surfaces or removed vegetation in Gothenburg since 2010 are included in the input data. Updating newly planted vegetation would have required in-situ measurements, which could not be performed at a city scale. Adding or removing single buildings or trees is influencing the thermal environment in the direct surrounding, is however neglectable on a district scale. It can moreover be assumed that newly planted trees are still rather small in size and would thus not drastically change the thermal environment on a district scale. A factor that cannot really be influenced is the maintenance performed on urban trees. Once in a while, street trees are maintained and branches cut away, that can regrow the following years. If the CDSM has been created in a year where certain groups of trees have just been maintained, this might have considerable influence on the vegetation cover and volume. This could hypothetically lead to cool and green spaces not being classified as such due to the temporary non-adjacent vegetation cover. Theoretically, the input data could have been newly created from available recent LiDAR data (Lindberg et al., 2013; Johansson, 2018). However, performing this at a city scale is very time- computation- and data intensive and not the focus of this study.

6.6.3 Spatial variation in meteorological input data

As the meteorological input data has been retrieved from the ERA5 reanalysis dataset, it does not represent spatial variations of air temperature and relative humidity within the city. This implies that locally, where air temperature and humidity deviate from the input data, T_{mrt} will deviate from the modelled values, potentially influencing the zonal statistics for some districts slightly. Relative humidity has been found to have very little influence on T_{mrt} (Onomura et al., 2015), so spatial variations in this parameter are negligible. Jähnicke et al. (2016) demonstrate that the effect of spatial variation is not remarkable when modelling T_{mrt} with SOLWEIG with gridded meteorological input instead of point data. For point data, deviations due to humidity

were neglectable in their observations. Since the UHI is a mainly nocturnal phenomenon, the SOLWEIG output also showed good accuracy during daytime hours for air temperature variation. They conclude that SOLWEIG is delivering good results for modelling T_{mrt} at a city scale with meteorological data as point inputs.

6.6.4 Distance to cool and green spaces

In the calculations of the distance to cool and green spaces, the buildings and inaccessible areas (such as water) have been excluded. This gives the values a simplified dimension of walking distance accessibility, which is also used as parameter in public reports (WHO Regional Office for Europe, 2016). The produced datasets can be useful to pinpoint situations of concern for example when a park is located very close spatially but cannot be accessed directly due to a water canal. However, this cannot be understood as a complete assessment of accessibility of cool and green spaces. There may be several uncrossable main streets or railways (e.g. the tram rails) that are not represented in the used Urban Atlas data. Additionally, buildings are assumed to be unpassable in the calculation. That means that opportunities to pass a building to access a public cool courtyard are for example not represented in the obtained datasets. The same applies for barriers to access certain places, such as fenced open courtyards or private gardens between the smaller houses in the outskirts of the city.

In general, there are many more factors to consider if one wants to conduct a complete analysis of the accessibility of areas. Particularly relevant for old adults and their special needs are for example slopes and gradients in the terrain (Alves et al., 2020). This can especially be relevant in a city with a pronounced topography, such as Gothenburg.

6.6.5 Population distribution

This study aims to assess access of old adults to cool and green spaces with a perspective on adaptation to a warmer climate in the future. However, the presented results are based on the present (2021) distribution of old adults in Gothenburg. The density of old adults in districts can and probably will change due to ageing of people younger than 80 years, mortality of old adults and migration between districts or into/outside the city. Considering the growing number of old adults in the city, it can be expected that most districts will increase in the density of old adults. Eventually this might lead to new hotspot areas that are not identified as such with the current age distribution. One factor that could increase the density of old adults rapidly in single districts is the opening of new elderly care institutions.

6.7 Implications of the study, recommendations and further research

This study can be used to pinpoint areas in Gothenburg to urban planners where intervention regarding heat mitigation measures for old adults and availability of urban vegetation might be prioritized. It discusses aspects regarding thermal conditions in different urban environments that are relevant for urban planning. Some guidelines for the planning of vegetation in a nordic setting can be derived from this work:

- In general, increasing vegetation is a suitable measure for heat mitigation and contributes to other aspects of human health and wellbeing for all citizens.

- Large mature trees are particularly valuable, as they shade a big area. The removal of these trees should be carefully elaborated or preferably avoided.
- However, solar access is essential during most of the year. Therefore, trees must be placed thoughtfully, especially in dense settings where solar access is rare in the winter.
- Therefore, deciduous tree species are favorable for nordic urban environments due to their higher transmissivity in the winter (Konarska et al., 2014).
- It must be carefully discussed whether neighborhoods should be adapted to the needs of old adults if the share of old adults is not higher than in other neighborhoods in the city.

Future research could extend this study by a more pronounced accessibility dimension. Alves et al. (2020) suggest guidelines for walkable neighborhoods for old adults, including for example the terrain slope. Incorporating these aspects into the cost raster and a network analysis could more closely investigate which of the identified cool and green spaces can actually be easily accessed by old adults. Furthermore, it is possible to use the produced results for analyzing how citizens perceive their access to cool and green spaces, especially in areas with a far distance to these spaces.

7 Conclusions

This study demonstrates that the urban thermal environment regarding heat-related risks for old adults in Gothenburg is generally not greatly varying throughout different densities of old adults. The average distance to cool and green spaces is slightly, but significantly, higher in districts with a high density of old adults. These findings imply that areas with many old adults in Gothenburg are on average slightly worse protected against heat-related risks for this part of the population.

Tree canopy cover has been found the most influential factor on thermal conditions as well as heat-related risks in urban environments. Hence, increasing vegetation, particularly canopy cover, is an effectful measure to mitigate heat risks for old adults, but it also provides more benefits for health and wellbeing to the citizens. Densely built districts in the center of Gothenburg tend to have little tree canopy cover. There, increasing vegetation can have the biggest effects on thermal conditions Five hotspot districts with very little vegetation and particularly far distance to cool and green spaces have been identified. These districts can serve as priority areas for measures regulating the thermal environment.

However, in densely built settings in nordic cities, an increase of vegetation comes with several tradeoffs regarding thermal conditions in the winter. Hence, it must be carefully evaluated if an increase of vegetation on a neighborhood level is always justified and the most beneficial solution for a sustainable development of cities not for single groups, but for all citizens.

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Appendix

Appendix 1: Meteorological input data

Local time	Air temperature (°C)	Relative humidity	Global radiation (W/m²)	Direct radiation (W/m²)	Diffuse radiation (W/m²)
0:00	16.9	0.59	0	0	0
1:00	16.1	0.61	0	0	0
2:00	15	0.64	0	0	0
3:00	14.4	0.67	0	0	0
4:00	13.9	0.71	6	40	4
5:00	15	0.7	67	319	31
6:00	17.2	0.63	172	484	58
7:00	19.6	0.55	306	645	71
8:00	22.1	0.49	444	732	85
9:00	24.1	0.42	573	792	94
10:00	25.3	0.37	682	832	100
11:00	26.1	0.36	762	854	105
12:00	27	0.34	806	864	108
13:00	27.7	0.32	812	865	108
14:00	28.4	0.31	780	856	107
15:00	28.6	0.31	708	835	101
16:00	28.4	0.31	591	774	96
17:00	28.1	0.29	476	731	88
18:00	26.9	0.34	315	573	81
19:00	25.3	0.4	201	508	59
20:00	23	0.5	96	364	40
21:00	19.8	0.66	20	160	12
22:00	17.9	0.74	0	0	0
23:00	15.9	0.79	0	0	0

Appendix 2: Overview over districts (Basområden) and age distribution