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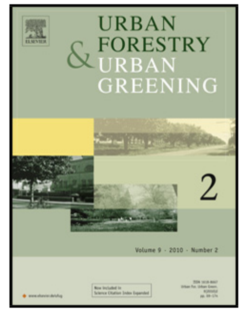

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Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany

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Highlights

- We discuss green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany.
- We quantified thermal effects of intensive green roof implementation using the ENVI-met model.
- For the first time, ENVI-met has been applied at the city's official planning scale.
- Results show that on a hot summer day, green roofs can significantly improve thermal comfort at the roof level.
- The average decrease in physiological equivalent temperature (PET) is by 9 Kelvin.

Abstract

Berlin currently experiences increasing environmental challenges especially through the combined effect of urbanization and climate change. The intensification of summer temperature extremes has become increasingly evident in recent years, urging the city to promote mitigation and adaptation measures for local heat load reduction. Green roofs have been widely recognized as an effective urban greening strategy to reduce heat stress in cities. This study thus analyses the effect of rooftop greening on outdoor thermal conditions in an inner-city prefabricated residential area in Berlin. The studied neighbourhood is one of the inner-city hot-spot areas of environmental loads, highlighting the need for green solutions. We quantified thermal effects of intensive green roof implementation using the ENVI-met model which, for the first time, has been applied at the city's official planning scale. The study thereby aims at overcoming the mismatch between research scales and planning scales, facilitating the knowledge transfer between the science community and urban practitioners, particularly in land use planning. Results indicate that on a hot summer day, green roofs can significantly improve daytime thermal comfort at the roof level with an estimated decrease in physiological equivalent temperature (PET) by 9 Kelvin. Green roofs can thus provide spaces of qualitatively increased thermal comfort compared to street-level areas. Overall, our results highlight the effectiveness of rooftop greening in terms of heat adaptation at the neighbourhood level. Therefore, this study suggests that these greening systems should be emphasized in future effect-oriented and sustainable urban planning assessments, especially of inner-city prefabricated housing estates.

Keywords

Green infrastructure, green roofs, heat stress, thermal comfort, ENVI-met, Berlin

1. Introduction

The combined effect of urbanization and climate change poses an increasingly critical environmental challenge to cities. Climate change amplifies environmental hazards especially through the enhanced risk of weather extremes. Urbanization is not only itself a driver of environmental problems in cities, it further forces planners and designers to find solutions in increasingly limited spaces. The city of Berlin—in line with many growing cities across Europe—currently undergoes strong densification processes with associated ecologic, economic and social consequences (Kabisch et al. 2017a; Wolff et al. 2018). Especially inner-city areas struggle with rising rents while being increasingly affected by multiple environmental loads like air pollution, green space deficits and noise pollution (SenSW 2015).

At the same time, the city already experiences clear impacts of climate change especially through intensified summer heat (Fenner et al. 2019). Maximum summer temperature is projected to increase by 2.3 to 3.5 °C by the end of this century while the number of hot days (T_{max}> 30°C) is expected to double (SenStadtUm 2016b). Recent years have already shown severe impacts of amplified heat in the city. Between 2001 and 2010, around 1600 deaths per year in Berlin were statistically attributed to heat stress, equalling about 5 % of all death cases in the city during that period (Scherer et al. 2013). Heat protection has therefore become a key objective in local urban development programs.

Berlin's official urban-climate development plan (SenStadtUm 2016a) clearly stresses the importance of creating new cool outdoor spaces in response to the increasing heat load especially in inner-city districts. In this context, the concept of Green Infrastructure (GI) has been identified as promising solution to existing urban-environmental challenges in Berlin, in particular providing simultaneous environmental, social and economic co-benefits (Raymond et al. 2017). GI is defined as green space networks that "maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life" (Benedict and McMahon 2006). This concept focuses on the integration of green spaces and associated ecosystem services in urban planning processes at different scales (Kabisch et al. 2017b).

However, in a densifying city like Berlin, space is a limiting factor to urban greening strategies. Especially in the compact city centre, the process of turning impervious surfaces into new green space is often conflicting with the creation of new housing structures. This highlights the need for space-sensitive greening strategies that are compatible with the urban densification process. These circumstances have increasingly drawn the attention of many cities to green roofs as sustainable urban greening strategy. Urban planners are today putting strong emphasis on the transition of the city's roof layer into a more nature-based setting. Green roofs offer the great advantage of providing multiple benefits while not claiming any ground-level construction space. In densely built urban environments, rooftops constitute a significant proportion of the urban surface. Greening these - still mostly unused - areas could bring important beneficial effects to the urban-environmental situation in Berlin.

Against this background, this study aims at investigating the effectiveness of rooftop greening as nature-based solution to the increasing heat challenge in central Berlin. More precisely, we estimate outdoor thermal effects of green roof implementation on prefabricated large-scale housing estates in an inner-city residential neighbourhood. The typical post-war building structures of the former GDR can be found in large parts of the city and are well suitable for green roofing due to their flat roofs, structural uniformity and favourable static characteristics. Their promising greening potential and abundance in inner-city areas highlight the relevance of closer examinations on related benefits such as temperature regulation. The objective of our investigation is thus to understand whether green roof implementation on these large-scale building structures can improve the local thermal situation during intensified summer heat in central Berlin.

For this, we use the ENVI-met model (Bruse and Fleer 1998) to quantify green roof effects on air temperature and thermal comfort in a prefabricated residential neighbourhood in Berlin Mitte. The study area of our analysis corresponds to the city planning unit named 'Karl-Marx-Allee' (KMA) and is located in the central district of Berlin. According to the Environmental Atlas Berlin, it is one of the inner-city hot-spot areas of environmental burdens, being affected by multiple environmental loads including heat stress (SenSW 2015). We focus on intensive green roofs (IGR) due to their additional potential benefit of providing new green space to the KMA community – an aspect which has not been further analyzed here but which is of critical importance considering the local green space shortages. So far, most of the existing studies on environmental performance of green roofs are focused on extensive green roof systems due to their wider distribution and easier implementation. By focusing on intensive green roofs, we aim at filling the research gap on IGR effects in urban environments. Increasing the scientific knowledge on IGR systems is an important step towards a more integrated green roof assessment in urban planning practices.

Different case studies all over the world have already investigated the performance of green roofs in the urban-microclimatic context (e.g. Taleghani et al. 2016, Morakinyo et al. 2017, Peng and Jim 2013). However, existing analyses on this topic are widely scattered in (spatial) scale and mostly conducted for individual buildings or building blocks in a city. Moreover, to date, the scales used by the science community are not conform with existing spatial units of urban planning practitioners. The resulting mismatch between research scales and planning scales can pose distinct barriers to the knowledge transfer between science and urban planning practice. Given the advanced complexity of urban-environmental challenges through the ongoing processes of urbanization and climate change, the exchange and cooperation between researchers and city practitioners become increasingly important. This study thus aims at bridging the urban research-practice gap by setting its focus on the matter of scale. For this purpose, the analysis in this work is conducted at the official LOR (i.e. life-world oriented spaces) planning level in Berlin. This brings novelty especially to the application of the numerical microclimate model used in this study which to date has been mostly restricted to smaller scales.

2. Green roofs as nature-based solution for heat reduction

Green roofs have a long history reaching back as far as the Hanging Gardens of Babylon (500 BC), one of the Seven Wonders of the Ancient World (Li and Yeung 2014). However, from ancient times up to the 18th century, green roofs were rather sparse amenities for the predominant purposes of representation and decoration and as such mostly remained an imperial privilege (Ahrendt 2007). Throughout the 19th century, modern advancements of building techniques and materials (i.e. discovery of reinforced concrete) have brought a crucial breakthrough in the construction world. This brought new structural facilities of green roof installation in Europe (Ahrendt 2007, Emilsson 2005). The following upswing of modern-day green roofs has its origins in Germany where in the late 19th century, a method was developed to replace the highly flammable tar as typical roofing material with sand and gravel membranes for protection against fire (Getter and Rowe 2006). As natural seeds soon colonized these roofs, they eventually became wild meadows, which remained intact throughout the following decades (Getter and Rowe 2006). Due to their function(s) and persistence, these roof systems became well recognized in the early 20th century as important principle of modern architecture. Ever since, vegetated roofs have become a widespread urban design tool for many cities in the world. In Germany, green roof markets rapidly expanded in the 1980s, encouraged by state legislation and municipal government support (Magill et al. 2011).

Today, green roofs live a new revolution as multifunctional greening strategy for tackling urban environmental challenges in cities all over the world. Germany is currently leading the global 'Green Roofolution', being the country with the highest number of green roofs installed and the most advanced green roof technology (Li and Yeung 2014).

In general, green roofs can be defined as "vegetative roof systems that contain live plants atop the roof membrane" (Cavanaugh 2008). They usually consist of the five standard layers: vegetation, growth substrate, drainage layer (allowing discharge of excess water), root barrier and waterproofing membrane (Getter and Rowe 2006). The most decisive layer is the substrate layer, which through its thickness defines the green roof type. In Europe, two types of green roofs are normally distinguished (Mentens et al. 2006): (1) extensive green roofs (EGR) with a maximum substrate layer depth of around 15 cm, mostly vegetated by sedum species, and (2) intensive green roofs (IGR) with a substrate layer depth of more than 15 cm. IGR systems allow for more complex vegetation including shrubs and smaller trees and may be used as roof gardens (Mohammad et al. 2012).

One of the most important characteristics of green roofs in the context of GI is their multifunctional performance in improving the urban environment. They can offer a wide range of cross-sectoral benefits to social-ecological systems through the delivery of different ecosystem services (ES).

Under climate change, the regulating effect of green roofs on outdoor thermal conditions is becoming an increasingly important benefit especially to urban environments. Green roofs can improve the urban microclimate especially through local heat reduction. Conventional roofs, often covered by dark-coloured material like bitumen, usually have a very low albedo. Due to their high absorption rate of incoming solar radiation, their surface can reach temperatures of up to 90°C on a summer day (ZinCo 2018). In return, they release considerable amounts of sensible heat to the atmosphere, which directly contribute to the so-called urban heat island (UHI) effect (i.e. higher temperatures in city compared to the surrounding suburban or rural areas) (Razzaghmanesh et al. 2016). Vegetated roofs can cool their direct environment especially through the effect of shading, surface reflection and evapotranspiration. While the first two effects reduce the energy uptake of roofs, the latter redirects the available energy to latent heat, also known as evaporative cooling. Consequently, green roofs heat up much less during the day, resulting in a lower heat transfer to the near-surface air layer. The overall cooling capacity of green roofs depends on specific roof and plant characteristics (e.g. height, wetness, foliage density) as well as the urban-climatological context of such systems (Herrera-Gomez et al. 2017). Changes in microclimatological parameters like air temperature and surface energy balance can further have positive effects on the local thermal comfort of humans. This highlights the great potential of green roofs as nature-based solution to increasing heat challenges in cities (Kabisch et al. 2017b, Xing et al. 2017).

Other benefits of green roofs such as runoff reduction, air purification, indoor climate regulation and associated air conditioning costs reduction as well as social recreational functions of green roof gardens are not further discussed here, as they are not part of the microclimate analysis of this study.

Berlin currently counts around 18,000 green roofs, equalling only 4% of the city's total roof area (SenSW 2017). This highlights the large, yet still unused potential of rooftop greening in the city. Around 85% of all installed green roofs are extensive green roofs given their lower installation efforts, structural requirements and maintenance demand (SenSW 2017). However, regarding the overall environmental performance, intensive green roofs generally carry a bigger potential

(Morakinyo et al. 2017) as they bring a wider range of socio-ecological co-benefits. The prefabricated GDR-time block buildings (i.e.WBS, PH, P and M types), which strongly dominate the building structure of our study area, are well suitable for rooftop greening due to their flat roof construction and their 'uniformness' which clearly facilitates a replicability of a test case including its impact. Regarding the structural demand, a comprehensive feasibility study by Müller (2017) found that the typical socialist building type (WBS 70), which is also represented in the present study area, meets all static requirements for green roof installations.

This study can be seen as a follow-up of the ADAM project (Adaptation and Mitigation Strategies) run by the Germany Environmental Agency from 2006 to 2009 (https://www.umweltbundesamt.de). The KURAS project (http://www.kuras-projekt.de) focussed on runoff regulation mainly and studied Wilmersdorf, a periurban area in Berlin. In this sense, we see our study also as a kind of follower of KURAS. A clear specific of our ENVI-met study is the focus on the prefabricated block buildings within the neighbourhood scale.

3. Material and methods

3.1 Study area

The study area (hereafter referred to as KMA area) is an inner-city residential neighbourhood situated along and around the western part of Karl-Marx-Alley in central Berlin. It has a size of around 80 hectare and is bordered by Alexanderplatz in the west, Straußberger Platz in the east, Mollstraße in the north and the Spree river in the south (Figure 1). During World War II, about 70 % of the building stock in the KMA area was destroyed. Population density declined from 660 inhabitants/ha (pre-war level) to only 100 inhabitants/ha by 1945. These conditions would last in the following post-war period until the late 50s, when the first reconstruction program of this area eventually started (Bezirksamt Mitte 2015a). On 19.10.1957, the Central Committee (ZT) of the Socialist Unity Party of Germany (SED) has made two major planning decisions for Berlin, which would notably influence the area's post-war development. First, the theory of housing complex should be advanced and promoted, and second, the preparation of the redesign of Berlin's centre should start immediately. The combination of these two objectives led to East Berlin's ambitious goal to redesign the city centre by building the first inner city large-scale socialist housing complex. The project intended the construction of 5,400 residential units, which should offer immediate social housing for about 16,200 residents within the KMA area in order to overcome the urgent post-war housing shortage in Berlin (Bezirksamt Mitte, 2015a).

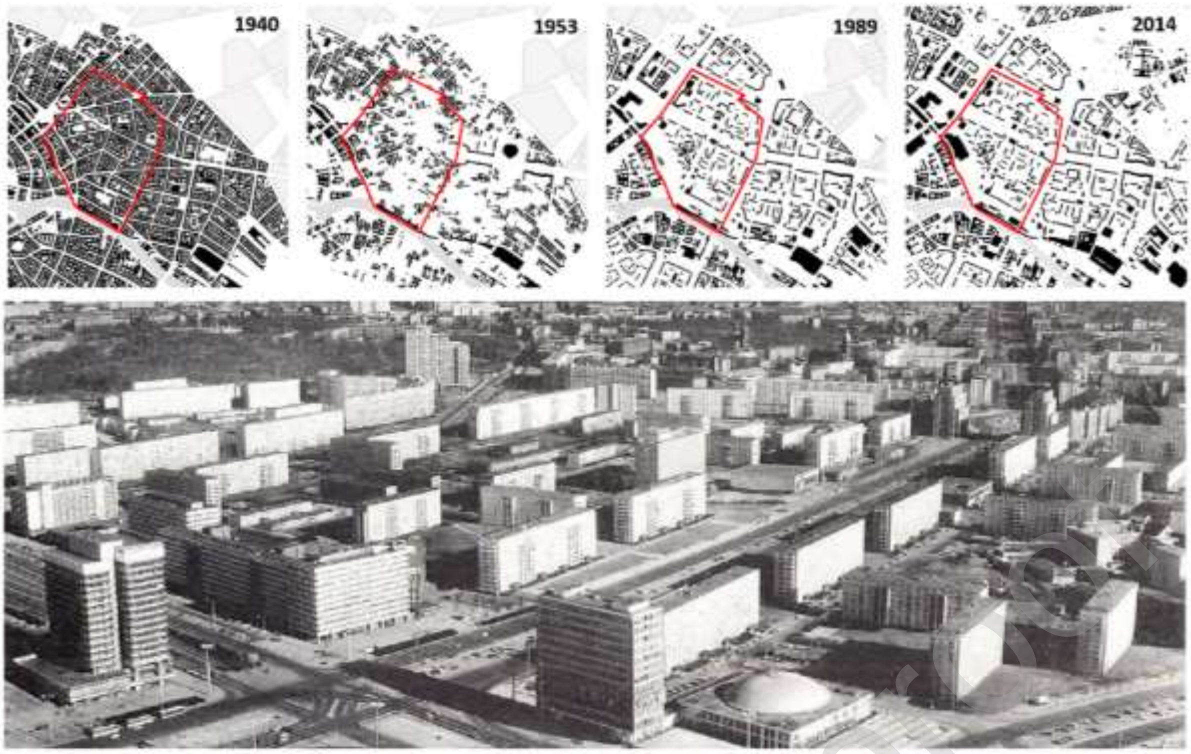

Figure 1. Diagrams of the KMA area (marked in red) for the years 1940, 1953, 1989, and 2014 (SenSW n.d.a) and (below) a photograph of KMA neighbourhood after its constructional completion in 1965 (Bezirksamt Mitte 2015b).

Since its completion in 1965, the area's building structure has remained mostly unchanged and is characterized by the clear geometric order of orthogonal string compositions (Figure 1). String compositions are a standardized construction of rectangular volumes made of prefabricated modules (Bezirksamt Mitte 2015a). After the German reunification in 1990, only few "post-socialist" constructions were added to the area. Building height varies from 1-story to high-rise (up to 18-story) buildings (Figure 2). Most structures have between 8 and 10 stories with a median height of 15.6 m (Bezirksamt Mitte, 2015c). Almost all buildings have flat roofs, which in total constitute more than 20 % of the total area. The majority of the buildings in the KMA area are renovated and in good conditions.

During the last decades, the KMA area has changed from a nearly tree-free to a moderately green neighbourhood with a notable presence of woody plants (Bezirksamt Mitte 2015c). This development is mainly the result of the greening concept developed by the landscape architect Hubert Matthes in 1963 which comprised (i) the geometric plantation of tree clusters at prominent public spaces, (ii) patchy tree plantation in decorative front yards of housing buildings, and (iii) single or double tree lines along main streets (Figure 2; Bezirksamt Mitte 2015c). The outcome of this greening concept makes the majority of the area's present-day vegetation stock.

Despite its overall green character, the KMA area is clearly underserved in terms of green space supply. The environmental monitoring assessment by the Environmental Atlas Berlin shows that green space is poorly provided in the neighbourhood. In Berlin, facilities for near-residential recreation are officially defined by a minimum size of 0.5 ha and a maximum distance of 500 m from the residence while the threshold for adequate green space provision is 6 m^2 per inhabitant (SenStadtUm 2016c). The KMA area currently has a mean green space provision rate of 5 m^2 per inhabitant (Bezirksamt Mitte 2017). Green spaces within the neighbourhood are rather small and scattered while spacious green facilities of high recreational quality are missing. The closest bigger public park, the Volkspark Friedrichshain, is more than 800 meters distant to the centre of the neighbourhood. Its accessibility is further dampened by the two main streets of Mollstrasse and KMA, which both lack adequate crossing possibilities for pedestrians (Bezirksamt Mitte 2017).

In general, the KMA area is framed by high-traffic roads posing distinct physical barriers to surrounding areas. This further highlights the need of adequate green space availability within the neighbourhood. Citizens' participation programs organized by the Mitte district office have clearly shown that the area's green space shortage is not only a matter of statistics but is strongly perceived by the inhabitants (Bezirksamt Mitte 2017).

Another important issue linked to this is the poor quality of public green spaces in the neighbourhood (Bezirksamt Mitte 2015a). For example, as many green facilities are located in near distance to heavily trafficked roads, they are highly noise-polluted which significantly reduces their recreational quality. Moreover, since they are in many cases organized as buffer zones between different functions, they can often rather be seen as green inter-spaces (Pahl-Weber et al. 2016) with little potential for recreational use. Most of the area's green facilities further lack sufficient maintenance and equipment (e.g. public seating) causing an overall low quality of stay (Bezirksamt Mitte 2017).

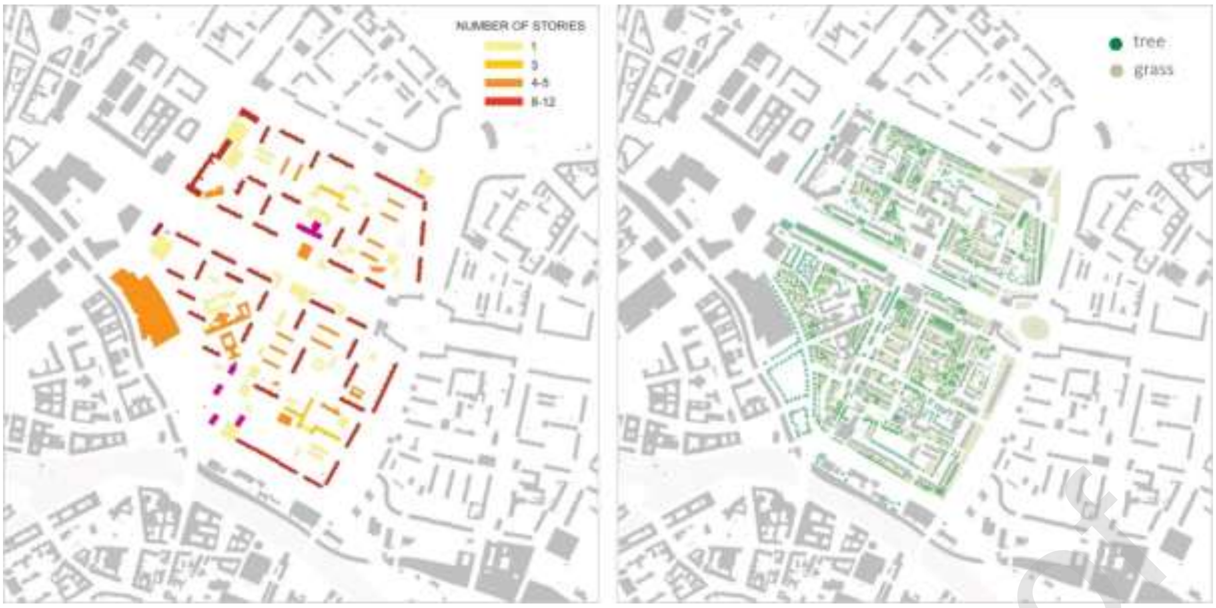

Figure 2. Left: Number of stories of individual buildings in the KMA area. Own figure based on Bezirksamt Mitte (2015c); Right: Distribution of green space in the KMA area. Own figure based on Kaulen (2012) and Bezirksamt Mitte (2017).

Today, the KMA area is home to more than 8,700 people (AfS 2019). With a total size of around 80 hectare, this makes a population density of about 11,000 people per km² which is above the mean district level of 9,715 people per km² and more than twice as high as the Berlin average of 4,200 people per km². During the last decade, the population has continuously grown with a total increase by 5.8 % from 2007 to 2017 (AfS 2013, AfS 2019). The neighbourhood is clearly characterized by an above-average proportion of elderly people with around 30 % of the inhabitants being >65 years old (AfS, 2019). Over recent years, the share of >80 years old people has significantly increased and is expected to further grow within the next years, posing new challenges to the future neighbourhood management.

According to the Environmental Atlas Berlin (SenSW 2015), the KMA planning area is one of the inner-city hot-spot areas of environmental burdens. More precisely, based on the integrated environmental load map of Berlin, the KMA area is the only residential planning area within the city centre where the four investigated ecological indicators (i.e. noise load, air pollution, availability of green spaces, and thermal load) all reach critical levels. At the same time, the neighbourhood shows a high demography-related sensitivity towards most urban environmental burdens. Older people (i.e. above 65 years) - who are strongly represented in this area - are more sensitive to thermal stress and air pollution owing to the increased cardiovascular and cardiopulmonary disease risk (e.g. Simoni et al. 2015, Cournane et al. 2017). Besides the elevated physiological sensitivity, older people further lack the capacity of adequate behavioural adaptation where social isolation and mobility constraints often lead to a low coping ability. As elderly people have a limited radius of action compared to younger population groups, the availability and accessibility of local environmental resources become even more important. Older people are thus more adversely affected by the near-residential green space deficit. This in turn can amplify the level of sensitivity to heat stress, highlighting the interconnectedness of different ecological factors. The distinct concentration of environmental burdens combined with the elevated sensitivity to such burdens lead to a (very) high vulnerability of the KMA area to the unfavourable urban-environmental situation, in particular to heat stress (SenSW 2016a).

3.2 Modelling thermal effects using ENVI-met

The effect of green roof implementation on the urban microclimate (i.e. local thermal situation) is investigated based on the application of the micro-scale numerical ENVI-met model (Bruse and Fleer 1998). ENVI-met is a three-dimensional non-hydrostatic model for the simulation of surface-plant atmosphere interactions in urban environments. It is developed for micro-scale simulations with a typical horizontal resolution between 0.5-10 m and is thus capable of resolving individual buildings in complex urban environments (ENVI-met n.d.). ENVI-met is a prognostic model based on the principles of fluid dynamics, thermodynamics and the laws of atmospheric physics (Bruse, M. 1999). Its model structure consists of a one-dimensional boundary model with vertical profiles of different meteorological parameters (up to the height of the planetary boundary layer) and a three-dimensional core model, which includes all atmosphere, soil, building and vegetation processes (Simon 2016). ENVI-met computes microclimatic dynamics during a diurnal cycle (24 to 48 hours) at time steps from 1 to 5 seconds for amongst others the following key variables (Bruse and Fleer, 1998): Wind speed and direction, air and soil temperature, turbulence, air and soil humidity, radiative fluxes, gas and particle dispersion. Its high spatial resolution combined with the detailed modelling of vegetation allows the simulation of small-scale interactions between individual buildings, surfaces and plants in complex urban structures (Morakinyo et al. 2017). A detailed description of the model physics with underlying equations can be found in Bruse and Fleer (1998).

ENVI-met has been validated by various studies for its ability to accurately simulate urban thermal conditions in different climates and countries such as US (Chow et al. 2011, Middel et al. 2014), China (Yang et al. 2013), Japan (Srivanit and Hokao 2013), South Korea (Jeong et al. 2015), Netherlands (Taleghani et al. 2014), Egypt (Mahgoub and Hamza 2013), and Germany (Müller et al. 2014, Lee et al. 2016). For example, Müller et al. 2014 evaluated the model performance through a comparison between field measurements and simulation results of diurnal variations of air temperature and relative humidity in Oberhausen, Germany. Given the high coefficient of determination of R^2 of 0.9

for both sets of parameters, they conclude that the model accurately reproduces observations. Lee et al. (2016) validated the human-biometeorological performance of the newest model version, ENVI-met 4, for a case study in Freiburg, Germany. They included mean radiant temperature, air temperature and physiologically equivalent temperature (PET) and found strong agreements with observations for all parameters (R^2 of 0.86, 0.85 and 0.77 respectively). Huttner (2012) evaluated the performance of the enhanced wall/roof module in terms of accuracy in energy flux and surface temperature simulations for a case study in Holzkirchen, southern Germany. The comparison between simulated and measured roof temperature showed an overall high agreement ranging from R^2 from 0.87 to 0.93 between different roof types. Peng and Jim (2013) conducted a model evaluation explicitly in terms of green roof simulation performance looking at air temperature on two green roofs and a bare roof in the city of Hong Kong. Based on a comparison analysis, they found a strong agreement between simulations and on-site measurements for both green roofs (R^2 0.95) and the bare roof (R^2 0.96).

The present analysis was conducted using the most recent version of ENVI-met, V 4.4, which was released in November 2018. Key advancements of this updated version include the new wall and roof greening module, which enhances the model's capability to simulate complex interactions between vegetation, substrate layer, and fixation materials on facades or roofs (Bruse 2018). This is highly relevant for the present analysis in order to simulate thermal effects of roof greening.

The 4.4 version further allows the usage of geo-data in vector format for generating the ENVI-met input files. In contrast to the usual time-intensive grid-by-grid editing, the new vector-based approach highly facilitates the digitizing process by offering the integration of vector graphics such as Shape files, CAD files or OpenStreetMap data. Model areas can thus more easily cover bigger urban areas, depending on the computational load capacity. So far, most studies using the ENVI-met software are limited to the scale of individual buildings or building block. The application of the ENVI-met model at the wider scale in this analysis (i.e. LOR planning area) is thus, to the best of our knowledge, novel. The newest ENVI-met version further offers the conversion of output files in the standardized NetCDF data format which is highly useful regarding post-processing and visualization of large three-dimensional data fields (Bruse 2018).

Data for building height, vegetation type and surface type were taken from the digital database of the Environmental Atlas Berlin (Umweltatlas Berlin, SenSW 2016b) and processed using the QGIS software (QGIS Development Team 2019). Based on this data, seven plant types were defined in the ENVI-met database for this study including the specification of albedo, height, root zone depth, leaf area density (LAD), and root area density (RAD). Building shapefiles were complemented by current construction projects for the KMA area, some of which are already under construction while others are planned for the near future. Respective data was taken from the digital city model provided by the Berlin Senate Administration for Urban Development and Housing (SenSW n.d.b) and pre-processed with the design and drafting software AutoCAD (Autodesk 2019). The model domain comprises around 170 buildings with a median height of about 18.4 m and a main orientation along the NW-SE axis of Karl-Marx-Allee.

Meteorological forcing data (i.e. air temperature, wind speed and wind direction) was provided by the automatic weather station of the German Weather Service (Deutsche Wetterdienst, DWD) which is situated near Alexanderplatz (52.5°N, 13.4°E), in approximately 600 m distance to the model domain. Respective station data is available at the DWD Climate Data Center (DWD Climate Data Center 2019). The simulation was performed for a hot summer day in order to assess the maximum beneficial cooling effect of green roofs in extreme heat conditions which are projected to increase in Berlin (SenStadtUm 2016b). Therefore, weather station data of the hottest day of the record summer of 2018, i.e. 08 August 2018, was used as meteorological forcing. The 24-hour simulation period started at 00 CET and ended at 24 CET.

The size of the ENVI-met model area simulated in this analysis is 930 m in east-west direction and 975 m in north-south direction (Figure 3 left). The spatial resolution was defined by a horizontal grid size of 5x5 m. Smaller horizontal grid sizes of 3 and 4 m were tested in the beginning, however led to unmanageable computation durations of more than one month for each scenario. One block building of the so-called P2-type covers about 100m x 12m and is well represented by a grid size of 5 m. Given the pronounced size of the study area, a grid size of 5 m was identified as best compromise between numerical effort and resolution requirements for the intended microclimatic analysis. Vertical grid size varies, starting with equidistant grids with a resolution of 1 m until the height of 2 m followed by telescoping grids with a telescoping factor of 10 % for levels above 2 m. This allows the inclusion of also higher buildings while keeping the number of vertical grids at a computable level. The simulation grid of the entire model domain thus counts 186x195 cells horizontally and 32 cells vertically. For the present analysis, a nesting area of 10 cells has been selected which enhances the stability of lateral boundary conditions for the core model (Bruse 1999). The model area was rotated by 26° counter-clockwise, according to the dominant alignment of building geometries, in order to avoid artificial roughness at building walls edges. An overview of input data and parameter settings can be found in Table 1.

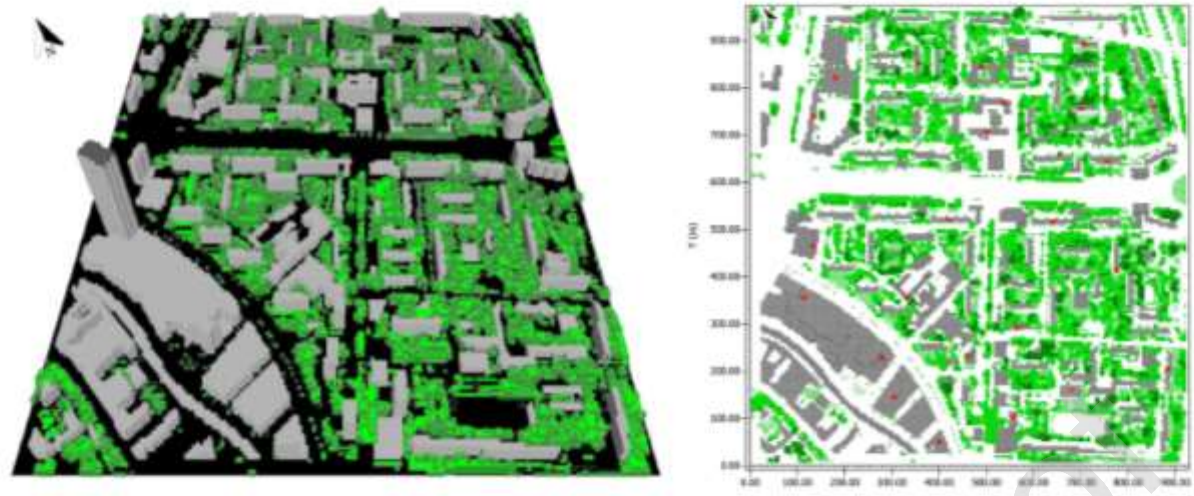

Figure 3. Left: 3D-map of model area, colour coded by three main input layers: buildings (grey), vegetation (green) and asphalt surface (black). Right: 2-D map of study area input file. Red marks show locations of the 24 roof points that were used for PET computations.

Two different rooftop scenarios were simulated for the model area (Fig. 4). The baseline scenario (BS) was developed based on the existing conditions. This scenario accordingly assumes standard conventional (i.e. non-vegetated) roof cover for all buildings in the study area. More precisely, roof surface was assigned to asphalt in the model, being representative for the predominant bitumen cover of flat roofs in the area. Ground surface is sealed by either asphalt or cement except for vegetated areas, which are attributed to sandy soil. Building wall and roof material were defined as concrete. All material types used in this study are part of the ENVI-met default database and further defined by key attributes like specific heat capacity, absorption or albedo. In the intensive green roof (IGR) scenario, all roof tops are assumed to be fully covered with shrub vegetation, with a plant height of 50 cm and a LAD of 2.5. Here, the substrate layer of the vegetated roofs is composed of sandy loam and has a thickness of 38 cm. Apart from the modified roof cover, all initial parameters remained unchanged in order to detect the isolated effect of the rooftop greening on the urban microclimate. It should be noted that in the IGR scenario, we hypothetically assume that all roofs in the model area can be fully greened disregarding the aspect of feasibility. The reason for this is our aim to estimate the maximum potential effect of roof top greening on thermal outdoor conditions independent from possible administrative, financial or structural greening limitations. The consideration of the latter requires in-depth analysis of individual buildings, which lies beyond the scope of this study, however, would be of importance for further detailed planning assessments.

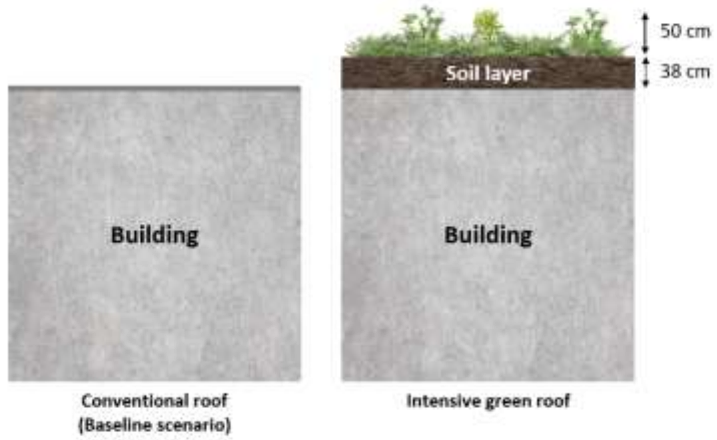

Figure 4. Schematic illustration of the two different rooftop scenarios as specified in the customized ENVI-met greening data base.

The model simulation ran on an Intel Core i5 processor at 1.6GHz with 8GB RAM on which each run took about 330 hours. The visualization, post-processing and analysis of the output data was done with the ENVI-met application Leonardo as well as the statistical programming language R (R Core Team 2018), using the 3.5.1 version.

3.3 Thermal comfort for the heat susceptibility assessment

Human thermal comfort (HTC), defined as "that condition of mind which expresses satisfaction with the thermal environment" (ISO 1984), is widely applied to assess the (microclimatic) effectiveness of urban greening strategies from the human-health perspective. Different indices have been developed to examine HTC, including the predicted mean vote (PMV), effective temperature (ET), standard equivalent temperature (SET), and physiologically equivalent temperature (PET). This study uses PET due to its broad recognition as adequate indicator for HTC, its standardized nature, and its well comparable unit of degree Celsius (Taleghani et al. 2016, Peng and Jim 2013). PET is a commonly used human-biometeorological index which quantifies thermal comfort by taking into account thermal hygric conditions, radiation and wind data, the human metabolic heat exchange rate, and other thermo-physiological parameters (see below) (Müller et al. 2014).

More precisely, PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Höppe 1999). The typical indoor setting is defined by a wind speed of v = 0.1 ms−1, a vapour pressure of vp = 12 hPa and a mean radiant temperature (T_{mrt}) equal to the air temperature (T_a). The index computation is built on a simplification of the Munich Energy-Balance Model for Individuals (MEMI) defined by Höppe (1999):

$S + W + R + M + C + E_{sk} + E_{res} + E_{sw} = 0$

where S is body heat storage, W is physical work, R is the net radiation for the body, M is the metabolic heat production, C is the sensible heat, E is the latent heat divided into fluxes (i) from or to the skin (E_{sk}), (ii) through sweating (E_{sw}), and (iii) via the respiratory system (E_{res}) (Teleghani et al. 2016). Table 2 gives an overview of different PET levels with corresponding human thermal perception and grades of physiological stress.

As PET offers a comprehensive investigation of thermal comfort, it makes a more adequate indicator for the effectiveness of adaptation measures like green roofs compared to meteorological parameters.

Here, PET is calculated using the RayMan Pro version 2.1 software (Matzarakis et al. 2007; 2010) based on the following input parameters: Air temperature (°C) , global radiation (Wm−2), surface temperature (°C), mean radiant temperature (°C), wind velocity (ms−1), air relative humidity (%), thermal resistance of clothing (Clo), and level of activity of humans (W). RayMan is an open-source modelling software that reliably estimates microclimatic changes in different urban structures, especially for situations with a relatively high position of the sun (Müller et al. 2014). It is widely used for PET assessments and has been applied in various analyses for mid-latitude cities with similar conditions (e.g. Kántor and Unger 2010, Matzarakis et al. 2007, Müller et al. 2014).

Meteorological forcing data was taken from the ENVI-met simulation output while thermo-physiological parameters were assumed for a representative proxy resident in the simulated neighbourhood with summer clothes (Table 3). As ENVI-met only allows extracting data values of the 3-dimensional buildings layer at single points, a set of equally distributed grid cells had to be defined that are located at the rooftop level. A total of 24 roof grid points were thus randomly selected which represent the area's roof-level situation in PET computations (see red marks in Figure 4 right).

4. Results

Results in this chapter all refer to microclimatic green roof effects on a hot summer day and focus on the daytime as this is the period with most human outdoor activity. More precisely, results are reported for 14:00 CET representing the typical time of a summer day with maximum heat load (as in the Environmental Atlas of Berlin). Results are distinguished between street/pedestrian level (z at 2.5 m) and roof or, respectively, podium level. The here presented results are based on the comparison between the two different rooftop scenarios that were simulated for the model area. The model output of the baseline scenario (BS) thus refers to the simulation of current conditions (i.e. conventional bare roofs) while the results of the intensive green roof scenario (IGR) show effects for the assumed case that all roof tops are fully covered by 50 cm high shrubs.

4.1 Air temperature

Table 4 shows the mean and maximum cooling effect (i.e. air temperature reduction) of the intensive green roof scenario in relation to the baseline scenario (Ta_{IGR}-Ta_{base}) at 14:00 CET for the roof level and the pedestrian level. With a mean temperature reduction of 0.04 °C, the cooling effect of intensive green roofs at the street level is very low. Vertical advection of cooled air generated by green roofs can only be found in front of single buildings with bigger roof areas in the west of the study domain (Figure 5). Maximum reduction of the pedestrian-level air temperature at 14:00 CET reaches values of 0.3 °C (Table 4). Figure 5 further indicates the influence of wind direction on the horizontal distribution of cooling intensity.

In general, local air temperature reduction is mostly restricted to the green roof locations. However, in the downwind part of the study area, cooled air is advected with the main easterly airflow toward the west. The downwind area thus shows slightly stronger cooling effects than the eastern part of the domain. At the podium level, mean daytime air temperature reductions by green roofs are 0.1 °C. Maximum cooling rates of up to 0.3 °C can again be found in the downwind part of the area at buildings with bigger roof areas (Figure 5). Podium-level cooling intensity was found to be independent from roof height (not shown).

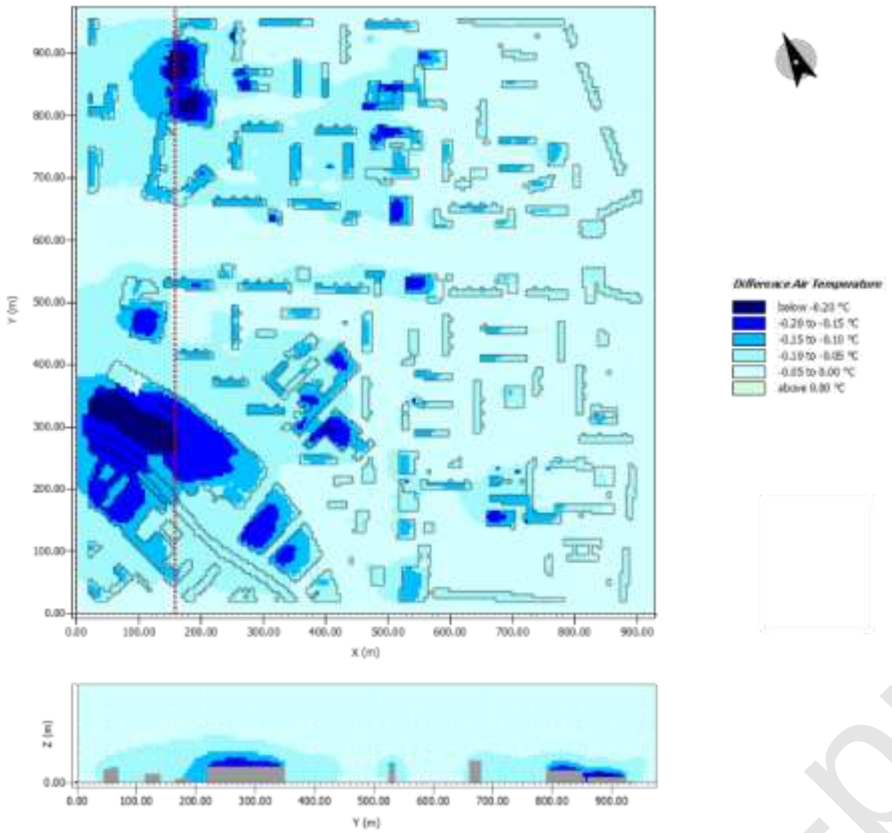

Figure 5. Air temperature (Ta) difference between the intensive green roof scenario and the baseline scenario (Ta_{IGR}-Ta_{base}) at 14:00 CET (top) for the whole KMA area and (bottom) along y-profile at x=157 m (marked by red dotted line).

4.2 Surface temperature

Figure 6 shows differences in surface temperature for all roof tops in the KMA area between the baseline scenario and the IGR scenario at 14:00 CET. Results indicate that rooftop greening leads to a clear decrease in surface temperature (Ts) by up to 26 °C in the model domain. The surface cooling is highly associated with the modification of the surface energy balance at the roofs as revealed in Figure 6.

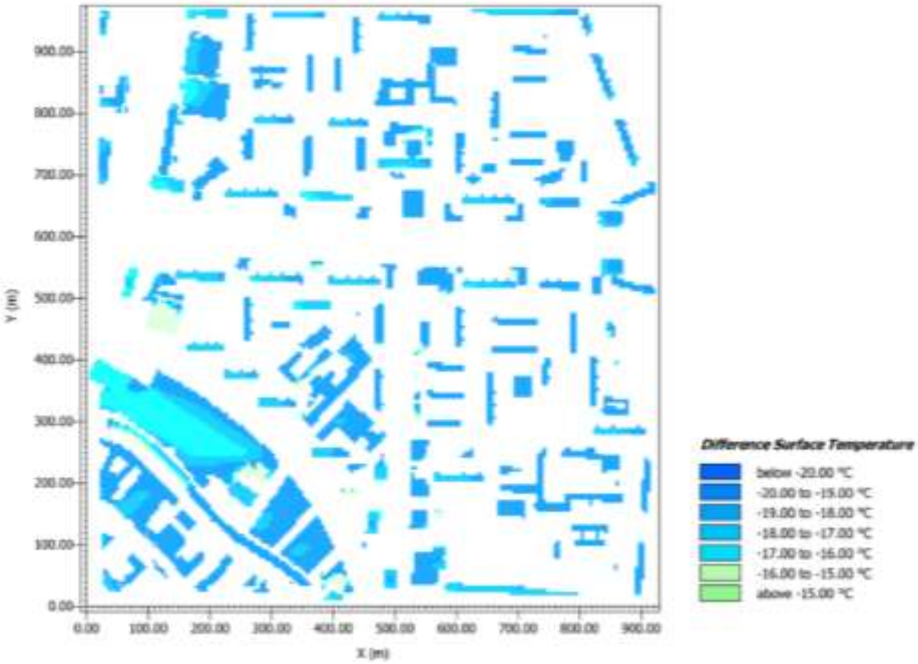

Figure 6. Surface temperature difference between the intensive green roof scenario and the baseline scenario (Ts_{IGR}-Ts_{base}) at 14:00 CET for all roofs of the KMA area.

4.3 Thermal comfort

Results further indicate that these changes in the radiation balance and associated surface temperature clearly affect the local thermal comfort on greened roofs. Table 5 shows mean PET values for both levels (rooftop and pedestrian) and scenarios (IGS and BS) at 14:00 CET. While street-level values show no variation in PET between the two scenarios, rooftop thermal comfort is considerably altered. In the IGR scenario, mean roof-level PET values are 9 °C lower than in the baseline scenario. Rooftop greening thus leads to a distinct increase in thermal comfort at the podium level. Moreover, mean PET at greened roofs is 4 °C lower than respective street-level values. Green roofs thus show a significantly increased level of thermal comfort compared to the average street-level situation.

Figure 7 shows the diurnal variation in mean PET at the street level and roof level under the IGR scenario. In general, PET shows a strong diurnal cycle with highest values between 12:00 and 15:00. As expected, strongest PET differences between the pedestrian level and the green roof level occur during sunlit hours reaching a maximum of +5 °C (PET_{street}-PET_{roof}) at 15:00 CET. During the night, PET differences are much smaller and values nearly converge after 10pm.

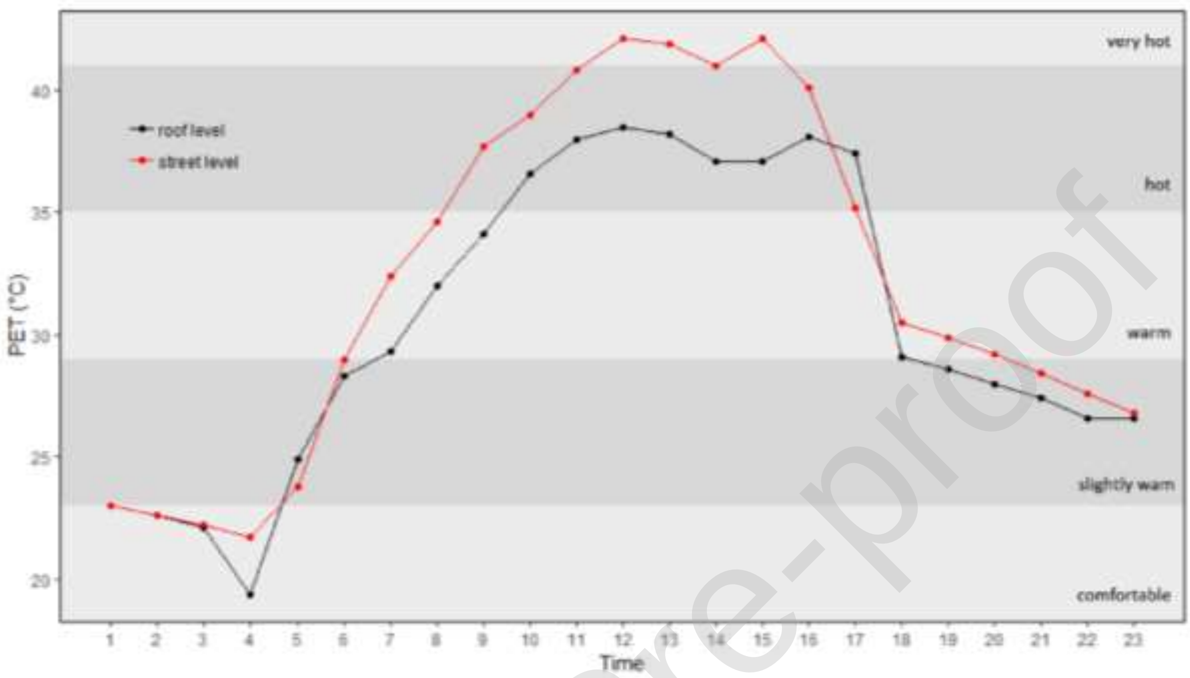

Figure 7. Diurnal profile of the mean PET at the street level (red line) and roof level (black line) under the IGR scenario at 14:00 CET. Street-level values are averaged over the whole model domain whereas roof-level values are averaged over the 24 roof data points. Respective thermal perception of different PET ranges is indicated by grey shading.

5. Discussion

Our results clearly demonstrate a negligible cooling effect of green roofs at the street level as both air temperature and PET show very little variation under the IGR scenario. This is in line with results by Morakinyo et al. (2017) who estimated the cooling effect of IGR for a standard neighbourhood of medium density (uniform building height of 30 m) under typical temperate climate conditions and found a minor reduction in pedestrian-level air temperature of less than 0.01 °C (at 15:00 CET). Moreover, this confirms findings by other studies showing that in areas with middle to high-rise buildings, the downward spill of cool air generated by green roofs barely reaches the street level (e.g. Mohsen et al. 2016, Peng and Jim 2013). Müller et al. (2014) found that roof greening effects on pedestrian-level air temperature become insignificant for building heights above 10 m. Herath et al. (2018) found similar results when generating micro-climatic data for the Colombo metropolitan region, Sri Lanka.

With a median podium height of about 18.4 m in the KMA area, it can thus be assumed that lateral and vertical advection of cool air generated by green roofs are significantly dampened by building height, inhibiting notable street-level effects. The insensitivity of street-level PET to rooftop greening is well comprehensible as PET is mainly driven by radiation which remains largely unaffected at the ground level under the IGR scenario. This finding is crucial for urban planning in so far, that rooftop greening does not replace ground green but can be seen as complementary, in particular when buildings are high.

Results further show that despite their limited effect on near-surface air temperature, green roofs significantly change the radiation and heat balance of the urban surface at the roof level. This is clearly reflected in distinct reductions in mean daytime surface temperature by 26 °C (Figure 6), which is linked to the strong decline in absorbed solar radiation of vegetated roofs. The increased surface albedo as well as radiation buffer through the vegetation layer significantly reduce the uptake of shortwave radiation by the roof surface. At the same time, vegetation enhances turbulence near the surface, intensifying heat exchanges between the surface and overlying air. It further modifies the partitioning of turbulent heat fluxes with amplified latent heat exchange through evapotranspiration (Arya 2001). Consequently, greened roofs heat up much less during the day compared to bare roofs as indicated by our results. Other experimental studies found similar magnitudes of daytime surface temperature reduction by green roofs ranging from 22 °C for Athens (Foustalieraki et al. 2017) to 30 °C for Singapore (Wong et al. 2003). As above, this is an important information for planners who are provided by a clear idea of how large the effect of vegetated green roofs is at rooftop level. Calculations of cooling/air conditioning energy budgets (for the building or an entire estate) can be fed using such data.

In consequence, the physiological equivalent temperature at the roof level is significantly reduced under the IGR scenario, implying a distinct increase in thermal comfort. Results show that under the baseline scenario, bare roofs heat up more intensely during the day and create an environment of strong thermal discomfort with a mean PET of 46 °C. In the same scenario, mean PET at the street level is much lower at 41 °C, indicating a more favourable yet very hot (Table 2) environment on a hot summer day. Rooftop greening clearly changes the relation between podium-level and street-level thermal comfort. Daytime podium-level PET is significantly reduced under the IGR scenario. Consequently, mean PET values of 37 °C now lie well below respective street-level values of 41 °C (at 14:00 CET). Comparing the associated thermal perception and physiological stress level, this brings a qualitative difference between the two environments. The findings thus reflect the great potential of green roofs as complementary heat adaptation strategy in the KMA area through the provision of near-residential outdoor spaces with increased levels of thermal comfort for urban dwellers.

Moreover, results indicate that T_a effects seem clearly outweighed by radiative effects in defining thermal comfort. This is in line with other studies showing that under dry and hot conditions, daytime outdoor PET is mainly driven by radiant temperature and less so by air temperature (Matzarakis 1999, Lee et al. 2016, Teleghani et al. 2016). We assume that the detected decrease in roof-level PET under the IGR scenario (Table 5) is mainly caused by lower surface temperature and associated reduction of radiant and turbulent heat transfers from the roof surface. Our findings thus highlight the usefulness of PET as indicator—also for urban planning and their monitoring systems—for thermal comfort as it includes a broad range of relevant parameters other than air temperature.

Other potential benefits of IGR implementation in the KMA area are implied by our results, however, were not further examined. For example, decreases in surface temperature of green roofs are associated with reductions in heat exchanges into indoor spaces, which in turn lead to significant energy savings for air conditioning of buildings (Wong et al. 2003). Vegetated roofs can further significantly reduce surface runoff by retaining considerable amounts of rainwater (Mentens et al. 2006). The associated regulation of excessive surface runoff during heavy rainfall events makes an important contribution to the local rainwater management. Moreover, green rooftops can positively affect air quality by filtering gaseous pollutants and removing particulate matter (PM) from the air (Morakinyo et al. 2017). In recent years, an increasing number of studies have shown that vegetating rooftops can significantly reduce the impact of urban air pollution in cities. Yang et al. (2008) quantified the actual air pollution removal by green roofs in Chicago using a dry deposition model. They found that a total of 85 kg urban air pollutants was removed per hectare green roof in a year with ozone (O_3) accounting for 52%, nitrogen dioxide (NO_2) for 27%, PM_{10} for 14%, and sulfur dioxide (SO_2) for 7% of the total. Their findings further indicate that while intensive green roofs with shrub vegetation can significantly contribute to air purification, extensive green roofs with sedum-grass vegetation has a minor impact. Green roofs can thus be applied as effective strategy for air pollution control in cities as supplement to urban trees, especially in compact urban densities (European Commission 2018, Dimitrijević et al. 2018). As accessible green facilities, vegetated roofs can further increase the green space availability in a neighborhood. In our case study, the assumed greening of all roofs in the IGR scenario would bring an additional 184,000 m^2 green space to the KMA neighborhood, equaling more than 20 % of the entire area. As such, green roofs provide valuable spaces of high recreational quality with associated health and social benefits if accessible. Their direct proximity to the living space is particularly important for elderly people with limited mobility. A critical aspect in this context is the accessibility of greened rooftops. In order to be potentially beneficial for all residents, it needs to be ensured that (i) the roof level of a building is municipal property—or in some cases even public—space and (ii) no physical barriers exist to reach the rooftop. For green roofs, the latter does not only include the horizontal accessibility (as for ground-level green spaces) but also concerns the vertical accessibility, namely the availability of an elevator. These aspects need to be carefully incorporated in the planning and design of rooftop gardens in order to guarantee accessibility to all population groups including elderly people with limited mobility.

Thus, integrating all discussed aspects of green rooftop functionality, urban land use planning can make multiple use of green roofs (Raymond et al. 2017) for different purposes in land use preparation plans of big cities with considerable numbers of prefabricated blocks.

There are also clear limitations of the model application—still existing—of which the four most important are stated:

(1) For the sake of computational feasibility, this study only simulated uniform plant features for the IGR scenario. Shrubs of medium height were chosen as typical vegetation cover of intensive green roofs. The shading effect of higher vegetation (i.e. trees) has therefore not been included in the IGR simulation. However, trees could not only be easily planted on green roof systems with > 30 cm soil layer thickness, they can also significantly contribute to human thermal comfort by reducing the direct radiative input. In the KMA area, ground-level T_{mrt} at 14:00 CET is on average 24°C lower in shaded areas (whether by buildings or by vegetation) than in unshaded areas (not shown), implying distinct differences in thermal comfort between the two situations. This is well in line with findings of other studies showing a strong negative effect of tree shading on PET due to distinct decreases in down-welling solar radiation that reaches the shaded surface (e.g. Taleghani et al. 2017, Cohen et al. 2012, Oliveira et al. 2011, Mayer et al. 2009, Gulyás et al. 2006). Matzarakis et al. (1999) found in an empirical study for Freiburg (southern Germany) that on a summer day, shading of tree crowns lead to mean radiant temperature (T_{mrt}) reductions of up to 30 °C and associated PET reductions up to 15 °C. The impact of tree shading clearly highlights the need for further green roof assessments with more diversified vegetation cover including plant types with higher relevance for microclimatic conditions.

(2) It is important to note that as all numerical models are an abstraction and simplification of the real world, results of this study carry associated uncertainties and can be, moreover, significantly model-dependent. This should be further investigated in future research under the use of different model approaches. Results presented here are also dependent on the simplified assumptions that were made for the IGR scenario. For example, roof-level greenery shading effects are not incorporated in the green roof scenario, which most likely influences the significance of the model output. The IGR scenario can certainly be optimized by a more differentiated and detailed selection of the most effective plant types (especially in terms of shape, dimensions, LAD). Due to the required time-intensive workload, especially for the given size of model area, this could not be

realized in the present analysis. Nevertheless, a more detailed specification of the vegetation cover on roofs would certainly lead to more realistic model results and should thus be pursued in future assessments.

(3) Another uncertainty source in ENVI-met results is the increasingly coarse resolution at higher z-levels. Due to the telescoping factor for vertical resolution, grid size increases with increasing height. This means that at the mean roof level, vertical resolution is clearly lower ($dz \approx 2.7$ m) than at the ground level ($dz \approx 1$ m). Small-scale physical processes like turbulence are thus less well captured at coarser scale levels. Under increased computational and time efforts, these vertical resolutions can be increased across all levels with positive implications especially for roof-level simulation results.

(4) The calculation of PET was based on a 'standard inhabitant' of the KMA neighbourhood, here defined as female adult wearing summer clothes. The results of the thermal comfort analysis may depend on assumed human characteristics (i.e. gender, age, height, weight, activity level, and clothing properties) as these parameters influence the metabolism and radiation exchange of a human with surroundings (Taleghani et al. 2016).

Finally, results here may also be influenced by the number and location of the roof points that were randomly chosen for the thermal comfort analysis.

6. Conclusions

This study investigated the effectiveness of intensive green roof implementation as a nature-based solution for heat stress reduction in the KMA area, Berlin. For this, we estimated thermal effects of intensive green roofs using the microclimatic ENVI-met model. Results show that, at the street level, rooftop greening has a negligible effect on both core indicators chosen, air temperature and PET. This can be attributed to the standard building height in the neighbourhood, which restricts cooling effects to the podium level. This implies that, in the KMA area, rooftop greening does not offer an effective solution for heat load reduction at the street level.

Results further indicate that, on a hot summer day, green roofs can significantly improve the thermal environment at the roof level. More precisely, PET decreased by 9 °C under the IGR scenario, clearly changing the relation between podium-level and street-level thermal comfort. Under such given conditions, green roofs provide spaces of qualitatively increased thermal comfort compared to street-level areas. This reflects the effectiveness of green roofs as adaptation strategy to the given heat stress situation on hot summer days in the KMA area.

This study applies a novel approach towards a harmonization between research scales and planning scales in urban green space analysis. We show that with a certain time effort (i.e. 330 hours per scenario on an Intel Core i5 processor), it is possible to successfully apply the ENVI-met model at the LOR-planning level of Berlin. Therefore, this work stresses (i) the usefulness of adapting urban planning scales in GI assessments due to the spatial structure of available urban data bases as well as (ii) the importance of using such scales to make research outputs better adaptable and applicable for the planning community. The latter is especially important for achieving an integrated sustainable neighbourhood management in Berlin. Overall, our findings indicate the great potential of green roofs in offering a beneficial and 'space sensitive' greening supplement for the KMA neighbourhood. Hitherto, rooftops in Berlin are a largely wasted resource, which significantly contributes to the UHI effect. In this sense, land use planning can use the results of this study to foster green roofing as mandatory in land use preparation plans. Greening these elevated areas would not only bring environmental benefits but would moreover provide new—in the best sense complementary to ground green—outdoor recreational and amenity spaces of increased thermal comfort to the urban municipality and upcoming terrain for urban planning. However, green roofs are no substitute for green spaces at the ground such as parks, gardens or street trees; they remain useful supplements.

Author statement

We, Maria Knaus and Dagmar Haase, are the authors of this manuscript.

Declaration of interests

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

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Table 1. Overview of input data and parameter settings for the model area in ENVI-met.

Model parameter	**Model Input Value**
Location	Karl-Marx-Allee, Berlin (33.53°N, 35.31°E)
Model Area	930 x 975 m (93 hectares)
Spatial resolution	Grid size: 186x195x32; dx=5, dy=5, dz=1m with telescoping 10% for z>2m
Simulation day	8 August 2018
Simulation duration	00:00 – 24:00 CET (24h)
Simple forcing	Air temperature: T_{min} 23°C; T_{max} 38°C wind speed: 2.6 m/, wind direction: 120°
Nesting Grids	10
Sealed surfaces	Asphalt / Concrete
Natural surfaces	Sandy soil / Vegetation

Table 2. PET levels for different grades of thermal perception by humans and physiological stress on humans (redrawn from Matzarakis et al., 1999).

PET	**Thermal perception**	**Grade of physiological stress**
<4	Very cold	Extreme cold stress
4	Cold	Strong cold stress
8	Cool	Moderate cold stress
13	Slightly cool	Slight cold stress
18	Comfortable	No thermal stress
23	Slightly warm	Slight heat stress
29	Warm	Moderate heat stress
35	Hot	Strong heat stress
41	Very hot	Extreme heat stress

Table 3. Thermo-physiological parameter settings as defined in the PET simulation using the Rayman model for a representative proxy resident in the KMA neighbourhood.

Model parameter	Assigned Value
Age	47 years old
Gender	Female
Height	167 cm
Weight	69.4 kg
Activity	80 W (walking)
Clothing insulation	0.5 Clo (summer clothes)
Emission coefficient (of the human body)	Standard value 0.97

Table 4. Mean and maximum cooling effect (i.e. air temperature reduction) of the intensive green roof scenario in relation to the baseline scenario (Ta_{IGR}-Ta_{base}) at 14:00 CET.

	Mean reduction effect (°C)	Mamimum reduction effect (°C)
Street level	-0.04	-0.3
Roof level	-0.1	-0.3

Table 5. Mean PET values [°C] for both levels (roof and street) and scenarios (IGS and BS) at 14:00 CET. Grey coloured column represents potential mitigation effects while blue coloured line displays potential adaptation effects. Street-level values are averaged over the whole model domain whereas roof-level values are averaged over the 24 roof data points.

	Intensive green roof scenario (IGS)	Baseline roof scenario (BS)	Difference (IGS-BS)
PET Roof level (PET_{rt})	37	46	-9
PET Street level (PET_{str})	41	41	0
Difference (PET_{rt} – PET_{str})	-4	+5	