Landsc Ecol (2023) 38:1697–1712
https://doi.org/10.1007/s10980-023-01644-8

RESEARCH ARTICLE

Localizing and prioritizing roof greening opportunities for urban heat island mitigation: insights from the city of Krefeld, Germany

Jana Brenner · Stefan Schmidt · Christian Albert

Received: 1 June 2022 / Accepted: 17 March 2023 / Published online: 6 April 2023

Abstract
Context Climate change may increase the frequency, intensity, and occurrence of urban heat islands (UHI) in cities worldwide, often with harmful impacts on citizens. Strategic planning and implementation of multifunctional green roofs promises to help mitigating UHI effects, but cities often lack up-to-date scientific understanding of best-suited locations.
Objectives The aim of this paper is to develop and apply a socio-ecological approach to explore and prioritize present and prospective opportunity spaces for roof greening based on remote sensing data to mitigate UHI effects.
Methods The city of Krefeld, Germany, serves as a case study. The research design consists of three steps, applied to the conditions of 2019 and a 2030 scenario: (i) Examining residents' vulnerability to heat, (ii) Assessing existing green roofs and potentials for greening, and (iii) Prioritizing opportunity spaces for roof greening to reduce UHI effects.
Results Findings showed that the area of high vulnerability due to combined high heat exposures and densities of sensitive residents in Krefeld accounts for almost 300 hectares in 2019 and may triple until 2030. More than 90% of evaluated horizontal roofs have no vegetation cover. Highest priority for roof greening is attributed to 59 ha and 113 ha of roofs in 2019 and 2030, respectively.
Conclusions The findings can inform strategic roof greening efforts for climate adaptation, e.g. for the extension of cadasters, and facilitate communication to increase understandings, public and policy support, and implementation.

Keywords Climate change · Spatial planning · Nature-based solutions · Climate adaptation · Urban green · City-scale

Introduction

Urban Heat Islands (UHI), i. e. urbanized areas in which higher temperatures are experienced than in the surrounding rural areas, are considered as one of the major societal challenges of the twenty-first century (Rizwan et al. 2008). UHI are extensively researched and documented for many cities across the globe (Santamouris 2020; Tuholske et al. 2021). UHI arise

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10980-023-01644-8.

J. Brenner (✉)
Institute of Environmental Planning, Leibniz University Hanover, Herrenhaeuserstr. 2, 30419 Hanover, Germany
e-mail: brenner@umwelt.uni-hannover.de

S. Schmidt · C. Albert
Institute of Geography, Ruhr University Bochum, Universitaetsstraße 150, 40485 Bochum, Germany
e-mail: Stefan.Schmidt-y9u@ruhr-uni-bochum.de

C. Albert
e-mail: christian.albert@rub.de

due to shifts in energy fluxes (increase absorptions of solar radiation, increase of sensible heat and decrease of latent heat flow) associated with anthropogenic land cover changes and human activities (Oke et al. 1991; Tzavali et al. 2015). When surveying urban climate and the UHI phenomenon it is important to consider new paradigms as described by Wang (2022) not to oversimplify the complex system determined by interactions and changes along the urbanization gradient. The intensity of UHI varies between 0.4 and 11 °C (Tzavali et al. 2015), and is much intense at night (Azevedo et al. 2016), exposing urban residents to higher thermal stress. Such exposure can have adverse impacts for human comfort and health, causing increased mortality and morbidity, especially amongst low-income and sensitive population groups such as the elderly, children or sick people (Mücke et al. 2013; Huang et al. 2022). For instance, during the European heatwave in 2003, more than 70,000 additional deaths were registered (Robine et al. 2008). UHI-related mortality is expected to increase by climate change and urban growth (Chapman et al. 2017). Projections indicate that urban heat stress intensify further in the future and negative impacts of UHI might exacerbate (Patz et al. 2005; Huang et al. 2019).

A key strategy to mitigate against further increases in temperatures in urban areas and the associated negative impacts on human health is to ‘green’ urban areas by increasing the abundance and cover of vegetation (Bowler et al. 2010; Huang et al. 2021). Vegetation around and on urban structures, e. g. buildings, can affect its moisture, aerodynamic and thermal properties, and so urban greening could lower the air and surface temperature through different processes such as evapotranspiration, shading drop and resistance to air flows (Manso et al. 2021).

Roof greening, i. e. multi-layered systems that cover the roof of a building with vegetation over a drainage layer of soil (Berardi et al. 2014), presents a popular strategy to moderate the UHI effect as it exploits otherwise unused house roofs, lowers the air temperatures around urban green roofs up to 4.2 °C (Al-Kayiem et al. 2020), reduces building energy use by around 0.7% compared to conventional roofs (Sailor et al. 2011), and provides other multiple co-benefits including the regulation of air quality, carbon regulation, storm water management, habitat provisioning and cultural services (Berardi et al. 2014; Manso et al. 2021). The effectiveness of roof greening to moderate UHI effects depends on the area and greening type of the green roofs (Santamouris 2014; Sun et al. 2016). In general, green roof fraction should be expanded, as the increase of vegetated areas linearly reduces UHI (Li et al. 2014; Sun et al. 2016; Sharma et al. 2018). Especially by increasing the number of green roofs on buildings that hold high potential to reduce temperatures and positively affect surrounding areas, as for example office and industrial buildings that are expected to have a high share of large and flat roofs and low buildings heights and are not greened yet for about 97% in Berlin, UHI can effectively be reduced (Coenradie et al. 2016; SenStadt 2016). Greening types are divided into extensive or intensive roof greening (Pfoser et al. 2013; Brune et al. 2017). Intensive greening generates higher cooling effects then extensive greening of roofs due to larger plants and thicker depth of planting mediums (Brune et al. 2017). However, extensive roof greening is more cost-saving, requires less maintenance and can be installed on a greater number of roof structures due to lighter weight (Getter et al. 2009).

Implementing roof greening is arguably particularly effective when planned at the neighborhood or city-scale (Peng and Jim 2013; Knaus and Haase 2020), however, substantial scientific knowledge gaps still exist. For instance, timely, cost-efficient, and spatially explicit datasets on structural and climatic conditions in urban areas are rare (Shao et al. 2021). This information is essential to derive local needs and potentials for mitigating UHI (Ansel et al. 2015; Wu and Biljecki 2021). Also, there is a lack of cost and time-efficient planning methods for conducting vulnerability analyses and investigating the greening potential of roofs to prioritize opportunity spaces and integrate them into urban planning (Coenradie et al. 2016; Wu and Biljecki 2021). Remote sensing could be a key tool to overcome these challenges (Wellmann et al. 2020). For example, remote sensing approaches have recently been used to investigate greening potentials and mitigate UHI (Karteris et al. 2016; Xu et al. 2020; Shao et al. 2021). Remote sensing approaches provide up-to-date datasets without costly and time-consuming on-site mapping and facilitate data processing through automation of work steps (Ansel et al. 2015; Shao et al. 2021). Recent approaches use geographic information systems (GIS), remote sensing techniques and high resolution imagery to assess roof greening potentials. Skoryi et al. (2022), for example, estimated roof greening potentials from imagery that were classified in a semi-automatic process using the software of Ansel et al. (2015), instead of manual thresholding. Thresholds were set for reference polygons and used for classification of lager areas across several tiles by the software. However, Skoryi et al. (2022) found difficulties in defining suitable thresholds without misclassifications.

So far, studies research focus either on technical aspects of developing and improving methods for green roof inventory by investigating greening type and spatial distribution using imagery (cf. Hoffert and Lumasegger 2010; Coenradie et al. 2016) or on identifying and evaluating the potential for greening (cf. Karteris et al. 2016; Santos et al. 2016; Xu et al. 2020; Shao et al. 2021), but not on both aspects, although combined approaches are required for decision support and climate adapted urban planning (Santos et al. 2016).

The aim of this paper is to demonstrate and apply a socio-ecological approach to explore and prioritize opportunity spaces for roof greening. Data for the present (2019) and future (2030) situation in the city of Krefeld, Germany was analyzed, Krefeld, was selected as a case study because UHI occur frequently (Möller et al. 2020) and North Rhine-Westphalia was one of the most heat-affected regions in Germany during the 2003 European heatwave (Robine et al. 2008). The following three research questions were addressed:

i. Which areas of Krefeld are characterized by high vulnerability to heat and thus require action to mitigate UHI?
ii. Which roofs have already been greened or hold the potential for greening within the areas of high vulnerability to heat?
iii. Which opportunity spaces for roof greening should be prioritized, taking into account vulnerabilities and cooling effects?

The remainder of this paper is structured as follows. Chapter 2 introduces the approach to prioritize areas for roof greening. In chapter 3 the approach is applied, and the results are presented for the case study of Krefeld. The following chapter 4 contains a critical discussion of the results and the applied approach as well as a reflection on the next steps to advance urban planning practices for an enhanced consideration of roof greening. The final chapter summarizes the findings of this study and provides recommendations for climate adaptation in Krefeld and the usability of the results for implementation of roof greening from a planning perspective.

Research design and methods

Study site

The city of Krefeld (51°20′ N, 6°34′ E) is part of the Rhine-Ruhr metropolitan region and is located in the urban agglomeration of Mönchengladbach, Duisburg and Düsseldorf, which has an increasing impairment by heat with significant impact on health and infrastructure (Die Bundesregierung 2020) (Fig. 1). With around an area of 137 km^2 and 234,000 inhabitants, the city is a regional center in the metropolitan area (Stadt Krefeld 2020a).

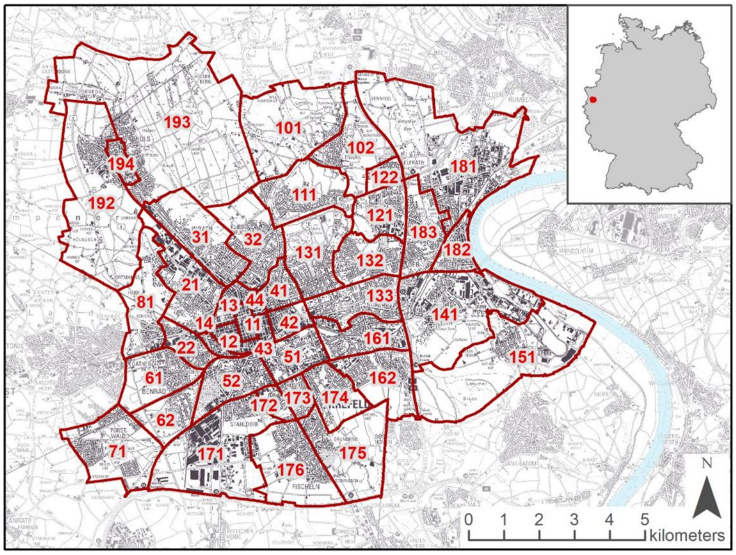
Concept for prioritizing roof greening

A modular approach with three consecutive steps was developed to identify priority areas for roof greening that contribute to lower UHI for the situation in 2019 and in 2030 (Fig. 2). First, the vulnerability of urban areas to heat was analyzed by assessing the heat exposure of urban structures and the heat sensitivity of urban dwellers and facilities. Second, an inventory of green roofs and potentials for greening was compiled by analyzing spectral data from aerial images of roof greening with the Differenced Vegetation Index (DVI). Third, the results from the vulnerability analysis and the inventories were intersected to identify opportunity spaces with high priority for roof greening to reduce UHI in the city of Krefeld.

Assessing heat vulnerability

The vulnerability to heat was assessed for 3,848.6 ha of settlement areas in 42 statistical districts of the city of Krefeld (Fig. 1) by valuation of the key indicators of heat exposure and sensitivity of the population (Table 1) (Wittig and Schuchardt 2012; Schulze Dieckhoff et al. 2018; HLNUG 2019).

The extent to which the population is exposed to heat depends on urban structures, e.g., type of



Vier Wälle	11	Gartenstadt	121
Südring	12	Elfrath	122
Stadtgarten/Drietendorf	13	Stadtwald	131
Hammerschmidtplatz	14	Sollbrüggen	132
Kempener Feld	21	Tierpark	133
Baackeshof	22	Linn	141
Inrath	31	Gellep-Stratum	151
Kliedbruch	32	Oppum-Bahnhof	161
Cracau	41	Oppum-Süd	162
Schinkenplatz	42	Stahldorf	171
Stephanplatz	43	Königshof-West	172
Bleichpfad	44	Königshof	173
Dießem	51	Niederbruch	174
Lehmheide	52	Fischeln-Ost	175
Gatherhof	61	Fischeln-West	176
Lindental/Tackheide	62	Hohenbudberg	181
Forstwald	71	Uerdingen-Markt	182
Benrad-Nord	81	Uerdingen-Stadtpark	183
Traar-West	101	Roßmuhle/Steeg	192
Traar-Ost	102	F1öthbach/Plankerdyk	193
Verberg	111	Hüls-Ortskern	194

Fig. 1 Map of Krefeld and its statistical districts (Stadt Krefeld 2019c). Background map: Digital Topographic map 1:50,000 (DTK50) (Geobasis NRW 2021)

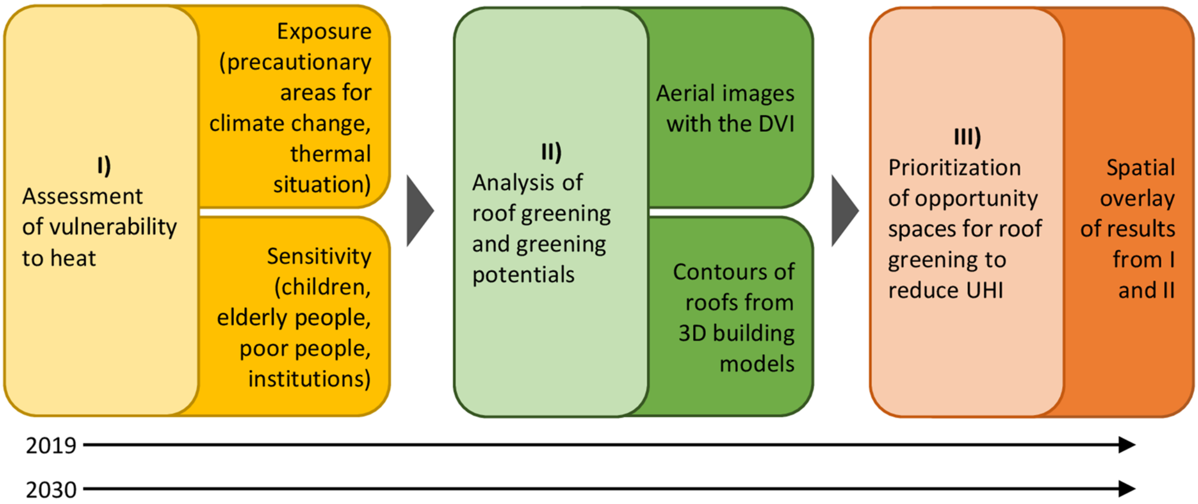


Fig. 2 Prioritization concept including three key steps and input data to estimate areas for roof greening

building, building density, degree of sealing, and urban climatic characteristics such as reflection and heat storage properties, cold air generation and fresh air supply (Gao et al. 2022). Heat exposure was determined by using a climate assessment map that shows the thermal situation and spatial distribution of settlement areas with heat stress in Krefeld modelled by LANUV NRW (2018a, b). The map divided areas into five tiers of heat stress based on their level of heat intensity from low (tier 1 = very favorable thermal situation, physiologically equivalent temperature (PET) < = 35 °C and air temperature < = 17 °C) to high (tier 5 = very unfavorable thermal situation, PET > 35 °C and air temperature > 20 °C). Areas of tiers 1 and 2 were merged as they represent areas with a (very) favorable thermal situation that were of minor relevance for the vulnerability assessment. The resulting tiers were translated to heat exposure from

Table 1 Matrix for the assessment of vulnerability to heat combining the indicators heat exposure and sensitivity

Sensitivity (people/ha)				Exposure			
Elderly people	Children	Poor people		High	Medium	Low	Very low
1–4 (0–21)	1–4 (0–6)	1–4 (0–36)	Very low	Very low	Very low	Very low	Very low
		5 (> 36)	Low	Medium	Low	Low	Very low
	5 (> 6)	1–4 (0–36)					
		5 > 36					
5 (> 21)	1–4 (0–6)	1–4 (0–36)	Medium	High	Medium	Low	Very low
		5 > 36					
	5 (> 6)	1–4 (0–36)					
		5 (> 36)	High	High	High	Medium	Very low
Presence of hospitals or facilities for disabled people			High	High	High	High	High

very low (former tier 1 and 2 (very) favorable thermal situation) to high (former tier 5 = very unfavorable thermal situation). For the assessment of the prospective exposure, precautionary areas of climate change were used, which represent areas with an increase in heat stress by 2050 according to models of regionalized climate projections of North Rhine-Westphalia assuming a one Kelvin temperature increase between 2021 and 2050 (LANUV NRW 2018a). Precautionary areas of climate change were also grouped and translated into four tiers of heat stress (Table 1).

How sensitive people are to heat depends on socio-spatial factors such as demographics and population density of the area. Heat sensitivity was assessed by using four sub-indicators representing population groups that are highly vulnerable to heat according to Bach et al. (2013) and HLNUG (2019). These population groups are the elderly (> 65 years), children (< 6 years), poor people (recipients of social and financial support according to the German Social Code (SGB II 2011/2021; SGB XII 2003/2021)), as well as ill and disabled people. Data from the population registry (Stadt Krefeld 2020a, b) and official spatial maps of settlement areas (Geobasis NRW 2019b) were used to calculate the population density of the heat sensitive population groups in settlement areas for the statistical districts of Krefeld (Table SM1). In accordance with HLNUG (2019), each heat sensitive population group was divided into five classes of population density by calculating the statistical quantiles (Table 1). Population data were not available for ill and disabled people; instead, the spatial locations of hospitals and facilities for people with disabilities (Stadt Krefeld 2019a, b) were considered for the further assessment. Hospitals and facilities for people with disabilities were buffered with a radius of 50 m and valued with high sensitivity based on the recommendations from HLNUG (2019).

To assess future heat sensitivity, population dynamics were modeled for the year 2030, using projections of population development for the elderly and children from Bertelsmann Stiftung (n. d.). The number of poor people in 2030 was calculated using a linear trend derived from data from 2009 to 2019, as no official projections were available. To estimate the population density of heat sensitive populations in settlement areas the same grouping approach was used as for the data of 2019. No changes were assumed for the number and location of the prospective development of hospitals and facilities for disabled people.

Analyzing roof greening and greening potentials

Roof greening was analyzed based on the presence of vegetation on roof areas detected from multispectral information of high-resolution (0.1 m ground resolution), digital orthophotos (DOP) Geobasis NRW 2019c) by calculating the DVI for rooftops in areas highly vulnerable to heat in Krefeld in 2019 and 2030. The DVI is a graphical indicator that accentuates the reflectance of electromagnetic waves that are not absorbed by green plants (0.7–1.3 μm bands) by subtracting the visible red reflectance from the near-infrared reflectance. After calculating DVI for each DOP, values were classified to distinguish between areas without vegetation, extensive roof greening that appears as drier and less vital vegetation and intensive roof greening characterized by dense vital vegetation. The definition of thresholds for the classification depends on feature reflectance, which may vary between different imageries due to e.g., time of the day, phenology, incident radiation, cloudiness, shooting angle and differing spectral information of vegetation (Jones and Vaughan 2010; Pafi et al. 2016). Automated approaches for threshold definition are inaccurate (Xie et al. 2010), thus thresholds defining four classes were set individually for each picture by human visual interpretation of each imagery and histogram (Pafi et al. 2016) (Table SM2). DVI values that could not be clearly assigned to one of the three classes were placed in the group “uncertain”.

To analyze DVI for rooftops, DOPs were overlaid with outlines of rooftops in Krefeld from level of detail 2 (LoD2) 3D building models in city geography markup language (citygml) format (Geobasis NRW 2019a) by using the software FME Desktop 2019 Quick Translator (Safe Software 2021) for further processing in ArcGIS 10.6.1 (Esri 2021). All kinds of buildings with flat roofs and pent roofs were selected as these are not too steep, allowing greening without need for thrust lock and erosion protection (Landeshauptstadt Stuttgart 2010; Pfoser et al. 2013). The rooftop outlines were manually adjusted to reduce misclassification caused by tilting effects of the used DOPs and to fit the visible roof boundaries of the imagery (Jensen 2007; Coenradie et al. 2016; Marconcini and Metz 2016). Neglecting correction of the tilting effects can lead to an overestimation of greened areas by about 15% (Hoffert and Lumasegger 2010; Ansel et al. 2015).

Potentials for roof greening were derived from the results of the analysis of roof greening under the following assumptions: roof areas without vegetation were assigned to a high potential; extensive roof greening and pixels classified as uncertain were classified with medium potential; and intensive roof greening was assigned to a low potential. Estimates of the potential for roof greening in 2030 were made based on the assumptions that no changes in the city’s DVI and roof inventory occur.

Prioritization of opportunity spaces for roof greening to reduce UHI

For the prioritization of areas for roof greening the spatial results from the heat vulnerability assessment and the analysis of roof greening and greening potentials were intersected and evaluated using ArcGIS Desktop 10.6.1 (Esri 2021). Roof areas highly affected by heat with a high or medium potential for greening were valued with the highest priority to reduce UHI, while roofs with low potential for greening were valued with medium priority.

Cooling effects of green roofs in Krefeld were assessed using the cooling rates identified by Li et al. (2014) according to the green roof fraction in Krefeld. They used a non-hydrostatic, regional climate model in conjunction with a physically-based urban canopy model to assess cooling impacts of green roof strategies and showed that as the green roof fractions increase, the near-surface temperature (two meter above ground) is reduced almost linearly. Estimated cooling rates on a city-scale varied between 0.0 and 0.59 °C depending on the coverage rate of green roof fractions (Li et al. 2014). To calculate changes of near-surface UHI cooling rates from Li et al. (2014) were attributed to the prioritized roof areas in respective to their share of the total roof area in settlement areas highly affected by heat in the 2019 and 2030 scenarios.

Results

The results of the 2019 heat vulnerability assessment showed that almost 90% of the assessed areas were classified as very low. High heat vulnerability was identified in 7% of Krefeld. These highly vulnerable areas are concentrated in the city center (Vier Wälle, Stadtgarten/Drietendorf, Südring, Bleichpfad, Stephanplatz and Schinkenplatz) and are characterized by a (very) unfavorable thermal situation with thermal stress due to high sealing rates and the highest density of elderly people in Krefeld (Fig. 3). Areas with a low heat vulnerability in 2019 were located in 2% of Krefeld, followed by medium vulnerability in 1%. These areas were identified in the southern parts of central Krefeld (Lehmheide and Dießem). The results for the estimation of the vulnerability in 2030 show that the areas affected by UHI will expand by

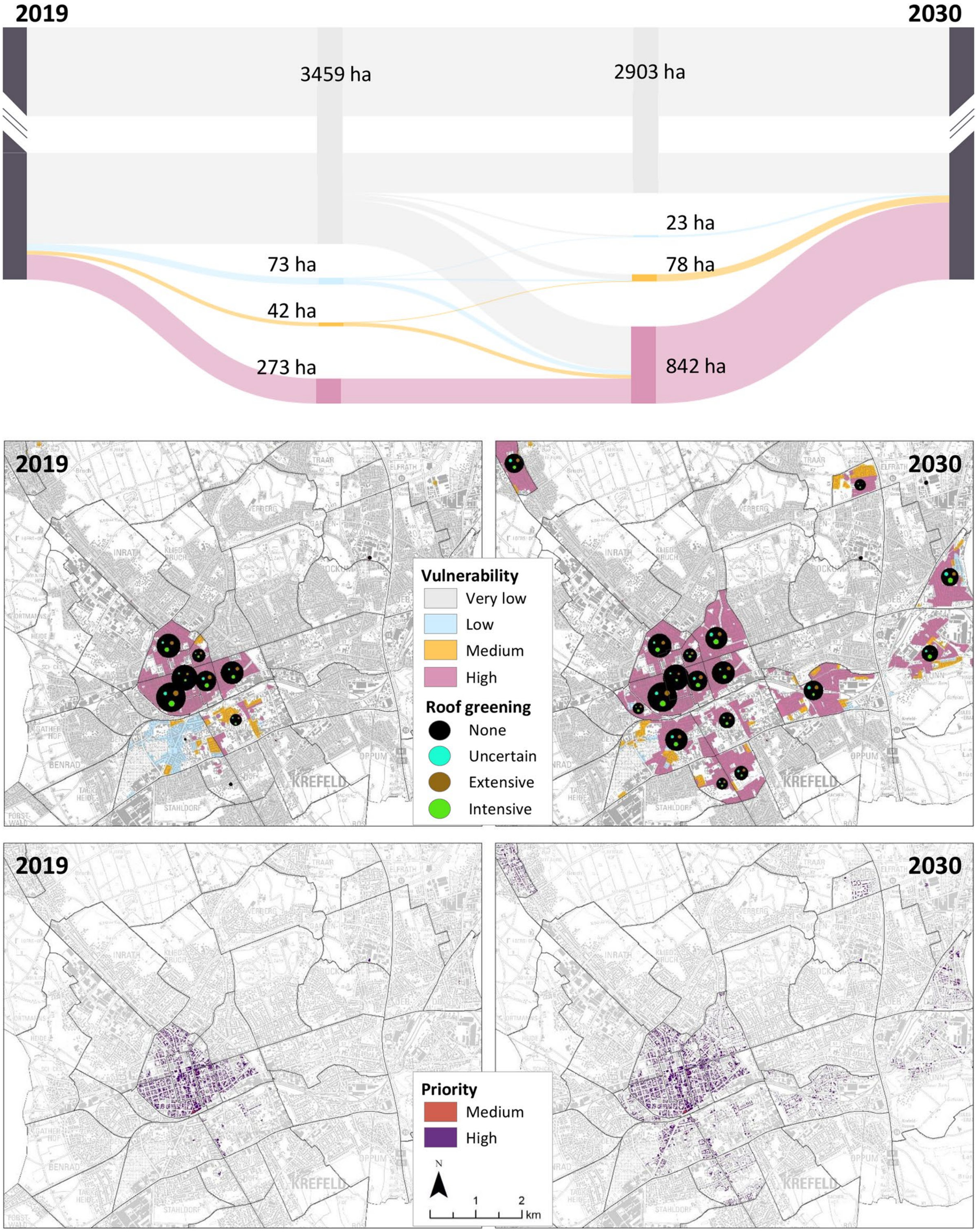
655 ha. Particularly, areas highly vulnerable to heat will triple in the future due to shifts from areas that have a very low degree of vulnerability in 2019 but are expected to be affected by climate change with temperature increase and consequential thermal stress. Due to changes in the heat sensitive population group of elderly people, with predicted growing numbers, vulnerability also increases (Fig. 3). These areas of high vulnerability will expand further outwards of the city, including districts south of the center and in eastern areas, as well as single districts further out (north-east Elfrath, east Uerdingen-Markt and Linn, as well as the suburb Hüls-Ortskern in the north-west). Areas with a medium level of vulnerability will almost double by 2030, whereas areas with low vulnerability will be reduced to one-third of their state in 2019. Medium and low vulnerability will in the future be found in small patches spread throughout the different districts of the city, except for the center (Fig. 3).

The majority of the investigated roofs, with 94% (57 ha), were not covered by vegetation in 2019 (Fig. 3). Intensive roof greening was found for two hectares in Krefeld. One hectare of the investigated roofs was covered by extensive greening. The results for 2030 showed with 93% (108 ha), the majority of the analyzed roofs remain uncovered by vegetation. Intensive roof greening was identified for a total of four hectares. Extensive greening covers a total of three hectares in Krefeld. The largest areas of green roofs (intensive and extensive) were identified in the Südring district (0.6 and 0.5 ha) in both 2019 and 2030. DVI values that could not be clearly assigned to one of the roof classes, without vegetation, extensive or intensive greening, covered one hectare in 2019 and 2 ha in 2030 in total for the city of Krefeld, with the largest area in the Südring district in 2019 and at Uerdingen-Markt (0.2 ha) in 2030.

The results of the prioritization of areas for roof greening in 2019 suggested that 49% (59 ha) of the total roof area in Krefeld that are located in areas highly vulnerable to heat have a high potential for roof greening and are therefore valued as high priority roof areas. Increasing green roof fraction by 49% would cause a cooling effect on the air temperature two meters above ground of up to approximately 0.2 °C in this area (Fig. 3) and contribute to the reduction of the near-surface urban heat island effect. In 2030, the ratio of opportunity spaces for roof greening remains similar to 2019. 44% (113 ha) of the total roof areas that are located in areas highly vulnerable to heat in Krefeld were classified as high priority roof areas (Fig. 3). Transforming these prioritized roofs into green roofs would change near-surface temperature by 0.2 °C. The largest high priority areas were found in the densely built-up inner-city districts of Südring and Vier Wälle (approximately 15 and 11 ha) in 2019 and 2030, respectively. Areas with medium priority for roof greening cover about 1.5% of the overall roof areas located in areas highly vulnerable to heat in 2019 and approximately 1.6% in 2030. The largest areas of medium priority for urban heat reduction in 2019 and 2030 were found in the Südring district (0.6 ha).

Discussion

This paper identified opportunity spaces for greening potentials of rooftops at the city-scale and suggested priority areas for further planning and implementation of roof greening measures with regard to a climate sensitive urban development. Although Krefeld is known as a garden city (Kuttler et al. 2003) with many green spaces (Fachbereich Stadtplanung 2015), the vulnerability to heat was already high in most areas of the city center in 2019. This is cause for concern as current assessments in Germany show that 92% of flat roof areas built in 2020 are not covered with vegetation (BuGG 2021). Furthermore, global phenomena such as urbanization (Kahlenborn et al. 2021), global warming (Die Bundesregierung 2020; Kahlenborn et al. 2021), and demographic change (Bunz and Mücke 2017) are driving local impacts, causing the expansion of UHI into the urban periphery and an increase of areas with high exposure and sensitivity to heat, as shown in the vulnerability assessment for Krefeld in 2030. The analysis resulted in 59 and 113 hectares (for 2019 and 2030, respectively) of opportunity spaces for roof greening in Krefeld, which is the amount of almost all flat roofs and pent roofs investigated in areas highly vulnerable to heat. These opportunity spaces can now be used in more detailed analyses of roof greening potentials, for example taking into account local experts' knowledge and information beyond available geodata.


2019
2030
3459 ha
2903 ha
23 ha
73 ha
78 ha
42 ha
273 ha
842 ha
2019
2030
Vulnerability
Very low
Low
Medium
High
Roof greening
None
Uncertain
Extensive
Intensive
KREFELD
2019
2030
Priority
Medium
High
N
1
2
km
KREFELD

◂**Fig. 3** Spatial changes of vulnerability to heat and prioritization of opportunity spaces for roof greening in 2019 and 2030. The alluvial diagram (top) shows the spatial changes (size of ribbons) of the vulnerability to heat in Krefeld (colored code of four classes: very low to high, in hectares). The maps show the results of the vulnerability assessment (polygons) and the analysis of roof greening and greening potentials (circles plotted scaled by 1.5) (middle map), and the results of the prioritization of areas for roof greening to reduce UHI in areas highly vulnerable to heat (bottom map). Background maps: statistical districts and DTK50 (Stadt Krefeld 2019c; Geobasis NRW 2021)

The analysis shows a potential cooling effect of 0.2 °C for temperature in two meter above ground, if prioritized opportunity spaces would be greened. This decrease of near-surface UHI temperature could reduce heat-related mortality, potentially by up to 5% (Santamouris and Osmond 2020). However, these values represent modelled approximations of the reality and depend on highly dynamic feedbacks between, for instance, the ambient air temperatures and humidities, the surface energy balance as well as individual behaviour and health status of residents (Givoni 1991; Tong et al. 2021; Gao et al. 2022). Quantitative models of urban microclimate conditions and effects on human health are affected by uncertainties (Evola et al. 2017). Simulations on cooling effects due to roof greening and impacts on human health vary broadly by the selection of a model and associated set-up of parameters and indicators, as well as quality of input data and scenario design (Krayenhoff et al. 2021). Thus, results from the different methods used for simulations are hard to compare and should be interpreted carefully (Brune et al. 2017).

The proposed approach was designed for application in spatial planning practice and thereby needed to be relatively simple but robust enough for decision-making (Barbier et al. 2008). Several options for method improvement in each step of the presented approach were identified:

Critique of methods applied for the assessment of vulnerability to heat

The vulnerability assessment considered the location of settlement areas, but ignored the adaptive capacities of heat-sensitive population groups (i.e., the ability to prepare for, respond to, and cope with heat events), given the lack of suitable tested methods and indicators (cf. Heiland et al. 2012; Hartz et al. 2013; UBA 2021). Future applications could try to advance this, for example by drawing on insights from valuation approaches of people's adaptive capacity as those by Siders (2019), Buth et al. (2015) and Hemberger and Utz (2014). The analysis of heat sensitivity in 2030 was conducted under simplified assumptions such as a linear projection of the population development of poor people in Krefeld as well as a constant number and location of the prospective development of hospitals and facilities for disabled people. The estimation of prospective, structural urban changes can partly be improved by considering official land-use plans that define the development of future building areas. The projection of population development of poor people in Krefeld could be optimized, for example by using more complex models to achieve higher accuracy of forecasts, but would require more data and capacities (George et al. 2004). The vulnerability assessment could further be improved by also considering greening potentials of buildings' roofs in industrial areas. In particular, industrial buildings with large and predominantly flat roof areas at low building heights should be considered as these are promising in terms of cooling effects (Rittel et al. 2011; Pfoser et al. 2013; Santamouris 2014; SenStadt 2016).

Critique of methods applied for analysis of roof greening and greening potentials

Presence and absence of green roofs in Krefeld was determined by calculating DVI. There are alternative indices that can be used, such as the normalized difference vegetation index (NDVI), the color index of vegetation extraction (CIVE), and the chlorophyll vegetation index (CVI). However, the DVI turned out to be most useful since it is less influenced by atmospheric distortion, shadow, and background noise (Roujean and Breon 1995; Jones and Vaughan 2010) and is suitable to identify even sparsely vegetated areas (Broge and Leblanc 2001; Barati et al. 2011; Xue and Su 2017). The inventory of roof greening was done for a prespecified investigation area, which was classified as highly vulnerable to heat in the first step of the approach. In reality, the boundaries of vulnerability to heat are fluid and not strictly delineated (LANUV NRW 2018a). Results of the vulnerability analysis of Krefeld show clear boundaries that come from the input datasets and were needed to select buildings for further spatial analysis and prioritization using GIS (Kuttler et al. 2013). Only buildings located completely within highly vulnerable areas were considered in the subsequent steps of analyzing roof greening and greening potentials as well as prioritizing opportunity spaces for roof greening. At the time of the study, only classic DOP were available for the identification and localization of green roofs. To achieve a higher accuracy in the localization process, true DOP should be used as these are corrected for image displacement caused by terrain relief and camera tilts as well as building tilting (Jensen 2007), thus reduce the time needed for correction of data from building outlines. The provision of true DOP in North Rhine-Westphalia is planned for 2021 (Bezirksregierung Köln 2020) and should be used in future research. A final error margin of green roof estimation was the accuracy of building polygons. For example, circa 0.4 ha of false polygon outlines of buildings that include vegetated inner courtyards were found. To reduce errors of building outlines in further studies, most recent data should be used and be proved by visual data inspection.

Furthermore, when analyzing roof greening additional roof types besides flat and pent roofs could be considered that are also suitable for greening. Those include, for instance, offset pent roofs, mixed roof types, or also more steeply inclined areas such as (flat) gable roofs. Most of the studies that investigated (potentials for) roof greening tend to underestimate the greening potential or the spatial extent of existing green roofs, because they only consider flat roofs (Ansel et al. 2015). However, the technical approaches today are more sophisticated enabling roof greening with slopes of up to 45°, if drainage and security measures are installed (cf. Pfoser et al. 2013; Brune et al. 2017). A further source of error related to inaccurate estimations of green roof area are DOPs distorted by different lighting conditions, e. g. gable roofs that are half shaded (Coenradie et al. 2016; Marconcini and Metz 2016). Additional steps are necessary to delineate and separately classify these shaded areas, for example through solar irradiation analysis as demonstrated by IP SYSCON (2020). The consideration of structural properties of buildings and rooftops could also be improved, for example regarding constructive and static characteristics of the buildings, accessibility of the roof areas, the overall building condition, and the duration of its planned maintenance and financial scope (Ansel et al. 2015; Cascone et al. 2018). Regarding the analysis of building statics for retrofitted greening, Ansel et al. (2015) provided a manual on how to estimate the bearing load of flat roofs from aerial photographs and identified roofs with potential for extensive greening.

Critique of methods applied for prioritization of opportunity spaces for roof greening to reduce UHI

Prioritizing opportunity spaces could include additional spatial indicators that influence the effectiveness of UHI mitigation, such as building height and urban design in terms of the ratio of building height to street width (Ng et al. 2012; Peng and Jim 2013; Santamouris 2014; Sun et al. 2016). These indicators can be derived from LoD2 building models, and used as an input to enhance estimations of potential local cooling effects from roof greening on the neighborhood or city-scale (cf. Rosenzweig et al. 2006; Peng and Jim 2013; Santamouris 2014; Sun et al. 2016). Also, a more integrative analysis of the multifunctional effects of green roofs may influence the prioritization of opportunity spaces (cf. Semeraro et al. 2021). Green roofs provide co-benefits that contribute to address multiple development goals, but also disservices that affect human well-being negatively such as allergenic pollen from roof plants or deteriorated water quality (van Seters et al. 2009; Gregoire and Clausen 2011). A framework to assess the co-benefits, trade-offs, and unintended consequences of green roofs is presented by Wang (2021). As a next step for integrating the study's results into planning and practical implementation of greening measures, pixel-based results should be aggregated to entire roof areas of buildings or building parts (cf. Ansel et al. 2015). Therefore, the classified pixels of a roof need to be reclassified to the vegetation class that holds the largest share within the respective building outline. From a practical point of view, it is furthermore recommended to set a threshold for minimum areas suitable for roof greening, as done by Ansel et al. (2015). The generated information should also be fed into planning discourses by utilizing multi-criteria decision analysis, as suggested - among others - by Langemeyer et al. (2020) and Venter et al. (2021) to evaluate potentials and prioritize areas for roof greening.

The transferability of the three-step approach depends on the availability and quality of the input data and would benefit from more automation of individual steps. For instance, the analysis of aerial images to identify green roofs should be performed with automated processes rather than human interpretation. To do so, automatic or semi-automatic classification methods should be tested to reduce the time required for manual classification through e.g. machine learning approaches (Shao et al. 2021). For example, Chen et al. (2022) proposed a segmentation decoder for the High-Resolution Network (HRNet) model that accurately detects urban green on a fine scale with improved performance on shaded green.

Conclusion

The approach to identify roof areas with potential for greening and priority for UHI reduction presented in this paper was developed through the modular combination of socio-ecological and remote sensing geodata in three consecutive steps. The results show that the approach can be applied to estimate opportunity spaces of roof greening. The opportunity spaces can subsequently be further assessed with more detailed data and input from local experts. The opportunity spaces also form a basis for deliberation in support of the creation of urban climate adaptation strategies. The Krefeld case study highlighted the urgency to respond to the negative impacts of urban heat, which will become even more critical in the future. While the settlement area identified as highly vulnerable to heat in 2019 was about 273 ha, the results of the 2030 scenario showed a tripling in size of the area of high vulnerability, and an expansion towards the outskirts. The majority of the investigated roofs ($>90\%$) were not covered with any vegetation in areas with population groups highly vulnerable to heat. Roofs located in those areas should therefore be considered in more detail for the implementation of greening measures, as they hold substantial potential for greening and lowering the UHI. According to the estimates and based on the assumption that all rooftops identified with high priority in Krefeld were greened, the near-surface UHI temperature could be mitigated by 0.2 °C and the heat-related mortality reduced by 5% (in both 2019 and 2030). The application of the presented approach provides valuable information that complements the data basis in green roof cadasters, as these were already established in the form of online GIS-applications in urban and rural areas in Germany to provide information for planners, decision-makers and citizens (Die Senatorin für Klimaschutz, Umwelt, Mobilität, Stadtentwicklung und Wohnungsbau 2019; Landratsamt Schweinfurt 2019; LANUV NRW 2021). The information provided in green roof cadasters varies in quality and quantity of the data. For example, in the recently published cadaster of the federal state of North Rhine-Westphalia (LANUV NRW 2021), information on potential for roof greening, storm water retention, fixation of carbon dioxide and dust binding is available. However, a documentation of existing green roofs and population's sensitivity to heat is not yet considered in the estimated potentials for roof greening of the cadaster. Complementing the cadaster with place-based socio-ecological information from the proposed approach can contribute to increase the relevance for practical usage. A more integrative cadaster may better educate citizens regarding UHI and promote greening strategies to cope with negative impacts of urban heat. The presentation of further ecosystem services provided by green roofs and their co-benefits highlight the added value of greening measurements. Identified and presented synergies can contribute to the realisation of multiple development goals from city scale (e.g. citys' climate concept as e.g. "KrefeldKlima 2030") to national scale (e.g. National Climate Adaptation Strategy) (GERTEC 2018; The Federal Government 2008). By adding the information on synergies from roof greening on a city-scale in the cadaster can support the visibility, communication, promotion, and ultimately the implementation of measurements. This could be supported, in particular, by complementing cadasters with monitoring of roof greening. Implementing roof greening on public buildings can present insightful best practice examples that may serve as role models for rapid outscaling (MULNV 2015; difu 2018). Developing and implementing strategies for roof greening in practice needs to consider the advantages and limitations of such approaches. As discussed in this paper, substantial spatial opportunities exist to harness green roofs for climate adaptation. However, planners and decision-makers need to consider the limited direct effects of green roofs on the thermal environment at the pedestrian level as experienced by citizens. In response, planners should consider the broad spectrum and diverging requirements, cooling effects, and co-benefits (Gunawardena et al. 2017; Han et al. 2022) of green and blue infrastructure actions available to maximize cooling such as tree planting, artificial wetlands, and green walls within integrated development strategies. If planned and implemented comprehensively across local to city scales, such coordinated efforts could yield substantially positive health effects (Iungman et al. 2023).

Future research may focus on further advancing the proposed approach with more detailed methods and automated interpretations. It could also explore the applicability of the approach in other data, climate, and governance contexts. In addition, further research could try to assess the effects of roof greening on other benefits and costs, for example in terms of impacts on biodiversity and recreation as well as on reduction of energy consumption for buildings cooling and heating. Future assessments of greater detail and broader scope could thereby provide more comprehensive accounts of the opportunities and implications of roof greening and allow citizens and decision-makers to make better-informed decisions.

Acknowledgements The work was realized within the PlanSmart Research Group funded by Grant 01UU1601A and B from the German Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung—BMBF). We thank Henrik Steegmanns of the Department for Statistics and Elections of the city of Krefeld for kindly sharing data.

Author contributions All authors contributed to the study conception and design. Methodology was developed by JB with guidance from SS. Material preparation, data collection and analysis were performed by JB. The original draft was written by JB and supervision, writing – reviewing and editing of the manuscript was done by SS and CA. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. The work was realized within the PlanSmart Research Group funded by Grant 01UU1601 A and B from the German Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung—BMBF).

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Al-Kayiem HH, Koh K, Riyadi TWB, Effendy M (2020) A comparative review on greenery ecosystems and their impacts on sustainability of building environment. Sustainability 12:8529

Ansel W, Zeidler J, Esch T (2015) Fernerkundliche Identifizierung von Vegetationsflächen auf Dächern zur Entwicklung des für die Bereiche des Stadtklimas, der Stadtentwässerung und des Artenschutzes aktivierbaren Flächenpotenzials in den Städten. Abschlussbericht des Entwicklungsprojektes gefördert unter dem Az 30299 von der Deutschen Bundesstiftung Umwelt. Deutscher Dachgärtner Verband e.V.

Azevedo JA, Chapman L, Muller CL (2016) Quantifying the daytime and night-time urban heat island in birmingham, UK: a comparison of satellite derived land surface temperature and high resolution air temperature observations. Remote Sensing 8:153

Bach C, Birkmann J, Kropp J, Olonscheck M, Setiadi N et al (2013) Abschätzung der Verwundbarkeit gegenüber Hitzewellen und Starkregen. Druckpartner moser, Bonn

Barati S, Rayegani B, Saati M, Sharifi A, Nasri M (2011) Comparison the accuracies of different spectral indices for estimation of vegetation cover fraction in sparse vegetated areas. Egypt J Remote Sens Space Sci 14:49–56

Barbier EB, Koch EW, Silliman BR, Hacker SD, Wolanski E et al (2008) Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319:321–323

Berardi U, GhaffarianHoseini A, GhaffarianHoseini A (2014) State-of-the-art analysis of the environmental benefits of green roofs. Appl Energy 115:411–428

Bertelsmann Stiftung (n. d.) Wegweiser Kommune. Entwicklung der Altersgruppen. Krefeld. Available online: https://www.wegweiser-kommune.de/daten/entwicklung-der-altersgruppen+krefeld+2012-2030+tabelle. Accessed 12 Oct 2021

Bezirksregierung Köln (2020) Digitale Orthophotos. https://www.bezreg-koeln.nrw.de/brk_internet/geobasis/luftbildinformationen/aktuell/digitale_orthophotos/index.html. Accessed 12 Oct 2021

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010) Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc Urban Plan 97:147–155

Broge NH, Leblanc E (2001) Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. Remote Sens Environ 76:156–172

Brune M, Bender S, Groth M (2017) Gebäudebegrünung und Klimawandel. Anpassung an die Folgen des Klimawandels durch klimawandeltaugliche Begrünung. Report 30 Climate Service Center Germany (GERICS), Hamburg

BuGG - Bundesverband GebäudeGrün e.V. (2021) BuGG-Marktreport Gebäudegrün 2021. Dach-, Fassaden- und Innenraumbegrünung. Deutschland. BuGG, Berlin

Bunz M, Mücke HG (2017) Klimawandel – physische und psychische Folgen. Bundesgesundheitsblatt 60:632–639

Buth M, Kahlenborn W, Savelsberg J, Becker N, Bubeck P et al (2015) Vulnerabilität Deutschlands gegenüber dem Klimawandel Climate Change 24/2015:689. UBA, Dessau-Roßlau

Cascone S, Catania F, Gagliano A, Sciuto G (2018) A comprehensive study on green roof performance for retrofitting existing buildings. Build Environ 136:227–239

Chapman S, Watson JEM, Slazar A, Thatcher M, McAlpine CA (2017) The impact of urbanization and climate change on urban temperatures: a systematic review. Landscape Ecol 32:1921–1935

Chen J, Shao S, Zhu Y, Wang Y, Rao F et al (2022) Enhanced automatic identification of urban community green space based on semantic segmentation. Land 11:905

Coenradie B, Haag L, Streng B, Schiffner S, Müller K (2016) Erhebung und Aufbereitung von Informationen zum Gründachbestand in Berlin. Abschlussbericht. Stadtverwaltung für Stadtentwicklung und Umwelt Berlin, Berlin

Die Bundesregierung (2020): Zweiter Fortschrittsbericht zur Deutschen Anpassungsstrategie an den Klimawandel. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimawandel_das_2_fortschrittsbericht_bf.pdf. Accessed 12 Oct 2021

Die Senatorin für Klimaschutz, Umwelt, Mobilität, Stadtentwicklung und Wohnungsbau (2019) https://www.gruendach.bremen.de/#s=startscreen. Accessed 7 Dec 2021

difu – Deutsches Institut für Urbanistik (2018) Klimaschutz in Kommunen. Praxisleitfaden. Buch- und Offsetdruckerei H. Heenemann, Berlin.https://backend.repository.difu.de/server/api/core/bitstreams/51cc26b3-d271-4d38-8947-a2a86a458c0c/content. Accessed 29 Mar 2023

Esri (2021) ArcGIS Desktop 10.6.1 quick start guide – ArcMap. Documentation. https://desktop.arcgis.com/en/arcmap. Accessed 12 Oct 2021

Evola G, Gagliano A, Fichera A, Marletta L, Martinico F et al (2017) UHI effects and strategies to improve outdoor thermal comfort in dense and old neighbourhoods. Energy Procedia 134:692–701

Fachbereich Stadtplanung (2015) Flächennutzungsplan der Stadt Krefeld. Begründung. Az.: 35.02.01.01–04KR-FNPneu-604. Stadt Krefeld, Krefeld

Gao Y, Zhao J, Yu K (2022) Effects of block morphology on the surface thermal environment and the corresponding planning strategy using the geographically weighted regression model. Build Environ 216:109037

Geobasis NRW (2019a) 3D-Gebäudemodell LoD2 (CityGML) - Paketierung: Einzelkacheln: Stand 2019a: dl-de/zero-2–0, https://www.govdata.de/dl-de/zero-2-0, https://www.geoportal.nrw/. Accessed 18 Jan 2021

Geobasis NRW (2019b) Digitales Basis-Landschaftsmodell (Shape) - Paketierung: gesamt NRW: Stand 2019b: dl-de/zero-2–0, https://www.govdata.de/dl-de/zero-2-0, https://www.opengeodata.nrw.de/produkte/geobasis/lm/basis-dlm/. Accessed 19 Feb 2021

Geobasis NRW (2019c) Digitale Orthophotos (JPEG2000, 10-fache Kompression) - Paketierung: Einzelkacheln: Stand 05.2019c: dl-de/zero-2–0, https://www.govdata.de/dl-de/zero-2-0, https://www.geoportal.nrw/. Accessed 17 Dec 2020

Geobasis NRW (2021) DTK50 - Digitale Topographische Karte 1:50 000 (Schwarz-Weiß, TIFF) - Paketierung: Einzelkacheln: dl-de/zero-2–0, https://www.govdata.de/dl-de/zero-2-0, https://www.geoportal.nrw/. Accessed 18 October 2021

George MT, Smith SK, Swanson DA, Tayman J (2004) Population projections The Methods and Materials of Demography. Elsevier, Amsterdam

GERTEC (2018) KrefeldKlima – Projekt: Einstiegsberatung kommunaler Klimaschutz in Krefeld. Abschlussbericht. Stadt Krefeld, Krefeld

Getter KL, Rowe DB, Robertson GP, Cregg BM, Andresen JA (2009) Carbon sequestration potential of extensive green roofs. Environ Sci Technol 43:7564–7570

Givoni B (1991) Impact of planted areas on urban environmental quality: a review. Atmos Environ 25B:289–299

Gregoire BG, Clausen JC (2011) Effect of a modular extensive green roof on stormwater runoff and water quality. Ecol Eng 37:963–969

Gunawardena KR, Wells MJ, Kershaw T (2017) Utilising green and bluespace to mitigate urban heat island intensity. Sci Total Environ 584–585:1040–1055

Han D, Zhang T, Qin Y, Tan Y, Liu J (2022) A comparative review on the mitigation strategies of urban heat island (UHI): a pathway for sustainable urban development. Climate Dev. https://doi.org/10.1080/17565529.2022.2092051

Hartz A, Saad S, Greiving S, Fleischhauer M, Lindner C (2013) Methodenhandbuch zur regionalen Klimafolgenbewertung in der räumlichen Planung. Systematisierung der Grundlagen regionalplanerischer Klimafolgenbewertung. BBSR im BBR, Bonn

Heiland S, Wilke C, Rittel K (2012) Urbane Anpassungsstrategien an den Klimawandel: Methoden- und Verfahrensansätze am Beispiel des Stadtentwicklungsplans Berlin. UVP-REPORT 26:44–49

Hemberger C, Utz J (2014) Das Konzept der Anpassungskapazität als Teil der Vulnerabilitätsbestimmung in der Stadt- und Raumplanung—Evaluation und Weiterentwicklung in der Praxis. LUBW, Karlsruhe

HLNUG - Hessisches Landesamt für Naturschutz, Umwelt und Geologie Fachzentrum Klimawandel und Anpassung (2019) Handlungsleitfaden zur kommunalen Klimaanpassung in Hessen. Hitze und Gesundheit. HLNUG, Darmstadt

Hoffert H, Lumasegger M (2010) Grünraumanalyse Wien. Dachbegrünung. Magistrat der Stadt Wien, Wien

Huang K, Li X, Liu X, Seto KC (2019) Projecting global urban land expansion and heat island intensification through 2050. Environ Res Lett 14:114037

Huang H, Yang H, Chen Y, Chen T, Bai L et al (2021) Urban green space optimization based on a climate health risk appraisal—a case study of Beijing city China. Urban For Urban Green 62:127154

Huang H, Zhou X, Qu Y, Zhang H (2022) Spatial effects of climate warming on the health risks due to urban heat exposure: a case study of China. DYNA-Ingeniería e Industria 97:162–168

IP SYSCON (2020) Abschlussdokumentation Standortanalyse und Potenzialberechnung für Gründachanlagen für das Bundesland Nordrhein-Westfalen. Unpublished.

Iungman T, Cirach M, Marando F, Pereira Barboza E, Khomenko S, Masselot P et al (2023) Cooling cities through urban green infrastructure: a health impact assessment of European cities. The Lancet. https://doi.org/10.1016/S0140-6736(22)02585-5

Jensen JR (2007) Remote sensing of the environment. An earth resource perspective, 2nd edn. Prentice Hall, Upper Saddle River

Jones HG, Vaughan RA (2010) Remote sensing of vegetation. Principles, techniques, and applications. Oxford University Press, New York

Kahlenborn W, Porst L, Voß M, Fritsch U, Renner K et al (2021) Klimawirkungs- und Risikoanalyse 2021 für Deutschland Kurzfassung. UBA, Dessau-Roßlau

Karteris M, Theodoridou I, Mallinis G, Tsiros E, Karteris A (2016) Towards a green sustainable strategy for Mediterranean cities: assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. Renew Sustain Energy Rev 58:510–525

Knaus M, Haase D (2020) Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin Germany. Urban For Urban Green 53:126738

Krayenhoff ES, Broadbent AM, Zhao L, Georgescu M, Middel A et al (2021) Cooling hot cities a systematic and critical review of the numerical modelling literature. Environ Res Lett 16:053007

Kuttler W, Graf A, Blankenstein S, Barlag AB (2003) Gesamtstädtische Klimaanalyse Krefeld unter besonderer Berücksichtigung von vier Plangebieten. Stadt Krefeld, Essen

Kuttler W, Dütemeyer D, Barlag AB (2013) Handlungsleitfaden – Steuerungswerkzeug zur städtebaulichen Anpassung an thermische Belastungen im Klimawandel. Dynaklim-Publikation 34, Duisburg

Landeshauptstadt Stuttgart (2010) Der Klimawandel – Herausforderung für die Stadtklimatologie. Schriftenreihe des Amtes für Umweltschutz

Landratsamt Schweinfurt (2019) https://solar-lk-schweinfurt.ipsyscon.de/start. Accessed 7 Dec 2021

Langemeyer J, Wedgwood D, McPhearson T, Baró F, Madsen AL et al (2020) Creating urban green infrastructure where it is needed—a spatial ecosystem service-based decision analysis of green roofs in Barcelona. Sci Total Environ 707:135487

LANUV NRW - Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2021): Gründachkataster NRW. https://www.lanuv.nrw.de/klima/klimaanpassung-in-nrw/fis-klimaanpassung-nordrhein-westfalen/gruendachkataster. Accessed 12 Oct 2021

LANUV NRW - Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018a) Klimaanalyse Nordrhein-Westfalen. LANUV-Fachbericht 86. LANUV, Recklinghausen

LANUV NRW - Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018b) Klima-Planungskarten für Nordrhein-Westfalen als Shape: Stand 2018: dl-de/zero-2–0, https://www.govdata.de/dl-de/zero-2-0, https://www.geoportal.nrw/. Accessed 18 Oct 2021

Li D, Bou-Zeid E, Oppenheimer M (2014) The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ Res Lett 9:055002

Manso M, Teotónio I, Silva CM, Cruz CO (2021) Green roof and green wall benefits and costs: a review of the quantitative evidence. Renew Sustain Energy Rev 13:110111

Marconcini M, Metz A (2016) A Suite of Novel EO-Based Products in Support of Urban Green Planning. In: Schrenk M, Popovich VV, Zeile P, Elisei P, Beyer C (ed) REAL CORP 2016. Smart Me Up! How to become and how to stay a Smart City, and does this improve quality of life? Proceedings of 21st International Conference on Urban Planning, Regional Development and Information Society. CORP, Wien, pp 57-66

Möller A, Pantiou M, Hummert K, Gräff HJ, Michali S et al. (2020) KrefeldKlima 2030 – Integriertes Klimaschutzkonzept für die Stadt Krefeld. Endbericht

Mücke HG, Straff W, Faber M, Haftenberger M, Laussann D et al (2013) Klimawandel und Gesundheit Allgemeiner Rahmen zu Handlungsempfehlungen für Behörden und weitere Akteure in Deutschland. BMG und BMU. https://doi.org/10.25646/220

MULNV - Ministerium für Umwelt, Landwirtschaft, Natur- und Verbraucherschutz Nordrhein-Westfalen (2015) Klimaschutzplan Nordrhein-Westfalen. Klimaschutz und Klimafolgenanpassung. MULNV NRW, Düsseldorf

Ng E, Chen L, Wang Y, Yuan C (2012) A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. Build Environ 47:256–271

Oke TR, Johnson GT, Steyn DG, Watson ID (1991) Simulation of surface urban heat islands under 'ideal' conditions at night part 2: diagnosis of causation. Bound-Layer Meteorol 56:339–358

Pafi M, Ferri S, Siragusa A, Halkia M (2016) Visual assessment of the Green European settlement map exploration and quality performance measures of the green component derived from the ESM algorithm. JRC Tech Rep. https://doi.org/10.2788/601488

Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005) Impact of regional climate change on human health. Nature 438:310–317

Peng L, Jim C (2013) Green-roof effects on neighborhood microclimate and human thermal sensation. Energies 6:598–618

Pfoser N, Jenner N, Henrich J, Heusinger J, Weber S (2013) Gebäude Begrünung Energie: Potenziale und

Wechselwirkungen. Technische Universität Darmstadt, Fachbereich Architektur

Rittel K, Wilke C, Heiland S (2011) Anpassung an den Klimawandel in städtischen Siedlungsräumen—Wirksamkeit und Potenziale kleinräumiger Maßnahmen in verschiedenen Stadtstrukturtypen. Dargestellt am Beispiel des Stadtentwicklungsplans Klima in Berlin. In: Böcker R (ed) Tagungsbeiträge der 4 Tagung des Kompetenznetzwerkes Stadtökologie. CONTUREC, Darmstadt, pp 67–78

Rizwan AM, Dennis YCL, Liu C (2008) A review on the generation, determination and mitigation of Urban Heat Island. J Environ Sci 20:120–128

Robine JM, Cheung SL, Le Roy S, van Oyen H, Griffiths C et al (2008) Death toll exceeded 70,000 in Europe during the summer of 2003. Biologies 331:171–178

Rosenzweig C, Solecki W, Parshall L, Gaffin S, Lynn B et al (2006) Mitigation New York city's heat island with urban forestry living roofs and light surfaces. A report to the New York State Energy Research and Development Authority, New York

Roujean JL, Breon F-M (1995) Estimating PAR absorbed by vegetation from bidirectional reflectance measurements. Remote Sens Environ 51:375–384

Safe Software (2021) FME Quick Translator. https://docs.safe.com/fme/html/FME_Desktop_Documentation/FME_QuickTranslator/Home_qt.htm. Accessed 14 Dec 2021

Sailor DJ, Elley TB, Gibson M (2011) Exploring the building energy impacts of green roof design decisions—a modeling study of buildings in four distinct climates. J Building Phys 35:372

Santamouris M (2014) Cooling the cities—a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol Energy 103:682

Santamouris M (2020) Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact Synergies with the global climate change. Energy Build 207:109482

Santamouris M, Osmond P (2020) Increasing green infrastructure in cities: impact on ambient temperature, air quality and heat-related mortality and morbidity. Buildings 10:233

Santos T, Tenedório J, Gonçalves J (2016) Quantifying the city's green area potential gain using remote sensing data. Sustainability 8:1247

Schulze Dieckhoff V, Becker D, Wiechmann T, Greiving S (2018) Raummuster: Demographischer Wandel und Klimawandel in deutschen Städten. Raumforsch Raumordn 76:211–228

Semeraro T, Scarano A, Buccolieri R, Santino A, Aarrevaara E (2021) Planning of urban green spaces: an ecological perspective on human benefits. Land 10:105

SenStadt - Senatsverwaltung für Stadtentwicklung und Umwelt Kommunikation (2016) Stadtentwicklungsplan Klima. KONKRET Klimaanpassung in der Wachsenden Stadt. SenStadt, Berlin

SGB II - Sozialgesetzbuch Zweites Buch vom 13. Mai 2011 (BGBl. I S. 850, 2094), das zuletzt durch Artikel 14 des Gesetzes vom 9. Juni 2021 (BGBl. I S.1614) geändert worden ist. [SGB II - Social Code Second book (II) of May 13th, 2011 (BGBl. I S. 850, 2094), as amended by Article 14 of the ordinance of June 9th, 2021 (BGBl. I S.1614)]

SGB XII - Sozialgesetzbuch Zwölftes Buch (XII) Artikel 1 vom 27. Dezember 2003 (BGBl. I S.3022, 3023), das zuletzt durch Artikel 1 des Gesetzes vom 2. Juni 2021 (BGBl. I S. 1387) geändert worden ist. [SGB XII - Social Code Second book (XII) Section 1 of December 27th, 2003 (BGBl. I S.3022, 3023), as amended by Article 1 of the ordinance of June 2nd, 2021 (BGBl. I S. 1387)]

Shao H, Song P, Mu B, Tian G, Chen Q et al (2021) Assessing city-scale green roof development potential using Unmanned Aerial Vehicle (UAV) imagery. Urban For Urban Green 57:126954

Sharma A, Woodruff S, Budhathoki M, Hamlet AF, Chen F et al (2018) Role of green roofs in reducing heat stress in vulnerable urban communities—a multidisciplinary approach. Environ Res Lett 13:094011

Siders AR (2019) Adaptive capacity to climate change: a synthesis of concepts, methods, and findings in a fragmented field. Wiley Interdiscip Rev Clim Change 10:e573

Skoryi M, Buchholz S, Büscher O, Wolff F, Mann G (2022) Analyse der thermischen Wirkung von Dachbegrünung mittels Stadtklimamodellierung. Endbericht zum Projekt ADAM Gefördert durch die Deutsche Bundesstiftung Umwelt unter der Fördernummer Az 34690/01. Deutscher Wetterdienst, Offenbach

Stadt Krefeld (2019a) Geodaten Behinderteneinrichtungen Stadt Krefeld: Stand 2019a. Fachbereich 62 Stadt Krefeld. https://www.offenesdatenportal.de/de/dataset?organization=krefeld

Stadt Krefeld (2019b) Geodaten Krankenhäuser Stadt Krefeld: Stand 2019b. Fachbereich 62 Stadt Krefeld. https://www.offenesdatenportal.de/de/dataset?organization=krefeld

Stadt Krefeld (2019c) Statistische Bezirke der Stadt Krefeld: Stand 2019b. Fachbereich 31 Stadt Krefeld. https://www.offenesdatenportal.de/de/dataset?organization=krefeld

Stadt Krefeld (2020a) Statistische Bezirke: Strukturdaten 2019: Stand: 31.12.2019 https://www.krefeld.de/C125765D003D65CE/files/bezirksatlas_2019_statistische_bezirke.pdf/$file/bezirksatlas_2019_statistische_bezirke.pdf?OpenElement. Accessed 12 Oct 2021

Stadt Krefeld (2020b) Bevölkerungszahlen nach statistischen Bezirken. Einwohner nach Altersgruppen in den statistischen Bezirken 2012/2019; Personen mit Leistungsbezug nach SGB II und nach SGBXII, Kap. 3 und 4* in den statistischen Bezirken jew. 2009–2017. Unpublished

Sun T, Grimmond CSB, Ni GH (2016) How do green roofs mitigate urban thermal stress under heat waves? J Geophys Res: Atmos 121:5320–5335

The Federal Government (2008) German Strategy for Adaptation to Climate Change. adopted by the German federal cabinet on 17 Dec 2008

Tong S, Prior J, McGregor G, Shi X, Kenney P (2021) Urban heat: an increasing threat to global health. BMJ 375:n2467

Tuholske C, Caylor K, Funk C, Verdin A, Sweeney S et al (2021) Global urban population exposure to extreme heat. PNAS 118:e2024792118

Tzavali A, Paravantis JP, Mihalakakou G, Fotiadi A, Stigka E (2015) Urban heat island intensity: a literature review. Fresenius Environ Bull 24:4537–4554

UBA - Umweltbundesamt (2021) Klimawirkungs- und Risikoanalyse 2021 für Deutschland. Teilbericht 1: Grundlagen. UBA, Dessau-Roßlau

Van Seters T, Rocha L, Smith D, MacMillan G (2009) Evaluation of green roofs for runoff retention, runoff quality, and leachability. Water Qual Res J 44:3–47

Venter ZS, Barton DN, Martinez-Izquierdo L, Langemeyer J, Baró F et al (2021) Interactive spatial planning of urban green infrastructure—retrofitting green roofs where ecosystem services are most needed in Oslo. Ecosystem Services 50:101314

Wang ZH (2021) Compound environmental impact of urban mitigation strategies: co-benefits, trade-offs, and unintended consequence. Sustain Cities Soc 75:103284

Wang ZH (2022) Reconceptualizing urban heat island: Beyond the urban-rural dichotomy. Sustain Cities Soc 77:103581

Wellmann T, Lausch A, Andersson E, Knapp S, Cortinovis C et al (2020) Remote sensing in urban planning: Contributions towards ecologically sound policies? Landsc Urban Plan 204:103921

Wittig S, Schuchardt B (2012) Hitze in der Stadt. Eine kommunale Gemeinschaftsaufgabe. Themenblatt: Anpassung an den Klimawandel. UBA KomPass, Dessau-Roßlau

Wu AN, Biljecki F (2021) Roofpedia: automatic mapping of green and solar roofs for an open roofscape registry and evaluation of urban sustainability. Landsc Urban Plan 214:104167

Xie Y, Li L, Wang H, Zhao X (2010) The Application of Threshold Methods for Image Segmentation in Oasis Vegetation Extraction. In 2010 18th International Conference on Geoinformatics (pp. 1-4). IEEE

Xu N, Luo J, Zuo J, Hu X, Dong J et al (2020) Accurate suitability evaluation of large-scale roof greening based on RS and GIS methods. Sustainability 12:4375

Xue J, Su B (2017) Significant remote sensing vegetation indices: a review of developments and applications. J Sens. https://doi.org/10.1155/2017/1353691