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Between vision and action: the predicted effects of co-designed green infrastructure solutions on environmental burdens

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Abstract

Green Infrastructure (GI) is gaining wide recognition in cooperative research projects seeking to find solutions for climate adaptation in urbanized areas. However, the potential effects of co-produced GI plans and the underlying preparation process are rarely evaluated. To bridge this gap, the aim of this article is to examine what works in addressing environmental burdens in the urban neighborhood of Dortmund Marten, Germany. As part of a larger transdisciplinary process, selective GI measures were delineated in the case study area through a cooperative workshop between scientists and urban planners. Workshop ideas were incorporated into a mitigative scenario considering a hot summer day to quantify the effects of the derived GI measures on thermal comfort and particulate matter dispersion (PM_{10} and $PM_{2.5}$). To evaluate the experiences of the science-practice collaboration, the viewpoints of researchers and urban planners on learning effects, knowledge integration, and GI planning were summarized and compared via an online survey. The results indicate that the proposed GI measures could reduce physiological equivalent temperature (PET) by 25 °C. At the same time, additional roadside trees could increase PM_{10} concentrations by up to 36 $\mu g/m^3$ due to wind blocking effects. Reflections on the science-practice workshop show that learning effects were higher for the participating researchers than for planning practitioners, while the integration of individual expertise during the workshop was more difficult for academics. These findings point to the importance of continuous reflections on individual understandings in cooperating stakeholder groups and the value of the evaluation of outcomes in transdisciplinary GI planning.

Keywords Urban planning · Transdisciplinarity · Heat · Air pollution · Numerical simulation

Introduction

Cities are in a state of permanent change, shaped by past design decisions influencing today's microclimate and social well-being. Urbanized areas in particular are confronted with more hazardous effects than those faced by their rural surroundings; in cities, air and noise pollution originating from a variety of emitters often accumulate, while urban heat islands (UHIs) are intensifying through dense building structures and climate change. Many cities worldwide are setting goals to achieve change, paving the way for the greater vision of sustainability (United Nations 2015). A prerequisite for this transformation is that cities act in a resilient manner, which means to exhibit robustness to climate extremes and establish a transformative capacity to anticipate future challenges (Folke et al. 2010). At the same time, it is assumed that heat-related health risks will increase with ongoing climate change and urbanization rates (IPCC 2021). In fact, notable correlations between vulnerable neighborhoods and exposure to multiple hazards have been observed more frequently, leading to an uneven distribution of environmental burdens and disadvantaged social groups (Pagliacci and Russo 2020). Thus, considering the need for transformative and resilient cities as a whole, it is vital to strengthen disadvantaged areas against environmental burdens.

Green Infrastructure (GI), a strategy with great appeal among academics and planning practitioners, is becoming increasingly prominent as a nature-based solution to minimize the adverse effects of existing climate conditions in cities and regions (Hoover et al. 2021; Meerow et al. 2021). Among the numerous definitions of GI (Shao et al.

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2021), there exists a growing interest in relevant politics, implementation, and trade-offs (Meerow 2020). Similar to man-made gray infrastructure, GI as an interconnected system should serve specific needs of people, a contrast to conventional, isolated green space planning (Benedict and McMahon 2006).

Within the urban context, a key justification for promoting GI is the attribution and maximization of multiple functionalities for society, ecology, and local climate to increase the efficiency of limited available space (Demuzere et al. 2014; Hansen and Pauleit 2014; Meerow 2020). This multifunctionality of GI can be categorized by urban planners in two ways: first, the capital concept (maximizing the public quality of life) and, second, the risk-based concept (minimizing environmental threats) (Matthews et al. 2015). For instance, risk-based benefits associated with GI comprise stormwater infiltration, air pollution reduction (Abhijith et al. 2017), or cooling functions in UHIs (Koc et al. 2018). The capital concept, however, seeks to promote public well-being, e.g., providing access to open spaces for obesity reduction (Coombes et al. 2010), building coping capacities by supporting people's ability to grow their own food (Barthel et al. 2010), or providing recreational facilities for stress reduction (Mansor et al. 2012).

Based on both concepts, GI can directly impact the vulnerability of an urban system and is thus widely interpreted as a resilience-strengthening measure (Liu et al. 2020). Taking into account the conceptualization of GI measures, collaboration among scientists, residents, and city administration constitutes a vital approach to socio-ecological problems, e.g., insufficient access to green and open spaces or air pollution due to nearby road traffic. Here, local planning departments occur at the intersection of research and society that need to translate scientific findings on complex environmental topics into policy decisions (Home and Bauer 2021). However, in reality, research is often perceived as existing in a theoretical bubble, detached from everyday life experiences, while municipalities tend to suffer from dependencies on conventional structures in the planning process (Puntub et al. 2022). Through the high discursive potential of GI, science and planning practice can share context-specific knowledge and benefit from each other to find tangible solutions for successful urban transformations. This collaboration, meanwhile termed 'ecology with cities', is inherently transdisciplinary by focusing on a transformation-oriented problem statement at the beginning of a mutual learning process and research outcomes relevant to both society and science (Byrne 2022).

While there are many advantages in mapping the status quo of environmental burdens and benefits in socio-ecological research (Fairburn et al. 2009; Glatter-Götz et al. 2019; Lakes et al. 2013; Ohlmeyer et al. 2022; Rüttenauer 2018; Shrestha et al. 2016), potential environmental burdens and benefits induced by intended policy interventions should be given the same attention. In this context, the investigation of the microscale plays an important role, as urban neighborhoods are the places where people shape their everyday lives and the effects of urban planning decisions become perceivable.

To determine what works for addressing environmental burdens at the microscale, this paper serves a double purpose: the first part of this study examines the benefits and trade-offs of GI measures in regard to environmental burdens considering primary health concerns among citizens. In detail, the outdoor effects of the aforementioned risk-based GI concept (minimizing environmental threats) are analyzed with the microclimate modeling software ENVI-met, namely, thermal comfort and air pollution. ENVI-met has been employed for a variety of previous urban greenery scenarios with respect to thermal comfort and air pollution (Balany et al. 2020; Rui et al. 2019; Tsoka et al. 2018) and is therefore appropriate for this study. The input for the analysis was a draft GI plan, which was the outcome of a collaborative workshop between science and planning practice during the transdisciplinary research project 'Zukunft-Stadt-Region-Ruhr' (ZUKUR). ZUKUR aimed to obtain urban planning solutions to reduce socio-ecological inequalities and to leverage climate resilience at the regional (Ruhr area), city-wide (city of Bottrop), and urban neighborhood scale (Dortmund Marten). In this work, the focus is on the neighborhood scale (microscale), with Dortmund Marten as the case study area:

> *Research question 1 (RQ1): What are the physical effects of GI on heat stress and air pollution at the microscale?*

The second part of this study is devoted to the underlying transdisciplinary process in the research project ZUKUR by exploring the strengths and challenges of science-practice collaboration in the realm of addressing environmental burdens through GI:

> *RQ2: How can science-practice collaboration stimulate the development of GI solutions at the microscale?*

The main aim of this study is therefore to analyze the product of a cooperative workshop as well as to provide insights into the process that has shaped the corresponding ideas of both science and planning practice. The simulation results contribute to an increased understanding of the effects of street trees, pocket parks and roof materials in terms of extreme summer conditions and air pollution. Furthermore, reflections of the participating researchers and planning practitioners on cooperation and GI planning will be discussed to improve future processes of knowledge exchange and greening interventions in urban neighborhoods.

Case study area and previous work

As one of the 80 cities with more than 100,000 inhabitants in Germany, the city of Dortmund ranks 59th in terms of its proportion of public and private green areas (Taubenböck et al. 2021) (Fig. 1a). In particular, large public open green spaces are more located throughout the southern districts of the city. In addition to an uneven distribution of green areas, an initial GIS-based Multi Criteria Fuzzy Analysis by Schaefer et al. (2020) revealed that health-related environmental burdens such as heat stress and noise pollution are clustered on different spatial scales across the entire city, with the Dortmund Marten subdistrict as one hotspot.

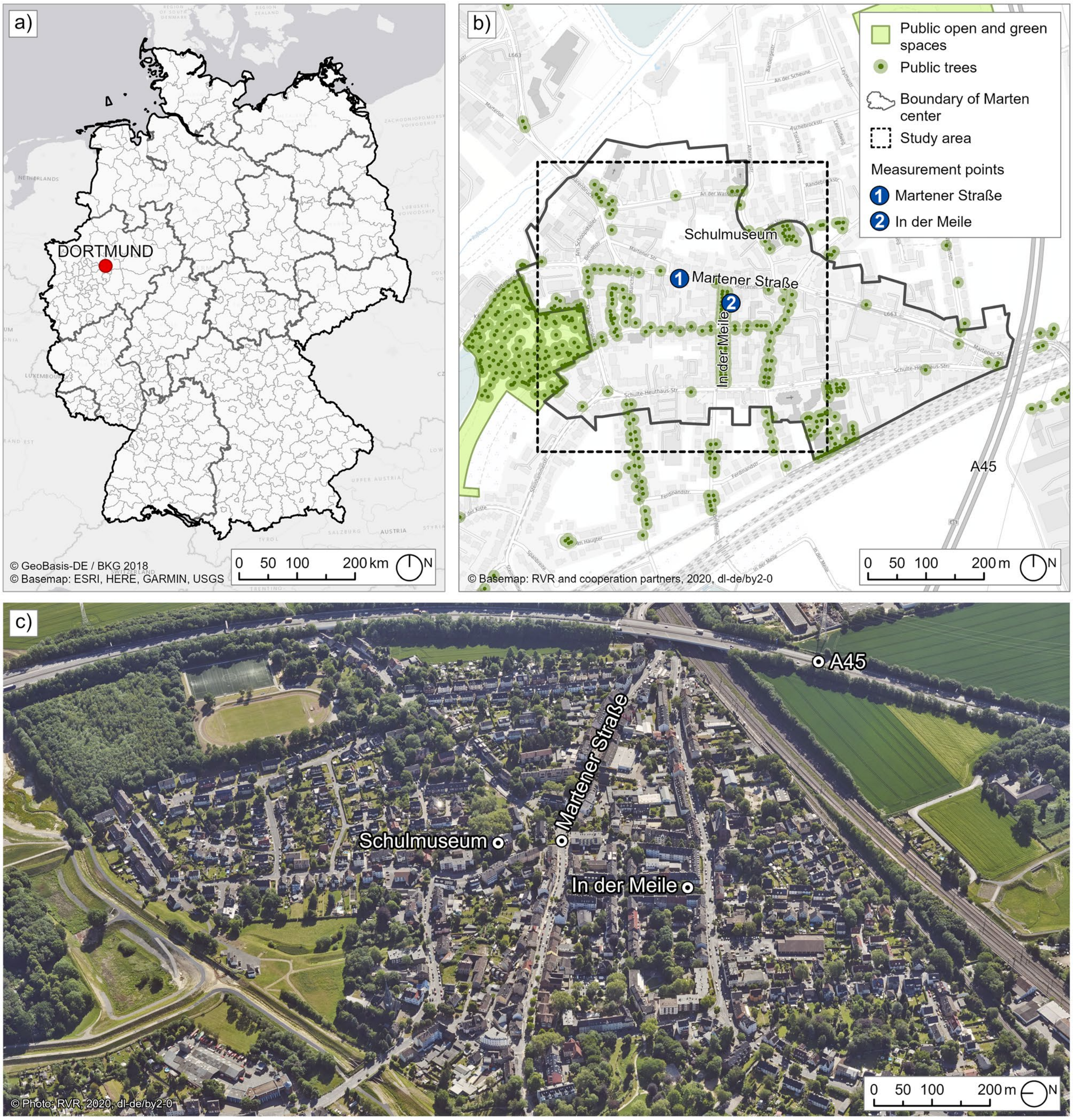


Fig. 1 **a** Location of the city of Dortmund in Germany; **b** study area (500 m × 500 m) in Dortmund Marten center, where 1 and 2 are the measurement points for model validation; **c** aerial view of the study area facing east

Dortmund Marten is located in the western part of Dortmund and has an above average unemployment rate of 11.8% (Stadt Dortmund 2019). The center is surrounded by heavily used one-way roads, representing the gray arteries of the study area (Fig. 1b). As this neighborhood serves as a transit hub with connections to several highways, such as A45 and Mallinckrodtstraße, high emissions are caused by commuter traffic. Furthermore, due to the low proportion of public green and open spaces, there is insufficient access to suitable climatic compensation areas. For instance, during the period from 1981–2010, Marten reached a yearly average of 10 hot days (> 30 °C peaks between 6:00 am and 6:00 pm), projected to increase to 35 by 2050, with the center of Marten as an UHI hotspot in Dortmund (Regionalverband Ruhr 2019).

According to the grades of thermal heat stress by Matzarakis and Amelung (2008), a preliminary questionnaire field survey on ambient air temperature sensation revealed that pedestrians perceived strong heat stress at Martener Straße on a hot day in summer (Schaefer et al. 2021). The questionnaire survey was coupled with meteorological measurements and took place at two hotspots with high traffic volumes (Fig. 1b) on 11th August 2020 during a heat wave occurring between 6th and 15th August 2020. The results indicated that pedestrians are very aware of outdoor heat stress, but 36% did not even consider any coping mechanisms. Most noted coping strategies referred to the indoor environment, e.g., air conditioning. This behavior suggests that additional public greening may contribute to outdoor heat stress reduction during daytime, especially among residents in Dortmund Marten who are unable to properly adapt on their own.

Methods

As illustrated in Fig. 2, this study is organized around the characteristic features of a transdisciplinary process (Scholz and Steiner 2015), with the TU Dortmund University and planning practitioners of the city of Dortmund as co-leaders of the neighborhood scale in the ZUKUR project.

For each spatial scale (region, city, neighborhood), a learning process between science and planning practice with regard to climate resilience and socio-ecological equalities was pursued. Through topic-specific workshops, new and applicable knowledge was to be jointly generated for urban planning practice, while accompanying spatial analyses delivered new insights for research.

In the beginning of phase 1, participatory mapping exercises with citizens of Dortmund Marten framed the first relevant environmental stressors at the neighborhood scale, such as air and noise pollution, access to public open and green spaces, and heat stress. After identifying environmental stressors for the local citizens, indicator-based mappings of environmental burdens and benefits were carried out by the researchers of TU Dortmund University. Through small discussion rounds with representatives of the city of Dortmund, different viewpoints were iteratively adapted and incorporated into the indicator mappings. At the end of phase 1, a public workshop with internal and external planning practitioners, citizens, and scientists was held to establish a common ground on socio-ecological challenges in Dortmund Marten.

This joint consensus statement induced a cross-disciplinary workshop on GI measures with scientists and urban planners, which comprised the main pillar of this study (phase 2). With the help of the preliminary mappings of environmental burdens and benefits in phase 1, municipal experts delineated concrete measures to qualify and connect GI at major hotspots in a draft GI plan. Through the application of a semi-structured online survey, potential learning effects and shared understanding of GI characteristics among local planning practitioners and scientists were identified at the end of phase 2.

Subsequently, the performance of the derived GI measures was quantified via the three-dimensional holistic microclimate modeling software ENVI-met version 5.0.2 (phase 3). The challenge here was to contextualize and evaluate the GI solutions proposed by urban planners by acknowledging the environment and local climate in Dortmund Marten. These real-world conditions were assessed through the field survey in the beginning of phase 3 and used for a mitigative GI scenario in this study. As can be seen in Fig. 2, the flexibility in adapting to new thoughts and evidence is reduced with every phase due to the increase in joint consensus and the decrease in the number of different stakeholder types involved. The next sections will focus on the workshop and online survey in phase 2 as well as the quantification of the effects of the draft GI plan in phase 3.

'Green Marten' cooperative workshop

As part of the ZUKUR project, a cross-disciplinary workshop was held on 2 March 2020. To ensure optimal knowledge sharing, all attendees represented different backgrounds, comprising six scientific researchers (including the author) of TU Dortmund University with research experience in risk planning, geospatial analyses, environmental planning, and urban development as well as five municipal representatives from the city of Dortmund, with expertise in climate adaptation, environmental planning, GI, and drainage. The workshop was held in the Meilenstein forum at the center of Dortmund Marten, acting as the arena for local collaboration at the neighborhood scale in the ZUKUR project.

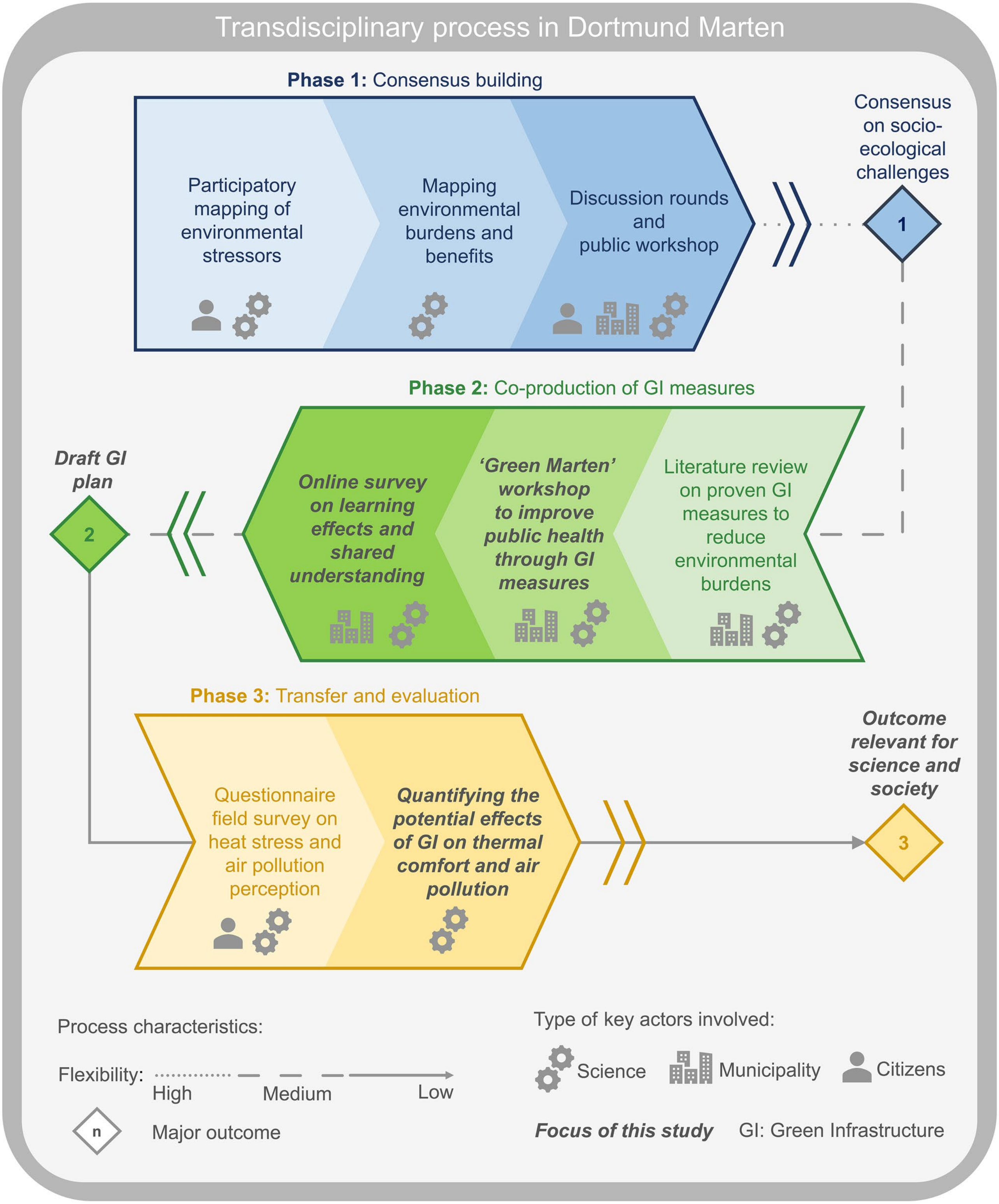


Fig. 2 Schematic overview of the applied transdisciplinary process in ZUKUR with resulting outcomes in Dortmund Marten, based on Hansen et al. (2021)

To achieve a joint problem definition, current environmental challenges in Dortmund Marten were introduced by the attending planning practitioners and ZUKUR research team at the beginning of the workshop. After presentations and an explanation of the session objectives, all participants entered into two mixed working groups to outline strategies and appropriate measures for GI considering climate adaptation and public health equities. Two printed maps of the study area helped to localize the proposed ideas (Fig. 3). During the group work, it became clear that space for greening intervention in Dortmund Marten is limited, shifting the focus on connecting and qualifying existing GI with the purpose of providing multiple benefits for society. For equity reasons, another precondition was that GI interventions need to be accessible within walking distance and publicly available for citizens in Dortmund Marten. With subject-specific knowledge of the specialists and GIS-based indicator maps of Schaefer et al. (2020), the first measures were outlined and mapped by both working groups to identify possible hotspots for action. The role of science was to provide information on current analysis results, while the practice participants contributed tangible measures in this area. As such, theoretical findings rooted in science could be adjusted based on practical experiences, and, furthermore, practical measures could be formulated on a sound basis. After the group working phase, the developed arguments

Fig. 3 Insights into the cooperative workshop and draft GI plan for the Dortmund Marten center, which indicates additional roadside trees at Martener Straße, unsealing procedures at Schulmuseum, and roof greening

of both groups were synthesized to frame constructive GI measures.

Both working groups emphasized a clear need for action regarding the street canyon of Martener Straße, mainly associated with the absence of shaded areas and a high traffic volume. Another hotspot for urban greenery intervention was the unused impermeable area at the Schulmuseum. The strategy here was to introduce amenities and aesthetic value through the addition of vegetated surfaces. As an outcome of the workshop, several adaptation measures, such as unsealing procedures, roof greening, and roadside tree planting, were highlighted in the study area as a draft GI plan (Fig. 3).

Microclimate simulation of the status quo

ENVI-met is a computational fluid dynamics (CFD)-based model developed by Michael Bruse (Bruse and Fleer 1998) for three-dimensional numerical simulation applications. The high spatial resolution and the detailed representation of vegetation forms in ENVI-met allow extensive microclimate scenario simulations considering real-world physics (Liu et al. 2021). Since the implementation of the MONDE tool in 2018, it has been possible to import vector-based GIS data into the modeling environment, which greatly eases input preparation. The input generation for microclimate modeling in this research relied on a data-driven approach employed by the author using GIS and remote sensing in a previous study of Dortmund Marten. A detailed description of the open geodata employed and the applied workflow is presented in Schaefer et al. (2021). The five main working steps were as follows:

1. Object-based classification of a digital orthophoto (1 m) was performed with mean height information derived by a normalized digital surface model.
2. Albedo information was extracted to determine dominant roof surface materials using pure pixels in calibrated Sentinel 2C multispectral satellite data at a 10 m resolution.
3. Physical parameters such as the specific heat capacity, emissivity, and density were added based on albedo and literature values as references.
4. Classified vector data and physical information (buildings, roof surfaces, trees, hedges, grasslands, sand areas, asphalt, and pavement) were imported into the ENVI-met database to establish a 2.5D model of Dortmund Marten.
5. To determine meteorological conditions, on-site measurements of the air temperature, relative humidity and PM_{10} and $PM_{2.5}$ concentrations at a 1.5 m height (breathing zone) were carried out using mobile particle counter devices PCE-PCO2 (Table 1). Data collection occurred during a hot day on 11th August 2020 between 05:00 am and 11:00 pm (except for 05:00 pm) at two measurement points (Fig. 1b) with 17 one-hour means at 60 s intervals.

It is worth noting that ENVI-met suffers limitations in traffic-induced particulate matter prediction, leading to considerable errors in the measured concentration, especially during rush hours (morning and afternoon) in Dortmund Marten (Schaefer et al. 2021). Given that it is not possible to adjust the hourly traffic volume (absolute number of cars per simulation hour) in the ENVI-met environment, the predicted particulate matter concentration varied little over time. To overcome this issue, the emission rates for each hour were recalculated in Microsoft Excel considering the total sum of all emission rates for the whole simulation duration. Consequently, the total sum of the emission rates remained unchanged, while fluctuations in the traffic volume could be simulated according to the traffic behavior observed during field measurements. Instead of the standard representation of line-based emission sources [µg/m*s] in the model, area-based implementation [$\mu g/m^2 * s$] of emitters (here, road traffic) throughout the whole road area simulated the stop-and-go effect more realistically in ENVI-met (Paas and Schneider 2016).

Green infrastructure scenario

The design ideas of the collaborative workshop constituted an appropriate point of departure to investigate their microclimate effects on the surrounding environment. Within this context, it is necessary to provide scientific evidence to determine whether the measure outcomes also meet the objectives set by the workshop participants.

Green roofs are widely acknowledged to mitigate the UHI effect through increased evapotranspiration (Berardi 2016). Green roofs are the sum of multiple construction layers, typically comprising the building itself, drainage materials, geotextile filters, and soil, with a vegetation layer at the outer end. Generally, there are two engineering types of urban green roofs in the literature, namely, intensive (soil layer depth > 150 mm) and extensive (soil layer depth ≤ 150 mm) roofs (Berndtsson 2010). However, a consensus is lacking regarding the specific soil layer depth of both green roof types, but it has been reported that intensive green roofs demand a much larger soil thickness than extensive roofs due to more complex vegetation forms and corresponding deeper root networks. As a consequence, especially for low-rise buildings, intensive green roofs, applied as roof gardens, generate a higher cooling contribution to the outdoor air temperature and building energy demand. In turn, these installations are more cost-intensive applications and require significantly greater maintenance efforts than those required by extensive green roofs (Aboelata 2021; Berndtsson 2010;

Table 1 Input parameters and meteorological conditions under the baseline and GI scenarios in ENVI-met version 5.0.2

Parameter	Description	Value
Model dimensions		
	Number of grid cells (x, y, z)	250, 250, 20
	Size of grid cells (x, y, z)	2, 2, 3
	Number of nesting grids	7
	Digital terrain model	Not applied
Simulation settings		
	Simulation day	11th August 2020
	Simulation start time	05:00 am
	Simulation end time	11:00 pm
	Output interval	60 min
	Wind speed at 10 m above ground level	2.2 m/s
	Prevailing wind direction	East (90°)
	Roughness length [m]	0.677
	Minimum air temperature (05:00 am)	21.1 °C
	Maximum air temperature (03:00 pm)	32.4 °C
	Minimum relative humidity (03:00 pm)	40.8%
	Maximum relative humidity (07:00 am)	71.7%
Air pollution settings		
	Background concentration of PM_{10}	17 µg/m^3
	Background concentration of $PM_{2.5}$	7 µg/m^3
Human parameters for PET calculation		
	Age	35 years
	Height	1.75 m
	Weight	75 kg
	Work metabolism	80 W
	Clothes	0.57, clothing in summer

Morakinyo et al. 2017). With respect to practicability in the study area, under this scenario, extensive green roofs with a soil layer of 200 mm and full coverage of the roof surface were considered. The application of a 200 mm soil thickness allows extensive green roofs and provides the opportunity for intensive green roofs in the future. Roof greening measures were applied to suitable roofs with a minimum area of 20 m^2 (Fig. 3) according to the green roof cadaster of the Regional Association Ruhr (RVR) (Regionalverband Ruhr 2022). The greening type was grass with a height of 30 cm.

To create a green connection with the avenue trees along the street 'In der Meile', 28 deciduous trees were added to the unshaded sidewalks along Martener Straße at intervals of 8 m, with the same height (15 m) and crown width (9 m) as those of existing trees. The 8 m interval was chosen because optimum cooling at the pedestrian level is achieved when the distance between trees matches the crown width (Zheng et al. 2018). This layout also avoided unnecessary shadow overlapping.

Even though GI measures are often large, interconnected systems within a region or city (Verdú-Vázquez et al. 2020; Wang et al. 2021), small and accessible parks of less than 1 ha are also capable of improving thermal comfort (Müller et al. 2014). Therefore, a pocket park (1,600 m^2) with grass and sandy soil surfaces below the dense tree cluster near the Martener Schulmuseum was implemented in the model environment to allow recreational use. Likewise, the additional evaporative cooling of vegetation lowers the air temperature, decreases wind velocity and increases atmospheric humidity between the Schulmuseum and its surrounding built-up environment, enhancing the cold island effect during hot days (Xue et al. 2019).

Finally, the GI scenario was simulated with the same meteorological and temporal parameters as those of the baseline scenario to quantify the direct impact of the applied GI measures during an extreme heat event (Table 1). The output files of both scenarios are provided in the availability of data and material section. To gain a comprehensive understanding of the design recommendations, relevant microclimate indicators were calculated, namely, the potential air temperature, relative humidity, wind speed, mean radiant temperature (MRT), roof and facade surface temperatures, and the physiological equivalent temperature (PET) for outdoor human thermal comfort (Liu et al. 2021).

In regard to air pollution, PM_{10} and $PM_{2.5}$ concentrations were simulated.

To evaluate the model prediction performance, the squared correlation coefficient (R^2), mean absolute percentage error (MAPE), root mean squared error (RMSE), and Willmott's index of agreement (*d*) (Willmott 1981) were calculated between the simulated and measured parameters.

Online survey

An online survey was conducted with the participants of the 'Green Marten' workshop to gain insights into the subjective experience of the science-practice working relationship. The intention of the survey was to identify the impact of the GI workshop relevant to planning practice and science. First, questions about potential learning effects and knowledge applications during the workshop were asked. In a second block, based on the findings of Matthews et al. (2015), expectations for successful GI planning were obtained. For every question, a five-point Likert scale was employed encompassing strongly agree, rather agree, neutral, rather disagree, and strongly disagree. The online questionnaire survey was created in LimeSurvey and sent to the five practice participants, other city department staff members and the scientific researchers of the workshop by direct mailing. The survey was conducted anonymously, while all participants were informed beforehand about the usage of their data in this research.

Results

Simulation validation

The statistical validation metrics for the air temperature and relative humidity measurements revealed a high agreement with the remote sensing-based ENVI-met baseline simulations (Fig. 4). Based on the adjustments in air pollution settings, particulate matter prediction could be greatly enhanced. However, compared to Martener Straße, the air pollution predictions at In der Meile still show lower agreement values with field survey measurements. These larger errors may be a result of different peak traffic hours and road designs. For instance, at Martener Straße, air pollution dispersion reaches traffic peaks at 09:00 am and 06:00 pm,

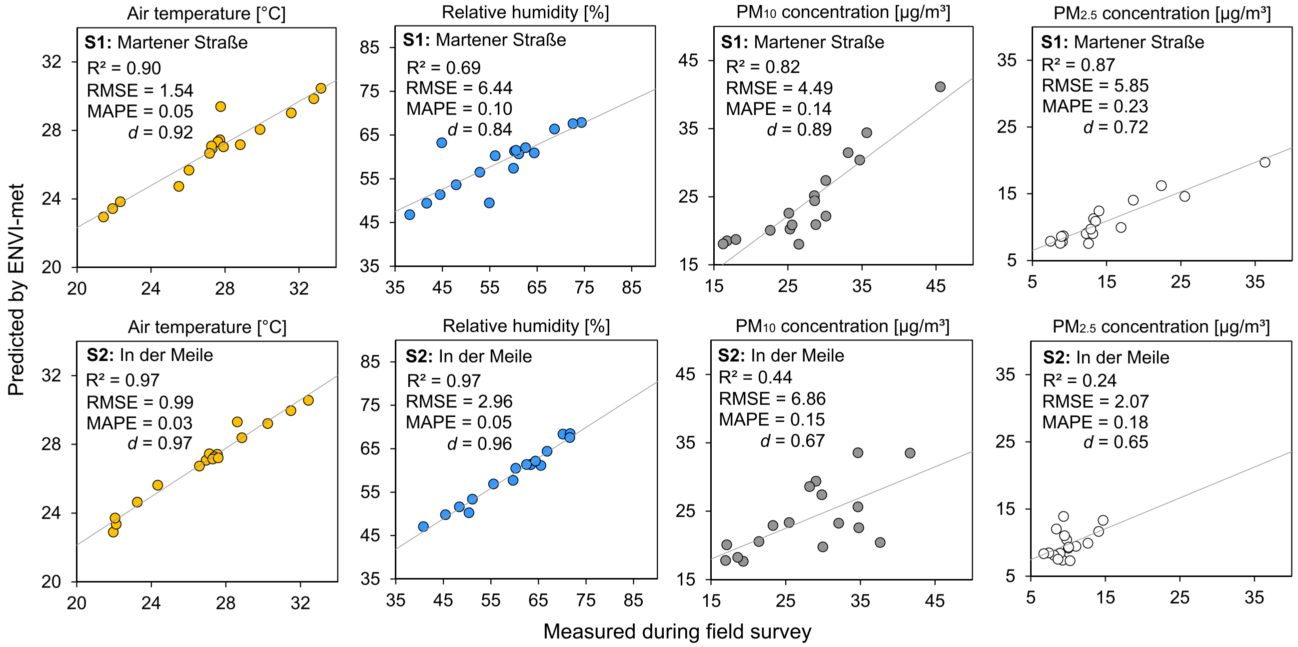
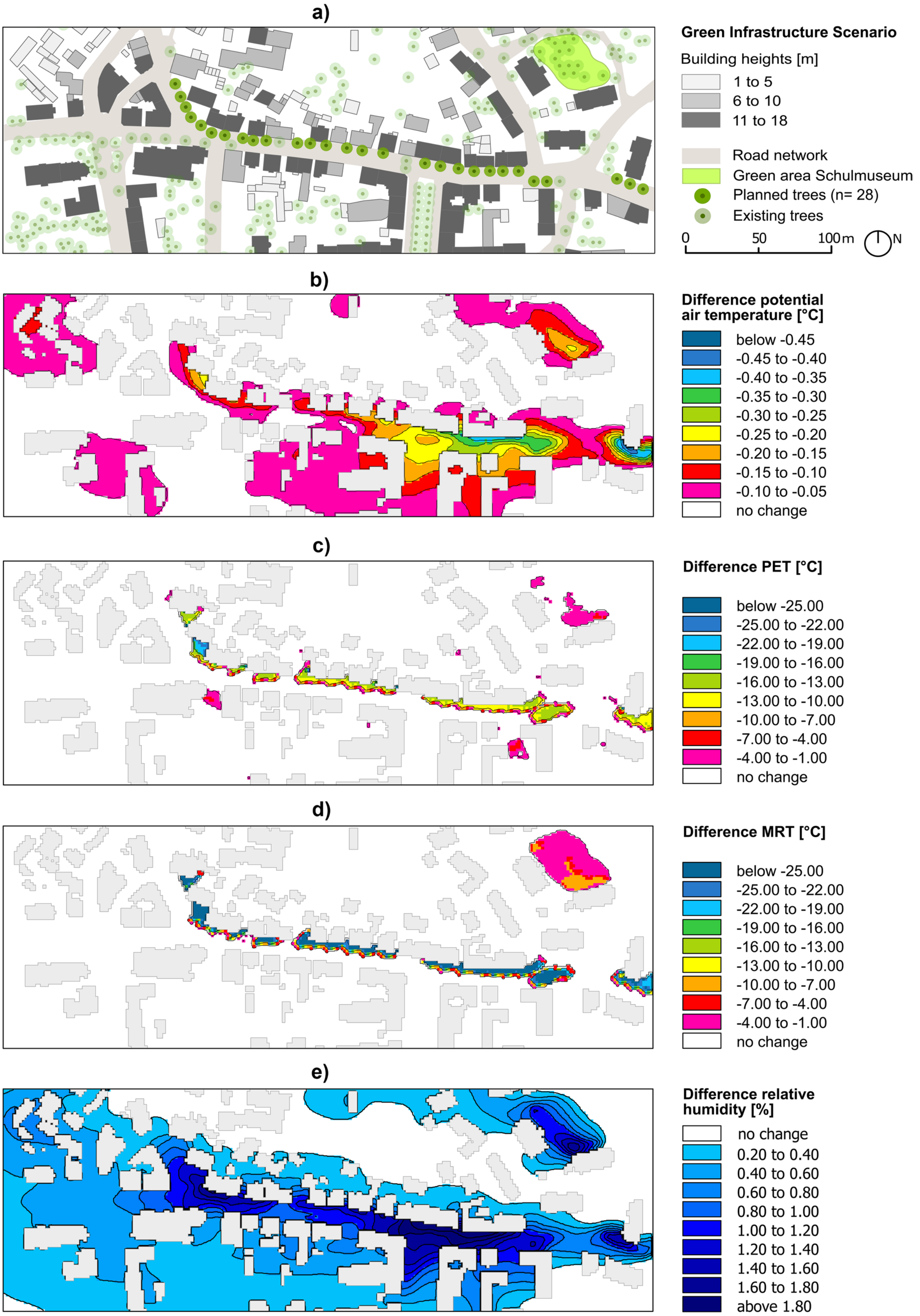


Fig. 4 Baseline scenario scatterplots of the measured and simulated parameters during each simulation hour ($n = 17$) with statistical performance indicators for model prediction accuracy assessment (R^2 = squared correlation coefficient, RMSE = root mean squared error, MAPE = mean absolute percentage error, *d* = index of agreement)


a)
Green Infrastructure Scenario
Building heights [m]
1 to 5
6 to 10
11 to 18
Road network
Green area Schulmuseum
Planned trees (n= 28)
Existing trees
0
50
100 m
N
b)
Difference potential air temperature [°C]
below -0.45
-0.45 to -0.40
-0.40 to -0.35
-0.35 to -0.30
-0.30 to -0.25
-0.25 to -0.20
-0.20 to -0.15
-0.15 to -0.10
-0.10 to -0.05
no change
c)
Difference PET [°C]
below -25.00
-25.00 to -22.00
-22.00 to -19.00
-19.00 to -16.00
-16.00 to -13.00
-13.00 to -10.00
-10.00 to -7.00
-7.00 to -4.00
-4.00 to -1.00
no change
d)
Difference MRT [°C]
below -25.00
-25.00 to -22.00
-22.00 to -19.00
-19.00 to -16.00
-16.00 to -13.00
-13.00 to -10.00
-10.00 to -7.00
-7.00 to -4.00
-4.00 to -1.00
no change
e)
Difference relative humidity [%]
no change
0.20 to 0.40
0.40 to 0.60
0.60 to 0.80
0.80 to 1.00
1.00 to 1.20
1.20 to 1.40
1.40 to 1.60
1.60 to 1.80
above 1.80

◂**Fig. 5** Impact of the GI scenario on the meteorological and thermal comfort parameters in the Martener Straße canyon and Schulmuseum at the pedestrian level of 1.5 m at peak temperatures (03:00 pm)

while at In der Meile, air pollution is constantly high due to the wind blocking effects of trees and buildings. Compared to the real world, such turbulence is more difficult to simulate in a cubic model, which leads to a higher chance of error during simulation (Schaefer et al. 2021).

Nevertheless, with a MAPE of 0.14 for PM_{10} and 0.23 for $PM_{2.5}$ at Martener Straße and 0.15 for PM_{10} and 0.18 for $PM_{2.5}$ at In der Meile, the generated output satisfied the requirements of a 'good' air quality dispersion model (Chang and Hanna 2004). Combined with the high agreements in air temperature and relative humidity, the numerical simulation output of ENVI-met can be considered to draw meaningful conclusions regarding the local microclimate and air pollution in Dortmund Marten.

Predicted GI performance in terms of the microclimate

Figure 5 reveals the effects of the proposed roadside tree plantings and green area near the Schulmuseum on microclimate metrics. Due to the east–west orientation of the street canyon, the presence of trees along Martener Straße could produce shading on the northern sidewalk. The effects on thermal comfort (expressed via MRT and PET) rapidly declined with increasing distance to the tree canopy (Fig. 5c, d). In contrast, the air temperature decreases by 0.4–0.1 °C and the relative humidity rises by 0.2–1.8% due to an increased evapotranspiration process across a larger area following the wind direction (Fig. 5b, e). As shown in Fig. 5b–d, the proposed replacement of impervious surfaces by a 1,600-m^2 pocket park near the Schulmuseum slightly influenced thermal comfort (PET = –4 °C).

In Martens microclimate, additional roadside tree plantings could reduce not only PET by 13–25 °C at 1.5 m but also the surface temperature of nearby building facades by 6–21 °C (Fig. 6). This effect is particularly relevant for heat sensation in adjacent retail stores or offices at ground level.

In regard to roof materials, maximum temperatures occurred between 12:00 and 02:00 pm (Fig. 7). When nighttime was reached between 09:00 and 11:00 pm, all roof materials shared a similar surface temperature of approximately 25 °C. The most notable temperature reduction by green roofs in comparison to zinc and bitumen roofs was up to 42 °C (Fig. 7). Where existing trees shaded roofs, the average cooling effect of –10 °C was considerably lower (Fig. 6). Green roofs on the upwind side also yielded a slightly positive effect on the resultant pedestrian air temperature and relative humidity levels during the daytime, as the temperature was reduced by 0.1 °C on the leeward side (Fig. 5b). However, the given building designs and heights in the study area imposed the greatest influence on the environment (He et al. 2019). As extensive green roofs generally provided no additional shading, with increasing building height, green roof cooling at the pedestrian level diminished, which is in line with the findings of Zhang et al. (2019). Conversely, the greater the distance between buildings, the more ventilation occurs, but exposure to solar radiation is also greater (Ali-Toudert and Mayer 2006), which cannot be compensated by the extensive green roofs.

Predicted GI performance in terms of air pollution

Compared to the reference case, the new tree patterns enhanced the obstacle effect, where wind speeds were reduced by up to 1 m/s, and the proposed patterns significantly inhibited particulate matter diffusion along the high-traffic Martener Straße (Fig. 8b-d). This disturbance to the ventilation corridor was also significantly influenced by the width and geometry of the canyon combined with the proposed tree plantings. This effect was particularly evident in the eastern part of the study area, where particulate matter was only increased by 7 μg/m^3 for PM_{10} and 3.5 μg/m^3 for $PM_{2.5}$, but the wind speed was still reduced by 0.6 m/s (Fig. 8b–d). Similar observations were reported in another study with respect to parallel wind directions (Gromke and Ruck 2012). The planned grass surface near the Schulmuseum did not affect the particulate matter concentration.

Reflections on science–practice collaboration and shared understanding in GI planning

Figure 9 shows a summary of the reflections on the 'Green Marten' workshop. One expert who did not attend the workshop completed the online survey on institutional expectations for GI planning, while another expert who participated in the workshop began the survey but did not complete the questions related to the institutional expectations for GI planning. Both urban planners and researchers were widely aware of the climatic and environmental conditions in Dortmund Marten. Surprisingly, the experts experienced no issues integrating their practical knowledge during the workshop, whereas the scientists reported less ability to integrate their expertise. In contrast, the overall learning outcome of the planning practitioners was rather neutral, while the majority of the participating scientists confirmed a learning effect through the workshop.

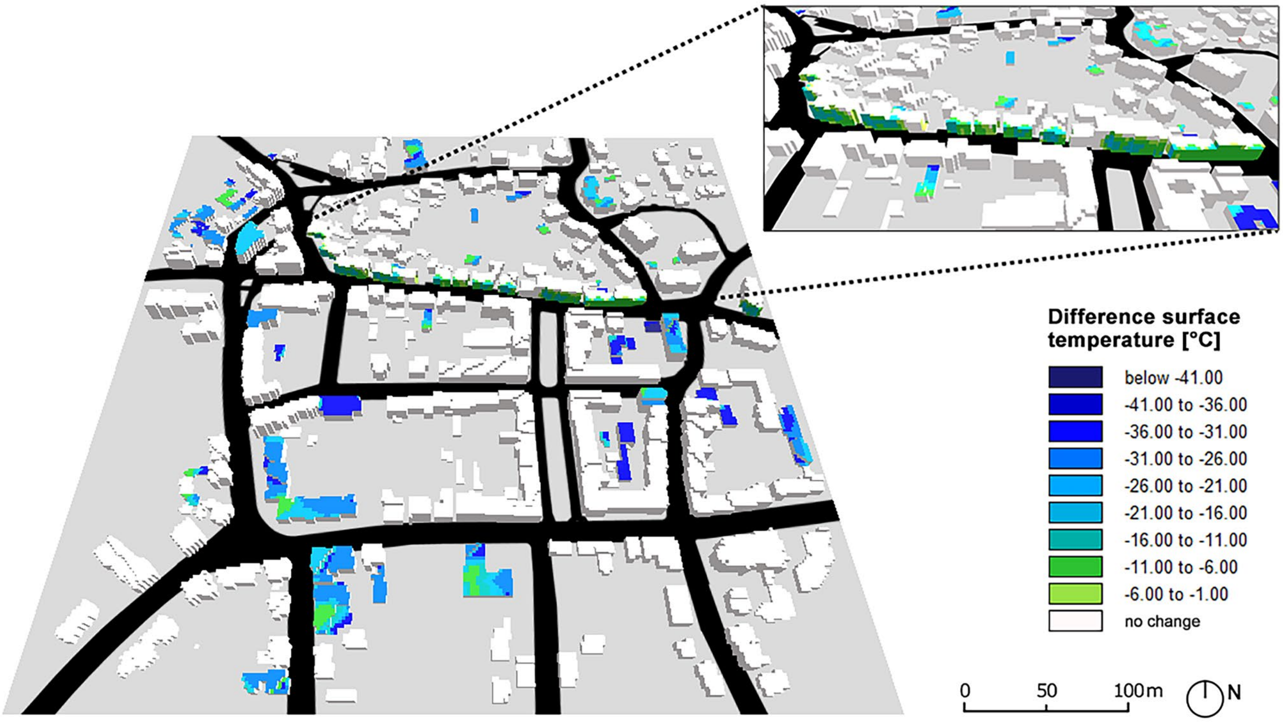


Fig. 6 Impact of green roofs and roadside trees on the building surface temperatures in the study area during peak-temperature hours (03:00 pm)

Figure 10 reveals the opinions and expectations of the survey respondents regarding GI planning. Overall, the survey outcome indicates that practitioners and scientists approached GI planning differently in regard to the deployment of new instruments and methods in the planning process. In addition to clear agreements on institutional

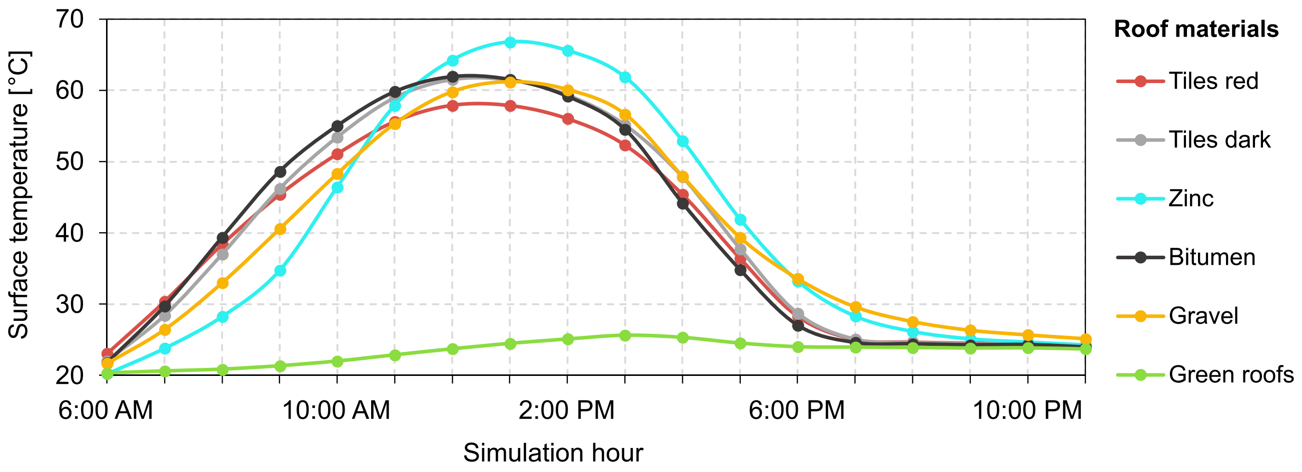


Fig. 7 Predicted surface temperatures for all roof materials in the study area (25 pixels/100 m^2 for all roof materials not affected by shading of tree crowns)

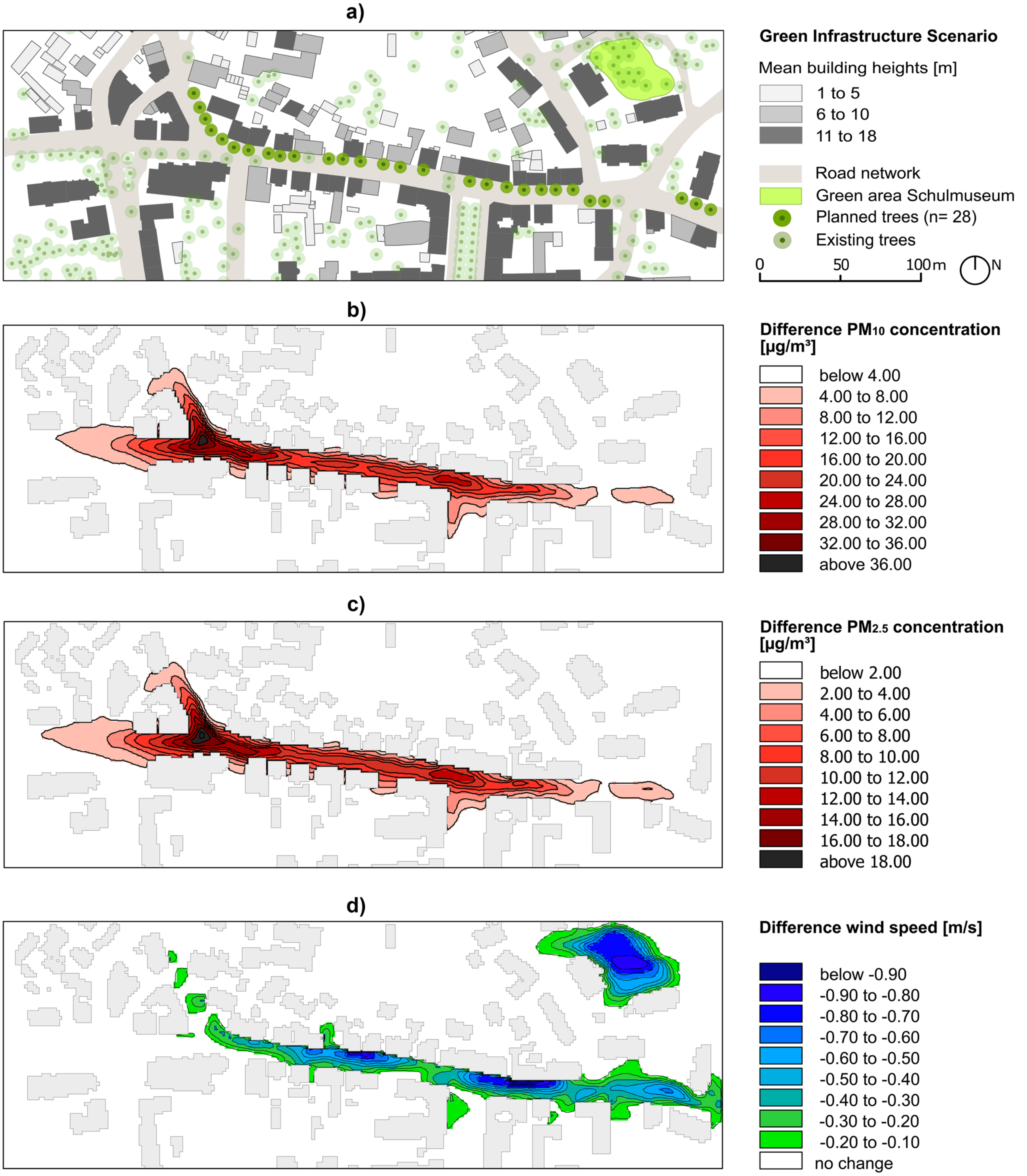


Fig. 8 Impact of the GI scenario on the wind speed, PM_{10} and $PM_{2.5}$ concentrations in the Martener Straße canyon and Schulmuseum during peak traffic hours at the pedestrian height (1.5 m) at 09:00 am

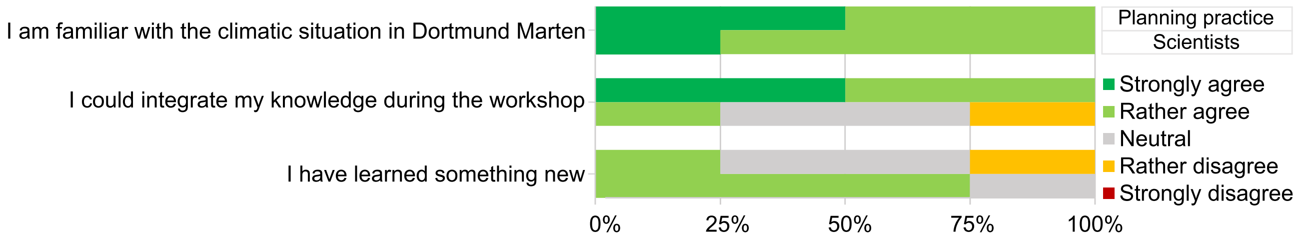


Fig. 9 Evaluation of the 'Green Marten' workshop impact on the planning practitioners ($n=4$), represented by the upper bars, and the scientists ($n=4$), represented by the lower bars

communication, land use planning integration and multifunctionality, diverging expectations on the visual appeal of GI occurred not only between science and practice but also within both groups. The same divergence of opinions was found regarding the statement on planning GI without much bureaucracy, particularly among planning practitioners.

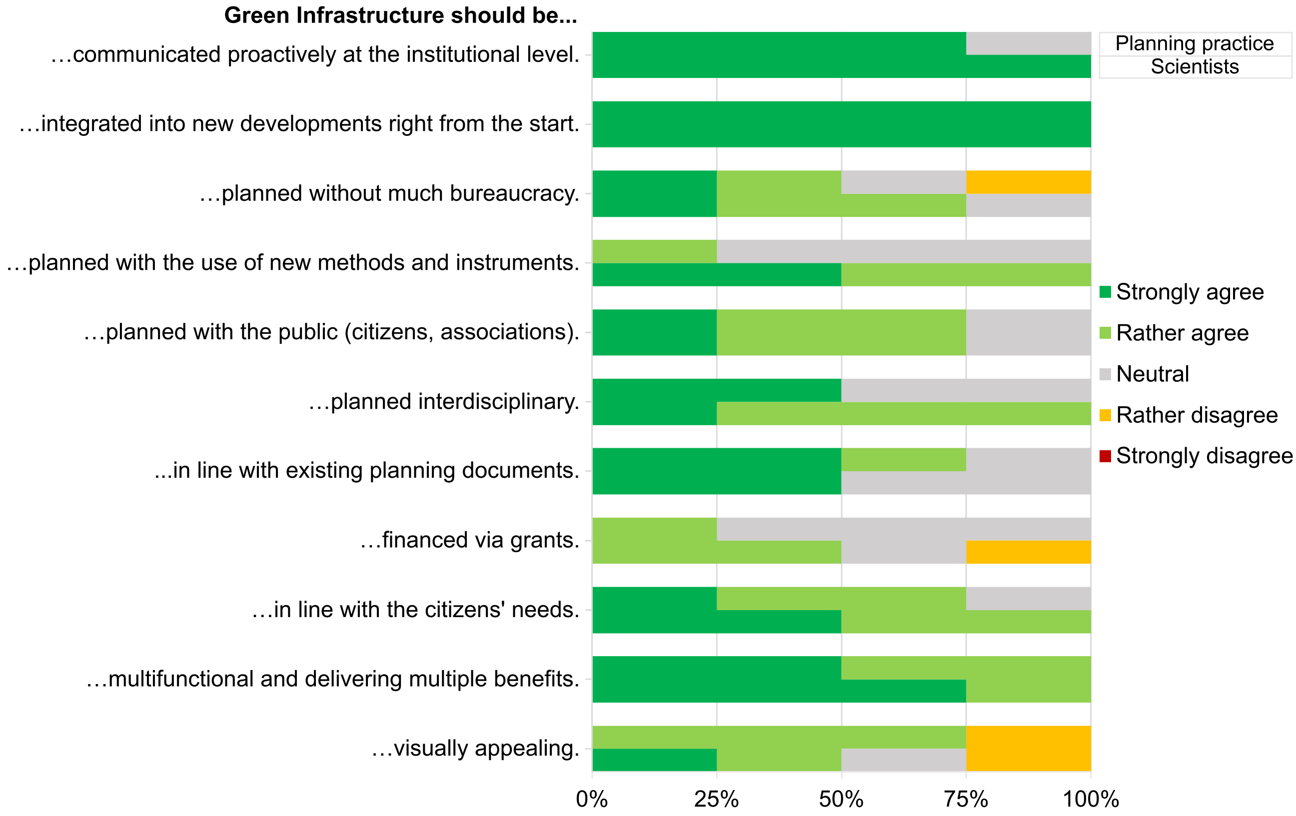


Fig. 10 Evaluation of the survey responses of planning practitioners ($n=4$), represented by the upper bars, and scientists ($n=4$), represented by the lower bars, in regard to expectations for GI planning

Discussion

In this study, a collaborative workshop within a transdisciplinary process induced a tangible GI concept at the neighborhood scale, which could be analyzed with the microclimatic simulation software ENVI-met. After presenting validated simulation results, the benefits and trade-offs of the derived GI measures will be discussed in "What works in addressing environmental burdens at the microscale?", which addresses RQ1. The strengths and limitations of the cooperation between science and planning practice in regard to GI planning will be critically explored in "How can science-practice collaboration stimulate the development of GI solutions?" and "Limitations and risks of the transdisciplinary approach" to provide answers to RQ2.

What works in addressing environmental burdens at the microscale?

What are the physical effects of GI on heat stress and air pollution?

Aerodynamic interactions along Martener Straße indicated that tree plantings did not per se enhance air pollution accumulation; instead, their orientation within this street canyon was the main influencing factor. Thus, both ends of the tree line along Martener Straße remain of interest for future installation. Another option for ventilation enhancement lies in increasing the distance between tree plantings, which could in turn reduce the cooling effect during the daytime due to a lower green cover ratio and fewer shadow casts (Rui et al. 2019). Likewise, the design or type of trees was not considered in the workshop, despite the importance of these factors in regard to temperature regulation, irrigation, and allergic reactions to pollen (Hoover et al. 2021; Rahman et al. 2020).

Although green roofs in Dortmund Marten should reach the highest cover ratio possible to accomplish the best cooling effect, care should be taken beforehand to determine whether a green roof in tree-shaded areas is appropriate and what its purpose is (cooling or surface runoff). This is especially relevant for roof materials with a high heat capacity, such as zinc, dark tiles, and bitumen. However, tree shade and green roofs are only effective in reducing the temperature during daytime, while during warm nights (> 20 °C during 6:00 pm and 6:00 am), other cooling strategies that enhance ventilation should be discussed and scientifically validated in the future.

The analyzed measures referred to passive climate adaptation strategies (tree planting, surface unsealing, and roof greening), which could be adjusted by the instruments of urban planning. However, human health is affected not only by high temperatures but also by a lack of cooling areas and individual vulnerabilities (Pickett et al. 2021). Therefore, in case the draft GI plan will be put into practice in the future, active strategies should be considered in parallel, e.g., accessible cooling centers for those without air conditioning, training modules for firefighters and early warning systems as a robust response to heat threats (Keith et al. 2020).

In terms of air pollution, it could only be concluded that additional road greening could lead to an increase in the surface roughness of the street canyon and thus increase particulate matter accumulation. In turn, there should be more studies involving different simulation tools over a longer period to calculate the particulate matter absorption degree of roadside trees. ENVI-met therefore serves as an accurate tool to identify the critical climatic functions of GI but not its cultural, educational, or recreational quality.

Socio-ecological challenges

In contrast to other GI programs focusing on public property, the presented GI suggestions affect both public (streets, open places) *and* private property (roofs), which occupy a remarkable proportion of urban land. The actual roof surface material was not considered in the cooperative workshop but could be identified and integrated into the modeling environment via remote sensing techniques, leading to more realistic results with the ability to capture the effect of replacing various roof materials with green roofs. Here, roof surfaces such as red and dark tiles that could reach particularly high temperatures on hot days are rarely suitable for greening interventions due to the gable roof design. With this knowledge, it can be asserted that adaptation measures for these specific roof types are less feasible and could leverage additional climate adaptation inequalities.

Although the project focused on socio-ecological issues in Dortmund Marten, attention should be given not only to risk minimization but also to poverty and exclusion reduction (Hamstead and Sauer 2021). Critically seen, urban greening interventions in deprived neighborhoods such as Dortmund Marten could foster green gentrification processes, thereby excluding minorities and low-income residents from their intended positive impacts (Anguelovski et al. 2019). As documented by the online survey, including the voices of the public represents an important aspect by the planning practitioners of Dortmund (Fig. 10). This empowerment was given in phase 1 of the research project as framing from the outset but should also be reinforced in the siting process to reduce mistrust among local residents and therefore increase the legitimacy of GI frameworks (Cook et al. 2021; Paavola and Adger 2006). With regard to the reduction in flexibility during the transdisciplinary approach, the inclusion of citizens in Dortmund Marten would have been meaningful in phase 2, especially when it comes to the planting of trees in front of people's houses.

Regarding socio-ecological inequalities in the long run, environmental factors and demographic data should be monitored via indicators to quantify advantages and disadvantages to the local population after GI implementation. The Urban Climate Resilience Index (UCRI) proposed by Schaefer et al. (2020) would serve as a suitable example. The Meilenstein office in Dortmund Marten should be consolidated as a fixed infrastructure, evolving into a persistent living laboratory to collect profound feedback on the analysis results while also giving attention to continuous optimization in response to citizen and stakeholder interaction. The basis for the above is that everyone should speak the same language, especially when it comes to the involvement of actors not familiar with scientific methods or terms.

How can science-practice collaboration stimulate the development of GI solutions?

Consensus versus knowledge gaining

The results of the online survey point to a low level of shared learning effects but a high level of shared values and perspectives between planning practice and science (Figs. 9 and 10). The minor learning effect on the practical side could refer to a preexisting knowledge of the environmental and climatic indicator mappings in Dortmund Marten of phase 1. Furthermore, and as a prerequisite for the 'Green Marten' workshop, the participating practitioners were experts in climate change adaptation and environmental planning. With this in mind, the learning effect might increase if planners with other backgrounds (e.g., infrastructure planning, biodiversity) were also integrated into the workshop. For the participating researchers, the knowledge gain during the workshop was comparably higher, as the urban planning practitioners communicated unknown barriers in GI implementation (e.g., maintenance costs and loss of parking lots). However, with each stage of progress in co-research, the learning effect tends to diminish as the core team develops more expertise on the topic.

Bureaucracy remains an important issue on the practical side. Scientific innovation efforts are therefore still in conflict with anchored routines in practice, which can also be obtained in the statement about using new methods and instruments in GI planning (Fig. 10). This communication issue also manifests in the difficulty the researchers experienced in integrating their expertise during the workshop, which warrants the installation of a mediator in future transdisciplinary collaborations. To obtain a better learning outcome on the practical side, instead of printed maps, the adoption of interactive map-based support systems (Shrestha et al. 2018) could steer the communication on environmental indicators.

The mix of consultation and co-creation throughout the transdisciplinary process ensured that the theoretical research outcome complements practical needs. For science, the derived GI measures of phase 2 are essential to confirm the authenticity of the developed scenarios so that the results can be further applied at early stages of future land-use planning procedures. In this light, there also exists strong agreement on the need to include GI in new urban planning projects right from the beginning, since retrofits in binding land-use plans may be impeded by several legal barriers.

The online survey revealed that the project involved several individuals with different interpretations of GI planning, even within both stakeholder groups. Joint consensus building is therefore an important factor to overcome uncertainties but should be re-evaluated in each phase to provide sufficient flexibility, with the ability to adapt intermediate results to new viewpoints or scientific evidence. Despite some existing tensions with the use of new methods, the broad consensus of both science and practice participants on GI characteristics became clear. Nevertheless, these tensions are especially worth investigating and discussing during co-research rather than only relying on commonalities.

Multifunctionality: the more, the better?

Overall, the investigated effects of the derived GI measures were rather monofunctional without documentable synergies, while potential secondary effects of the capital GI concept were beyond the scope of this study. Accordingly, other functionalities (including aesthetic, educational and biodiversity value) of the suggested GI measures were respected but less relevant for the workshop participants. This monofunctional framing of GI originated in the group consensus to advance socio-ecological equity by targeting critical GI functions such as heat mitigation and air pollution reduction. Although the proposed greening interventions at the Schulmuseum will not significantly affect thermal comfort and air pollution, unsealing procedures still contribute to the visual aspects of the location or generate educational benefits for local ecosystems. On the other hand, with every demand on additional functions of GI, the cumulative effects diminish, as not all functions serve the same beneficial objective (Hansen and Pauleit 2014). It is therefore crucial to define what kind of multifunctionality is pursued and which functions should dominate at the beginning of the workshop.

A matter of scale?

The geographic area of the Dortmund Marten center only covered an investigation scope of 500 m × 500 m. Since Dortmund Marten is surrounded by large agricultural sites in the north, east, and south (Fig. 1c), the joint focus on GI interventions in the core area of Dortmund Marten is reasonable. Surprisingly, this spatial limitation turned out to be a benefit during the cooperative workshop, forcing all attendees to formulate precise and space-saving GI measures. Furthermore, the actual size of the study area made it possible to evaluate the proposed measures in ENVI-met within a reasonable computing time. Larger areas of interest would have been needed to be treated with other simulation tools at the meso-scale (Heldens et al. 2020). Thus, as a learning for city administration, the investigation scope should be as small as possible to formulate clear and cohesive measures that can induce short-term impulses for local residents. This downscaling to a small section of realistic complexity complements the conclusions of other cooperative research projects in the context of urban climate adaptation (Sieber et al. 2022). Nevertheless, city-wide or region-wide strategic documents about GI planning should be carried out and cross-referenced in parallel to be in line with long-term mission statements.

Since the proposed GI interventions are not only framed by a small group of researchers and practical experts but also tailored to the specific conditions in Dortmund Marten, the produced measures of the workshop are not one-to-one transferable to other neighborhoods. Indeed, the resulted draft GI plan is highly context specific and dependent on the backgrounds of both scientists and practitioners. On the other hand, the described simulation methods allow replication in other urban settings with similar data availability. Considering the above, especially in Dortmund, remote sensing-based modeling input generation could be applied to the whole city pattern and employed to evaluate other greening interventions in terms of public health factors.

Limitations and risks of the transdisciplinary approach

The transdisciplinary process helped to combine unrelated knowledge with regard to a specific task by developing a strategic focus on reducing environmental burdens in a deprived neighborhood. Due to the heterogenous spectrum of the workshop participants and the mixed working groups, decisions on GI measure placement were not dominated by a certain stakeholder group, which cannot be taken for granted regarding other transdisciplinary approaches (Hansen et al. 2021). For society, the microclimate simulation results could be utilized as an empirically validated public resource, which provides informative environmental data for complex real-world problems.

However, as transdisciplinarity is a transformation-oriented process over time periods of several years to decades, the transferability of such approaches should be treated with caution. Furthermore, in the case of ZUKUR, the time schedule and willingness of urban planning practitioners set the pace for active collaboration. Hence, the uptake of transdisciplinary collaborations is a privilege to those who possess the personal and financial resources to conduct a mutual learning process over a longer time period. Funded research projects such as ZUKUR are always temporary and seek to achieve a specific goal, but real transdisciplinarity can only succeed if all participants also maintain a commitment to change after project funding. In the case of a typical research project funded over three years, there is always a risk that science and practice will merely enter into a ‘temporary relationship’, losing momentum and curiosity by the end of the project. Accordingly, the simulation results were generated after project funding and therefore not fed back with the public or representatives of the urban planning department, which is a pending limitation of this study.

It is worth noting that the draft GI plan was a legally nonbinding outcome of a cooperative research project with no real-life conflicts for the participating planning practitioners to fear, which is why the results are not comparable to traditional planning procedures. The reality is that the urban planning participants cannot represent the entire city administration and, thus, rather act as contact people than having the final political power to implement the GI ideas of the workshop. This can be a source of frustration for researchers who often expect a transfer of scientific results to the real world. In general, it is also important for scientists not to be instrumentalized by the political agenda of the city administration, which can clearly manipulate the co-research in a biased direction. Especially -but not only- for academics, fluctuations in the number of staff members should also be expected during the learning process, which requires a suitable transfer of information to every new project participant.

Conclusion

This case study combined reflections from urban planning practitioners and academia on joint collaboration with microclimatic simulations to evaluate the strengths and challenges of transdisciplinary research projects as well as the outdoor effects of GI measures on extreme heat and air pollution in the neighborhood of Dortmund Marten.

Overall, the derived GI measures exhibited a positive effect on outdoor heat stress and building surface temperature reduction but were highly place-dependent with few synergistic effects. As a trade-off, new tree patterns in a given street canyon could increase the obstacle effect, which in turn could lead to an increase in PM_{10} and $PM_{2.5}$ concentrations. Indeed, it is recommended to plant new roadside trees at both ends of the street canyon to maintain ventilation while still decreasing thermal heat stress. After defining *what* must be accomplished and *where* this should occur, the question arises as to which measure should be implemented by *whom* and *when*. The answer lies on the institutional side, while the validated simulation output comprises an informative resource for society and urban planners prior to GI installations at the microscale.

Based on the online survey, it turned out that certain challenges remain in knowledge integration and learning effects between science and planning practice. Furthermore, the article showed the relevance of self-reflection and joint consensus building during the concept development process, while flexibility to adapt to new viewpoints should remain high throughout the project. The focus on a small geographic area allowed the precise development of GI measures, which is recommended when working cooperatively on complex real-world problems and uncertainties.

In conclusion, the multifunctional character of GI alone cannot serve as a policy panacea for heat mitigation or air pollution reduction in urban areas. Nevertheless, the outcomes of the presented research project have demonstrated that GI can be directed as a driver for transdisciplinary co-production processes. However, the integration of these cooperative procedures in administrative and academic structures still requires great effort in communication on both sides. For the larger vision of urban resilience, new urban planning projects must focus even more proactively on a balanced mix of sustainable building materials, nature-based solutions, and experimental knowledge generation between scientists, urban planners, and the public.

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Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The author has no conflicts of interest to declare that are relevant to the content of this article.

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