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Research Article

Ecosystem-based adaptation to climate change through residential urban green structures: co-benefits to thermal comfort, biodiversity, carbon storage and social interaction

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Abstract

Climate change adaptation is essential to mitigate risks, such as extreme weather events triggered by global warming and amplified in dense urban environments. Ecosystem-based adaptation measures, such as urban greening, are promoted in cities because of their flexibility and their positive side effects, such as human health benefits, ecological effects, climate mitigation and a range of social benefits. While individual co-benefits of greening measures are well studied, often in public green spaces, few studies quantify co-benefits comprehensively, leaving social benefits particularly understudied. In this study, we perform biophysical and socio-cultural assessments of co-benefits provided by semi-public, residential greening in four courtyards with varying green structures. We quantify effects on thermal comfort, biodiversity, carbon storage and social interaction. We further assess the importance of these co-benefits to people in the neighbourhood. Subsequently, we weight the results from the biophysical assessments with the socio-cultural values to evaluate how even small differences in green structures result in differences in the provision of co-benefits. Results show that, despite relatively small differences in green structures, the residential courtyards with a higher green volume clearly generate more co-benefits than the residential yards with less green, particularly for thermal comfort. Despite differences in the valuation of co-benefits in the neighbourhood, socio-cultural weights did not change the outcome of the comparative assessment. Our results highlight that a deliberate management strategy, possibly on neighbourhood-scale, could enhance co-benefits and contribute to a more sustainable urban development.

Keywords

courtyards, PET, biophysical assessment, socio-cultural valuation, climate adaptation

Introduction

Global warming and climate change will continue leading to increasing extreme weather events, such as heat waves, drought and flooding (IPCC 2014). With almost 75% of Europe's population living in cities (EUROSTAT 2016), urban areas are particularly vulnerable due to their agglomeration of people, economic activities and infrastructure systems (Revi et al. 2014). Poor urban design can amplify the impacts of climate change, i.e. the prevalence of built structures and the lack of green spaces lead to higher urban temperatures and the extent of impervious surfaces reduces natural drainage which can intensify flooding (Revi et al. 2014, EEA 2017). Adaptation is essential to mitigate those risks and contribute to a more resilient future.

Adaptation measures can be manifold. They can cover technical engineering ('hard') approaches and information, policy and capacity building ('soft') approaches, but, in the last decade, a third group, ecosystem-based ('green') approaches, has rapidly gained attention (Jones et al. 2012). Ecosystem-based approaches to climate change adaptation (EbA) are internationally acclaimed measures that use biodiversity and ecosystem services to adapt to the adverse effects of climate change and promote sustainable development (CBD 2009). Measures range from urban farming and gardening, to urban green spaces, green roofs and facades, urban forests, trees, rain gardens, retention basins, retention ponds and infiltration basins (McVittie et al. 2018). EbA measures are particularly endorsed in urban environments, because they can be applied at different scales from city-wide to small parcels, they are adaptable and can be combined with hard engineering and co-benefits, such as reduced heating or cooling bills, may encourage uptake (McVittie et al. 2018). The approach is further recognised for its capacity of social empowerment and benefits for marginalised, vulnerable communities (Woroniecki et al. 2019). In addition, EbA often provides temperature regulation benefits in- and outside of buildings by providing evapotranspiration, shadow/radiation cover and insulation, which, in comparison to other sectors, is a particular issue in dense urban systems (McVittie et al. 2018).

It is widely acknowledged that EbA measures provide additional benefits that make communities more climate-resilient and concurrently more sustainable, but certain aspects remain understudied. For instance, green spaces are most frequently studied within the context of urban EbA (Brink et al. 2016), with a strong focus on public green spaces.

Private and semi-public, residential yards make up a large share of urban green spaces (Texier et al. 2018, Haase et al. 2019, Texier et al. 2018), but their potential for climate EbA is rarely considered. Further, while benefits of EbA are widely recognised, few studies provide a comprehensive, evidence-based quantification of co-benefits (Munroe et al. 2012, McVittie et al. 2018, Ojea 2015, Ojea 2015,). Particularly, social benefits of EbA are understudied (Brink et al. 2016).The following sections will review particular benefits of urban greening.

One of the most studied benefits is thermal regulation. For instance, from public health research, much is known about the adverse effects that high temperatures have on the human body, such as heat exhaustion, heat cramps and heat stroke, which lead to increased mortality, especially in urban heat islands (Kovats and Hajat 2008, Parsons 2014). An increasingly large body of literature in the interdisciplinary sciences (i.e. landscape science, urban development) now studies the effects of urban design on heat stress and people's health (Jamei et al. 2016). Studies often either investigate on the city- or multi-city-level to gain an understanding of characteristics that have an effect on the city's microclimate, frequently using the widely available land surface temperature (e.g. Connors et al. 2013, Zhou et al. 2017) or focus on the effects of urban design and green infrastructure in more detail within one or few case studies within a city (e.g.Zölch et al. 2016). Studies in the latter category often build on knowledge from the field of biometeorology and use micro-climatic modelling (e.g.Zölch et al. 2019) or measurements of meteorological parameters or indices to assess the impact of heat stress for different urban environments on thermal comfort (e.g. Klemm et al. 2015).

Urban biodiversity, an important sector to profit from EbA measures in cities, has long been studied in the field of ecology. First records of botanical urban studies date back as far as the 17th century focusing on single biotopes (Sukopp 2008), but socio-ecological investigations of how urbanisation affects biodiversity has become a central topic in research during the past decades (Wu 2014). Urban biodiversity can be assessed by a large variety of different metrics, such as the frequently used species richness or structural elements, but also by indices for evenness, abundance, distribution or variation (Farinha-Marques et al. 2011). Approaches that incorporate a mix of these methods into an overall biodiversity score enable an easier understanding for non-ecologists and are thus particularly relevant for management and decision-making (Farinha-Marques et al. 2011).

Another co-benefit of EbA, mostly studied in forest science, but also relevant in urban areas as municipalities set their climate migitation targets, is carbon storage in above-ground biomass that is considered a major contributor to the mitigation of global warming and adaptation to climate change (Vashum 2012). Here, methods estimate carbon stock, based on tree biomass estimations, often based on allometric equations. Allometric equations for biomass estimation build on the physical relationships between various parameters of trees, such as the diameter at breast height, height of the tree and tree species. Though typically designed to assess forest carbon, allometric equations are being employed in the urban context, mostly to estimate above-ground carbon stored in trees at city-level (e.g. Hutyra et al. 2011, Strohbach and Haase 2012) or to investigate the effect of environmental parameters on specific tree species to establish more accurate metrics for the urban context (Yoon et al. 2013Dahle et al. 2014, Yoon et al. 2013).

With EbAs in urban areas, also social benefits can be achieved. Multiple social benefits of urban green spaces (Hutyra et al. 2011) are studied in disciplines like psychology, medicine and the social sciences, such as the effects on human health, the provision of recreational opportunities, psychological well-being, aesthetic enjoyment and social cohesion. While the effect of green spaces as a facilitator for social interaction that may stimulate social cohesion is widely acknowledged (e.g. Peters et al. 2010, Kabisch et al. 2015, Braubach et al. 2017, Kabisch et al. 2015, Peters et al. 2010), the effects are studied less coherently and less frequently in detail. The majority of studies that investigate the social effects of urban parks frequently employ participatory approaches, such as interviews, focus groups or questionnaires with local residents (Konijnendijk et al. 2013, Kabisch et al. 2015, Konijnendijk et al. 2013).

Further, a more socio-ecological research explores people´s values for specific benefits. Though the general importance of urban greening is recognised in research and policy, local assessments have shown that values differ considerably in different geographical settings (Haida et al. 2016, Schmidt et al. 2016). Local assessments of socio-cultural value can indicate attitudes, perceptions and preferences towards ecosystem services and further benefits provided by urban greening (e.g. Özgüner 2011, Zhang et al. 2020). Implementing knowledge on socio-cultural values enables the targeting of land management or, in our case, urban development, by identifying priorities in the area (Bryan et al. 2010). Socio-cultural values of benefits provided by urban greening thus indicate which benefits are appreciated by people at a particular setting.

In this study, we examine differences in benefits of urban green spaces generated specifically in residential areas to highlight the potential of EbA by qualifying these green spaces. In an effort to combine knowledge from health research, ecology, socio-ecological research and to show the potential to implement EbAs in residential green spaces, we set out to quantify co-benefits of residential green infrastructure in four courtyards in the city of Potsdam, Germany. These courtyards feature a similar built structure, but slightly varying green structures. While the effects of urban greening have been previously studied mostly individually as illustrated above, we study a comprehensive set of co-benefits and focus on the small differences within a comparable set of study areas, i.e. green residential courtyards. Research questions are:

1. How do gradual differences between residential greenspaces impact the provision of co-benefits to the neighbourhood?
2. How important are co-benefits to residents?
3. How do gradual differences between courtyards make a difference in meeting local demands?

To ultimately identify differences and compare in the provision of co-benefits and how courtyards meet local demands for ecosystem service, based on the preferences of residents, we use a multi-method approach. We quantify greenness of the courtyards as their primary characteristics. Then, we conduct biophysical assessments for four co-benefits in each courtyard. Specifically, we:

1. quantify the effect of urban green structures on thermal comfort, an important indicator for thermal comfort,
2. assess structural biodiversity and species richness in the four courtyards,
3. quantify differences in carbon stocks and
4. estimate the potential for social interaction facilitated by design and structure of the courtyards.

We investigate how important these benefits are to residents in the neighbourhood through survey-based preference assessment. Ultimately, we compare how courtyards meet social demands by weighting the outcomes of the biophysical assessment with the socio-cultural values of the co-benefits.

Study area: Four courtyards in Potsdam-Drewitz, Germany

Located in the south-east of the north-eastern German city of Potsdam, Potsdam-Drewitz, built in 1988, contains one of the last housing estates in the former GDR. Five-storeyed large-panel buildings, owned by multiple residential housing companies, characterise the neighbourhood and host a total of 7,600 inhabitants in approx. 3800 apartments (LHP 2021). Compared to the city's mean, residents are slightly younger (i.e. 41.2 years old), the unemployment rate is roughly 3.6% higher (i.e. 8.5%) and the portion of benefit recipients is 2.8% higher (i.e. 20.2%) (LHP 2021).

The Municipality of Potsdam aims to enhance green structures in Drewitz. Key measures, partly derived from the garden city movement, include converting a four-lane street with parking into a two-lane street with less parking, developing an urban park on the spare area and developing courtyards (Masterplan Drewitz).

To quantify co-benefits of urban green infrastructure, we compare four courtyards with similar built structures, but varying green structures (Fig. 1). While the selected courtyards slightly differ in size (2609 – 3158 m²), the buildings in courtyards 1 and 3, as well as 2 and 4, are similarly orientated with the opening of the building being located either at the north-eastern (courtyards 1 and 3) or north-western corner (courtyards 2 and 4). The courtyards all, yet to a varying extent, predominantly consist of unsealed surfaces, such as soil, grass, shrubs, plant beds and trees and are managed by different housing associations.

Methods, data resources and analysis

We use a multi-method approach to quantify co-benefits of urban green infrastructure in the four courtyards (Fig. 2). First, we quantify tree crown volume to classify courtyards according to their level of greenness. To address research question 1, we then conduct biophysical assessments for the benefits "thermal comfort", "biodiversity", "carbon storage" and "social interaction", using on-site measurements and satellite image-based mapping.

To address research question 2, we further conduct an interview-based survey in the neighbourhood to better understand how important residents perceive different ecosystems services. Finally, we calculate rank sums and further weight them to understand how the courtyards meet the local demand for ecosystems services.

Figure 1.

Location of courtyards and meteo stations; white rectangles indicate the study area (courtyards 1-4), white crosses indicate meteo stations. Size of courtyards 1: 2609 m², 2: 3158 m², 3: 3114 m², 4: 3141 m²; data: GeoBasis-DE/LGB.

Classification of courtyards by tree crown volume

Before analysing co-benefits, we classified courtyards according to their tree crown volume. Tree cover has demonstrably been a predictor for various benefits (Palliwoda et al. 2020). Due to their positive mircoclimatic, ecological and social effects (Sandström et al. 2006), we use tree crown volume as a proxy for the "greenness" in the courtyards. We collected data on extant trees during an on-site habitat mapping in July 2020 using TruPulse 360 laser technology for measurements. We used its Height Routine for crown height and the Missing Line Routine for crown diameter measurements and recorded crown shape by visual approximation. We used the allometric formula of Troxel et al. to estimate crown volume with varying constants to account for the crown shape (Troxel et al. 2013):

CROWN VOLUME = (CROWN DIAMETER)² x (CROWN HEIGHT) x (SHAPE CONSTANT)

The quantification of tree crown volumes serves the purpose of characterising the greenness in the four courtyards, but it does not contribute to the actual assessment of co-benefits.

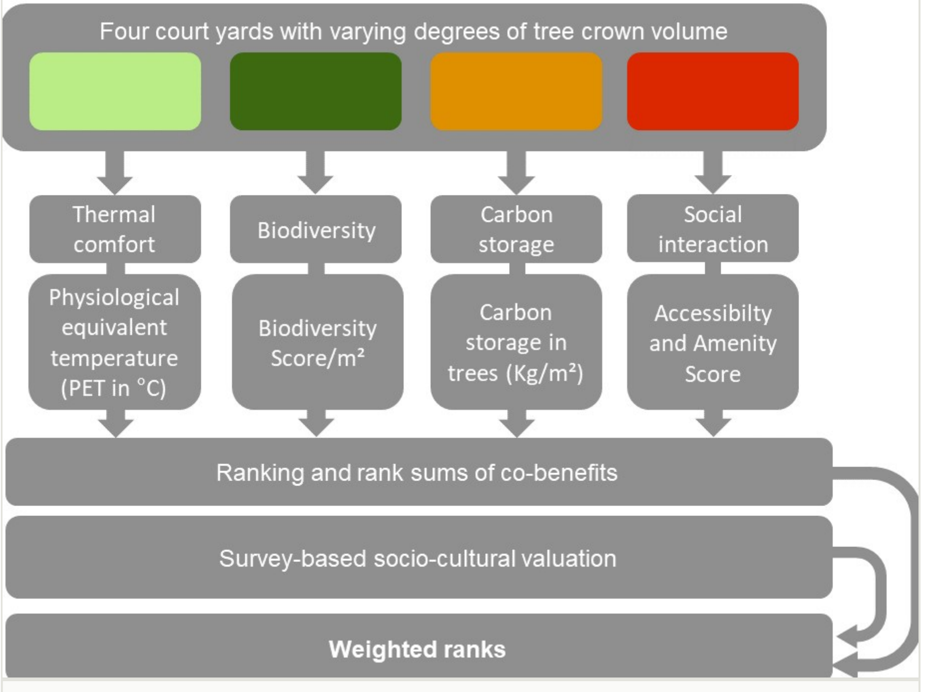

Figure 2.

Multi-method study design.

Thermal comfort

To quantify the impact of green structures on human health, we use a well-established human-biometeorological index that quantifies thermal comfort, the physiological equivalent temperature (PET). PET assesses thermal comfort in a temperature dimension index measured in degrees Celsius (°C), enabling its interpretation by non-meteorologists (e.g. urban planners). This is an advocated approach for the physiologically relevant evaluation of the thermal component of urban climate in Germany (VDI 1999). PET transfers the actual bioclimate "to an equivalent fictive indoor environment in which the same thermal stress can be expected" (Mayer and Höppe 1987). The index indicates the air temperature at which, in an indoor setting, the human energy budget is sustained by the same mean skin temperature and sweat rate as calculated for the actual outdoor conditions (Mayer and Höppe 1987). Heat stress can be characterised according to grades of physiological stress resulting from experienced PET (Table 1).

Table 1.

Ranges of physiological equivalent temperature (PET) for different grades of thermal perception, adapted from Matzarakis et al. (1999).

PET (°C)	**Thermal perception**	**Grade of physiological stress**
- 18	Very cold to slightly cool	Extreme to slight cold stress
> 18 - 23	Comfortable	No thermal stress
> 23 - 29	Slightly warm	Slight heat stress
> 29 - 35	Warm	Moderate heat stress
> 35 - 41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

Table 2.

Items for the assessment of social interaction opportunities.

Item	**Unit**
Accessibility	
Path length per area	*m/m²*
Amenities	
Benches	*Count*
Clothes lines	*Count*
Bike racks	*Count*
Private/community garden	*Area*
Playground	*Area*
Safe and clean environment	
Lanterns	*Count*
Waste bins	*Count*
Accessibility and amenity score	**Total rank sums**

Table 3.

Benefits subject to valuation

Item	Benefits
Human health	Urban green spaces increase physical well-being (human health) (e.g. they provide fresh air, shadow, they reduce air temperatures, they provide space for physical exercise)
Climate mitigation	Urban green spaces increase climate protection (e.g. by storing carbon in trees)
Biodiversity	Urban green spaces increase biodiversity (e.g. by providing habitats for plants and animals)
Social interaction	Urban green spaces provide an area to enhance social cohesion (e.g. as a venue for social gatherings, for collective gardening)

Table 4.

Tree crown volume in the four courtyards.

Courtyard	1	2	3	4
Area (m²)	2609	3158	3114	3141
Tree crown volume (m³)	4003	7272	1646	1425
Tree crown volume (m³/m²)	**1.53**	**2.3**	**0.53**	**0.45**

Figure 3.

Location of meteorological stations in the courtyards

We measured air temperature (Ta), relative humidity (rH), horizontal wind velocity (v) and global radiation (G) as microclimatic parameters at four stationary meteo stations in the four courtyards on 97 days from 12 June to 17 September 2020 (Fig. 3). We used Onset's HOBO USB Micro Station data logger with digital sensors (i.e. S-THB-M002, S-WSB-M003, S-LIB-M003), including solar radiation shields for Ta and rH sensors (i.e. RS3-B) for the respective parameters, logging measurements every 10 minutes. The meteo stations were sited, based on recommendations of the World Meteorological Organisation to obtain measurements that are "approximately representative of the locality" (Oke 2006). Sitings did not intend to create similar conditions within the courtyards (e.g. similar distance from trees/shading), but rather represent the courtyard's individual interior. On-site, experts of the German National Meteorological Service advised us regarding the siting and assisted with the correct installation of the meteo stations. Stations were positioned in agreement with the different housing associations in areas where they least interfered with the public use of the courtyard, yet all surrounded by buildings to avoid additional drafts caused by the open passages (see Fig. 1). They were mounted at approx. 2m height at pre-existing poles for clothes lines and, in court yard 1, installed solitarily outside the footpath.

To obtain an overview of microclimatic conditions in the four courtyards, we calculated mean values of Ta, rH, v and G over all measured values between 9am and 9pm, the assumed daytime at which the courtyards are mostly used by inhabitants. We used these calculated means to model the PET using the radiation and human-bioclimate Rayman model (Matzarakis et al. 2007, Matzarakis et al. 2010) for each courtyard. To test if microclimatic parameters differed significantly between the courtyards, we used the non-parametric Kruskal-Wallis rank sum test (Kruskal and Wallis 1952) and post-hoc Dunn's test to reveal which courtyards differed significantly by pairwise comparisons (Dunn 1964).

Biodiversity

We based the biodiversity assessment on data we have collected in July 2020 during an on-site habitat mapping in the four study areas. For the biodiversity assessment, we used an approach developed by Tzoulas and James (2010) for urban systems, based on species richness and structural diversity. First, we detected different habitats, based on aerial photos of the courtyards. We measured land cover of different vegetation structures and collected additional data on the diversity of vascular plants (i.e. species) within these habitats. While Tzoulas and James (2010) advise to use their approach for sites about 1 ha or larger and conduct the biodiversity assessment for at least 10% of the site area, we used their approach for the entire area of the four courtyards (approx. 0.3 ha per study site, total of 1.2 ha).

To assess urban biodiversity, we combined structural elements and diversity of vascular plants into an overall biodiversity score (Tzoulas and James 2010, Table 2) The biodiversity score is based on the diversity of vegetation structures (i.e. for every vegetation structure that was mapped within one habitat, we allocate one point), rare occurrence of built surfaces (i.e. > 25% of built structures within a habitat led to a progressive deduction of points, < 25% led to a progressive gain) and the diversity of vascular plants (i.e. one point extra for every six different vascular plant genera present). Land cover was additionally recorded, based on a checklist in combination with the Domin cover scale to better compare sites (Tzoulas and James 2010, Table 1). Domin values indicate the proportions of land cover of different vegetation structures for each habitat and were visually estimated.

To better fit our study design, we slightly adapted Tzoulas' and James' approach. To utlise the biodiversity assessment in our small-scale study areas, we created habitat types for better fit, avoiding a general classification (i.e. residential area with/without gardens). We identified habitat types as lawn, flowerbed, path, private allotment and playground. For each habitat, we identified habitat type, the Domin value of cover for each vegetation structure (see Tzoulas and James 2010, Table 1), the number of different vascular plant genera and calculated the sums of the biodiversity scores. To account for the different habitat sizes, we weighted biodiversity scores by multiplying the habitat fraction by the biodiversity score and dividing by the total area of the courtyard. We divided the weighted biodiversity score by the total area of each courtyard in order to compare courtyards despite their different sizes. We assessed biodiversity scores for a total of 112 habitats in the four courtyards.

Carbon storage

To estimate tree carbon stocks per courtyard, we used above-ground biomass as a proxy. We, therefore, applied allometric equations specified by mapped tree parameters. We mapped tree species and diameter at breast height (dbh) for all trees located in the four courtyards in July 2020. Then, we employed allometric equations for above-ground biomass taking into account the physiological relationships amongst tree volume, dbh and wood density. The allometric equations are based on large-scale inventory measurements in North America that specifiy forest carbon budgets for different tree species (Chojnacky et al. 2014), but have been found suitable in other geographical contexts (e.g. Strohbach and Haase 2012). Following a common procedure to account for uncertainties concerning tree growth in an urban environment, we reduced above-ground biomass by 20% (Strohbach and Haase 2012). As carbon content is reportedly about 50% of the dry weight biomass of trees (Jo 2002, Strohbach and Haase 2012), we converted the above-ground biomass to a carbon estimate by multiplying by 0.5.

Following Chojnacky et al. (2014), the allometric formula is:

$$\ln(\text{biomass}) = \beta 0 + \beta 1 \ln(\text{dbh})$$

where $\beta 0$ and $\beta 1$= coefficients specific to tree taxa, dbh= diameter at breast height at 130cm in cm. $\beta 0$ and $\beta 1$ were retrieved from Chojnacky et al. (2014), Table 5), specific gravity was retrieved from Miles and Smith (Miles and Smith 2009), dbh is based on our own measurements. For one tree species, the formula required diameter measurements at root collar (drc).

Table 5.

Differences of microclimatic parameters and PET between courtyards, based on daily means and Kruskal-Wallis-Test results.

Microclimatic parameters	p-Value	Chi²	Courtyard 1 2 3 4			
Daily mean air temperature (Ta)	0.63	1.7				
Max daily mean			32.8	32.3	32.9	33.5
Min daily mean			15.9	15.8	16.1	16.1
Mean			22.9	22.6	22.9	23.2
Daily mean relative humidity (rh)	0.55	2.1				
Maximum			92.0	92.3	89.8	90.8
Minimum			30.5	31.6	31.2	29.7
Mean			55.0	56.2	55.1	53.6
Daily mean wind velocity (v)	$< 2.2e^{-16}$	153.2				
Max daily mean			1.2	0.7	1.4	1.8
Min daily mean			0.008	0.002	0.007	0.1
Mean			0.2	0.1	0.4	0.7
Daily mean global radiation (G)	$< 2.2e^{-16}$	234.1				
Max daily mean			119.0	248.8	471.0	544.6
Min daily mean			23.0	44.7	62.1	63.9
Mean			80.3	135.8	230.5	301.3
Physiological Equivalent Temperature (PET)	$1.1e^{-12}$	58.7				
Max daily mean			**34.7**	**36.8**	**42.3**	**45.5**
Min daily mean			**13.3**	**15.3**	**16**	**14.3**
Mean			**23.2**	**26.2**	**28.7**	**29.4**

If we encountered multi-stemmed trees (≤6 stems), we measured each stem individually at breast height and calculated their quadratic sum, following a common procedure (Vaz Monteiro et al. 2016, Magarik et al. 2020, Vaz Monteiro et al. 2016). If multi-stems exceeded six stems, we measured dbh at 30 cm above ground, in accordance with Magarik et al. (2020). Dead trees were excluded from our analysis.

Social interaction

Structural and natural assets facilitate social interaction within urban green spaces. Previous studies have shown that green space design affects the level of social interaction (Rasidi et al. 2012,Krellenberg et al. 2014, Rasidi et al. 2012). These studies show that accessibility, as well as existing amenities, such as playgrounds and benches, facilitate social contact. To assess the opportunities for social interaction arising from residential urban green, we review accessibility and green space quality, based on availablity and quality of items in the four courtyards (Table 2). We count path length as an indicator for accessibility and frequency (benches, clothes lines, bike racks, lanterns, waste bins) or respectively area (private/community garden, playground), all relative to area to assess amenities per area in each courtyard. As the quality of the items was the same in all courtyards (i.e. intact), we consider these amenities to equally enable social contact. Lanterns and waste bins are included as they are thought to contribute to a clean and safe environment, as maintenance of infrastructure and facilities is found to encourage public use (Wen et al. 2018). We subsequently rank courtyards for each item in ascending order, equal values receiving equal scores. The sum of all items builds the final accessibility and amenity score.

Socio-cultural assessment

To assess the use and perception of urban green spaces, specifically the importance of individual co-benefits to residents in the neighbourhood, we conducted an on-site, tablet-based face-to-face survey during four days in August 2020. We selected respondents randomly and approached them on a green crossing in the urban park in the centre of the neighbourhood (n=100). Additionally, an online survey was available in August (n= 4), whose link was distributed on-site (for non-responders) and across two community e-mailing lists (Suppl. material 1, Question 7). The respondents were asked to indicate how important various benefits (Table 3) provided by urban green spaces (not limited to residential green spaces) are for them personally, by allocating a total of 100 points across these benefits (Schmidt et al. 2017; Suppl. material 1, Question 7). We used the mean of allocated points across all respondents as a percentage to weight the performance of individual co-benefits in each court yard.

Comparative assessment of co-benefits

To evaluate the complex information from the previous assessments, we ranked courtyards for every co-benefit and weight them subsequently according to socio-cultural preferences. For the ranking, we attributed points (maximum 4 points) in ascending order, starting with the most favourable outcome, i.e. lowest physiological equivalent temperature, highest biodiversity score, highest total carbon storage, highest potential for social interaction. Hence, the most favourable assessment results will generate the highest number of points. Equal values will receive equal scores. We weight these ranks, based on the socio-cultural preferences of residents for these co-benefits derived in the survey. All data analysis were performed with the software R version 3.5.2.

Results

Classification of courtyards by tree crown volume

The estimation of tree crown volume showed that our sample compares two courtyards with more (CY 1 = 1.53 m^3/m^2, CY 2 = 2.3 m^3/m^2) and two courtyards with less tree crown volume per area (CY 3 = 0.53 m^3/m^2, CY 4 = 0.45 m^3/m^2; Table 4).

Courtyard 2 by far has the highest tree crown volume, which can likely be explained with its high number of trees and their comparably high mean crown height (Suppl. material 2). The crown volume in courtyard 1 is second highest and higher than in court yard 3 despite accommodating fewer trees, as trees are, on average, higher (10.2 m height compared to 7.7 m height).

From here on, we refer to courtyards 1 and 2 to those study areas with "higher tree crown volume" and to courtyards 3 and 4 to study areas with "less tree crown volume". We colour code our subsequent graphs according to their ranked tree crown volume with light green (courtyard 1), dark green (courtyard 2), orange (courtyard 3) and red (courtyard 4).

Thermal comfort

Results from the microclimatic measurements in the four courtyards (CY) with varying tree crown volume on 97 days reveal first differences (Table 5, Suppl. material 3). Mean daily (9am – 9pm) air temperature and relative humidity vary considerably between courtyards, for mean daily air temperature between 22.6°C and 23.2°C and for relative humidity between 56.2 and 53.6%, but without statistical significance. Courtyard 2 with the highest crown volume is the one with the overall lowest mean air temperature (CY 1: 22.6°C) and highest relative humidity (CY 2: 56.2%). In contrast, we measured significant differences in wind velocity and global radiation between courtyards. Mean daily wind velocity and mean daily global radiation are much higher in courtyards with less tree crown volume (wind: CY 4: 0.7 m/s, CY 3: 0.4; global radiation: CY 4: 301.3 W/m², CY 3: 230.5 W/m²) than in those with higher crown volume (wind: CY 2: 0.1, CY 1: 0.2, global radiation: CY 1: 80.3 W/m², CY 2: 135.8 W/m²).

We used the microclimatic measurements to feed into the modelling of the PET (Fig. 4). Here, we observe significant differences amongst the four courtyards, where all but courtyards 3 and 4 vary significantly. Highest differences in daily mean temperature were found on 8 August, with the maximum value reached in courtyard 4 with the lowest tree crown volume at 45°C (“extreme heat stress”, see Table 1) and minimum value in courtyard 1 with the second highest tree crown volume, at 34.7°C (“moderate heat stress”).

Biodiversity

The courtyards cover five habitat types that vary with regard to their internal vegetation structures and genera (Suppl. materials 4, 5). Regarding habitat types, courtyard 3 has a slightly smaller fraction of lawn and higher fraction of playground and private gardens compared to the rest. Path area is very similar amongst courtyards, approximately 20% and fractions of flower beds vary to a smaller degree (4-11%).

Domin values for vegetation structures vary between courtyards. Despite not accommodating the highest amount of trees, courtyard 3, on average, has the highest domin values for low and high trees, meaning it either has most habitats that are dominated by low and high trees or domination values are higher than in the other study areas.

The biodiversity assessment considers structural and genera diversity for each habitat individually (Fig. 5). Courtyard 4 shows the lowest score of the weighted biodiversity index per m², but scores generally show little differences (Table 6). Maximum overall biodiversity scores in courtyards 2 and 3 exceed maximum scores in courtyards 2 and 4 by 3 and 2 points, respectively.

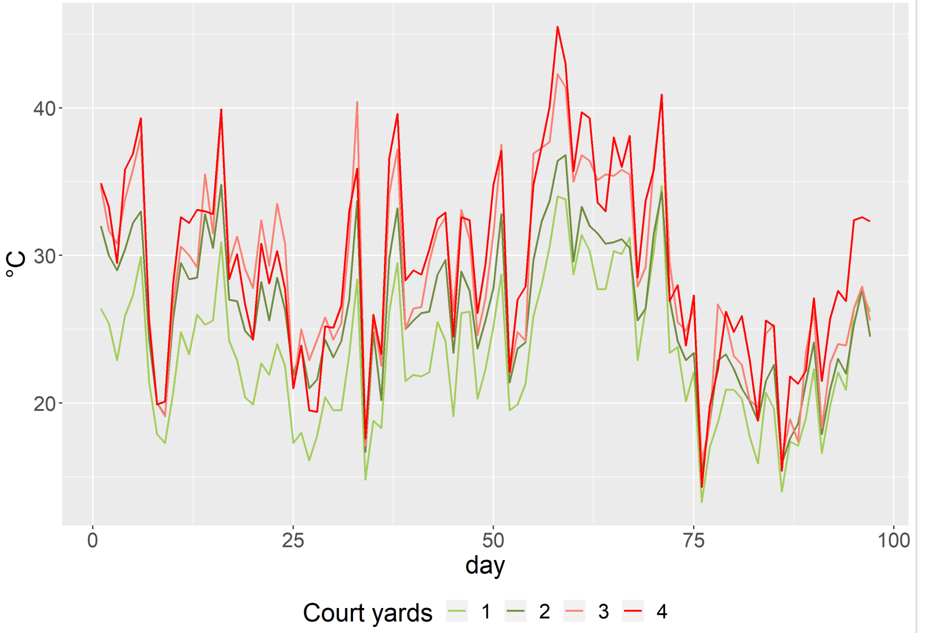

Figure 4.

PET values in °C, based on microclimatic measurements between 9am and 9pm in the four courtyards.

Table 6.

Results of biodiversity assessment, based on Tzoulas and James (2010).

Courtyard		1	2	3	4
Total area in m²		2609	3158	3114	3141
Number of habitats		24	31	29	28
Area fraction per habitat type	lawn	0.61	0.6	0.5	0.7
	flowerbed	0.11	0.1	0.04	0.05
	path	0.17	0.2	0.2	0.2
	playground	0	0.04	0.07	0.02
	private allotments	0.1	0.04	0.16	0
Vegetation structures		Mean Domin values			
High trees		0.5	0.7	1.1	0.7

Low trees	1.2	0.7	1.7	0.5
Bushes	6.6	3.7	3.2	1.9
High grass forbs	2.3	2.8	2.8	1
Low grass forbs	3.9	4	4.7	1.6
Ground flora	0.1	2	1.5	1.7
Built	2.1	1.8	2.0	2.2
Genera diversity	Number of vascular plants genera			
Min	0	0	0	0
Max	9	9	11	7
Mean	3.1	3.1	3.1	2.1
Biodiversity score				
Min	-4	-4	-4	-4
Max	10	13	13	11
Mean	6.79	6.84	7.3	5.2
Mean weighted biodiversity index (Habitat size*biodiv score/Total area)	6.36	6.92	6.29	5.72
Weighted biodiversity index per 100 m²	**0.24**	**0.22**	**0.20**	**0.18**

Figure 5.

Biotopes and biodiversity scores, based on habitat mapping and biodiversity assessment.

Carbon storage

The assessment of above-ground biomass and respective carbon storage in between courtyards shows more foreseeable results. Most trees are located in courtyards 2 and 3, but trees, on average, are more than 5m higher in courtyard 2 (Fig. 6, Table 7). Taking into account the varying area of the courtyards, courtyard 2 with highest crown volumes provides the largest capacity to store carbon. Courtyards 1 and 4 have fewer trees and mostly smaller trees. Most carbon is stored in larger trees (Fig. 6). The comparatively high value of above-ground biomass in courtyard 4 is due to an individual locust tree (Suppl. material 6). This explains the high average carbon stock per tree in courtyard 4.

Table 7.

Results of the assessment of carbon stocks, based on allometric equations after Chojnacky et al. (2014).

Courtyard	1	2	3	4
Number of trees	19	27	31	12
Mean stem diameter	19.3	27.8	17.6	24.6
Mean tree height in m	10.2	12.8	7.5	9.5
Total carbon stock in kg	1518	5426	2188	1571
Total carbon stock per tree in kg	79.9	201	70.6	130.9
Carbon in Mg ha^{-1}	**5.8**	**17.2**	**7.0**	**5.0**

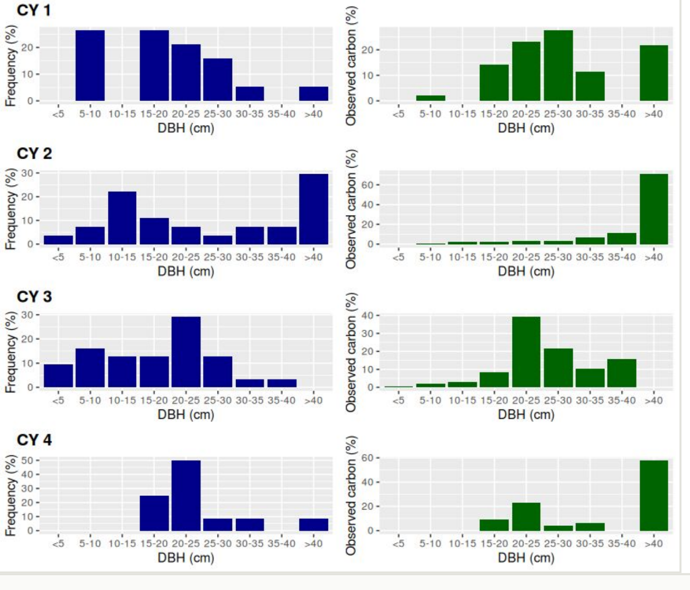

Figure 6.

Frequency and observed carbon of trees in the courtyards.

Social interaction

The total opportunities for social interactions enabled by accessibility of amenities, i.e. the accessibility and amenities score, in each courtyard are rather similar (Table 8). Accessibility varies between courtsyards with courtyard 1 measuring the longest paths, also the provison of amenities is different in all four courtyards (Fig. 7). Private and community gardens only exist in three of the four courtyards. Playground size varies between courtyards, with one courtyard not providing one at all. Urban furniture, such as benches, waste bins, clothes lines, bike racks and lanterns are distributed rather unevenly (Suppl. material 7).

Table 8.

Results from the accessibility and amenity assessment, based on each item’s rank score (data see Annex 6).

Courtyard	1	2	3	4
Accessibility				
path length	4	3	2	1
Amenities				
garden	3	2	4	1
playground	1	3	4	2
benches	4	3	1	2
clothes lines	1	2	4	3
bike racks	1	3	1	2
Safe and clean environment				
waste bins	3	2	1	2
lanterns	3	2	1	2
Total Accessibility and Amenity Score	**20**	**20**	**18**	**15**

Preferences of residents from socio-cultural valuation

Socio-cultural valuation of the four co-benefits reveals that the capacity to improve human health and for carbon storage provided by urban green spaces are more important to the residents of the neighbourhood than their capacity to increase biodiversity or provide opportunities for social interaction. While carbon storage on average was assigned almost 29 out of the available 100 points (SD: 18), closely followed by benefits for human health (28 points, SD: 15), biodiversity (23 points, SD: 13) and social interaction (20 points, SD: 15) were awarded considerably less. While all of the listed benefits were being perceived to be of value, human health and carbon storage were attributed point scores that were above average. More people assigned points of 10 and lower for social interaction than for any of the other benefits (Fig. 8).

Comparative assessment of co-benefits

Similar to the biophysical assessments, the rank sums indicate that the courtyards with more tree crown volume clearly generate more co-benefits than the ones with less (Table 9). It is courtyard 1 that ranks first in three out of four benefits, although tree crown volume is higher in courtyard 2 (2.3 m³/m² compared to 1.53 m³/m² in courtyard 1). Tree crown volume in courtyards 3 and 4 are much lower with 0.53 and 0.45 m³/m², respectively and both feature large areas of grassland. Courtyard 4 performs lowest in all benefits.

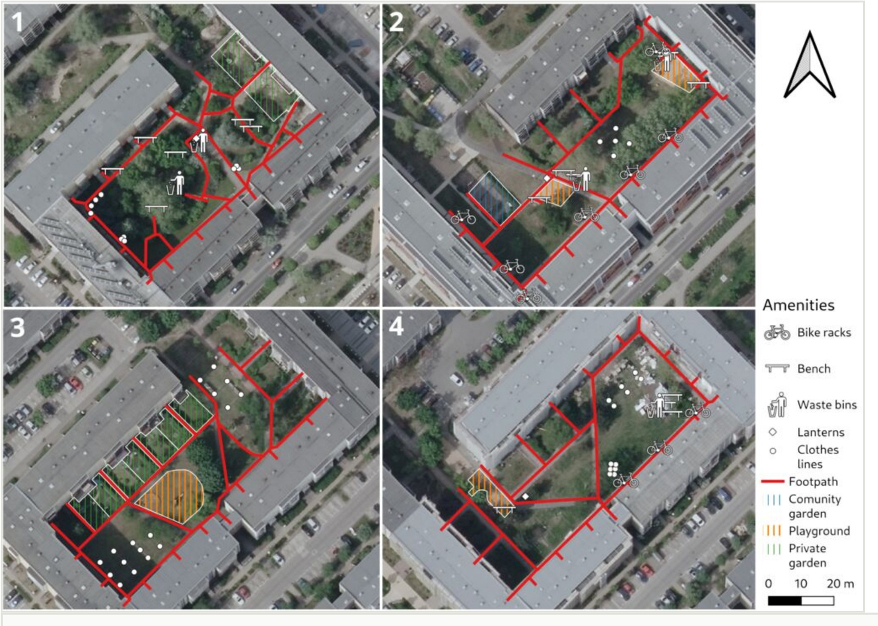

Figure 7.

Accessibility and amenities in the fourcourtyards.

Table 9.

Results of comparative assessment of co-benefits (higher rank scores indicate more favourable outcome of the assessment).

Courtyard	1	2	3	4	
	Biophysical assessment Rank scores				Socio-cultural weight
Human health	4	3	2	1	0.28
Biodiversity	4	3	2	1	0.23
Carbon storage	2	4	3	1	0.29
Social interaction	3	3	2	1	0.20
Total ranks sums	**13**	**13**	**9**	**4**	
Weighted score	**3.2**	**3.3**	**2.3**	**1.0**	

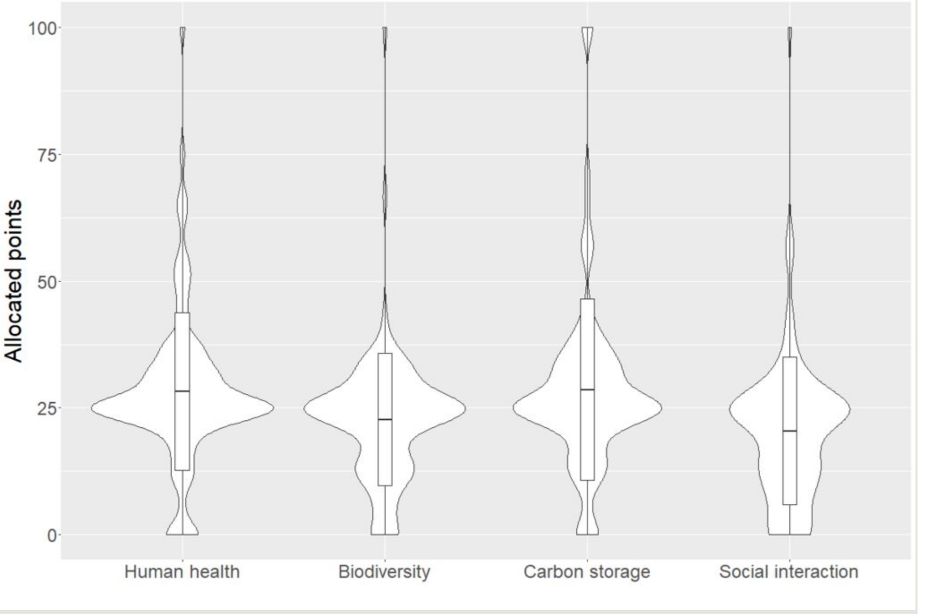

Figure 8.

Mean standard deviation and distribution of assigned weights per benefit

Weighting the rank sums with socio-cultural preferences only slightly changes the outcome of the ranking in the presented case study. With the highest socio-cultural value assigned to carbon storage and the lowest value to social interaction, the difference between courtyard 1 and 2 increases. At the same time, the difference between courtyard 2 and 3 increases with the weighting, mainly because social interaction has been assigned a lower weight than biodiversity.

Discussion

The capacity of ecosystem-based adaptation to provide additional benefits that increase the climate resilience, as well as sustainability of communities, has been widely acknowledged in literature (Wamsler et al. 2016, Raymond et al. 2017, Wamsler et al. 2016). Individual benefits have long been studied in various academic fields, for example, health effects of heat waves in public health research, biodiversity in urban green spaces in ecology, above-ground carbon storage in forest science and social benefits of urban green spaces in social sciences. Yet, to the best of our knowledge, there are no empirical studies that comprehensively evaluate the potential of EbA measures. This research contributed to fill this gap by focusing on urban green structures within residential courtyards and identifying differences in the provision of various co-benefits. Our work highlights how even small differences in green structures and tree crown volume result in differences in the provision of co-benefits and gives a coherent overview of the effects in multiple fields.

Thermal comfort

The positive effect of green structures on thermal comfort is increasingly studied in human biometeorology and urban development studies (Sodoudi et al. 2018, Hami et al. 2019, Sodoudi et al. 2018). Our results indicate that the courtyards with more tree crown volume have significantly lower physiological equivalent temperatures than the courtyards with less tree crown volume. This highlights the ability of trees to cool down the environment and increase thermal comfort, which is in line with similar findings in literature (Aram et al. 2019). Courtyard 1, which indicates the highest cooling effect, in our assessment only has the second highest tree crown volume. Our quantification of green structures is limited to tree crown volume and foregoes bushes and shrubs because we found those more difficult to assess due to the varying trimming measures in the courtyards. Courtyard 1, however, accommodates, in addition to trees, also a high number of shrubs (Table 6). These are likely to show beneficial effects on its cooling capacity and explain the higher cooling effect. Zhang (Zhang 2020) has demonstrated the cooling effect of shrubs that, like the cooling effect of trees, is enabled by the transpiration process, as well as by the shading effect of the leaves. However, their cooling capacity is highly dependent on maintenance measures (e.g. trimming) which is especially relevant in a highly managed environment like residential housing.

Our study highlights the cooling effect of residential green structures, whose presence may determine whether you feel very hot (“extreme heat stress”) or warm (“moderate heat stress”). Considering the ageing demographic and the likely increase of heat waves in the area (DWD 2019), this may lead to increasing health implications in the coming years. We show that density of urban green structures within residential courtyards is decisive to mitigate heat stress for residents.

Biodiversity

Next to microclimatic effects, urban green infrastructure has a vital role for the conservation of urban biodiversity. Past studies found that urban green spaces have the potential to conserve and restore native vegetation (Aronson et al. 2014) and threatened species (Ives et al. 2016). However, several studies point out challenges arising from the close interaction of urban nature and people, such as urban growth, management conflicts and trade-offs arising from social and ecological needs (Shwartz et al. 2014, Aronson et al. 2017).

Assessing biodiversity in a highly cultivated environment, such as residential courtyards, brings challenges, but also opportunities. In the case of Potsdam-Drewitz, courtyards are individually managed by the adjacent housing companies. Thus, our assessment arguably indicates to what extent structural diversity and plant diversity fit into design and management stipulations of the respective housing companies. The results show little differences in between courtyards as the basic construction (e.g. paths, lawn, flowerbeds) is similar and structural differences (e.g. regarding trees, shrubs) are balanced with species and habitat diversity. A joint management strategy, possibly on neighbourhood-scale, could support the conservation of biodiversity while also preserving social interests.

Goddard et al. (Goddard et al. 2010, Goddard et al. 2017), for instance, highlight the role of gardens and residential yards for species conservation and connectivity, but also their explicit value for wildlife experience in urban environments. Given the willingness and facility to cooperate in its strategic management, residential green structures offer an opportunity to coordinate interests to conserve biodiversity, as well as social concerns equally.

Carbon storage

Urban green spaces are of utmost importance for carbon storage as urban soils and trees have the capacity to act as a sink for atmospheric carbon dioxide. Urban trees play an important role in reducing carbon dioxide by fixing carbon during photosynthesis and subsequently storing it as biomass (Nowak et al. 2013, Richter et al. 2020). Though urban green spaces are a rather small contributor to the global carbon stock, municipalities are aware and interested in carbon sinks. In Potsdam, for instance, the municipal climate mitigation plan (LHP 2017) explicitly includes carbon sinks in green spaces to achieve climate neutrality by 2050.

In line with Stephenson et al. (2014), our results reveal that more carbon is stored in those residential yards with more and larger trees. While the value of urban trees for carbon storage is undisputed, studies highlight the effect of maintenance practices to impact tree growth and mortality (Nowak et al. 2002, Strohbach et al. 2012).

Residential yard management can increase tree health and longevity through maintenance activities that positively affect the facility for carbon storage. Nowak et al. (2002) identify several measures to maximise net benefits of urban forestry on atmospheric carbon dioxide, such as planting long-lived, low-maintenance and moderate to fast-growing species that grow large and are suitable to site conditions, employing maintenance activities to increase tree survival and longevity, minimising fossil fuel-based management activities, using wood from removed trees and planting trees in energy-conserving locations. Several of these measures can be implemented in residential yard management, such as the targeted planting of suitable species, applying low-maintenance activities (e.g. watering, tree-cut) and planting trees in energy-conserving locations around buildings. They may even generate synergies, for instance, if activities are low-maintenance, they can be carried out by residents, which may result in social bonding, as well as financial savings.

Social interaction

Finally, urban green spaces have the potential to serve as a venue for social interaction to foster social bonds. Studies detail the positive and negative impact of access and quality for social interaction. For instance, certain design characteristics, such as fields and open space, playgrounds, pathways, shelters and seats are found to facilitate social interaction (Rasidi et al. 2012). Aram et al. (2019) investigate the effect of green spaces on periodic markets in Iran and show that attendance and social interactions are significantly higher in those neighbourhoods with green spaces close-by the market sites. They highlight the importance of the aesthetic quality of green spaces and the sufficiency of urban furniture as factors for increased attendance and social interactions. Troy et al. (2016) associate residential yard quality with crime; they find that crime negatively correlates with yard trees, garden hoses/sprinklers and pervious areas. Positive correlations were found with litter and desiccated or uncut lawns. Residential yards have the potential to amplify the positive and reduce the negative social effects by effective management.

Our results reveal little, but perceivable differences in the total amount of access and amenities between residential yards; a more detailed analysis, including a systematic user observation and/or user interviews, could improve our knowledge in terms of actual social interaction. Despite accommodating a large percentage of gardens in courtyard 3, these are private. This means occupants are likely to be more enticed to spend time outside which may lead to encountering neighbours, but, on the other hand, may also be motivated by connecting with nature or retreat or relaxation purposes, which would not necessarily lead to more interaction with others (Dunnett and Qasim 2000, Gross and Lane 2007). The majority of studies on social cohesion employ participatory approaches, such as interviews, focus groups or questionnaires with local residents to investigate the social effects of urban parks (Konijnendijk et al. 2013, Kabisch et al. 2015). Though our analysis provides a reference point for the potential of social interaction, it can clearly be expanded by interviews with residents and observations of use and interaction to reveal the actual effects of residential green structures and amenities for social cohesion.

Social weighting and assessment of co-benefits

One of the great advantages of EbA measures is the generally high agreement that qualified residential green structures are an asset and enhance quality of life in the neighbourhood. The socio-cultural valuation is important to understand better the preferences and potential conflicts that residents might encounter with the qualification of residential green structures. The neighbourhood survey shows that the co-benefits of urban green structures, in general, are not equally important to residents. While the benefits for health and well-being and climatological benefits have been widely acknowledged, biodiversity benefits and the role of urban green structures as a venue for social interaction were more contested. Little is known about the perceived vs. actual importance of urban green spaces for biodiversity of city dwellers. Hand et al. (2016) show that socially more deprived neighbourhoods hold less perceptible biodiversity, making it more difficult for people to connect to nature. Nature relatedness and eco-centricity are important influences on the valuation of biodiversity as an ecosystem benefit (Lin et al. 2017, Southon et al. 2018). Regarding the critical outlook on green spaces fostering social interaction, a possible explanation could be that residents' feelings of personal safety are challenged by groups that meet at urban green spaces (Jansson et al. 2013). This can be reinforced by littering and vandalism, both issues which have come up during the survey. While the ecological and social benefits of urban green spaces are well documented (e.g. Kabisch et al. 2015, Lepczyk et al. 2017), our survey enables us to understand local public preferences, as well as reservations. It informs planners and housing companies about challenges that design and management of EbAs need to address.

The comparative assessment of co-benefits shows that the residential courtyards with a higher green volume clearly generate more co-benefits than the residential yards with less green. The differences are too large that socio-cultural weights do not change the outcome of the assessment. So far, little research has assessed the multiple benefits of residential green structures, based on comparative empirical data. Our results empirically demonstrate the multiple advantages of urban residential green structures and highlight their importance for a sustainable urban development.

Methodological approach

We adopt a multi-method approach that enables us to see how even small differences in the green structure affects the provision of different co-benefits. Our approach is not intended to reward or demote the management in the residential courtyards and the ranking is not meant to discourage adjacent housing companies or disqualify their work. The comparative assessment solely serves the purpose to trace the effects of residential green structures and highlight the potential of co-benefits.

Further, we need to point out limitations of the methods we used and aspects that could be improved in future endeavours. In our analysis of thermal comfort, we recorded microclimatic data at one representative spot in each courtyard over a time period of three months. Using spatially-explicit microclimatic data instead could give us insight on the spatial variability (Hart and Sailor 2009, Grilo et al. 2020) which, on the local scale, is not sufficiently studied. Of course, this requires more or different equipment, i.e. more measuring stations and depends on the availability of suitable sites. An alternative approach could be the selective use of an airborne thermal camera to record land surface temperatures, which could possibly lead to very different results (Schwarz et al. 2012). Additionally, analysing the potential of residential green structures for night-time cooling could be an important issue to explore in further studies. As measurements need to be interpreted differently than day values, night values were omitted in this study to keep the assessment unambigious.

Our scoring system for the potential for social interaction has a few limitations on its own. The ranking does not consider differences in certain amenities for the potential to encourage social interaction. It equally assesses benches and lanterns, the latter of which may enhance the feeling of safety during the dark hours and encourage a visit, but probably has a less obvious effect on whether people interact with each other than a bench. In addition, with the same of amount of items (e.g. lanterns), small differences in courtyard sizes make the difference in the assessment and must, therefore, be interpreted with caution. An evidence-based rating could serve as a basis for applying weights in the scoring. Secondly, assessing amenities only in the very inside of the courtyard leads to misrepresentations; courtyard 1 has a large playground located on the other side of the building pointing north-west that is not considered in the ranking. Lastly and most importantly, our approach should not be mistaken for an analysis of actual social interaction and as a first indication of the potential of the residential courtyards. As mentioned above, actual social interaction needs to be established by observing and interviewing residents, as it can be affected by several other reasons than green space (Mehta 2009, Enssle and Kabisch 2020, Mehta 2009Mehta 2009, a task that unfortunately was not feasible during this study.

Condensing the findings of the biophysical assessment down to rank scores and rank sums across all four benefits, leads to a considerable loss of detail by spreading the different value ranges of all benefits equally between 1 and 4. This pragmatic approach, however, allows us to overcome different units between benefits and generate a basis to incorporate socio-cultural weights. It further enables us to identify differences between courtyards with similar green endowment.

Opportunities of residential green for ecosystem-based adaptation

Urban residential green structures give rise to multiple benefits, which have the potential to increase sustainable urban development and must not to be overlooked in urban climate adaptation action. Texier et al. (2018) point out that, due to residential green spaces' substantial share in the total amount of urban green structures, much of the policy that could alter urban green structures is actually not in the hands of public decision-makers. This highlights the importance of providing incentives to land owners and leaseholders to commit to climate adaptation and is in line with the findings of McNamara et al. that adaptation is best when its locally led (McNamara et al. 2020). The German Federal Institute for Research on Building, Spatial Development and Urban Affairs (BBSR) lists climate adaptation and mitigation, health protection, biodiversity and social interaction and cohesion amongst those functions provided by urban green spaces that qualify for funding within urban development schemes (BBSR 2019). In the corresponding white paper, the German Environmental Ministry encourages the strengthening of green spaces in residential areas (BMUB 2018). While the greening of cities is promoted in national politics and supported with funding, a successful implementation of green measures depends on several aspects; it requires a strong internal leadership to promote the advances, the formulation of sustainability targets and effective communication with ecological and social experts (Richardson and Lynes 2007). Additionally, in the case of multiple housing companies sharing an area, joint objectives need to be agreed and the effort needs to be shared amongst all companies. Involvement of residents in planning and construction can have positive impact on satisfaction and social cohesion (Sommer et al. 1994). Changing the green structure in residential courtyards may require a lot of effort, but, as our study shows, can lead the way towards more sustainable urban development.

Conclusions

Despite comparatively small differences in between green structures within the courtyards, our analysis enables us to see, partly vast, differences amongst co-benefits of residential green structures in the courtyards. Especially, its cooling capacity and significant impact on human thermal comfort (i.e. heat stress) are noteworthy and make it an effective measure for ecosystem-based adaption. Though the differences in biodiversity, carbon storage and potential for social interaction reveal fewer, possibly more predictable results, our analysis highlights that a deliberate management strategy, possibly on neighbourhood-scale, could enhance co-benefits and contribute to a more sustainable urban development.

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Supplementary materials

Suppl. material 1: Questionnaire User Survey Potsdam Drewitz, August 2020 doi

Authors: Katja Schmidt
Data type: textfile
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Suppl. material 2: Tree height in the four courtyards_ doi

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Data type: occurences
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Suppl. material 3: Mean values of microclimatic parameters between 9am and 9pm, based on measurements in the four courtyards (CY): CY 1: light green, CY 2: dark green, CY 3: orange, CY 4: red doi

Authors: Katja Schmidt
Data type: microclimatic measurements
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Suppl. material 4: Habitat types in the four courtyards doi

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Data type: occurrences
Brief description: Habitat types in the four courtyards
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Suppl. material 5: Results from habitat mapping and biodiversity scores. Domin values = 1: < 4% cover with few individuals; 2: < 4% with several individuals; 3: < 4% with many individuals; 4: 4–10%; 5: 11–25%; 6: 26–33%; 7: 34–50%; 8: 51–75%; 9: 76–90%; 10: 91–100% cover_ doi

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Suppl. material 6: Results from tree mapping and allometric equations, indicating above-ground biomass and carbon stocks doi

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Suppl. material 7: Accessibility and amenities assessment doi

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