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Relationship Between Urban Tree Diversity and Human Well-being: Implications for Urban Planning

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ABSTRACT

Green spaces and trees are key elements for enhancing human well-being in cities. Despite recognizing the significance of urban greenery for human health, the role of urban biodiversity in shaping well-being remains poorly understood. This study focused on the interplay between tree genera diversity, perceived urban biodiversity, and the subjective well-being of urban residents in Karlsruhe, Germany. A map-based online questionnaire involving 302 participants investigated well-being locations and perceptions of biodiversity. Tree genera diversity was assessed for nine genera using remote-sensing and ground data. A novel approach of spatially correlating societal mapping results and tree genera cover maps revealed a clear preference for green spaces in the built-up urban environment. The relations between computed tree genera diversity and subjective well-being were unclear. However, there was a significant relationship between the perceived biodiversity of urban green spaces and subjective well-being. The amount of tree cover, the abundance of large trees, as well as the perceived species diversity beyond tree genera, lead to increased well-being of the urban population. At the same time, a perceived unkemptness of urban areas had a negative effect on the residents' well-being. This should be considered in future research and the design of urban green spaces.

1. Introduction

Biodiversity is declining worldwide due to mainly human-driven activities like environmental pollution, climate change, and land use changes (Anderegg et al. 2020). These losses in biodiversity affect the stability of the earth's systems that provide the conditions for the welfare of humankind. Thereby, human health is directly and indirectly threatened by the ongoing loss of biodiversity (Richardson et al. 2023).

Urban areas are recognized as sites of a unique combination of built and natural ecosystems. Urban forests are among the most diverse urban greenspaces. They are defined as "networks or systems comprising all woodlands, groups of trees, and individual trees located in urban and peri-urban areas; they include, therefore, forests, street trees, trees in parks and gardens, and trees in derelict corners" (Salbitano 2016). Scientific studies highlight that increased tree species diversity positively influences the diversity of other organisms by providing various ecological niches, supporting a wide range of flora and fauna (Alvey 2006).

However, the urban forests and their biodiversity are under pressure due to ever-increasing urbanization and densification of cities built-up area in European middle-sized cities (Haaland et al. 2015). Biodiversity was identified the second-most reported vulnerable sector to climate risks in urban areas of Europe (EEA 2024). Numerous policy frameworks, such as the EU Biodiversity Strategy for 2030, therefore, highlight the importance of protecting and enhancing urban ecosystems and call for a systematic integration of green infrastructure into urban planning (EEA 2024). Further, the authors explicitly highlight the need to integrate biodiversity and health-related policies to ensure cities'

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resilience to climate change impacts (Reckien et al. 2022). This is of particular importance as the urban biodiversity loss may negatively influence the health of the ecosystem and public health in cities.

Urban forests are essential in promoting human well-being in the city by providing numerous positive effects for physical and mental recreation and stress reduction (Beckmann-Wübbelt et al. 2021). They provide a large number cultural ecosystem services (CES), which the MEA defines as "the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (MEA 2005). Pröbstl-Haider (2015) shows that CES contributes to physical and mental recreation, increases the aesthetic values of a place (Nowak et al. 2018; Mundher et al. 2022), and provides space for spiritual and religious experiences (Davies et al. 2017). Furthermore, CES offers opportunities for environmental education (Nowak et al. 2018; Vogt 2020), serves as a source of inspiration (Riechers et al. 2016), and provides a location for social interactions (Mundher et al. 2022).

The COVID-19 pandemic has increased attention on the connections between human health, ecosystem functions (Mackenzie and Jeggo 2019), and the provision of CES in urban areas (Beckmann-Wübbelt et al. 2021). Tost et al. (2019) found that higher exposure to urban green space profits the cortex region of the human brain and thereby reduces psychological and emotional stress among humans. Studies further showed that urban forests mitigate thermal stress in humans by reducing physiologically equivalent temperature (PET) through shedding and transpirational cooling (Ketterer and Matzarakis 2014, Marando et al. 2019).

However, although research on the relationship between urban green spaces and human health increased during the past years, fewer studies focused on the indirect and direct relationship between biodiversity and human well-being in urban areas.

Zhu et al. (2021) exposed humans to pictures of different types of urban forests in a 5-minute virtual reality experiment while measuring their brain activity to see how it reacts to the different levels of diversity. They found that structurally diverse urban forests with three layers of vegetation structure resulted to the highest reduction of emotional stress. Gillerot et al. (2022) in their study in forest sites across Europe found that the tree species diversity had a significant, albeit small influence on the cooling effect, which influence human well-being. Ferrini et al. (2020) identified a complex structure of urban forests as an important factor for buffering noise and acoustic stress. Despite these studies, little knowledge yet exists about how people perceive biodiversity and how the perceived and actual biodiversity influences their subjective well-being.

Even though numerous definitions of biodiversity exist in ecology, including various taxonomic, size, and genetic aspects and complexity, it is stated in the literature that people perceive biodiversity primarily through visual indications, which is largely influenced by their perception of tree diversity (Gonçalves et al. 2021). However, the structural properties such as size, foliage color, and crown architecture of trees play a crucial role in people's perceptions and valuations of tree diversity, which can differ even within the same taxa such as among cultivars (Cameron et al. 2020).

This study therefore included different aspects of biodiversity in the analysis. For the ecological data input, this study focused on urban tree genera diversity as an indicator of biodiversity. Additionally, subjective perceptions of biodiversity were assessed and spatially correlated with the ecological data input to create a better understanding of the numerous aspects influencing people's perception of biodiversity.

In their constitution, the WHO identifies human well-being as an essential component of human health (WHO 1946). Although there is no standardized definition for well-being, the term generally describes how well individuals are doing in life, including social, health, material, and subjective dimensions of well-being (OECD 2013). Human well-being is a multidimensional concept whereby the dimensions are systemically connected and interact. Among them, the mental dimension, which refers to the psychological, cognitive, and emotional quality of a person's life, as well as the social dimension, which refers to how well people are connected to others in their local and broader community, are crucial aspects of overall well-being. In the literature and everyday language, the term 'well-being' is equated with related but distinct terms like 'quality of life', 'life satisfaction' or 'happiness'. Besides that, there are different conceptual subdivisions of the concept of well-being described by Diener et al. (2018).

This study focused on the sub-concept of subjective well-being. The Organization for Economic Co-operation and Development (OECD 2013) describes high subjective well-being as "good mental states, including all of the various evaluations, positive and negative, that people make of their lives and the affective reactions of people to their experiences" (OECD 2013, p. 10). They emphasize that the value of the subjective well-being concept consists of providing insights into the impact of interventions by considering a variety of objective well-being outcomes and synthesizing them into an overall perception of well-being. A better understanding of subjective well-being is fundamental as this can serve as a guideline for a wide range of policy considerations (OECD 2013). A study by Koivumaa-Honkanen et al. (2001) emphasized that higher subjective life satisfaction was associated with a reduction in the suicide rate, underlining the concrete positive impacts of committing on people's mental well-being.

Since policymakers and researchers agree that biodiversity is essential for promoting human well-being, especially against the backdrop of ongoing urbanization (Botzat et al. 2016), this study aimed to identify aspects that influence people's biodiversity perceptions in the urban context and investigate how positive effects can be used to improve human well-being.

Such recommendations are of particular relevance in European middle-sized cities, such as Karlsruhe, that are undergoing densification, whereby effects on the abundance and quality of urban green spaces and biodiversity are often overlooked (Haaland et al. 2015).

Therefore, this study evaluates:

(a) how the tree genera diversity was related to people's reported subjective well-being in the urban setting?
(b) how perceived biodiversity was associated with the subjective well-being? and
(c) what is the role of individual biodiversity aspects in people's subjective well-being?

We hypothesized that the computed and perceived urban biodiversity has a positive effect on people's subjective well-being.

2. Material and method

2.1. Methodological overview

The approach of this study was to spatially correlate the distribution of tree genera diversity and people's perceptions and evaluations of diversity regarding their subjective well-being. Therefore, a map-based questionnaire survey as well as spatial information on the urban tree genera diversity in the area of Karlsruhe city, derived from remote sensing, served as data input. By integrating research methods from social science as well as ecological perspectives and remote sensing, the study takes an interdisciplinary approach to address challenges in the human-nature-relationship. The methodological approach allows for a more holistic understanding of urban sustainability and can lead to more effective and comprehensive solutions (Crane et al. 2021). This has been increasingly recognized and supported by both the research community and funding agencies (Van Noorden 2015). Fig. 1 illustrates the conceptual approach of the spatial integration and the multiple data input.

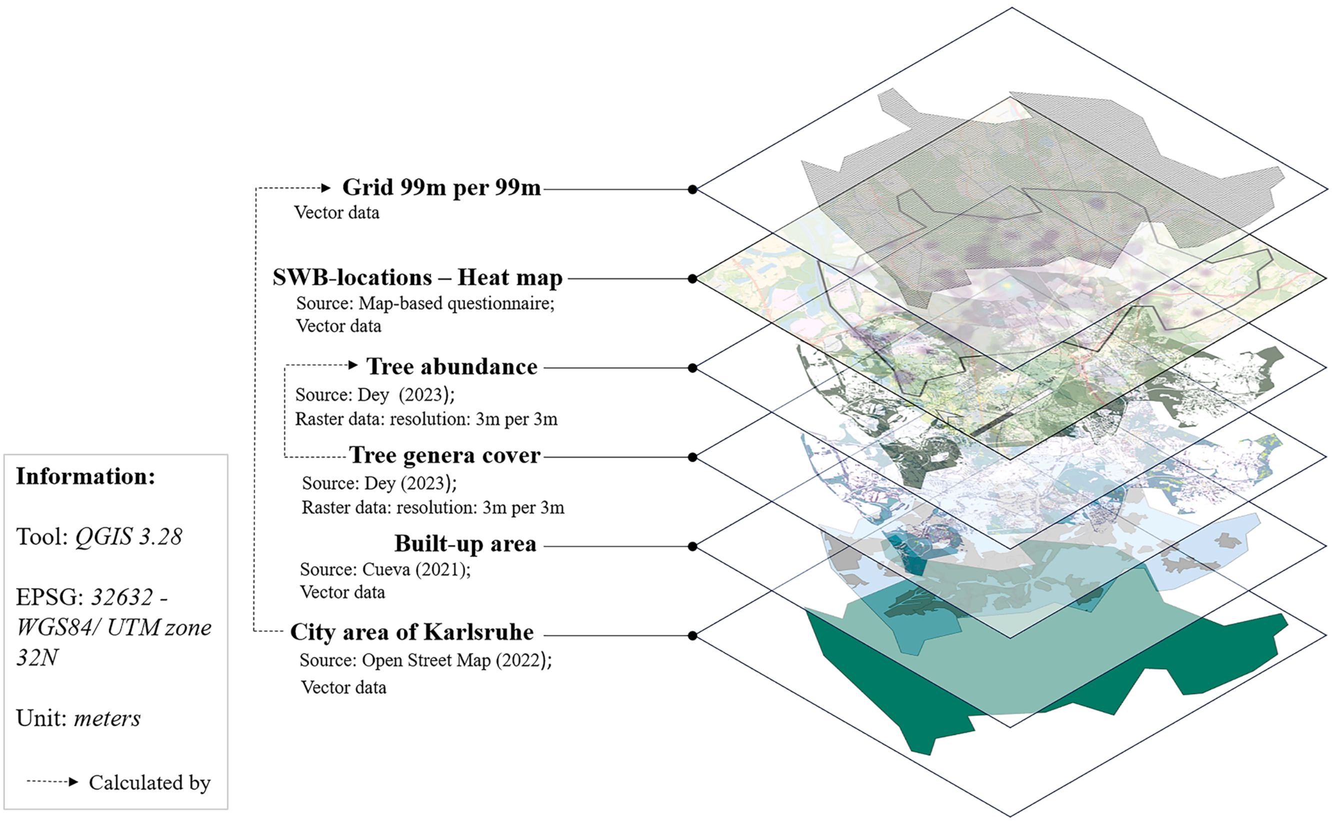

Fig. 1. Overview of the conceptual approach and data input for the analysis.

2.2. Study area

The study took place in the city of Karlsruhe in southwest Germany. Located in the Upper Rhine Valley, the city is an eminent study site, as it is particularly confronted with double trouble of climate change impacts due to its geographic location (Rannow et al. 2010) as well urbanization (Siedentop and Fina 2010). The complete city area covered about 171 km^2. The built-up area made up the largest part of the complete city area (~44%), followed by forest area (~29%), and agricultural area (~23%). The tree canopy of the complete city area was about 47%, with a high percentage of tree canopy in the forest area (~92%), about one third of tree canopy in the built-up area (~31%), and the lowest percentage of tree canopy in the agricultural area (~27%). Table 1 shows an overview of the study area characteristics as derived from the land use data and the tree genera canopy data. Karlsruhe is one of the warmest and sunniest cities in Germany (DWD 2023; Multiannual averages 1981–2010). Although climate projections for Karlsruhe are subject to location-related uncertainties, an increase in hot days (Tmax $\geq$ 30°C) from 12 days (1971-2000) to about 44 days (2071-2100) can be expected. Tropical nights (Tmin >20°C) are also expected to increase from 0 (1971-2000) to about 19 (2071-2100) (LoKlim 2022). Due to the location in the Upper Rhine Valley, the heat is often accompanied by high air humidity in summer, which is an additional health burden, especially for vulnerable populations. Together, this leads to the need for cooling climate adaptation measures in the city.

Table 1
Overview of the spatial characteristics of the study area with the count of subjective well-being (SWB) locations selected as locations of high SWB by the participants. Tree canopy (%) was estimated by Dey (2023).

	Km^2	Land use [%]	Tree canopy [%]	Total count of SWB-locations (% of city area)
City Total Area	171.39	100	47.11	714 (100%)
Forest area	49.38	28.81	92.38	142 (19.9%)
Built-up area	75.58	44.10	31.49	530 (74.2%)
Agricultural area	39.41	22.99	27.08	33 (4.6%)
Rest	7.02	4.1	0	9 (1.3%)

Note. n = 302.

2.3. Questionnaire and survey

An online questionnaire was created with the tool Maptionnaire (www.maptionnaire.com), which enables querying geographically locatable information. One advantage of this method is its ability to capture many locations with less material and time effort. The questionnaire was structured in two parts – a map-based part and a socio-demographic part.

Before starting the questionnaire, a filter question was posed to ensure participants' basic knowledge of the city. An interactive map of Karlsruhe was presented on the next page. Participants were requested to choose up to three locations in the Karlsruhe public space, which they stated to be particularly important for their well-being. Attention was paid not to introduce any green space-related topics before the mapping exercise to avoid a bias in the choice of locations towards greener areas. While a respondent chose a location, a pop-up window provided questions about this place. Participants were asked to evaluate their well-being at the indicated location on a five-step emoji-based scale (Alismail and Zhang 2018). The emoji-based scale was used for certain questions, as they are independent from language and easy to understand (Alismail and Zhang 2018). A further advantage is their ability to have an engaging effect on the participants (Alismail and Zhang 2018). Although there might be differences in the interpretation of emojis by different cultures, this has no significance for surveys in a single-culture context. Alismail and Zhang (2018) stated that emoji-based scales are a suitable tool for emotional self-assessment and according to Kaye et al.

(2017) for the assessment of personal perceptions. The following questions were about how the participants evaluate various biodiversity aspects at the location on a five-step Likert scale (Likert 1932).

The second part of the questionnaire contained sociodemographic questions. Additionally, it included a section about participants' environmental pre-education on biodiversity issues in their education, work, and personal interests, measured with a five-step Likert scale. For all mandatory questions, an option was given not to answer the question.

Two rounds of pre-tests were run for questionnaire improvement, including eight academics with different disciplinary backgrounds and five persons with a non-academic background, of different age classes, and with different technical devices such as smartphone and computer (Rea and Parker, 2014). As the questionnaire was provided in German and English language, both versions as well as the user-friendliness, especially for the mapping exercise, were checked. The advices of the pre-testers were incorporated into the questionnaire. Technical terms have been replaced by simple language without compromising the meaning. The English version of the questionnaire can be found in the supplementary material.

The survey ran from September 22th, 2023 to October 30th, 2023. A random sampling approach was chosen for the study. The questionnaire was spread via mailing lists of colleges, schools, and civic associations in Karlsruhe. About 2,000 flyers were handed out at public events and put in mailboxes in several city areas. These measurements were supplemented by tear-off sheets, posters, and signs placed in waiting areas of medical offices and health insurance companies. Further advertising measures were posts on social media channels, such as 'facebook', 'X', and 'Instagram'.

2.4. Data analysis

2.4.1. Data acquisition and harmonization

2.4.1.1. Primary data. The questionnaire data was downloaded on November 1st 2023 from 'Maptionnaire' in the format of an Excel file. The sheets of this file contained the answers of each participant, as well as the geographical information about participants' subjective well-being locations. Additionally, the subjective well-being locations were provided as shapefile, which is a file format for vector geodata. Its attribute table contained the location-related answers, referring to the Excel file. The subjective well-being locations including the associated answers that were located outside of the city boundaries of Karlsruhe were excluded from the analyses, as well as data of participants who indicated an age under 18 due to legal requirements. Additionally, data was deleted from empty cases in the localization of subjective well-being locations on the map and in sociodemographic information.

A total number of 657 people filled out the questionnaire, of which 338 completed the questionnaire. After scrutinizing and filtering the data as described, 302 valid answers were included in the analysis.

The spatial information about the location of subjective well-being was imported in QGIS in order to later on spatially correlate the information with the diversity of tree genera canopy at the locations. The spatial distribution of subjective well-being locations was visualized in QGIS as a heatmap, weighted with the value of participants' indicated subjective well-being at these locations. The subjective well-being values at the locations were analysed descriptively.

2.4.1.2. Secondary data. The administrative city boundaries of Karlsruhe were retrieved from the Federal Agency for Cartography and Geodesy (in German *Bundesamt für Kartographie und Geodäsie*, BKG) to restrict data to the city area (BKG 2021).

Furthermore, information about the distribution of tree genera was required to spatially correlate the measured tree diversity and participants' subjective well-being locations. The genera-wise tree cover data was created in 2023 by machine learning algorithms combining high resolution spatial-temporal remotely sensed PlanetScope imagery trained by digital twin tree canopy covers (Dey 2023). The analyses resulted in a spatial dataset with the canopy of nine tree genera with an accuracy of 72.5%, and a resolution of three meters by three meters. The identifiable tree genera were *Platanus* (plane), *Tilia* (lime), *Acer* (maple), *Quercus* (oak), *Carpinus* (hornbeam), *Fraxinus* (ash), *Magnolia* (magnolia), *Aesculus* (horse chestnut), and *Pinus* (pine). Not identified tree genera were labelled as 'other'. It is important to note, that this data can make no statements about single trees since it shows the tree canopy. Incidentally, the data provides no information about single tree species, but about tree genera, which represent a group of species.

The data was imported in the geodata program QGIS, where all layers were set to the same values of the coordinate reference system (EPSG 32632 – WGS84/ UTM zone 32N). A grid with a cell size of 99 meters by 99 meters (9,801m^2), covering the city area, was created as base for the analysis of the diversity index of tree genera canopy. This cell size was regarded as suitable, as a trade-off between the minimizing factor of providing enough grid cells to make a statement about specific locations, and the maximizing factor of providing enough grid cells that contain several tree genera, as well as multiple subjective well-being locations to get meaningful results. For exact scaling, the edge length of 99 meters was chosen as a multiple of the tree genera canopy data resolution of three meters by three meters. The exact match of data was required to calculate the diversity index in each grid cell.

2.4.2. Statistical analyses

Based on the above-described data acquisition and editing, various analyses were carried out to answer the research questions. 'R' version 4.2.2 (RStudio 2022), 'QGIS' version 3.28 (QGIS Development 2022), and Excel (Microsoft Corporation 2018) were used for the analysis.

2.4.2.3. Descriptive statistics. Tree genera canopy and its diversity

The percentage of general tree cover was assessed in QGIS based on the tree genera canopy data. The Shannon Diversity Index was used to calculate the diversity of tree genera canopy (Spellerberg and Fedor 2003). To do so, the tree genera canopy data was merged with the 99-per-99-meter grid layer. The formula of the Shannon Index was implemented in 'R' and applied on the tree genera canopy data for each grid cell. The following formula describes the Shannon Diversity Index H' of a population (in this case urban tree population):

$$H' = \sum_i pi \cdot \ln pi \text{ with } pi = niN$$

The population consists of N individuals of different genera. n_i of them belong to one genus. p_i is the proportion of the respective genera i of the total number of individuals N. For a given number of genera, the Shannon Index reaches its maximum H_{max} when all genera are equally populated (Spellerberg and Fedor 2003).

The Shannon Index provides a comprehensive measure that takes into account both the abundance (the number of different genera) and evenness (the distribution of individuals among genera) of different genera in a given area, resulting in a single numerical value. It is a widely adopted measure applied across various disciplines. In the context of urban forestry, the Shannon Index offers insights into the richness and equitability of urban tree species or genera. This is particularly relevant for capturing the complexity of tree genera composition, especially in cities, where the variety and distribution of tree genera contribute to the overall ecological health of the area (Magurran 2004). In urban contexts, the index compares diversity across different urban areas, enabling the identification of areas with unique tree communities (Pielou 1975).

Sociodemographic divergences in subjective well-being

Using Excel software, descriptive statistics of participants' sociodemographic characteristics, including age, gender, home country, having children, educational degree, current occupation, gross income per month, and environmental pre-education, were performed.

The mean values of the participants' subjective well-being were examined on an emoji-based five-step Likert scale across age classes, gender, parenthood, education level, and income classes to gain deeper insights into their subjective well-being as a function of sociodemographic characteristics.

2.4.2.4. Inference statistics. Correlation and regression analyses were performed to get insights into the relationships between the subjective well-being and the computed diversity of the tree genera canopy, the perceived tree species diversity, as well as the perception of several biodiversity aspects, as shown in Table 2.

Correlation analyses

Correlations were calculated with the method 'Kendall's tau', which was applied in 'R' using the 'cor.test' function of the 'stats' package, as the data required a non-parametric test (Laerd Statistics 2020). Kendall's tau is, in contrast to Spearman's rho, more appropriate when there are many ties in the ranks of the data, as it was the case here. An approximate permutation test was run to get a more exact p-value, using the 'perm.relation' function of the 'wPerm' package, method = 'kendall'. The respective numbers of permutation resulted from the trade-off between accuracy and the available computing power.

Regression analyses

Ordinal logistic regression analyses were performed to reveal the influence of participants' sociodemographic characteristics on their perception of several biodiversity aspects at their selected subjective well-being locations. Ordinal logistic regression analyses further allowed insights into the relationship of participants' subjective well-being and their perception of biodiversity aspects. Table 3 provides an overview of the variables included in the analyses.

For each regression calculation, the models were tested for underlying assumptions in 'R', such as the assumption of proportional odds. The 'Brant Test' was performed to test for the assumption of parallel slope of log-odds of the reduced model. The independent variables were checked for multicollinearity with taking the value of five of the variance inflation factor (VIF) as a threshold value. The goodness-of-fit of the final model was assessed by the pseudo-R^2 of Nagelkerke. The model's significance of prediction was evaluated with the likelihood-ratio output of the final model compared against the null-model (intercept-only model). The significance of the contribution of each independent variable was assessed by the 'Wald Test'.

Table 2
Overview of the examined relations between subjective well-being (SWB) and biodiversity indicators, and the analysis methods used.

Relation to be examined	Analysis method used			
	Correlation analysis		*Regression analysis*	
	Performed?	Method details	Performed?	Method details
SWB – tree cover	Yes	Kendalls's Tau; 1) 200; 2) 2,000 permutations	No	
SWB – Computed diversity	Yes	Kendalls's Tau; 1) 5,000; 2) 10,000 permutations	No	
Computed diversity – Perceived diversity	Yes	Kendalls's Tau; 10,000 permutations	Yes	Ordinal Logistic Regression
SWB – Perceived diversity	Yes	Kendalls's Tau; 10,000 permutations	No	
SWB – Biodiversity aspects	Yes	Kendalls's Tau; 2,000 permutations	Yes	Ordinal Logistic Regression

Note. SWB = Subjective well-being; the computed diversity refers to the tree genera canopy; the perceived diversity refers to the tree species diversity; Correlations with SWB were always examined for 1. Count of SWB-locations in single grid cells, and 2. SWB-values at locations. The number of permutations for each correlation analysis differed based on the complexity of the calculation and computing power.

Table 3
Overview of the personal characteristics of the surveyed participants and the aspects of biodiversity that were available in the questionnaire to describe the subjective well-being (SWB) locations.

Demographic/ personal variables	Biodiversity aspects available for participants to describe their selected SWB-location
Age	Number of birds
Gender	Number of insects
Educational degree	Tree density
Current occupation	Age and size of trees
Income	Difference of tree species
Environmental pre-education	Unkemptness of green spaces
SWB at selected location	Unkemptness of trees

3. Results

3.1. Respondents' profile

In total, responses from 302 respondents was included in the analysis. Table 4 gives an overview of the participant's demographic characteristics.

3.2. Sociodemographic divergences in subjective well-being at the selected locations

The descriptive analyses showed that the mean values regarding the subjective well-being of different age classes were slightly higher for the youngest group (18 to 25 years) and the oldest group (>60 years), precisely 4.6, than the mean values for the age groups in between (26 to 60 years), precisely 4.5. Regarding the gender, females showed slightly higher subjective well-being values (4.6) than males (4.5). In contrast, there was no difference in participants' subjective well-being regarding whether they had children. However, slight differences were measured for the educational level. The highest mean values for subjective well-being in this regard were observed among the participants who were current students, precisely 4.7, followed by participants with a degree from a secondary school or a university degree, precisely 4.6, and the lowest value of 4.4 for participants with a completed apprenticeship or another educational degree. The mean values of subjective well-being for different income classes showed a slight increase with higher income. The lowest value (4.3) was observed for participants with a monthly income lower than 450€, while the highest value (5.0) was observed for participants with a monthly income over 7,000€. Participants who indicated an irregular income were in the midfield with a value of 4.5.

3.3. Relationship between subjective well-being and tree cover

The count of subjective well-being locations per grid cell, as well as the measured subjective well-being at the locations were considered as subjective well-being indicators. The correlation between tree cover and count of subjective well-being locations resulted in a significant positive relation τ (17,575) = 0.02, (CI_{95}: 0.005, 0.03); p-value = .01. The correlation between tree cover and subjective well-being at the locations resulted in a significant positive relation as well τ (834) = 0.08, (CI_{95}: 0.026, 0.137); p-value = .006.

3.4. Relationship of the subjective well-being and the measured tree genera diversity

Most respondents placed their subjective well-being locations in

Table 4
Demographic information of the respondents.

Attribute	Characteristic	Absolute	Percentage [%]
Age (n=290)	18 - 25 years	58	20.0
	26 - 40 years	119	41.0
	41 - 60 years	80	27.6
	>60 years	33	11.4
Gender (n=290)	Female	160	55.2
	Male	126	43.4
	Both, female and male	0	0.0
	None	2	0.7
	Other	2	0.7
Children (n=290)	Yes	111	38.3
	No	179	61.7
Educational degree (n=287)	Still in school	2	0.7
	Graduation from a	36	12.5
	secondary school	26	9.1
	Completion of an	219	76.3
	apprenticeship	4	1.4
	Degree of a university or		
	college		
	Other		
Current occupation (n=287)	Fill-time employed (min. 35	127	44.3
	hours per week)	58	20.2
	Part-time employed (min.	68	23.7
	15 hours per week)	5	1.7
	Trainee, pupil, student	18	6.3
	Parental or other leave	11	3.8
	Retiree, pensioner		
	Other		
Gross monthly income (n=265)	<150€	3	1.1
	150€ - <450€	20	7.5
	450€ - <1000	41	15.5
	1000€ - <3000€	113	42.6
	3000€ - <5000€	70	26.4
	5000€ - <7000€	11	4.2
	>7000€	3	1.1
	Very irregularly	4	1.5
Environmental pre-education…			
…in education (n=284)	Not at all	103	36.3
	Rather no	74	26.1
	Neutral	33	11.6
	Rather yes	46	16.2
	Very much	28	9.9
…in work (n=280)	Not at all	108	38.3
	Rather no	74	26.3
	Neutral	38	13.5
	Rather yes	41	14.5
	Very much	19	6.7
…in personal interests (n=288)	Not at all	17	5.9
	Rather no	32	11.1
	Neutral	64	22.1
	Rather yes	125	43.3
	Very much	50	17.6

green spaces near the city center (see Fig. 2A). The five most frequently chosen places were the park areas ‘Schlosspark’ and ‘Günther-Klotz-Anlage’, the forest areas ‘Hardtwald’ and ‘Oberwald’, and the zoo. The Shannon Diversity Index showed the highest values at the district ‘Waldstadt’, the nature conservation area ‘Fritschlach’, the Main Cemetery, the wooded hill ‘Turmberg’, and the rural suburbs ‘Bergdörfer’.

Correlations were calculated for the measured diversity of tree genera canopy, the count of subjective well-being locations in the grid cells (cell size: 9,801 m^2), and the indicated subjective well-being at the locations. There was no significant relation between the measured diversity of tree genera canopy and the count of subjective well-being locations τ (16,034) = 0.00, (CI_{95}: -0.017, 0.011); *p*-value = .63, or the subjective well-being values τ (905) = 0.04, (CI_{95}: -0.017, 0.107); *p* = .17. Fig. 3 shows the relationship of the subjective well-being and the measured tree genera diversity.

3.5. Relationship of the computed and the perceived tree species diversity

The correlation between the computed tree genera canopy diversity and the perceived tree diversity resulted in a significant medium positive relation.

Regression analyses complemented the relation between computed and perceived tree species diversity to reveal the influence of participants’ sociodemographic characteristics on their perception of several biodiversity aspects at their selected locations.

The regression models showed that females perceived a significantly higher abundance of trees at their selected locations than males. Furthermore, they significantly tended to have a higher perception of general biodiversity at the selected locations, a higher perception of tree diversity, and a significantly higher perception of the age and size of trees.

Females’ higher perception of biodiversity did not arise from a selection of locations with a higher diversity of tree genera canopy. This was tested with a correlation analysis of the participants’ gender and the Shannon Diversity Index at their selected locations.

Participants’ preoccupation with environmental issues in work was significantly associated with a higher perception of general biodiversity.

Furthermore, the regression models showed a significant relation between a participants’ higher age and their perception of a higher tree age and size.

The regression models included a non-significant relation between higher education levels and a higher perception of tree diversity. Table 5 summarizes the regression results.

3.6. Relationship between perceived tree species diversity and subjective well-being

The correlation between perceived tree species diversity (M = 3.17, SD = 1.07) and subjective well-being at locations resulted in a significant medium positive relation τ (906) = 0.18, (CI_{95}: 0.11, 0.26); *p*-value < .001 (10,000 permutations).

3.7. Perception of other biodiversity aspects influencing the subjective well-being

The correlation between perceived overall biodiversity at locations and the subjective well-being at selected locations (M = 4.54, SD = 0.66) resulted in a significant positive relation τ = 0.14, (CI: 0.076, 0.214); *p*-value = .001 (2,000 permutations).

The ordinal logistic regression analysis showed that participants’ evaluations of the age and size of trees and the general species diversity significantly influenced their indicated subjective well-being at their selected locations. Conversely, the unkemptness of green spaces had a significant negative influence.

The odds of the perceived age and size of trees and the perceived general species diversity showed similar values. Comparatively, the odds of the perceived unkemptness of green spaces were lower. Table 6 summarizes the regression results.

4. Discussion

4.1. Representativeness of the study

The sample size in this study was 0.1% of Karlsruhe’s population. The sample of this study represented the entire population of Karlsruhe to varying degrees in terms of sociodemographic aspects. The sample’s distribution of gender, nationality, and income represented the population of Karlsruhe sufficiently (Stadt Karlsruhe 2024; Statistische Ämter des Bundes und der Länder 2022). Regarding age, the sample shows a slight inclination toward younger people (Stadt Karlsruhe 2024). The

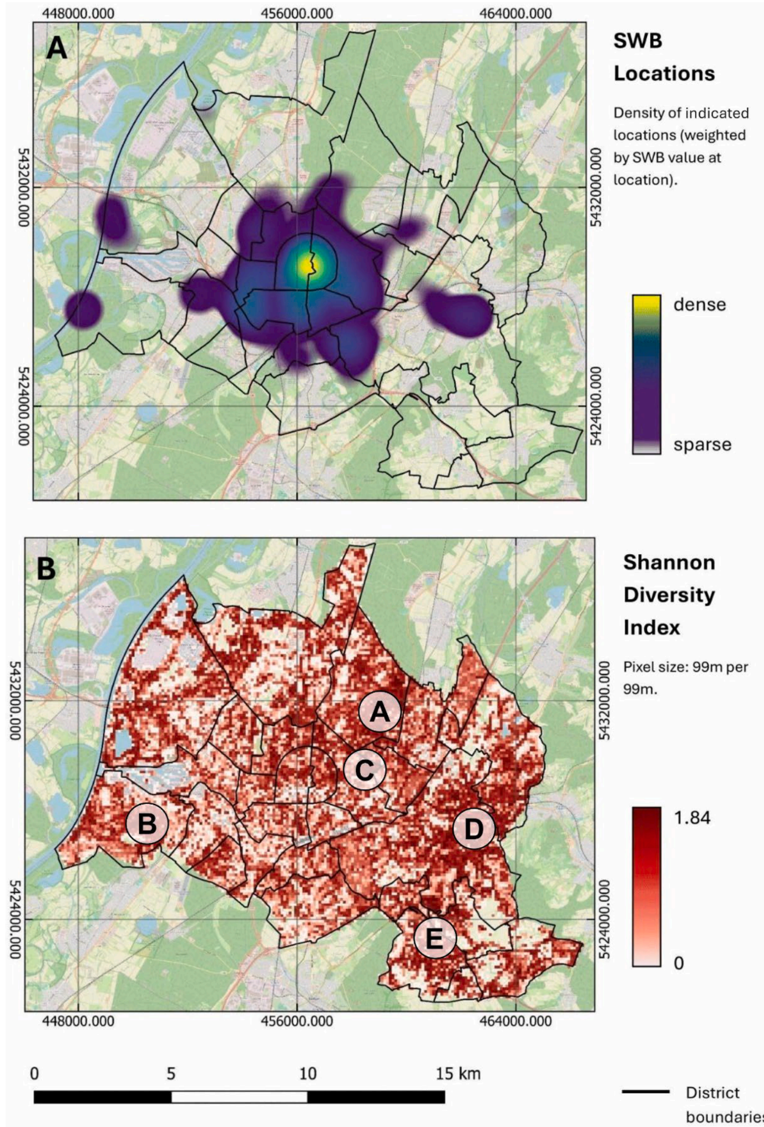

Fig. 2. A) Density map of participants' indicated subjective well-being (SWB) locations weighted by SWB values (n=714); B) Spatial distribution of the Shannon Diversity Index of the tree genera canopy (resolution 99m per 99m); A-E: Hotspots of high Shannon Diversity Index (A: Waldstadt, B: Fritschlach, C: Main cemetery, D: Turmberg, E: Bergdörfer).

proportion of participants with a university or college degree was over-represented by 75%, considering the proportion of 36% with the same degree among the population of Karlsruhe (Statistisches Bundesamt 2022).

During the questionnaire design, we specifically focused on using an easy to understand, non-scientific language to try and make the questionnaire accessible for everyone. Further, we used various distribution channels such as mailing lists, social-media, as well as flyers that we distributed to households and during events. This was, to reach different groups of the population in which we succeeded in terms of gender, nationality and income distributions. Future studies could use additional paper-based questionnaires for older people with low digital literacy. However, experience from past studies showed little return rates (Beckmann-Wübbelt et al. 2021). Further, collaborations with Citizen's and sports associations as well as NGOs might enhance the diversity of residents reached. The sample's sociodemographic deviations, compared to the residents of Karlsruhe, have to be considered in the contextualization of the results in this study.

The role of different cultural backgrounds could not be considered in this study due to an insufficient number of cases. However, there is a need for insights into cultural differences, as migration can influence demographic structures (Hanewinkel and Oltmer 2017)

4.2. *The relationship between computed and perceived biodiversity and the urban residents' well-being*

The results of this study showed a correlation between an increased amount of tree cover with both the number of locations as well as indicated well-being at these locations. This is supported by other international studies, such as Wang et al. (2020), on aesthetic preferences of green spaces and their relation to mental well-being. Their results showed that an increased number of trees resulted in an increased aesthetic preference and a higher therapeutic potential of the area in eastern China. Similarly, Mouratidis (2019) in his study in Oslo, Norway, found that an increased tree cover boosted the sense of safety and well-being of the residents. The size and quality of urban greenspaces was further decisive for its cooling capacity (Bai et al. 2024; Zhang et al. 2025) which in turn effects the thermal comfort and well-being of the urban population (Lee et al. 2025). Thereby, cooling capacities vary by seasons (Lin et al. 2025; Jia et al. 2025). Findings of Tost et al. (2019)

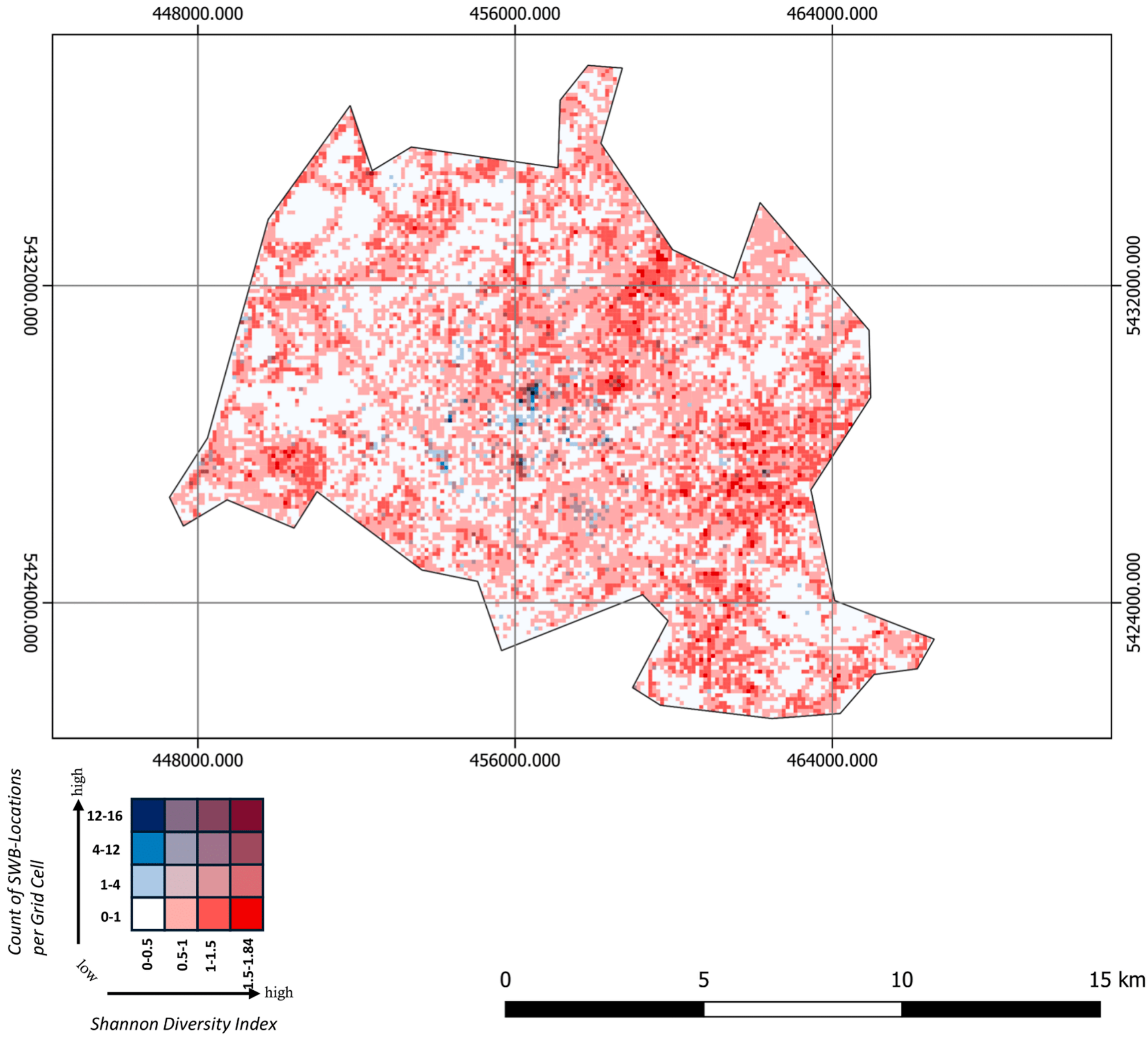

Fig. 3. Map showing the spatial relationship between the number of subjective well-being locations of the respondents and the Shannon Diversity Index indicating the tree genera diversity.

Table 5
Regression results for the relationship between participants' characteristics (independent variable (IV)) and perceptions of several biodiversity aspects (dependent variable (DV)) at their selected locations.

Biodiversity aspects (DV's)	Participants characteristics (IV's)	*β*	*SE β*	*CI₉₅ (β)*		*Wald* (χ^2)	*OR*	*CI₉₅ (OR)*	
				LL	*UL*			*LL*	*UL*
Perception of general biodiversity. *Model fit:* *$\chi 2(2) = 10.31$, p = .006*	Gender	-0.40*	0.17	-0.74	-0.06	5.45*	0.67	0.48	0.94
	Working experience with env. issues	0.14*	0.07	0.00	0.28	4.03*	1.15	1	1.32
Perception of tree abundance. *Model fit:* *$\chi 2(1) = 4.19$, p = .04*	Gender	-0.36*	0.18	-0.70	-0.02	4.16*	0.7	0.49	0.99
Perception of tree diversity. *Model fit:* *$\chi 2(2) = 9.26$, p = .01*	Gender	-0.43*	0.17	-0.77	-0.1	6.4*	0.65	0.46	0.91
	Education	0.19	0.12	-0.05	0.43	2.5	1.21	0.96	1.54
Perception of age and size of trees. *Model fit:* *$\chi 2(2) = 12.15$, p = .002*	Gender	-0.52**	0.18	-0.88	-0.16	8.15**	0.6	0.42	0.85
	Age	0.28**	0.11	0.07	0.5	6.96**	1.33	1.08	1.65

Note. β = unstandardized regression coefficient; *SE β* = standard error of the coefficient; *CI* = Confidence interval; *LL* = lower limit; *UL* = upper limit; *Wald (χ2)* = Wald test ('waldtest' function in 'r') for significance of individual coefficients with degrees of freedom in brackets; *OR* = Odds ratios; * p<0.05, ** p<0.01, *** p<0.001.

Table 6
Regression results for the relation between participants' perception of several biodiversity aspects (IV's) and their subjective well-being (DV) at their selected locations.

Variable	*β*	*SE β*	*CI₉₅ (β)*		*Wald (χ²)*	*OR*	*CI₉₅ (OR)*	
			LL	*UL*			*LL*	*UL*
Perceived Age and size of trees	0.36***	0.10	0.16	0.56	12.53***	1.43	1.17	1.74
Perceived general species diversity	0.24*	0.10	0.04	0.44	5.35*	1.27	1.04	1.55
Perceived unkemptness of green spaces	-0.21*	0.10	-0.42	-0.02	4.75*	0.80	0.66	0.98

Note. β = unstandardized regression coefficient; *SE* β = standard error of the coefficient; *CI* = Confidence interval; *LL* = lower limit; *UL* = upper limit; *Wald (χ2)* = Wald test ('waldtest' function in 'r') for significance of individual coefficients with degrees of freedom in brackets; *OR* = Odds ratios; Observations: 507; Model fit: $\chi2(3)$ = 37.8, p = < .001; Residual Deviance: 759.14; * p<0.05, ** p<0.01, *** p<0.001.

revealed a positive effect of urban green spaces, particularly in neighborhoods with increased psychiatric disease rates and less green infrastructure. They furthermore suggested compensation of lower neural regulatory capacity through increased green space exposure. These research outcomes are confirmed by Marselle et al. (2021), stating that even unintentionally regularly exposure to urban trees in the neighborhood holds the potential to reduce the risk of depression, particularly for people from socially disadvantaged groups. However, studies across Europe and the US report, that urban tree cover and accessible urban green space in urban areas is yet unevenly distributed with especially low-income, underprivileged and vulnerable neighborhoods showing no to very low tree cover (Sun et al. 2022). Konijnendijk (2023), in his 3-30-300 rule, addressed the challenge of well-distributed, qualitative greenspaces accessible in all neighborhoods. The results of this study highlight and support the importance of such approaches.

Besides looking at the tree cover and its impact on well-being, a major aim of this study was to identify whether the biodiversity of the urban forest correlates with places of subjective well-being of the urban population. In this study, we did not find a correlation between the measures of tree genera diversity and either the number of well-being locations or the rating of the respondents' well-being. However, we albeit identified a correlation between perceived biodiversity and subjective well-being. Furthermore, the perceived biodiversity correlated with the measured diversity. There might be several factors influencing this relational triangle, which is illustrated in Fig. 4.

Notably, the results should be interpreted in the light of the utilized methods. Hence, the question arises if the results would change with the choice of another grid size as a base for calculating the diversity index. Furthermore, the results depend on the scale on which an ecosystem is observed. Botzat et al. (2016) point out that most studies conducted below the ecosystem level indicate beneficial biodiversity effects. However, universal patterns remain elusive due to the limited number of studies and their lack of comparability. Furthermore, the approach of observing tree genera could be extended to more detailed tree species to get more expressive results. The data availability of only nine tree genera should be broadened. On the other hand, the correlation between the perceived biodiversity and subjective well-being might be overestimated due to the methodological approach. De Vries and Snep (2019) highlight potential biases when using the same source to access biodiversity and human health indicators. Nevertheless, in this study the computed tree diversity correlated with the perceived biodiversity, indicating that the participants did show a sound understanding of biodiversity in the indicated locations. The results, therefore, suggest that other aspects of diversity may be more decisive for the provision of well-being benefits of the urban forest, looking beyond solely the tree genera diversity. The most important biodiversity aspects that were identified to enhance human well-being are discussed in the following.

4.3. Biodiversity aspects influencing the subjective well-being of urban residents

The results of this study showed that tree age and size, species diversity, and the unkemptness of the indicated location were the most important factors in explaining the perceived subjective well-being of the respondents. Thereby the results call for a larger amount of big trees

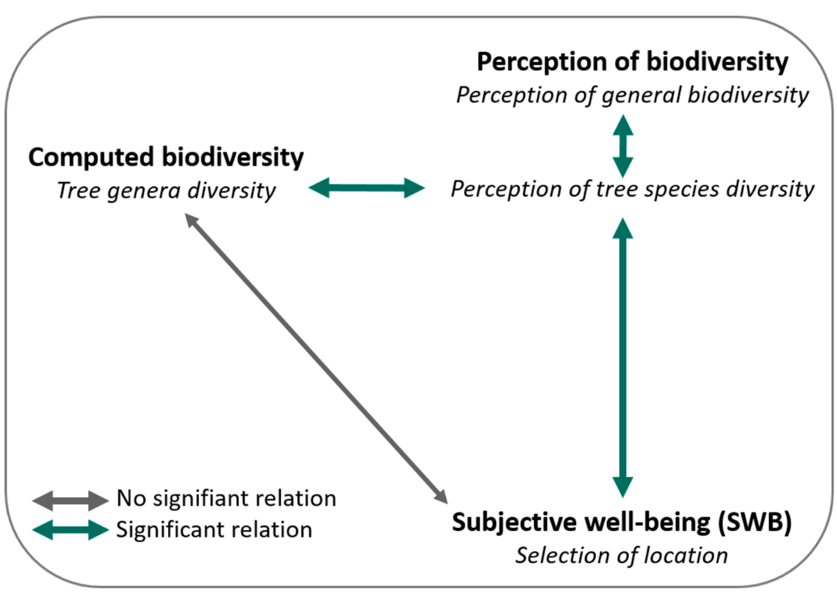

Fig. 4. Graphical summary of the relational triangle between the perceived tree species diversity, the computed tree genera diversity and the subjective well-being of the respondents at the indicated locations.

in the city. It is supported by Hall et al. (2011) that old trees have high charismatic values. Further, Wang and Zhao (2017) in their study on landscape preferences in China stated that growth status and tree maturation were the two most important factors in explaining the indication of favored location. Beyond aesthetic benefits, old and large trees in urban areas allow intensive transpiration and a high cooling effect (Stumpe et al. 2024), leading to improved health and well-being of the population. Further, tree size correlates with biomass accumulation, total stored carbon, and carbon sequestration (Stephenson et al. 2014). Tree canopy size and its correlated characteristics, such as canopy crown width, leaf area, and leaf area index, are further known to be closely related to air purification and rainfall interception ecosystem services (Holder and Gibbes 2016; Wang et al. 2020; Yang et al. 2016). Old trees are essential for the abundance of microhabitats in the urban area, which can be seen as a proxy indicator for biodiversity (Laux et al. 2022). However, there are also trade-offs related to keeping large trees in the city as they generally have larger amounts of deadwood that inherent the potential for accidents. Large trees have more litter and are related to higher maintenance costs. It will be a major task of urban planning to find solutions to solving such trade-off situations. The results of this study underline the importance of old and large trees in the city for the population's well-being. The results are a very important argument for preserving old trees in urban planning processes when weighing up the preservation of trees against cutting them down.

Besides the abundance of large and old trees, the overall diversity of urban greenspaces beyond the attention on tree genera diversity positively influenced the subjective well-being of the respondents. It is suggested by Cameron (2020) that people's evaluation of the charisma of a plant species can differ, even within the same taxa. Further, Goodness et al. (2016) found a close interconnectedness between functional traits and the provision of cultural ecosystem services. The authors suggest that focusing on functional traits rather than species may lead to enhancing the preservation of ecosystem functions and ecosystem services in urban areas. At the same time, species diversity, including coniferous as well as broadleaf species and a high structural diversity were identified an important aspect of constant cooling throughout seasons in Harbin, China (Jia et al. 2025), an important ecosystem service that leads to an improved human well-being in urban areas. An increased species diversity in the urban forest is also recommended to lower the risk of allergy impacts and thereby improve the health of the urban population (Cariñanos and Casares-Porcel 2011).

Lastly, the results of the study showed that the unkemptness of urban greenspaces had a negative effect on the subjective well-being of the respondents. Although, a study in China showed that increasing tree species diversity leads to a reduction of anxiety levels and increasing positive reactions (Wei et al. 2022). Further, Jiang et al. (2014) state that planting trees in bare residential areas results into a steep increase in preference and stress recovery. However, Koole and van den Berg (2005) point out that this is only the case to a certain degree of naturalness, above which the effects could become negative. Van den Berg et al. (2014) state that very dense vegetation may compromise restoration by evoking feelings of insecurity. Further, Berlyne's study (1971) showed that the highest preference was appointed to greenspaces with a medium degree of complexity rather than the highest naturalness. Authors so far doubt whether such a degree of unkemptness would ever be reached within European urban areas. The results of this study show that locations do achieve a level of unkemptness that negatively influences the well-being of the residents. It needs to be further studied how this perception differs among age, gender, culture, and educational level within Germany, Europe as well as other parts of the world. Future research should further focus on how unkemptness negatively influences well-being considering especially aesthetic as well as security aspects in order to inform urban greenspace planning.

4.4. *Implications of our results to urban planning*

The results of the study highlight the importance of tree species diversity and the abundance of old trees in the city to improve the residents' subjective well-being. These findings are supported by numerous international studies that highlight the positive effects of species and structural diversity of urban forests and greenspaces on its cooling capacity, the reduction of stress, and the minimization of allergy impacts. Thereby, the results highlight that beyond the focus on single tree species, the consideration of tree species diversity will enhance the capacity of urban forestry and urban planning to create health-promoting urban greenspaces. The results should therefore be taken up by urban foresters, horticulturists, urban planners, landscape architects, and engineers, which play an important role in a shift toward more biodiverse and health-promoting cities. Examples for approaches and related challenges are being discussed in the following.

According to Galle et al. (2021) the quantitative assessment of tree species diversity is a valuable tool for policymakers and tree managers to make informed decisions about suitable tree species and planting strategies. Furthermore, repeated observations of the urban tree species or genera diversity over time could provide insights about changes in this regard. On the one hand, this approach could show possible positive outcomes of previous interventions. Subsequently, Cameron et al. (2020) point out that despite the loss of native biological diversity, it can increase in urban green spaces due to targeted species selection. On the other hand, the observation of changes in the tree species diversity can reveal hotspots of ongoing biodiversity loss.

The results of this study may enhance the relevance of design-supporting frameworks for urban greenspaces as developed by Jia et al. (2023) by adding a component of biodiversity and thereby contributing to human as well as the ecosystem's health simultaneously.

However, increasing the diversity of tree species in the urban context is accompanied by management challenges, for example, an additional effort in leaves removal due to the different leaf-shedding periods of different tree species. In this context, the previous point should be mentioned, according to which ecosystem-related disservices are rather low in the public perception, compared to some urban-related disservices. However, the perception of ecosystem disservices should be observed during the process of increasing urban biodiversity. Following this, interventions to strengthen people's environmental concerns through environmental information and education might enhance the acceptance of urban dwellers to urban biodiversity projects.

The measurement and characterization of ecosystem services or disservices, as well as their localization remains challenging for urban planning (Gould et al. 2019). Geo-information systems (GIS) provide a solution for this by holding opportunities for spatial visualizations of ESS (Sherrouse et al. 2011). At the same time, they allow this information to be accessible to the urban population through participative platforms, which can improve the benefits of urban green spaces to people (Brown et al. 2012).

The diversity hotspots of tree genera canopy in Karlsruhe were identified at the main cemetery, the district 'Waldstadt', the nature conservation area 'Fritschlach', the area around the 'Turmberg', and areas at the 'Bergdörfer' (Bergwald, Grünwettersbach and Hohenwettersbach). As these areas were mainly managed with a special regard to tree species and nature conservation, they are examples of a successful practice.

Interestingly, a significant proportion of participants' subjective well-being locations were areas, which are declared as habitats for insect or plant species that are relevant for biodiversity promotion (Stadt Karlsruhe 2021). This underlines the importance of urban biodiversity management for both, species conservation and urban dwellers well-being.

The study in Karlsruhe, Germany, addresses the severe challenges of adequately considering the amount and quality of urban greenspaces during continuous population growth and need for creating appropriate living space. These challenges are faced by many mid-sized cities within Europe and worldwide. The findings underscore the importance of maintaining green spaces and enhancing its diversity amidst urban expansion. By understanding the value of urban forests to residents, cities can develop comprehensive and collaborative conservation strategies that simultaneously promote biodiversity and human well-being. These insights are not only relevant to Karlsruhe but also offer valuable guidance for other cities experiencing similar pressures.

Referring to the previous discussion, the future challenge for urban forestry is to consider the computed tree species diversity to support urban ecosystems, and to bring this together with influencing factors on people's perceptions of tree species diversity, to support their subjective well-being. This relation warrants further research.

4.5. Limitations of the study and direction of future research

Generally, the quality of the subjective well-being measurement underlies some restrictions that also apply in this study. People's indications are always influenced by distortion due to their memory (Diener et al. 2018). In its guideline on the measurement of subjective well-being, the OECD (2013) points out that comparing the subjective well-being drivers is difficult. For example, a wide range of co-variates and sociodemographic variables have to be included in the analysis and the relevant drivers' co-variates to capture the complexity of the entire concept (OECD 2013). Another challenge is the integration of a large sample size to identify possible subordinate drivers, as well as drivers that are important for minorities within the population (OECD 2013). Further, the utilization of an online map-based questionnaire is accompanied by the limitation of lacking knowledge about the spatial accuracy of participants' indications on the map, which might influence the results.

Regarding the tree genera diversity, the potential of the sensitivity to rare species of the Shannon Diversity Index (Gotelli and Colwell 2001), could not be fully exploited due to the limitation on the restriction to nine tree genera. This limits the informative value of this study, as these insights might contribute to the conservation of threatened urban tree species (Gotelli and Colwell 2001). These rare tree genera are summarized under the category 'other' in this study, which obscures the potential of higher diversity values at places with trees of several rare species, for example in the botanical garden. However, the hotspots of tree genera canopy categorized as 'other' were mainly located at places where the diversity of tree genera canopy was rather high. Hence, it might diminish the diversity index at these places, but this should not affect the general tendency of the results. We did not find a significant relation between the measured diversity of tree genera canopy and urban dwellers' subjective well-being at a location, which may be due to the limited dataset of only nine tree genera used to calculate the biodiversity at the location.

Future research necessitates enhanced data on actual biodiversity, encompassing tree species, shrubs, flowering plants, grasses, and additional structural components. Furthermore, studies might benefit from incorporating functional trait information as recommended by Goodness et al. (2016). To transfer the findings, it is crucial to identify causal relationships between the quality of urban green spaces and the physical and mental well-being pathways. The findings of this study indicate that tree cover density, tree size, and species diversity could serve as initial focal points for future investigations to reveal causal relationships. Additionally, longitudinal studies to track changes over seasons and time should be emphasized. This could provide a more comprehensive understanding of the dynamics between urban green spaces and well-being.

5. Conclusion

The perceived biodiversity of the urban forest positively correlated with the respondents' subjective well-being. The amount of tree cover, the abundance of large trees, and the perceived species diversity increase the urban population's well-being. The results of the study, therefore, emphasize the need for an increased tree species diversity and a number of old and large trees to enhance the residents' well-being. How this can be prioritized and integrated into urban planning needs to be studied. A perceived unkemptness of urban areas had a negative effect on the residents' well-being at the location. This should be considered in the design of future urban green spaces. At the same time, future research should focus on how the naturalness of urban green spaces is perceived differently by residents of different ages, cultural and educational backgrounds. Overall, the study emphasizes the importance of a better understanding of the factors influencing perceived biodiversity to complement urban planning decision-making.

CRediT authorship contribution statement

Johanna Krischke: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Angela Beckmann-Wübbelt:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration. **Rüdiger Glaser:** Writing – review & editing, Supervision. **Sayantan Dey:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Somidh Saha:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The Authors declare no Competing Financial or Non-Financial Interests.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106294.

Data availability

The data derived from the questionnaire survey is made available via https://doi.org/10.6084/m9.figshare.26798551.

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