Landsc Ecol (2024) 39:152
https://doi.org/10.1007/s10980-024-01937-6

RESEARCH ARTICLE

Disentangling associations of human wellbeing with green infrastructure, degree of urbanity, and social factors around an Asian megacity

Pramila Thapa · Mario Torralba · Nils Nölke · Koushik Chowdhury · Harini Nagendra · Tobias Plieninger

Received: 27 December 2023 / Accepted: 1 July 2024 / Published online: 8 August 2024

Abstract

Context Often called a 'Garden city', Bengaluru is renowned for its green infrastructure. However, the association of human wellbeing with the amount of tree cover (as an example of green infrastructure), degree of urbanization, and local people's socio-demographics has not been explored.

Objective We investigated how human wellbeing is related to the amount of tree cover at household and neighborhood levels, the degree of urbanity, and underlying social factors among respondents.

Methods The study was conducted in 61 towns along the rural–urban gradient of Bengaluru, surveying 836 respondents in total. Data on multiple dimensions of respondents' wellbeing was collected between December 2016 and May 2017. The percentage of tree cover at the household and neighborhood levels was obtained based on WorldView-3 images. Logistic regression models were applied to assess correlations between human wellbeing and tree cover. Kruskal–Wallis tests, Mann–Whitney tests, and cross tabulation with chi-square tests were conducted to investigate relations of human wellbeing with the degree of urbanity, and with social factors.

Results We found that several variables of human wellbeing were positively associated with tree cover. Measures of wellbeing also differed along the rural–urban gradient and among social groups.

Conclusions Though urbanization is often considered to promote material wellbeing, non-material aspects (e.g., community activities and social relationships) are also important components of overall human wellbeing in urbanizing landscapes. Holistic interactions among natural, spatial, and social factors should be considered while designing interventions

P. Thapa (✉) · K. Chowdhury · T. Plieninger
Faculty of Organic Agricultural Sciences, University of Kassel, Steinstr 19, 37213 Witzenhausen, Germany
e-mail: pthapa.green@gmail.com

P. Thapa
Social-Ecological Systems Institute, School of Sustainability, Leuphana University of Lüneburg, Universitätsallee 1a, 21335 Lüneburg, Germany

M. Torralba
Institute of Environmental Studies, Vrije University Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, The Netherlands

N. Nölke
Chair of Forest Inventory and Remote Sensing, University of Göttingen, Büsgenweg 5, 37077 Göttingen, Germany

H. Nagendra
Centre for Climate Change and Sustainability, Azim Premji University, Burugunte Village, Survey No 66, Bikkanahalli Main Rd, Sarjapura, 562125 Bengaluru, Karnataka, India

T. Plieninger
Department of Agricultural Economics and Rural Development, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany

for equitable urban landscapes that promote human wellbeing and ecological restoration.

Keywords Green spaces · Landscape sustainability science · Nature-based solutions · Remote sensing · Tree cover · Urbanization

Introduction

Although annual urban population growth rate is slowing globally (Vollset et al. 2020) from 2.7% in the 1980s to 1.6% in 2022, it remains high in the Global South, especially in South Asia (2.3%, 2022) and Sub-Saharan Africa (3.9%, 2022) (World Bank, 2023a). At least 56% of the world's population currently lives in urban areas, and that figure is expected to increase to 70% by 2050 (World Bank 2023b). These elevated levels of rapid urban population growth are putting pressure on land use and land cover (Genet 2020), and consequently on ecosystem services and human wellbeing (Thapa et al. 2021). Therefore, environmental and societal benefits and harms are likely to be inequitably distributed, threatening human wellbeing among urbanites (Liotta et al. 2020).

Urban landscapes are commercial, institutional, and residential hubs that support people by providing employment, education, and entertainment opportunities. The availability of economic and social resources in cities is an important pull factor for immigrants (Ghafoor and Akbar 2022). However, cities also have some challenges, e.g., unhealthy urban lifestyles. Due to predominantly sedentary urban lifestyles, people tend to have more chronic health issues, such as diabetes and cardiovascular diseases. Respiratory diseases are other health challenges that are more common in urban areas with high levels of air pollution (Gryech et al. 2022). As for social aspects, despite the mostly increased access to social networks (Connell and Keen 2018), the less community-oriented lifestyle in cities may reduce the social safety nets of urbanites, which can have implications in several dimensions of human wellbeing. These negative impacts are particularly severe in unplanned cities, which commonly consist of dense urban slums with poor hygienic conditions, and which are especially abundant in the Global South. Exposure to flash floods, dirty ditches, and waterborne communicable diseases such as diarrhea, cholera, etc. are common in unplanned cities, making urbanites more vulnerable to poor health (Khan et al. 2024).

Green infrastructure, which has a great potential of fostering human wellbeing in cities, is defined as a network of natural and semi-natural elements of environmental features designed to deliver multiple ecosystem services to benefit people (de Macedo et al. 2021). It is one of the important components of sustainable urban landscapes and is known for its role of strengthening human-nature relationships among urbanites (Hoyle and Sant'Anna 2023). It brings a wide range of benefits to humans, including promotion of physical and mental health (Grigoletto et al 2023), increase in social interaction among humans, climate regulation (Choi et al. 2021), and overall improvement in life satisfaction (Jiang and Huang 2022).

Urbanization is often aimed at the improvement of human wellbeing. The urban infrastructure such as transportation systems, residential buildings, communication systems, education systems, sewage and water systems, etc. are all are designed to foster human wellbeing. However, as a side-effect of urbanization, soil sealing, densification of built-up areas, air, water and sound pollution, decrease of urban green infrastructure, etc. pose challenges to ecosystem functionality and impoverish human wellbeing. Urbanites are likely to be more vulnerable to climate change impacts than rural dwellers (Ren et al. 2022). Urban heat islands have increased the number of illnesses, hospitalizations, and even deaths, especially among children and elderly people. Increasing green vegetation, especially tree cover, has potential to regulate urban pollutants and simultaneously to foster recreation, physical and social activities, which ultimately decrease health risks among the urbanites (Kraemer and Kabisch 2022).

Tree cover—one of the important elements of green infrastructure—has been considered as a nature-based solution to a wide range of societal challenges (Langemeyer and Baró 2021). It naturally regulates air and water by absorbing pollutants through gaseous, water, and energy exchange (Ren et al. 2018). The reduction of pollutants in air and water decreases air- and water-borne diseases, e.g., asthma, bronchitis, typhoid, and cholera (Hartig et al. 2014). Often, shades of larger canopy of tree cover can be a place for rest and physical recovery, especially on hot

days (Thapa et al. 2023). In some European countries, tree cover has helped reduce premature death associated with urban heat island effects (Iungman et al. 2023). Access to tree covers also offers opportunities for creativity and inspiration (Zhang et al. 2022). Regular access to tree cover for outdoor leisure and social activities in urbanizing landscapes promotes social cohesion, which ultimately fosters overall wellbeing (Dallimer et al. 2012). Thus, tree cover appears to contribute to human wellbeing and to landscape sustainability along multiple dimensions, although these interactions have rarely been disentangled.

Human wellbeing is typically mediated by several social factors. For example, men particularly have better access to health, education, and employment facilities compared to women (Azad et al. 2020). As for occupation, the majority of farmers in the Global South are smallholders and subsistence farmers (Bisheko and Rejikumar 2023). Though farmers seem to have a higher level of wellbeing than non-farmers, the growing uncertainty due to climate change, market fluctuation, and technologies could have a particularly strong influence on their wellbeing (Béné et al. 2019). Similarly, in South Asian countries, such as Nepal, and India, caste-based inequalities are culturally deep-rooted and often shape access to resources and services (Sengupta et al. 2021). Moreover, the number of years lived in a town can influence sociocultural integration, access to services, and exposure to a lifestyle. Other factors such as community engagements and local agencies for community engagement can also contribute to the wellbeing of the residents (Atkinson et al. 2020).

Studies on the interactions between human wellbeing and green infrastructure have mainly focused on the dimension of health (Sugiyama et al. 2008; Helbich et al. 2018; Kim and Miller 2019; Grigoletto et al. 2023), and most of them were conducted in urban landscapes of the Global North. Fewer studies have focused on the links between human wellbeing and green infrastructure in the Global South, and those that do exist (see, e.g., Mansor and Said 2008; Gopal and Nagendra 2014) typically did not investigate multiple dimensions of wellbeing. To our knowledge, the roles of rural–urban gradients and underlying social factors to human wellbeing have also not yet been assessed in a single study. Such information may be of use for informing policies that foster urban landscape sustainability. By combining remotely sensed tree cover data with a social survey, this study aims to disentangle the associations of multiple dimensions of human wellbeing with the amount of tree cover, at household and neighborhood levels, while also considering the degree of urbanity and social factors. We examined the following specific research questions:

- How is human wellbeing associated with the amount of tree covers at household and neighborhood levels in an urbanizing landscape?
- How is human wellbeing expressed along a rural–urban gradient?
- How is human wellbeing associated with social factors such as gender, farming background, caste, and the number of years lived in the current town?

Methods

Study area

The study was conducted in Bengaluru (12°44′ 06″ N; 77° 24′ 05″ E to 13°12′ 48″ N; 77° 44′ 17″), the capital of the state of Karnataka in southern India. Bengaluru is India's IT hub and is colloquially known as the 'Silicon Valley of India'. It is a rapidly expanding megacity and is situated on the Deccan Plateau between the Western and Eastern Ghats. It has an altitude of approximately 920 m above sea level and a mean annual rainfall of between 700 and 900 mm (Sudhira and Nagendra 2013). At the time of its establishment in 1537, Bengaluru was a small mud fort that continuously underwent changes due to its governance and geographical area during turnovers between the different rulers before India's independence. The area of Bengaluru has since rapidly expanded, from 69 km^2 to 741 km^2 as of 2019 (Ramachandra and Aithal 2019). Over the last two decades, the population density in Bengaluru has grown from 7,881 persons/km^2 in 2001 (Ramachandra and Kumar 2008) to 19,190 persons/km^2 in 2024. As of 2024, Bengaluru has a total population of 14 million inhabitants (World Population Review 2024).

Green infrastructure is an inherent part of Bengaluru's urban landscape. Bengaluru hosts trees in streets, home gardens, public parks, heritage parks, and sacred groves (Nagendra and Mundoli 2019). Thus, it has become known as a 'garden city'. The practices

of planting trees and creating gardens in Bengaluru, both in private and public places, date back to the pre-colonial era. These practices were continued or even promoted by several different rulers for both their material and non-material benefits, and to protect Bengaluru from potential invaders (Nagendra 2016). Though trees have been grown in Bengaluru for multiple reasons (e.g., food, wood, medicinal values, shade, air purification, and religious and spiritual purposes), they are currently most prominently appreciated for their aesthetic values and cooling effects (Thapa et al. 2023). Green infrastructure near houses is mainly of large canopy size, and domestic trees are predominantly intended for fruit production (e.g., mango, jackfruit, guava, or drumstick trees). However, some green infrastructure is also grown for ornamental, aesthetic, and regulating values (e.g., bougainvillea) and medicinal values (e.g., neem). Other green infrastructures, such as silver oak and teak trees, are cultivated in the field margins, and rain trees, pongemia, and tamarind are mainly found along the margins of roads. Traditional sacred platforms and temples are also rich in tree species, particularly banyan, peepal, and neem. Thus, Bengaluru hosts green infrastructure both in private and public spaces at landscape scale (Thapa et al. 2023).

Concept of human wellbeing

Human wellbeing can be defined as a state in which the basic human needs for quality life are met. It includes resources and opportunities that can be objectively measured (Gilbert et al. 2016). However, studies such as Aguado et al. (2018) and Atkinson et al. (2020) have highlighted that wellbeing also has a subjective component. Subjective wellbeing is expressed in an individual's life circumstances and is mediated by the cultural context (Gilbert et al. 2016). Moreover, comprehensive wellbeing—including both subjective and objective indicators—is often considered to better represent reality than a subjective or objective indicator used alone (Lambert et al. 2020). This study was designed around the wellbeing framework proposed by Rogers et al. (2012), which covers eight dimensions: physical and economic security; material living standards; health; work and leisure; agency and political voice; social relationships; stable ecosystems; and education. To operationalize this framework, we considered at least one indicator variable per dimension, combining subjective and objective indicators (Table 1).

Selection of households

This study was based on a household survey conducted between December 2016 and May 2017. The survey covered households within the two transects (Northern Transect: 77.5645° E, 13.0617° N; 77.6100° E, 13.0614° N; 77.6112° E, 13.4072° N; 77.5632° E, 13.4067° N and Southern Transect: 77.5404° E, 12.9149° N; 77.58161° E, 12.8952° N; 77.5385° E 12.7445° N; 77.4776° E 12.6677° N; 774,058° E, 12.6676° N; 77.3946° E, 12.7548° N, Hoffmann et al. 2017) along the rural–urban gradient of Bengaluru (Fig. 1). To account for the differences along Bengaluru's rural–urban gradient, each transect was divided into three strata (urban, transitional, and rural), according to the distance to the city center of Bengaluru and the proportion of built-up infrastructure (Hoffmann et al. 2017). For a total of six strata (three in each transect), approximately 10 towns per stratum (61 in total, or approximately 30% of the total towns located within the two transects) were selected for the survey. The household lists of each town were accessed through local child health care centres. These child health care centres, locally known as *Anganwadi* centres, are units that provide health and pre-school services for children under 6 years of age. They are also responsible for maintaining a list of households in their respective towns (Purushotham et al. 2022). Approximately 20 households per selected town were randomly surveyed. A total of 1,275 households were surveyed for the study. All the households were georeferenced. In the case that selected households were too close in proximity to one another, only one household within the group was included in the study. In the end, 836 surveyed households were considered in the analysis.

Household survey

The household survey collected information related to: A) socio-demographic information (gender of the household head, number of years lived in the town, caste, education level of the household head, and whether the household performs farming activities); and B) information on human wellbeing (Table 1). For each wellbeing dimension, indicator questions

Table 1 Overview of dimensions of human wellbeing and indicators considered in this study

Dimension of wellbeing and its respective variables	Description	Categories	No. of responses
1. Physical and economic security			
Social safety net	Number of people trusted within and outside the village to depend upon in times of hardship	(1) Less than 10 people (2) 10–50 people (3) More than 50 people	815
2. Material living standards			
Land ownership	Ownership of a piece of land	(1) Land owners (2) Landless	815
3. Health			
Physical health	Absence of a physical disease among the household	(1) Healthy (2) Unhealthy	784
4. Work and leisure			
Employment	Employment status of the respondent	(1) Employed (2) Unemployed	836
Park visitation frequency	Frequency at which the respondent visits a park	(1) At least once a year (2) At least once a month (3) At least once a week	311
5. Agency and political voice			
Community participation frequency	Frequency of respondent's participation in community activities	(1) At least once a year (2) At least once a month (3) At least once a week	361
6. Social relationships			
Sense of belonging	A psychological feeling of social or cultural connectedness to a group during the social interaction	(1) Not at all (2) Slightly (3) Moderately (4) Quite a bit (5) Very much	809
7. Stable ecosystems			
Climate shock intensity	Experience of any climate-related shock in the past 12 months, and its intensity	(1) Severe (2) Moderate (3) Mild	718
8. Education			
Formal education level	Highest education level of the household head	(1) No formal education (2) Up to high school (3) Diploma and above	799

were designed to reflect that dimension. For example, for the dimension of physical and economic security, we asked: 'How many people within and outside the town do you know who you could depend on in times of hardship?' For the dimension of stable ecosystems, we asked 'How intensely do you experience climate shocks? (Response scale: 1. Severely, 2. Moderately, 3. Mildly). Locally trained research assistants collected the responses. Questions were asked to the household heads and in the local language- and recorded in English. The survey began with an introduction to the research study and its aim. Informed consent was collected from each respondent before beginning the survey.

Measurement of tree cover

The tree cover was mapped based on a WorldView-3 image acquired in November 2016 under cloud-free conditions. A deep learning multi-class classification method called U-Net (Ronneberger et al. 2015) was employed to classify the WorldView-3 image into three classes: tree cover, impervious surface, and built-up areas. The U-Net employs a convolutional network architecture designed for image segmentation

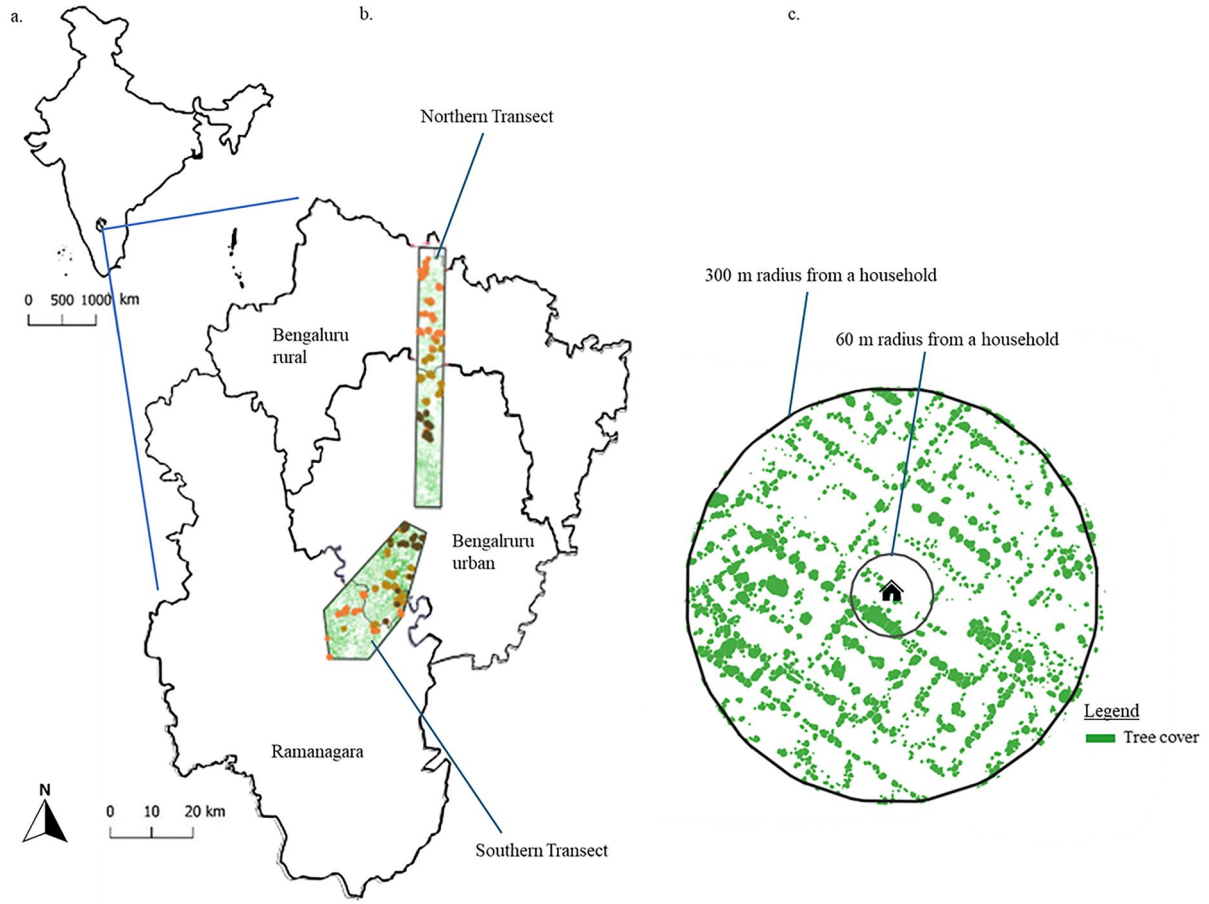

Fig. 1 **a** Location of Bengaluru in the map of India. **b** Study areas showing clusters of surveyed households in orange dots (rural), brown dots (transitional), and black dots (urban), and within Northern and Southern transects along the rural–urban gradient of Bengaluru. The transects shown in green visualize tree cover as derived from WorldView-3. **c** Exemplary tree covers at 60 m and 300 m radii from a household

and has demonstrated efficacy in handling diverse image classification tasks leading to a better performance in delineating boundaries and differentiating between complex classes in high-resolution satellite imagery.

The overall accuracy (OA) achieved was 89% for tree cover, 92% for impervious surface, and 87% for built-up areas. For this study, the class "tree cover" was extracted from the classified image (e.g., Fig. 2). Subsequently, the tree cover map was vectorized, resulting in polygons that were intersected with the household buffers to determine the proportional tree cover within the specified radius. Specifically, the amount of tree cover was extracted at the household level, considering a 60 m radius around each house, in accordance with the methodology employed by Netusil et al. (2014). Additionally, tree cover was assessed at the neighborhood level incorporating a 300 m radius around each house, as per the method described by Konijnendijk (2022). Pearson's correlation coefficient showed that tree cover at the household and neighborhood levels was moderately correlated ($r(835) = 0.42$, $p < 0.001$) .

Data analysis

To assess associations between human wellbeing and tree cover, logistic regression models were run for each human wellbeing variable as a response variable, and with tree cover in a 60 m radius or tree

Fig. 2 Two images illustrating higher (left) and lower (right) degrees of tree cover in Bengaluru. The false-color satellite images are WorldView-3 images with 30 cm resolution

cover in a 300 m radius as an independent variable in each model. Binary logistic regression models were run for binary variables of human wellbeing and for the ordinal variables for which only three possible answers were given (after converting them to binary variables). For the ordinal variables with responses scored on five-point Likert scales, ordinal logistic regression was performed. We calculated Odds Ratio (OR) for both binary and ordinal logistic regressions. Odds ratio, in our case, presents the likelihood of association between the tree cover with the respective human wellbeing. Post correlation assessment such as pseudo R^2, receiver operating characteristics (ROC), and Hosmer–Lemeshow (HL) test (Hosmer et al. 2013) were run. To assess if the distribution of human wellbeing was significantly different among urban, rural, and transitional areas, binary variables were cross-tabulated. For all ordinary variables, Kruskal–Wallis tests and post-hoc tests (with Bonferroni correction) were performed, investigating wellbeing variables by urban, rural, and transitional town groupings. To understand the association between human wellbeing variables and social factors, cross-tabulation between binary wellbeing variables and the given social factors was performed. For the ordinal variables, Mann–Whitney U tests were run for gender and farming backgrounds, and Kruskal–Wallis tests and post hoc tests (with Bonferroni correction) were run for caste and the number of years lived in the current town. All analyses were performed using IBM SPSS Statistics Version 29.0.1.0 (171).

Results

Association between tree cover and human wellbeing dimensions

Several of the variables of human wellbeing were positively associated with tree cover (Table 2). For example, in regard to physical and economic security, the higher the tree cover, higher was the (medium-sized) social safety net both at the household ($OR = 1.01$, $p < 0.01$) and neighborhood levels ($OR = 1.02$, $p < 0.05$). As for the dimension of material living standards, the percentage of households owning land was significantly higher in areas of higher tree cover, both at the household ($OR = 1.03$, $p < 0.05$) and neighborhood levels ($OR = 1.04$, $p < 0.05$). In terms of health, households in which all members were reported to be physically healthy were positively associated with tree cover at the household ($OR = 1.17$, $p < 0.01$) and neighborhood levels ($OR = 1.27$, $p < 0.05$). For the work and leisure dimension, being employed was not correlated with tree cover. However, park visitation frequency was higher in areas of higher tree cover, at both the household ($OR = 1.09$, $p < 0.01$) and neighborhood levels

Table 2 Associations between the degree of tree cover at household (HH, radius: 60 m) and neighborhood (NBH, radius: 300 m) levels with human wellbeing variables

	Physical and economic security				Material living standards		Health		Work and leisure		Park visitation frequency			
	Medium safety net		Big safety net		Land ownership		Physical health		Employment		Monthly		Weekly	
	HH	NBH	HH	NBH	HH	NBH	HH	NBH	HH	NBH	HH	NBH	HH	NBH
B (SE)	0.02 (0.01)	0.02 (0.01)	0.01 (0.01)	−0.01 (0.01)	0.03 (0.01)	0.04 (0.01)	0.16 (0.01)	0.19 (0.04)	0.02 (0.01)	0.02 (0.01)	0.15 (0.03)	0.02 (0.04)	−0.02 (0.01)	−0.02 (0.01)
OR	1.01**	1.02*	1.01	0.99	1.03*	1.04*	1.17**	1.27**	0.98	1.02	1.09**	1.28**	0.99*	0.99**
Wald Chi	11.28	10.67	0.44	0.50	11.56	11.09	0.12	0.20	4.39	4.30	126.76	96.90	5.20	6.90
P-value	<0.01	<0.01	0.50	0.479	<0.00	<0.00	0.73	0.65	0.03	0.03	<0.00	<0.00	<0.02	<0.01
Pseudo R2	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.005	0.03	0.021	0.01	0.01
ROC value	0.59	0.59	0.54	0.54	0.57	0.57	0.50	0.50	0.53	0.53	0.61	0.61	0.45	0.45
H–L test	0.20	0.16	0.08	0.17	0.88	0.41	0.23	0.65	0.50	0.73	0.61	0.11	0.06	0.06
	Community participation frequency				Climate shock intensity				Education				Social relationships	
	Monthly		Weekly		Moderate		Mild		Up to high school		Diploma and above		Sense of belonging	
	HH	NBH	HH	NBH	HH	NBH	HH	NBH	HH	NBH	HH	NBH	HH	NBH
B (SE)	0.03 (0.01)	0.03 (0.01)	−0.01 (0.01)	−0.01 (0.01)	0.00 (0.01)	0.00 (0.01)	0.00 (0.01)	0.00 (0.01)	−0.01 (0.01)	−0.01 (0.01)	0.00 (0.01)	0.00 (0.01)	0.00 (0.01)	0.00 (0.01)
OR	1.03*	1.04*	0.99	0.99	1.00	1.00	1.00	1.00	0.98*	0.98	1.00	1.00	1.00**	1.00**
Wald Chi	7.52	8.23	0.24	0.24	0.31	0.34	0.01	0.03	3.97	3.24	0.05	0.05	7.90	8.44
P-value	<0.01	<0.01	0.62	0.62	0.57	0.56	0.92	0.85	<0.05	0.07	0.83	0.83	<0.01	<0.01
Pseudo R2	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
ROC value	0.60	0.60	0.51	0.51	0.51	0.51	0.51	0.51	0.55	0.55	0.45	0.45		
Log Likelihood													− 136.31	− 435.36
H–L test	0.30	0.35	0.53	0.24	0.55	0.47	0.84	0.46	0.63	0.46	0.26	0.29		

Significance levels: **p < 0.01, *p < 0.05; *p<0.05. B: Beta coefficient, SE: Standard error, OR: Odds Ratio. References categories of human wellbeing variable are not presented in the table. They are: small safety net (physical and economic security), landless (material living standards), unhealthy (physical health), unemployed (employment), yearly (park visitation frequency), yearly (community participation frequency), severe climate shock intensity (stable ecosystems), and no formal education (education)

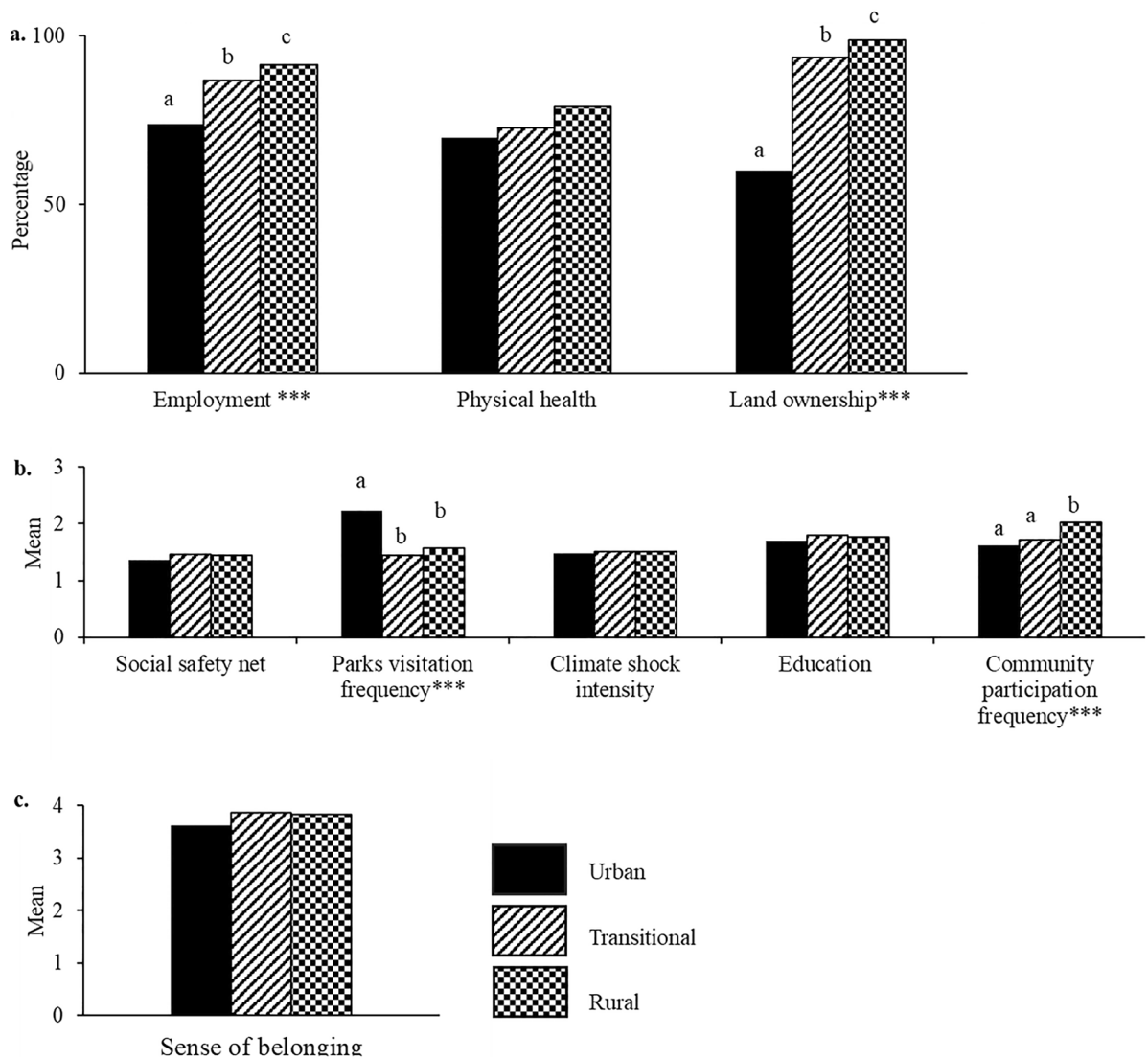

Fig. 3 The distribution of human wellbeing along the rural–urban gradient **a** graph representing the percentage of binary wellbeing variables: employment, physical health, and land ownership **b** graph of mean value of three-point Likert-scale wellbeing indicators. **c** graph of mean value of five-point Likert-scale wellbeing indicator. Significant difference levels indicated with $^{**}p < 0.01$ and $^{***}p < 0.001$; and differences with and the different alphabets on top of the bars a, b, and c (same alphabets mean not different), with Chi-square test for binary indicators and Kruskal–Wallis H tests for ordinal indicators

(OR = 1.28, $p < 0.01$). Likewise, in terms of agency and political voice, a monthly community participation frequency was correlated with areas of higher tree cover at both the household (OR = 1.03, $p < 0.05$) and neighborhood level (OR = 1.05, $p < 0.05$). In contrast, households in which the head of the household had a high school education level were negatively correlated with tree cover at the household level (OR = 0.98, $p < 0.05$). The dimensions of work and liesure and stable ecosystems were not associated with tree cover at either the household or neighborhood levels.

Differences in wellbeing along the rural–urban gradient

Several wellbeing variables differed between urban, transitional, and rural landscapes (Fig. 3). The percentage of households owning land was higher in rural and transitional areas than in urban areas ($X^2 = 171.98$, $p < 0.01$). Physical health was similarly distributed along the gradient. Employment levels were higher in transitional areas than in rural or urban areas ($X^2 = 216.85$, $p < 0.01$), and park visitation rates were highest in urban and transitional areas ($H = 44.38$, $p < 0.001$). Community participation frequency was higher in rural areas than in urban and transitional areas ($H = 18.93$, $p < 0.001$). We did not find statistically significant differences for the remaining indicators.

Social factors related to human wellbeing

Some of the wellbeing dimensions were mediated by the sociodemographic backgrounds of the respondents (Table 3). A higher proportion of male-headed households had all family members in a physically healthy state as compared to female-headed households ($X^2 = 7.22$, $p < 0.01$). Similarly, males had a stronger sense of belonging than females had (Mann–Whitney $U = 63{,}102.50$, $p < 0.05$). Only one indicator—the social safety net—was higher among non-farming households than among those with a farming background (Mann–Whitney $U = 70{,}789.00$, $p < 0.05$). As for caste and number of years lived in the current town, we did not find strong associations with the wellbeing variables.

Discussion

Landscape sustainability science (LSS) focuses on the dynamic relationships between landscape-specific ecosystem services and human wellbeing, using spatially explicit methods to understand and improve these relationships (Wu 2013). Thus, LSS research aims at investigating how landscape patterns shape the long-term dynamics of human–nature interactions and foster human wellbeing (Wu 2012, 2021; Opdam et al. 2018). Current knowledge in urban sustainability science is mostly dominated and shaped by examples and researchers from the Global North (Nagendra et al. 2018). Green infrastructure is often prioritized in the Global North as a key component of LSS strategies to support human wellbeing in urban environments (Liberalesso et al. 2020). Though cities of the Global North and the Global South are distinctly different (Nagendra et al. 2018), there is strong evidence that green infrastructure plays a paramount role in terms of both landscape structures and ecosystem services and ultimately in human wellbeing also in the Global South (Thapa et al. 2023). However, a specific contextualization of green infrastructure in the Global South is needed because green infrastructure designed and implemented in the Global North does not per se fit into the context of the Global South (Nagendra et al. 2018). In the current era, urbanization is a major process of change that is relevant to landscape sustainability. As it pertains to green infrastructure, urbanization often poses threats of degrading green infrastructure and associated ecosystem services (Miroshnyk et al. 2022). Green infrastructure, however, is an integral part of urban ecology, as it contributes to urban ecological system and makes cities livable (Thapa et al. 2021; Konijnendijk 2022). This exploratory study by its nature found associations of human wellbeing with green infrastructure, spatial degree of urbanization, and social factors, taking the rapidly urbanizing city of Bengaluru as a case study.

Relationship between human wellbeing and tree cover around households

Tree cover, as an example of green infrastructure, is an important natural element in urban planning (Kanniah 2017). Bengaluru has deep-rooted and multifaceted associations with trees, indicating that they act as nature-based solutions in diverse pathways (Dhyani et al. 2021). Trees are appreciated for their regulating services, livelihoods, and cultural significances in the context of Bengaluru (Thapa et al. 2023). Our results indicated positive relationships between tree cover and various indicators of wellbeing, such as social safety net, physical health, park visitation frequency, and community participation

Table 3 Descriptive statistics of the different wellbeing indicators across gender, farming background, caste, and number of years living in the current town

Wellbeing variables		Gender			Farming background			Caste				Number of years lived in the current town			
		Binary variables													
		Female	Male	Chi sq	Yes	No	Chi sq	General	SC&ST	OBC	Chi sq	< 10	10–30	> 30	Chi sq
Land ownership	*Mean (SD)*	0.91 (0.28)	0.91 (0.29)	0.01	0.90 (0.30)	0.92 (0.27)	1.08	0.93 (0.26)	0.87 (0.34)	0.92 (0.27)	5.64	0.96 (0.21)	0.94 (0.24)	0.90 (0.3)	2.64
	Landowners (%)	91.26	90.98		90.23	92.38		92.64	87.10	92.23		95.65	93.98	90.16	
Physical health	*Mean (SD)*	0.67 (0.47)	0.77 (0.42)	7.22 **	0.76 (0.43)	0.74 (0.44)	0.57	0.75 (0.43)	0.77 (0.42)	0.73 (0.45)	0.84	0.67 (0.48)	0.77 (0.43)	0.76 (0.43)	1.87
	Healthy (%)	67.44	77.45		76.13	73.74		75.29	76.89	73.00		66.67	76.54	75.55	67.44
Employment	*Mean (SD)*	0.87 (0.33)	0.87 (0.34)	0.03	0.88 (0.33)	0.85 (0.35)	0.98	0.86 (0.35)	0.85 (0.36)	0.9 (0.3)	2.62	0.87 (0.34)	0.84 (0.37)	0.87 (0.33)	0.99
	Employed (%)	87.30	86.86		87.83	85.44		14.32	14.67	10.05		13.04	16.47	12.63	87.30
	Ordinal variables														
Wellbeing variables (Mean (SD))	Female	Male	MWU	Yes	No	MWU	General	SC&ST	OBC	KWH	< 10	10–30	> 30	KWH
Social safety net	1.47 (0.61)	1.43 (0.58)	56248.00	1.40 (0.57)	1.50 (0.61)	70789.00*	1.44 (0.56)	1.39 (0.59)	1.49 (0.64)	3.35	1.60 (0.58)	1.37 (0.53)	1.44 (0.59)	5.52
Park visitation frequency	1.61 (0.80)	1.70 (0.82)	9044.00	1.64 (0.79)	1.77 (0.87)	9715.50	1.77 (0.84)	1.54 (0.79)	1.70 (0.81)	4.95	1.44 (0.73)	1.82 (0.87)	1.67 (0.82)	2.44
Community participation frequency	1.81 (0.74)	1.90 (0.75)	12362.00	1.89 (0.76)	1.85 (0.72)	14566.00	1.88 (0.73)	1.82 (0.75)	1.91 (0.78)	0.61	2 00 (0.82)	1.85 (0.83)	1.89 (0.74)	0.52
Sense of belonging	3.63 (1.18)	3.87 (1.14)	63102.50*	3.86 (1.12)	3.73 (1.21)	80416.50	3.84 (1.13)	3.81 (1.15)	3.79 (1.20)	0.13	3.93 (1.14)	3.73 (1.21)	3.81 (1.15)	0.86

Table 3 (continued)

Wellbeing variables (Mean (SD))	Ordinal variables												
	Female	Male	MWU	Yes	No	MWU	General	SC&ST	OBC	KWH	< 10	10–30	> 30	KWH
Climate shock intensity	1.48 (0.65)	1.51 (0.63)	47763.50	1.49 (0.61)	1.53 (0.66)	58750.00	1.49 (0.62)	1.51 (0.63)	1.53 (0.65)	0.25	1.30 (0.51)	1.58 (0.65)	1.52 (0.64)	5.62
Education	1.77 (0.64)	1.76 (0.58)	55938.00	1.76 (0.58)	1.77 (0.61)	74711.50	1.75 (0.58)	1.79 (0.62)	1.74 (0.58)	0.85	1.74 (0.65)	1.81 (0.66)	1.76 (0.58)	0.43

Significance level = **p < 0.01, *p < 0.05; Chi sq.: Chi-square; MWU: Man-Whitney U test; KWH: Kruskal–Wallis H test; SD: Standard Deviation; SC&ST: Scheduled Castes and Scheduled Tribes; OBC: Other Backward Class

frequency. People often sit at the bases of large canopy trees to avoid the scorching sun during summer days, when the average daytime temperature is approximately 36 °C. The tree bases have also been important places for small local businesses and social cohesion, with people often setting up their commercial activities of bicycle repair and maintenance, clothes sales and tailoring, fruit sales, etc. at the base of trees (Basu and Nagendra 2020). Several recreational and social activities such as group exercise, doing yoga, drinking tea, etc. are often hosted near the base of a large tree. Together, these activities promote social cohesion and improve social safety nets (Dhyani et al. 2021). This finding is in line with those of Wan et al. (2021) who reported in their review that the social cohesion and safety net increased with the availability of tree cover as a green infrastructure. Despite the benefits that trees provide in cities, the amount of tree cover is globally degreasing (except in Europe) due to urban expansion and densification (Nowak and Greenfield 2020). Moreover, with the increase of built-up and impervious surfaces, urban soil quality and fertility usually deteriorate, which negatively affects the growth, development, canopy cover, and functioning of remaining trees. The Leave area index of trees is also usually lower in urban areas ecological functioning such as carbon sequestration and cooling effect of the trees (Ren et al. 2018). Given the (potential) consequences of urbanization, the extent of global urban tree cover changes are still to be explored. Understanding such changes could help guide sustainable urban policies and improve environmental management for livable cities (Nowak and Greenfield 2020).

We found that increased tree cover at both household and neighborhood levels was associated with higher community participation frequency. This may be because the greenery often encourages people to go out into nature and engage in community events, such as cleaning the community, performing communal homages (e.g. community feasts, worship of family deities (Mundoli et al. 2017)), performing and maintaining a community plantation (Nagendra 2016), or organizing public meetings and petitions at community levels (Trentanovi et al. 2021). With tree cover, people are also motivated to interact with each other, as well as with domestic pets, and wildlife (Taylor and Hochuli 2015). Birds and other wild animal species are common in Bengaluru, which are also

supported by natural spaces such as Bannerghatta National Park and Lal Bagh Royal Garden. Such spaces act as refuges for urban wildlife (Jaganmohan et al. 2018), and people are often attracted to visiting such parks during their leisure time. This is also confirmed by our finding that park visitation frequency was higher with increased tree cover. However, the relationship between park visitation and tree cover could be bidirectional, i.e., tree cover could be both an inspiration for or a result of increased park visitation. People may be more motivated to visit a park if the amount of tree cover is high, which are often a hotspot for biodiversity and a place of knowledge. Conversely, those who visit a park more frequently may have stronger incentives for increasing the existing cover. However, parks in the urban landscapes of the Global South are frequently gated. Especially, people with minority backgrounds often disproportionately experience barriers to accessing green infrastructure (Hamstead et al. 2018). In addition, absolute tree cover and tree cover per capita are decreasing in cities of the Global South (Zhang et al. 2023). Thus, we recommend that city governments should prioritize such nature-based solutions not only to promote ecological restoration but also to foster just human-nature relations. Care should be taken to ensure equitable access to green infrastructure and tree cover, supporting participation in community events and frequent park visits across different societal groups.

Our results highlight a positive association between tree cover and land ownership. This could also be a two-way association, as those who own a piece of land have a clear motivation for planting trees on it. Given the dry and hot summer weather conditions in Bengaluru, people often desire to own land that has trees or is near to trees, to enjoy their multiple benefits such as shade, air purification, water regulation, aesthetic values, and provision of fresh seasonal fruits and vegetables. Thus, planting trees or owning land with trees on it appears to be associated with higher overall wellbeing. Katusiime and Schütt (2020) similarly reported in their review that tree cover and land ownership were positively related. However, this was not always the case. In Chicago, USA, land ownership rather improved general vegetation cover but decreased amount and quality of mature tree cover (Gobster et al. 2020). We found that formal education level was negatively associated with tree cover at the household level. This might be because in our study area educated people generally live in highly urbanized areas where space for planting trees is limited. On the other hand, Li et al. (2019) found that formal education level was positively associated with tree cover; in their study, more students opted for higher education in areas with greater tree cover. These cases show that tree cover has been positively associated with various indicators of human wellbeing. Therefore, cities should have an adequate amount of tree cover to foster the comprehensive wellbeing of locals (Wu et al. 2023).

Dimensions of human wellbeing along the rural–urban gradient

Urbanization is a key aspect of landscape development processes. Urbanization also influences lifestyles. We found that the degree of urbanization was related to some dimensions of human wellbeing. Our study revealed differences in land ownership, employment, park visitation frequency, and community participation frequency along the rural–urban gradient. Another study reported higher levels of wellbeing being perceived in rural areas in countries of the Global North, and in urban areas in countries of the Global South (Requena 2016). Thus, it is important to consider the particular world region when assessing wellbeing along the rural–urban gradient. Ecosystem services are major factors that contribute to human wellbeing. Often unplanned urbanization happening in cities of the Global South comes at the cost of local landscape quality and ecosystem services (Davoren and Shackleton 2021). Though ecosystem services along the rural–urban gradient have been studied extensively (Kroll et al. 2012; Larondelle and Haase 2013; Baró et al. 2017; Thapa et al. 2023), human wellbeing along this gradient has rarely been studied. Materialistic lifestyles and market-driven consumption patterns are some of the generally perceived characteristics of urban life (Aguado et al. 2018). Our study aimed to expand beyond the limited material dimension of wellbeing. It found that urbanites valued also non-material aspects such as visiting parks more than people in rural and transitional areas. This finding is in the line with Zhu et al. (2020). Given the higher amount of tree cover in urban Bengaluru, people might have been motivated to visit parks more often than those in rural areas during their leisure. In rural Bengaluru, people are more engaged in farming

activities, which often keep people connected to nature, which may be why they feel less motivated to visit parks. In contrast to our finding, Shores and West (2010) found that park visitation frequencies were lower in urban areas than in rural areas. This finding suggests that urbanites are not limited to material wellbeing in Bengaluru but also enjoy non-material benefits such as recreation from green infrastructure. As for land ownership, fewer urbanites than rural people owned land in our case. The observed difference in land ownership rate between urban and rural people could be due to the higher price of urban land relative to rural land as was also shown to be the case in India in general (Binoy et al. 2022).

Community participation frequency was also higher in rural areas than in urban areas. Despite evidence that urbanization promotes material wellbeing (Chen et al. 2020), it is important to also consider non-material aspects, such as community participation and a sense of belonging, which are crucial components of human wellbeing. It is often expected that with more options for community engagement in urban areas, an urban lifestyle could support more frequent community engagement, but this was not the case in Bengaluru. Bengalurians have more frequent community engagement in rural areas than in urban areas. In contrast, in Nova Scotia (Canada) community engagement was relatively low in rural area mainly due to limited budget and ageing rural population (Reid and Howard 2016). The findings of Russell et al. (2023) in the USA, the UK and Guatemala also indicated less community engagement among rural people. Higher rates of unrecognized mental health, and physical health issues such as alcoholism and smoking observed in rural areas might have also reduced the frequency of community participation in rural areas in those countries (Tolonen et al. 2018). In Bengaluru, the relatively slow pace of life in rural areas might have motivated people to participate in community events, which might also have fostered a wider social safety net. We also found a higher employment rate (e.g., in crop and livestock farming sectors) people in rural areas. Though urban areas usually have better employment opportunities, the larger populations in urban areas may quickly fill the vacant positions, resulting in a relatively higher unemployment rate in urban areas than in rural areas. On the other hand, rural people in Bengaluru can often engage themselves in farming activities rather than simply stay idle.

In terms of the physical health dimension, we didn't find differences along the rural–urban gradient. However, in cities of the Global South, urbanites often have multiple lifestyle-related health issues (e.g., diabetes, cardiovascular diseases, etc.). Despite the existence of health facilities in urban Bengaluru, a considerable share of households had at least one family member with a disease, especially in better-off neighborhoods. In worse-off neighborhoods such as slums, the health of urbanities is threatened particularly by infectious diseases due to poor hygiene, e.g., HIV, tuberculosis, or diarrhea (Flies et al. 2019).

Relationship between human wellbeing and underlying social factors

Our results indicated that social factors were associated with some of the variables of human wellbeing. Gender and farming backgrounds are among the social factors that were associated. Starting with gender, higher percentages of male-headed households had all family members physically healthy compared to female-headed households. Our findings agree with those of Lebni et al. (2020), who found relatively lower levels of health among household members in female-headed households. The typically lower levels of formal education and health awareness among women in Bengaluru could be a potential explanation for this trend (Lebni et al. 2020). In Bengaluru, there is also a gendered pattern in diseases. Females tend to have more communicable diseases, while males tend to have more non-communicable diseases such as diabetes and cardiovascular diseases (Geetha et al. 2021). Male respondents also reported a higher sense of belonging than females did. In a patriarchal society as is the case in Bengaluru, males have more freedom of choice to go out and learn in general; this might lead to have their higher sense of belonging to the given ranges of settings than females have. However, a study by Pilarska (2017) did not uncover differences in sense of belonging between males and females.

Another association was identified between farming background and social safety net. Social safety nets are social risk management tools that one can rely upon during periods of hardship. These were found to be larger among non-farming households than among farming households. However, farmers—the majority

of whom are smallholders in Bengaluru—are often so vulnerable to poverty that they hardly invest in creating and maintaining social safety nets for themselves. Even (poor) farmers in the Global North rarely make efforts to establish social safety nets (Gunderse and Offutt 2005). Policy level acknowledgment and accounting larger operating systems and societal factors in which farmers are imbedded may foster social safety net among farmers (Becot and Inwood 2020).

Surprisingly, we did not find an association between caste and any wellbeing dimension. However, associations between caste and wellbeing have been reported by Fontaine and Yamada (2014), who found that the wellbeing of people from higher castes was three times greater than that of lower-caste people. Members of the Scheduled Tribes (ST) and Scheduled Castes (SC) have few social networks to rely upon during hardships. In India, where health and education services are relatively expensive, lower-caste people often have poor access to resources and cannot afford access to high-quality health and education. Lack of good education and good healthcare often keeps them out of job markets, and also prevents them from maintaining social safety nets (Beegle et al. 2018). It seems that strong disparities exist among castes in Bengaluru, which is negatively impacting the wellbeing of those from lower castes. People from lower castes are often stuck in a vicious cycle referred to as a poverty trap (Kumar 2022). However, in urbanizing contexts, the caste system tends to melt; marginalized caste people are often supported with income-generating activities by different organizations and the government so that they can uplift themselves from the poverty traps. This may be a reason why we did not find strong differences in the wellbeing among people from caste groups. Similarly, we did not find any relations between human wellbeing variables and the number of years lived in the current town, also known as 'groundedness'. Bahno et al. (2023) argued that groundedness depends not only on time but also on the shared values of the people. When people have a shared ethnicity or language, they often stand together and enjoy a larger safety net and higher levels of perceived wellbeing, even in a town in which they have only lived for a short time. Bengaluru is a multicultural and multilingual city with different groups of people from several native origins. People with shared cultural, lingual, and native backgrounds often tend to support each other and foster a better quality of life.

Limitations

Our study combined remote sensing data with socioeconomic survey data in a new way. The combination of the two datasets came with certain compromises. We had to fit the design into suitable analytical approaches based on the data we had. This may be a reason why we found limited associations between the variables of wellbeing and the other factors we considered. Another limitation is that tree cover was only considered quantitatively; we didn't consider qualitative aspects of tree cover such as configuration and density. Qualitative characteristics of tree cover could be important in revealing multidimensional aspects of human wellbeing, such as social background of the people (Wu et al. 2023) because higher tree cover per se may not mean a higher level of wellbeing. In addition, considering and assessing time series data on tree cover in relation to human welling would be helpful since amount tree cover is rapidly changing (mostly decreasing) with time and with urban expansion (Dong et al. 2020).

Conclusion

Trees are a valuable component of green infrastructure and play a critical role in landscape sustainability. Our study comprehensively investigated linkages of human wellbeing with tree cover, as well as spatial and social factors across multiple wellbeing dimensions in an urbanizing landscape. The results revealed associations between tree cover and multiple human wellbeing dimensions such as material, health, social, and recreational ones. We found that hiland ownership gher degrees of tree cover were related to material possessions such as land ownership, better physical health, more frequent park visits, and more frequent community engagement. Land ownership, park visitation frequency, and community engagement frequency differed along the rural–urban gradient. Gender and farming backgrounds were important socio-demographic characteristics that showed associations with human wellbeing. Trees

could thus provide important nature-based solutions to urban sustainability challenges. While designing such nature-based solutions, the multifunctionality of trees should be promoted both at household and neighborhood levels. In the process, inclusivity of diverse social groups should be prioritized to foster equitable and sustainable human-nature relationship in cities. For a sustainable urbanizing landscape, non-material wellbeing such as sense of belonging to the landscape and community engagement is also important (Demuzere et al. 2014; Loveridge et al. 2020). The number and amount of urban trees, forests, and protected areas should be increased and made accessible to all existing social groups. To design sustainable urban landscapes that promote comprehensive human wellbeing and ecological restoration, it is vital to consider the holistic interactions among tree cover and dynamic dimensions of wellbeing, including consideration of factors such as the rural–urban gradient and underlying socio-demographic characteristics of locals. Such understanding of nuances in interactions among these ecological, spatial, and social elements may inform sustainable urban policies and improve environmental management for livable cities.

Acknowledgements Our sincere thanks to all the respondents, research assistants, and field supervisors who facilitated and made the household survey possible. We also thank Ms. Sujana Silwal for helping with data cleaning. All authors acknowledge Prof. Dr. Meike Wollni and Dr. Anjali Purushotham for making the data on human wellbeing and social demographics available for this study. We also thank Dr. Linda Steinhübel-Rasheed and Dr. Anjali Purushotham for helping us understand the data. Many thanks also to Dr. Thomas Krikser and Dr. Irina Kuzyakova for their statistical advice during the data analysis.

This study was possible with funds from the German Research Foundation (DFG) in the second phase of project C03/FOR2432 entitled "Social-ecological dynamics, ecosystem services uses, and governance of green and blue infrastructure in urbanizing environments" with reference number 279374797.

Author contributions P.T., M.T., and T.P. developed the concept of the research and contributed to the literature search. P.T. did the majority of the data analysis with the support of K.C., M.T., and T.P. N.N. extracted the data on tree cover and developed Figure 1 and Figure 2. P.T. wrote the majority of the manuscript with the support of M.T., N.N., K.C., H.N., and T.P.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability The dataset used for this study is available in the 'Zenodo' https://doi.org/10.5281/zenodo.10432826.

Declarations

Competing interests The authors declare no competing interests.

References

Aguado M, González JA, López-Santiago C, Montes C (2018) Exploring subjective well-being and ecosystem services perception along a rural–urban gradient in the high Andes of Ecuador. Ecosyst Serv 34:1–10. https://doi.org/10.1016/j.ecoser.2018.09.002

Atkinson S, Bagnall AM, Corcoran R, South J, Curtis S (2020) Being well together: individual subjective and community wellbeing. J Happiness Stud 21(5):1903–1921. https://doi.org/10.1007/s10902-019-00146-2

Azad AD, Charles AG, Ding Q, Trickey AW, Wren SM (2020) The gender gap and healthcare: associations between gender roles and factors affecting healthcare access in Central Malawi, June–August 2017. Archives of Public Health 78:1–11. https://doi.org/10.1186/s13690-020-00497-w

Bahho M, Vale B, Milfont TL (2023) An investigation into heritage, sustainability, and place attachment: the Ōtātara case study. Herit Soc. https://doi.org/10.1080/2159032X.2023.2230832

Baró F, Gómez-Baggethun E, Haase D (2017) Ecosystem service bundles along the rural-urban gradient: insights for landscape planning and management. Ecosyst Serv 24:147–159. https://doi.org/10.1016/j.ecoser.2017.02.021

Basu S, Nagendra H (2020) The street as workspace: assessing street vendors' rights to trees in Hyderabad, India. Landsc Urban Plan 199:103818. https://doi.org/10.1016/j.landurbplan.2020.103818

Becot FA, Inwood SM (2020) The case for integrating household social needs and social policy into the international family farm research agenda. J Rural Stud 77:185–198. https://doi.org/10.1016/j.jrurstud.2020.05.005

Beegle K, Honorati M, Monsalve E (2018) Reaching the poor and vulnerable in Africa through social safety nets. In:

Beegle K, Honorati M, Monsalve E (eds) Realizing the full potential of social safety nets in Africa. The World Bank, Washington, pp 49–86. https://doi.org/10.1596/978-1-4648-1164-7_ch1

Béné C, Wam B, Kambala MK, Ndiaye A (2019) Resilience of local food systems and links to food security—a review of some important concepts in the context of COVID-19 and other shocks. Food Secur 12(4):805–822. https://doi.org/10.1007/s12571-020-01098-y

Binoy BV, Naseer MA, Anil Kumar PP (2022) Factors affecting land value in an Indian city. J Prop Res 39(3):268–292. https://doi.org/10.1080/09599916.2021.2014937

Bisheko MJ, Rejikumar G (2023) Major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia: a systematic literature review. World Dev Sustain. https://doi.org/10.1016/j.wds.2023.100070

Chen MX, Zhou Y, Tang Q, Liu Y (2020) New-type urbanization, well-being of residents, and the response of land spatial planning. J Nat Resour 35(6):1273–1287. https://doi.org/10.31497/zrzyxb.20200602

Choi C, Berry P, Smith A (2021) The climate benefits, co-benefits, and trade-offs of green infrastructure: a systematic literature review. J Environ Manage 291:112583. https://doi.org/10.1016/j.jenvman.2021.112583

Connell J, Keen M (2018) Urban transformations: from marginal to resilient Melanesian cities? Dev Bull 80:103–108

Dallimer M, Irvine KN, Skinner AM, Davies ZG, Rouquette JR, Maltby LL, Gaston KJ (2012) Biodiversity and the feel-good factor: understanding associations between self-reported human well-being and species richness. Bioscience 62(1):47–55. https://doi.org/10.1525/bio.2012.62.1.9

Davoren E, Shackleton CM (2021) Urban ecosystem disservices in the global south. In: Shackleton CM, Cilliers SS, Davoren E, du Toit MJ (eds) Urban ecology in the global south. Cities and nature. Springer, Cham, pp 265–292. https://doi.org/10.1007/978-3-030-67650-6_11

de Macedo LSV, Picavet MEB, de Oliveira JAP, Shih WY (2021) Urban green and blue infrastructure: a critical analysis of research on developing countries. J Clean Prod 313:127898. https://doi.org/10.1016/j.jclepro.2021.127898

Demuzere M, Orru K, Heidrich O, Olazabal E, Geneletti D, Orru H, Faehnle M (2014) Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. J Environ Manage 146:107–115. https://doi.org/10.1016/j.jenvman.2014.07.025

Dhyani S, Majumdar R, Santhanam H (2021) Scaling-up nature-based solutions for mainstreaming resilience in Indian cities. Ecosystem-based disaster and climate resilience: integration of blue-green infrastructure in sustainable development, 279–306. https://doi.org/10.1007/978-981-16-4815-1_12

Dong Y, Ren Z, Fu Y, Miao Z, Yang R, Sun Y, He X (2020) Recording urban land dynamic and its effects during 2000–2019 at 15-m resolution by cloud computing with Landsat series. Remote Sens 12(15):2451. https://doi.org/10.3390/rs12152451

Flies EJ, Mavoa S, Zosky GR, Mantzioris E, Williams C, Eri R et al (2019) Urban-associated diseases: candidate diseases, environmental risk factors, and a path forward. Environ Int 133:105187. https://doi.org/10.1016/j.envint.2019.105187

Fontaine X, Yamada K (2014) Caste comparisons in India: evidence from subjective well-being data. World Dev 64(24683006):407–419. https://doi.org/10.1016/j.worlddev.2014.06.025

Geetha K, Vijayalakshmi D, Yatnatti S, Dittrich C, Patil DS (2021) Nutritional status of women across rural–urban interface of Bengaluru. The rural-urban interface: an interdisciplinary research approach to urbanisation processes around the Indian megacity Bengaluru 135–141. https://doi.org/10.1007/978-3-030-79972-4_14

Genet A (2020) Population growth and land use land cover change scenario in Ethiopia. Int J Environ Protect Policy 8(4):77–85. https://doi.org/10.11648/j.ijepp.20200804.12

Ghafoor N, Akbar MR (2022) Socioeconomic determinants of migration in the city of Lahore, Pakistan. J Knowl Econ 13(4):3029–3049. https://doi.org/10.1007/s13132-021-00844-4

Gilbert A, Colley K, Roberts D (2016) Are rural residents happier? A quantitative analysis of subjective wellbeing in Scotland. J Rural Stud 44:37–45. https://doi.org/10.1016/j.jrurstud.2016.01.002

Gobster PH, Hadavi S, Rigolon A, Stewart WP (2020) Measuring landscape change, lot by lot: greening activity in response to a vacant land reuse program. Landsc Urban Plan 196:103729. https://doi.org/10.1016/j.landurbplan.2019.103729

Gopal D, Nagendra H (2014) Vegetation in Bangalore's slums: boosting livelihoods, well-being and social capital. Sustainability 6(5):2459–2473. https://doi.org/10.3390/su6052459

Grigoletto A, Toselli S, Zijlema W, Marquez S, Triguero-Mas M, Gidlow C et al (2023) Restoration in mental health after visiting urban green spaces, who is most affected? Comparison between good/poor mental health in four European cities. Environ Res 223(February):115397. https://doi.org/10.1016/j.envres.2023.115397

Gryech I, Ghogho M, Mahraoui C, Kobbane A (2022) An exploration of features impacting respiratory diseases in urban areas. Int J Environ Res Public Health 19(5):3095. https://doi.org/10.3390/ijerph19053095

Gundersen C, Offutt S (2005) Farm poverty and safety nets. Am J Agr Econ 87(4):885–899. https://doi.org/10.1111/j.1467-8276.2005.00776.x

Hamstead ZA, Fisher D, Ilieva RT, Wood SA, McPhearson T, Kremer P (2018) Geolocated social media as a rapid indicator of park visitation and equitable park access. Comput Environ Urban Syst 72:38–50. https://doi.org/10.1016/j.compenvurbsys.2018.01.007

Hartig T, Mitchell R, De Vries S, Frumkin H (2014) Nature and health. Annu Rev Public Health 35:207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443

Helbich M, Klein N, Roberts H, Hagedoorn P, Groenewegen PP (2018) More green space is related to less antidepressant prescription rates in the Netherlands: a Bayesian geo additive quantile regression approach. Environ Res 166:290–297. https://doi.org/10.1016/j.envres.2018.06.010

Hoffmann EM, Jose M, Nölke N, Möckel T (2017) Construction and use of a simple index of urbanisation in the

rural–urban interface of Bangalore, India. Sustainability 9(11):2146. https://doi.org/10.3390/su9112146
Hosmer DW Jr, Lemeshow S, Sturdivant RX (2013) Applied logistic regression, 3rd edn. Wiley, Hoboken
Hoyle HE, Sant'Anna CG (2023) Rethinking 'future nature' through a transatlantic research collaboration: climate-adapted urban green infrastructure for human wellbeing and biodiversity. Landsc Res 48(4):460–476. https://doi.org/10.1080/01426397.2020.1829573
Iungman T, Cirach M, Marando F, Barboza EP, Khomenko S, Masselot P et al (2023) Cooling cities through urban green infrastructure: a health impact assessment of European cities. Lancet 401(10376):577–589. https://doi.org/10.1016/S0140-6736(22)02585-5
Jaganmohan M, Vailshery LS, Mundoli S, Nagendra H (2018) Biodiversity in sacred urban spaces of Bengaluru, India. Urban for Urban Green 32:64–70. https://doi.org/10.1016/j.ufug.2018.03.021
Jiang Y, Huang G (2022) Urban residential quarter green space and life satisfaction. Urban for Urban Green 69:127510. https://doi.org/10.1016/j.ufug.2022.127510
Kanniah KD (2017) Quantifying green cover change for sustainable urban planning: a case of Kuala Lumpur, Malaysia. Urban for Urban Green 27:287–304. https://doi.org/10.1016/j.ufug.2017.08.016
Katusiime J, Schütt B (2020) Linking land tenure and integrated watershed management—a review. Sustainability 12(4):1667. https://doi.org/10.3390/su12041667
Khan MA, Dakyaga F, Chilinde G, File DJMB (2024) Urban marginality: everyday practice of building resilience to flood in the informal settlement of Dar es Salaam. Geo J 89(3):103. https://doi.org/10.1007/s10708-024-11117-3
Kim G, Miller PA (2019) The impact of green infrastructure on human health and well-being: the example of the Huckleberry Trail and the Heritage Community Park and Natural Area in Blacksburg, Virginia. Sustain Cities Soc 48(March):101562. https://doi.org/10.1016/j.scs.2019.101562
Konijnendijk CC (2022) Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: introducing the 3–30–300 rule. J for Res 34:821–830. https://doi.org/10.1007/s11676-022-01523-z
Kraemer R, Kabisch N (2022) Parks under stress: air temperature regulation of urban green spaces under conditions of drought and summer heat. Front Environ Sci. https://doi.org/10.3389/fenvs.2022.849965
Kroll F, Müller F, Haase D, Fohrer N (2012) Rural–urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29(3):521–535. https://doi.org/10.1016/j.landusepol.2011.07.008
Kumar A (2022) Land and caste relations in North Bihar: observations from two villages. Rev Agrar Stud 12(1):90–113. https://doi.org/10.25003/RAS.12.01.0007
Lambert L, Lomas T, van de Weijer MP, Passmore HA, Joshanloo M, Harter J et al (2020) Towards a greater global understanding of wellbeing: a proposal for a more inclusive measure. Int J Wellbeing. https://doi.org/10.5502/ijw.v10i2.1037
Langemeyer J, Baró F (2021) Nature-based solutions as nodes of green-blue infrastructure networks: a cross-scale, co-creation approach. Nat Based Solut 1:100006. https://doi.org/10.1016/j.nbsj.2021.100006
Larondelle N, Haase D (2013) Urban ecosystem services assessment along a rural–urban gradient: a cross-analysis of European cities. Ecol Ind 29:179–190. https://doi.org/10.1016/j.ecolind.2012.12.022
Lebni YJ, Gharehghani MAM, Soofizad G, Khosravi B, Ziapour A, Irandoost SF (2020) Challenges and opportunities confronting female-headed households in Iran: a qualitative study. BMC Womens Health 20:1–11. https://doi.org/10.1186/s12905-020-01046-x
Li D, Chiang YC, Sang H, Sullivan WC (2019) Beyond the school grounds: links between density of tree cover in school surroundings and high school academic performance. Urban for Urban Green 38:42–53. https://doi.org/10.1016/j.ufug.2018.11.001
Liberalesso T, Cruz CO, Silva CM, Manso M (2020) Green infrastructure and public policies: an international review of green roofs and green walls incentives. Land Use Policy 96:104693. https://doi.org/10.1016/j.landusepol.2020.104693
Liotta C, Kervinio Y, Levrel H, Tardieu L (2020) Planning for environmental justice-reducing well-being inequalities through urban greening. Environ Sci Policy 112:47–60. https://doi.org/10.1016/j.envsci.2020.03.017
Loveridge R, Sallu SM, Pesha IJ, Marshall AR (2020) Measuring human wellbeing: a protocol for selecting local indicators. Environ Sci Policy 114:461–469. https://doi.org/10.1016/j.envsci.2020.09.002
Mansor M, Said I (2008) Green Infrastructure network as social spaces for well-being of urban residents in Taiping, Malaysia. Environ Res 11:28–30
Miroshnyk NV, Likhanov AF, Grabovska TO, Teslenko IK, Roubík H (2022) Green infrastructure and relationship with urbanization–Importance and necessity of integrated governance. Land Use Policy 114:105941. https://doi.org/10.1016/j.landusepol.2021.105941
Mundoli S, Manjunatha B, Nagendra H (2017) Commons that provide: the importance of Bengaluru's wooded groves for urban resilience. Int J Urban Sustain Dev 9(2):184–206. https://doi.org/10.1080/19463138.2014.982124
Nagendra H (2016) Restoration of the Kaikondrahalli Lake in Bangalore: forging a new urban Commons. Kalpavriksh, Pune
Nagendra H, Mundoli S (2019) Cities and Canopies: Trees in Indian Cities, Penguin Random House India Private Limited
Nagendra H, Bai X, Brondizio ES, Lwasa S (2018) The urban south and the predicament of global sustainability. Nat Sustain 1(7):341–349. https://doi.org/10.1038/s41893-018-0101-5
Netusil NR, Levin Z, Shandas V, Hart T (2014) Valuing green infrastructure in Portland, Oregon. Landsc Urban Plan 124:14–21. https://doi.org/10.1016/j.landurbplan.2014.01.002
Nowak DJ, Greenfield EJ (2020) The increase of impervious cover and decrease of tree cover within urban areas globally (2012–2017). Urban for Urban Green 49:126638. https://doi.org/10.1016/j.ufug.2020.126638
Opdam P, Luque S, Nassauer J, Verburg PH, Wu J (2018) How can landscape ecology contribute to sustainability

science? Landsc Ecol 33(1):1–7. https://doi.org/10.1007/s10980-018-0610-7
Pilarska A (2017) Contributions of cognitive-motivational factors to the sense of identity. Curr Psychol 36:468–482. https://doi.org/10.1007/s12144-016-9435-1
Purushotham A, Mittal N, Ashwini BC, Umesh KB, von Taubadel S, C, Vollmer, S, (2022) A quantile regression analysis of dietary diversity and health outcomes among children and women in the rural-urban interface of India Anjali. Food Policy 107(1):102216. https://doi.org/10.16309/j.cnki.issn.1007-1776.2003.03.004
Ramachandra TV, Aithal BH (2019) Bangalore. The Wiley Blackwell Encyclopedia of Urban and Regional Studies, A.M. Orum (Ed.) https://doi.org/10.1002/9781118568446.eurs0014
Ramachandra TV, Kumar U (2008) Wetlands of greater Bangalore, India: automatic delineation through pattern classifiers. Electron Green J 26:2. https://doi.org/10.5070/G312610729
Reid H, Howard V (2016) Connecting with community: the importance of community engagement in rural public library systems. Public Library Q 35(3):188–202. https://doi.org/10.1080/01616846.2016.1210443
Ren Z, Du Y, He X, Pu R, Zheng H, Hu H (2018) Spatiotemporal pattern of urban forest leaf area index in response to rapid urbanization and urban greening. J for Res 29(3):785–796. https://doi.org/10.1007/s11676-017-0480-x
Ren Z, Zhao H, Fu Y, Xiao L, Dong Y (2022) Effects of urban street trees on human thermal comfort and physiological indices: a case study in Changchun city, China. J for Res 33(3):911–922. https://doi.org/10.1007/s11676-021-01361-5
Requena F (2016) Rural–urban living and level of economic development as factors in subjective well-being. Soc Indic Res 128:693–708. https://doi.org/10.1007/s11205-015-1051-1
Rogers DS, Duraiappah AK, Antons DC, Munoz P, Bai X, Fragkias M, Gutscher H (2012) A vision for human well-being: transition to social sustainability. Curr Opin Environ Sustain 4(1):61–73. https://doi.org/10.1016/j.cosust.2012.01.013
Ronneberger O, Fischer P, Brox, T (2015) U-net: Convolutional networks for biomedical image segmentation. In Medical image computing and computer-assisted intervention–MICCAI 2015: 18th international conference, Munich, Germany, October 5–9, 2015, proceedings, part III 18 (pp. 234–241) Springer International Publishing. https://doi.org/10.1007/978-3-319-24574-4_28
Russell K, Rosenbaum S, Varela S, Stanton R, Barnett F (2023) Fostering community engagement, participation and empowerment for mental health of adults living in rural communities: a systematic review. Rural Remote Health 23(1):1–13. https://doi.org/10.22605/RRH7438
Sengupta S, Guchhait SK (2021) Inequality in contemporary India: does caste still matter? J Dev Soc 37(1):57–82. https://doi.org/10.1177/0169796X21998387
Shores KA, West ST (2010) Rural and urban park visits and park-based physical activity. Prev Med 50:S13–S17
Sudhira HS, Nagendra H (2013) Local assessment of Bangalore: graying and greening in Bangalore–impacts of urbanization on ecosystems, ecosystem services and biodiversity. Urban Biodivers Ecosyst Serv Chall Oppor Glob Assess. https://doi.org/10.1007/978-94-007-7088-1_7
Sugiyama T, Leslie E, Giles-Corti B, Owen N (2008) Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social interaction explain the relationships? J Epidemiol Community Health 62(5):e9. https://doi.org/10.1136/jech.2007.064287
Taylor L, Hochuli DF (2015) Creating better cities: how biodiversity and ecosystem functioning enhance urban residents' wellbeing. Urban Ecosyst 18(3):747–762. https://doi.org/10.1007/s11252-014-0427-3
Thapa P, Torralba M, Buerkert A, Dittrich C, Plieninger T (2021) Ecological and social outcomes of urbanization on regional farming systems: a global synthesis. Ecol Soc 26(3):24. https://doi.org/10.5751/ES-12579-260324
Thapa P, Torralba M, Bhaskar D, Nagendra H, Plieninger T (2023) Green in grey: ecosystem services and disservices perceptions from small-scale green infrastructure along a rural-urban gradient in Bengaluru, India. Ecosyst People 19(1):2223307. https://doi.org/10.1080/26395916.2023.2223307
World Bank (2023a) Urban population growth (annual %) https://data.worldbank.org/indicator/SP.URB.GROW. Accessed 07 Aug 2023
World Bank (2023b) Urban Development: Overview. https://www.worldbank.org/en/topic/urbandevelopment/overview. Accessed 07 Aug 2023
Tolonen H, Koponen P, Borodulin K, Männistö S, Peltonen M, Vartiainen E (2018) Differences in participation rates between urban and rural areas are diminishing in Finland. Scand J Public Health 46(7):755–757
Trentanovi G, Campagnaro T, Kowarik I, Munafò M, Semenzato P, Sitzia T (2021) Integrating spontaneous urban woodlands into the green infrastructure: unexploited opportunities for urban regeneration. Land Use Policy 102:105221. https://doi.org/10.1016/j.landusepol.2020.105221
Vollset SE, Goren E, Yuan CW, Cao J, Smith AE, Hsiao T et al (2020) Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. Lancet 396(10258):1285–1306. https://doi.org/10.1016/S0140-6736(20)30677-2
Wan C, Shen GQ, Choi S (2021) Underlying relationships between public urban green spaces and social cohesion: a systematic literature review. City Cult Soc 24:100383. https://doi.org/10.1016/j.ccs.2021.100383
World Population Review (2024) Bangalore population 2023. https://worldpopulationreview.com/world-cities/bangalore-population. Accessed 2023 August
Wu J (2012) A landscape approach for sustainability science. In: Weinstein MP, Turner RE (eds) Sustainability science: the emerging paradigm and the urban environment. Springer, New York, pp 59–78
Wu J (2013) Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landsc Ecol 28(6):999–1023. https://doi.org/10.1007/s10980-013-9894-9

Wu J (2021) Landscape sustainability science (II): core questions and key approaches. Landsc Ecol 36(8):2453–2485. https://doi.org/10.1007/s10980-021-01245-3

Wu W, Tan W, Wang R, Chen WY (2023) From quantity to quality: effects of urban greenness on life satisfaction and social inequality. Landsc Urban Plan 238:104843. https://doi.org/10.1016/j.landurbplan.2023.104843

Zhang C, Wang C, Chen C, Tao L, Jin J, Wang Z, Jia B (2022) Effects of tree canopy on psychological distress: a repeated cross-sectional study before and during the COVID-19 epidemic. Environ Res 203:111795. https://doi.org/10.1016/j.envres.2021.111795

Zhang P, Dong Y, Ren Z, Wang G, Guo Y, Wang C, Ma Z (2023) Rapid urbanization and meteorological changes are reshaping the urban vegetation pattern in urban core area: a national 315-city study in China. Sci Total Environ 904:167269. https://doi.org/10.1016/j.scitotenv.2023.167269

Zhu J, Lu H, Zheng T, Rong Y, Wang C, Zhang W et al (2020) Vitality of urban parks and its influencing factors from the perspective of recreational service supply, demand, and spatial links. Int J Environ Res Public Health 17(5):1615. https://doi.org/10.3390/ijerph17051615