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A sensitivity analysis in four European cities

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Original article

Examining green space characteristics for social cohesion and mental health outcomes: A sensitivity analysis in four European cities

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ABSTRACT

Introduction: In recent decades, there has been a rise in mental illnesses. Community infrastructures are increasingly acknowledged as important for sustaining good mental health. Moreover, green spaces are anticipated to offer advantages for both mental health and social cohesion. However, the mediating pathway between green space, social cohesion and mental health and especially the proximity and characteristics of green spaces that trigger these potential effects remain of interest.
Methods: We gathered data from 1365 individuals on self-reported social cohesion and mental health across four satellite districts in European cities: Nantes (France), Porto (Portugal), Sofia (Bulgaria), and Høje-Taastrup (Denmark). Green space data from OpenStreetMap was manually adjusted using the PRIGSHARE guidelines. We used the AID-PRIGSHARE tool to generate 7 indicators about green space characteristics measured in distances from 100–1500 m, every 100 m. This resulted in 105 different green space variables that we tested in a single mediation model with structural equation modelling.
Results: Accessible greenness (900–1400 m), accessible green spaces (900–1500 m), accessible green space corridors (300–800 m), accessible total green space (300−800), and mix of green space uses (700–1100 m) were significantly associated with social cohesion and indirectly with mental health. Green corridors also showed negative indirect and direct associations with mental health in larger distances. Surrounding greenness and the quantity of green space uses were not associated with social cohesion nor indirectly with mental health. We also observed no positive direct associations between any green space variable in any distance to mental health.
Conclusions: Our results suggest that accessibility, connectivity, mix of use and proximity are key characteristics that drive the relationship between green spaces, social cohesion and mental health. This gives further guidance to urban planners and decision-makers on how to design urban green spaces to foster social cohesion and improve mental health.

1. Introduction

The prevalence of mental illness has constantly increased in recent decades (Ferrari et al., 2022). Depending on the analysis technique, mental illnesses could be attributed to between 4.9% (Ferrari et al., 2022) - 16% (Arias et al., 2022) of global disability-adjusted life years (DALYs) in 2019. Mental health encompasses the absence of mental illness and the presence of psychological well-being (Bratman et al., 2019) and is defined by the WHO as “a state of mental well-being that enables people to cope with the stresses of life, realize their abilities, learn well and work well, and contribute to their community” (WHO - World Health Organization, 2023). Community structures are considered an important factor in maintaining good mental health (Santini et al., 2020) and are related to the built environment (Giles-Corti et al.,

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2016). Especially, urban green spaces are increasingly recognized for their positive impacts on both mental health and social cohesion (WHO Regional Office for Europe,2016, 2021).

The current body of evidence suggests a number of positive effects of direct contact with green spaces on mental health (Bratman et al., 2019; WHO Regional Office for Europe, 2016, 2021). These effects are divided into short-term and long-term effects (Bratman et al., 2019; WHO Regional Office for Europe, 2021). According to a recent review, green space exposure is associated with positive *short-term* effects on affect, vitality, restorative outcomes, stress, hyperactivity, and brain activity, as well as *long-term* effects on overall mental health, mental illness, satisfaction with life, quality of life, wellbeing, sleep quality, social contacts and suicide rate (WHO Regional Office for Europe, 2021). Still today, the two main theories on how direct contact with nature improves mental health are the Attention Restoration Theory (ART) and the Stress Reduction Theory (SRT). ART assumes that interaction with nature triggers restorative mechanisms, with positive changes in psychological states, cognitive functioning and performance (Ulrich, 1984). The SRT assumes a stress-reducing effect of green spaces, on the one hand through the absence of environmental stressors, on the other hand through the presence of calming sounds of nature (Kaplan, 1995). Beyond these individual-based restoration theories, two more theories have emerged to provide a framework for how environments such as green spaces can contribute to social and communal well-being (Hartig, 2021). The Relational Restoration Theory (RRT) emphasizes the social and relational aspects of restoration. The Collective Restoration Theory (CRT) suggests that groups or communities can experience a sense of restoration together, not just as isolated individuals.

However, the exact mechanisms remain under investigation. For example. it is not yet clear whether passive effects of surrounding neighbourhood green spaces (in contrast to actual direct contact with nature) on mental health can also be expected, especially through increased social cohesion. There is evidence for both partial effects, from green space to social cohesion (Giles-Corti et al., 2016; Wan et al., 2021) and from social cohesion to mental health (Santini et al., 2020). So far, however, the research results of the entire impact pathway are inconclusive according to recent reviews (Dzhambov et al., 2020; Zhang et al., 2021). Moreover, a recent review by Astell-Burt and colleagues on green space and reduced loneliness acknowledged the intuitive link through social connections but also acknowledged the general scarcity of literature (Astell-Burt et al., 2022). In addition, a variety of definitions and study designs exist (Taylor & Hochuli, 2017). Thus, it remains unclear which type and characteristics of green spaces are related to social cohesion and mental health (Clarke et al., 2023; WHO Regional Office for Europe, 2021) and what proximity to the residence is required for an association (Clarke et al., 2023; Wan et al., 2021).

This study, therefore, investigates the link between green spaces, social cohesion and mental health in a comprehensive sensitivity analysis for 7 different green space indicators and 15 relative proximity measures from 100 m-1500 m. The aim is to identify the differences between green space types, characteristics and their relative proximity to the place of residence in their direct and indirect impact on mental health. We hypothesize a stronger link between social cohesion and green space than to greenness (Cardinali et al., 2023b), and an indirect effect on mental health (Rugel et al., 2019; van den Berg et al., 2019). Greenness refers to the degree of vegetation of an area often without taking accessibility into account, whereas green spaces are usually defined as publicly accessible areas covered with vegetation. With our results, we aim to help disentangle the influence of specific green space characteristics and provide important insights for urban planners and public health decision-makers on how to design public green spaces to help promote local social cohesion and mental health.

2. Methods

2.1. Study design and sampling

The Urban Inclusive Innovative Nature (URBiNAT) project aims to contribute to an understanding of the effects of nature-based solutions on residents in low to middle-income satellite neighbourhoods. URBiNAT collected data from 1365 participants in Europe: 439 in Porto Campanhã (Portugal), 293 in Nantes Nord (France), 432 in Sofia Nadezhda (Bulgaria) and 201 in Høje-Taastrup as part of Greater Copenhagen (Denmark). These neighbourhoods, developed for the more disadvantaged social classes, share several common characteristics. Built predominantly in the second half of the 20th century, they are satellite neighbourhoods, e.g. districts built purposely on the outskirts of the city and partly or fully planned according to the principles of the functional (car-dependant, mono-functional) city. However, they differ in geographical and cultural context, distance to the city centre, public transport, dominance of car-centric infrastructure, and especially green spaces (see Fig. 1).

To be eligible for participation, individuals had to be at least 14 years old. Participants were chosen randomly, and the surveys were conducted by local survey companies hired by the cities and instructed by the research team. In Porto and Sofia, surveys were administered in person, while in Nantes and Høje-Taastrup, they were conducted over the phone. Upon contact, individuals were briefed about the project's objective, the survey's role, and asked for informed consent. Before, the survey had been approved by the URBiNAT project's ethics committee. No incentives were provided for participation. The survey in Porto was conducted around August 2019. In Nantes and Sofia, surveys were carried out around December 2019, while data from Høje-Taastrup was collected in August 2021.

2.2. Green space

We obtained the necessary spatial data for the four study areas from OpenStreetMap in January 2023 and manually corrected it to the timestamp of the survey conduction and controlled for bias with the help of the PRIGSHARE Reporting Guidelines (Cardinali et al., 2023b, Table A1). We adjusted the retrieved spatial data manually based on site visits, aerial pictures and GoogleStreetview. Furthermore, in order to be able to analyse the green corridors around survey participants, we manually (1) connected green infrastructure that was interrupted by a road but has a crossing, (2) merged green spaces directly next to each other, and (3) added linear green spaces that consist of walkable pathways with greenery. A table with the inclusion/exclusion criteria for the spatial data can be viewed in the appendix (Table A2).

As a basis for greenness indicators, we calculated the Natural Difference Vegetation Index (NDVI) with sentinel 2 data in 10×10 m resolution from the ESA (European Space Agency, 2021) from cloud-free time points in the month of the survey conduction in the city (see Fig. 2 for exact dates). The NDVI is calculated with rasterised satellite images in near-infrared and red light (NDVI=(NIR-Red)/(NIR+Red)) (Tucker, 1979). Its values range from -1.0 to 1.0, where 0.2–0.5 usually is associated with sparse vegetation like shrubs or grassland and values of 0.6 and higher show dense vegetation like trees. Sealed surfaces range around 0.0–0.1 and negative values originate from water bodies and clouds. For this study, we manually set larger water bodies like the rivers in Porto and Nantes to missing, as recommended by Markevych et al. (2017).

Based on this curated data and the geocoded addresses of individuals, we constructed seven indicators (see Fig. 3) in distances from 100 m to 1500 m, every 100 m, with the help of the AID-PRIGSHARE tool (Cardinali et al., 2023a). Firstly, we assessed greenness with two indicators based on NDVI, surrounding greenness with Euclidean buffers (A), and accessible greenness with network distance (B). Secondly, we assessed green space with three public green space indicators: accessible

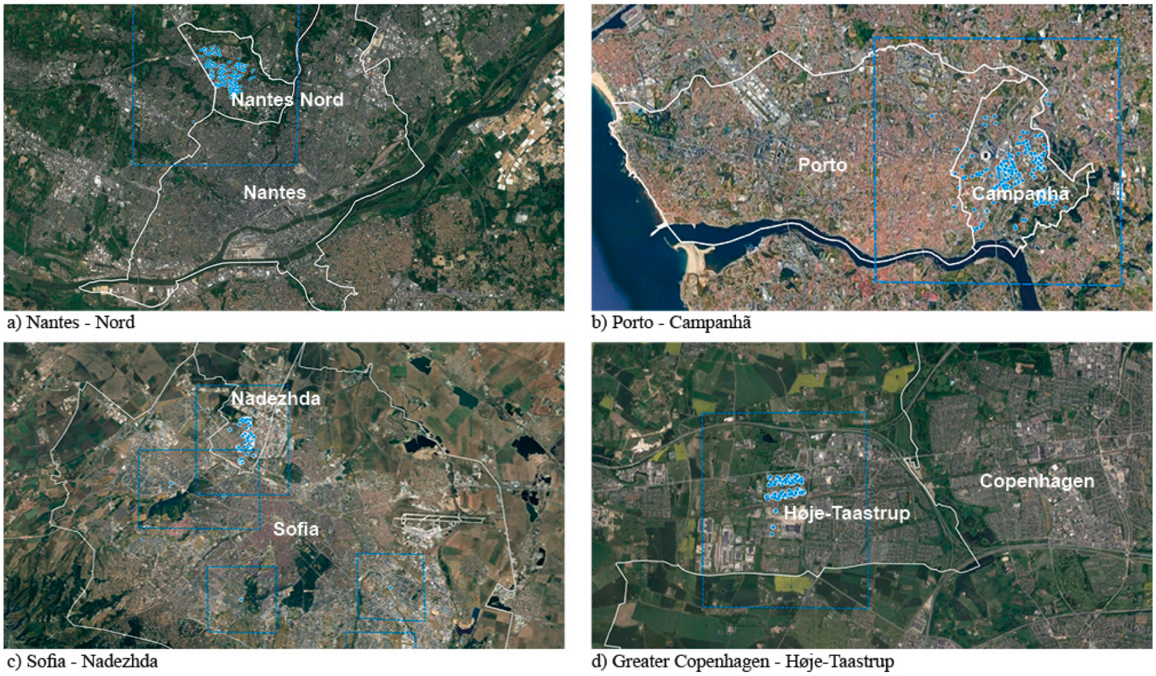

Fig. 1. Study areas overview: a) Nantes - Nord (France); b) Porto - Campanhã (Portugal), c) Sofia - Nadezhda (Bulgaria), d) Greater Copenhagen - Høje-Taastrup (Denmark); white line indicates administrative borders; blue dotted line indicates the study area(s); blue points indicate the residential address of the study participants (Cardinali et al., 2024).

green spaces in network distance (C), green corridors accessible from network distance, basically a measure for a green mobility network accessible from specific distances (D), and total accessible green space, where individual private or semi-public green spaces from the individual plot are added to the green corridor indicator for each individual (E). Thirdly, we manually assessed green space usability by counting points of green space uses (playgrounds, public gardens, sports fields, social facilities, cultural facilities and walking entries to bigger green spaces) present in the accessible green spaces through open street map data, Google Street View and expert knowledge from local site visits. To represent the quantity of green space uses we counted the total number of uses in green spaces within network distance (F). To measure the mix of uses we counted the number of different uses (G). All network distances were measured through 25 m buffered service areas, recognized to be more precise, especially in the smaller buffers compared to isochrones (Frank et al., 2017).

2.3. Social cohesion

According to recent reviews, social cohesion is still defined very heterogeneously (Clarke et al., 2023; Fonseca et al., 2019), but usually refers to the ability of a community to ensure the well-being of all its members (Council of Europe, 2008). Social cohesion also refers to the level of engagement and social trust among community members (Speer et al., 2001). We captured this construct with the 5-point Likert scale item of self-rated satisfaction with participants' neighbourhood relations (conviviality, mutual aid, solidarity) from 1 (not at all satisfied) to 5 (very satisfied) of the environmental quality of life scale (Fleury-Bahi et al., 2013). The item was used as an ordinal variable in the analysis.

2.4. Mental health

Mental health was assessed through the Mental Health Continuum Short Form (MHC-SF) (Keyes, 2018). The 14-item MHC-SF is a known reliable and robust scale to obtain differentiated results on emotional, social, and psychological well-being in line with the definition of the World Health Organization as "a state of mental well-being that enables people to cope with the stresses of life, realize their abilities, learn well and work well, and contribute to their community" (WHO - World Health Organization, 2023). Each item is scored from 1–5 with a higher summary score indicating better mental health (see supplementary material A3 for a table with the items). The total sum of the scale ranged from 14–70 and was used as a numerical variable in the model.

2.5. Context variables

In line with the PRIGSHARE Reporting Guidelines (Cardinali et al., 2023b), we obtained data on potential confounders in personal, local, urbanicity, and global context.

To assess the *personal context*, we gathered data on age (in years), sex (male, female, diverse), employment status, years of education, and monthly net income, as all of them may change the measured relationship (Browning & Lee, 2017; Markevych et al., 2017; van den Bosch & Ode Sang, 2017). To harmonize between cases across countries, monthly net income was centred around the mean minimum wage of the country and is shown in percentages of minimum wage. In addition, we collected data on whether the respondents had a disability since this might limit their engagement with green spaces and could have an influence on their well-being. We also collected data on the number of years a respondent lived in the neighbourhood since this may influence their place attachment, ability to rate social cohesion, their momentary well-being and their long-term exposure to green space characteristics in the neighbourhood.

We controlled for *local context* variables that might affect social cohesion and mental health (Cardinali et al., 2023b). We used the satisfaction with shops, leisure facilities, and public transport measured with 5-point Likert scale items, measured from 1 (not at all satisfied) to 5 (very satisfied) as part of the environmental quality of life questionnaire (Fleury-Bahi et al., 2013) as a proxy to account for those local context variables. We did not include data on neighbourhood safety, although it might influence open space use (van den Bosch & Ode Sang, 2017) since it is potentially on the pathway between social cohesion and mental health.

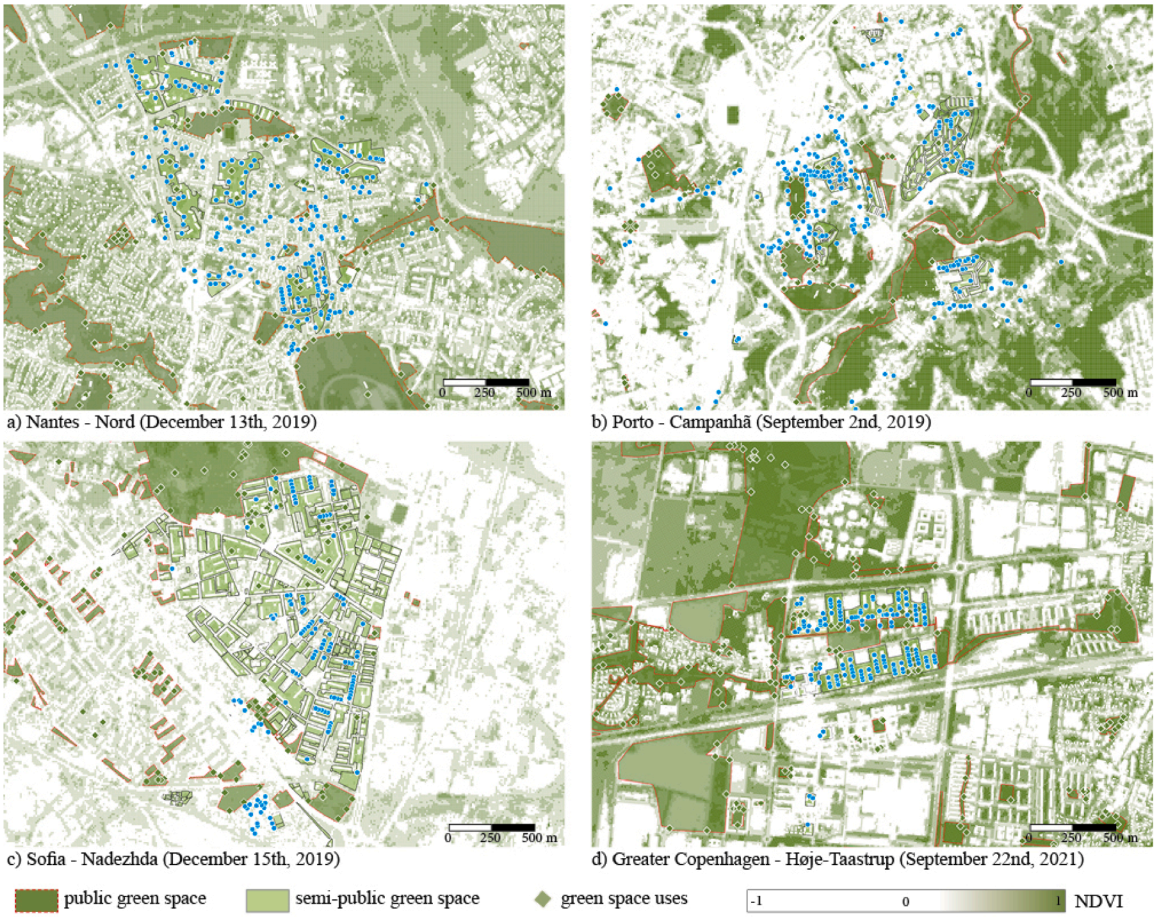

Fig. 2. Study areas green space: a) Nantes - Nord (France); b) Porto - Campanhã (Portugal), c) Sofia - Nadezhda (Bulgaria), d) Greater Copenhagen - Høje-Taastrup (Denmark); blue points indicate the residential address of the study participants. For better readability only the study areas are covered (e.g. some respondents do not live in the main study area) and private green space is not shown (Cardinali et al., 2024).

To control for the *urbanicity context*, we obtained rasterized 2018 population density data (*residents/km²*) from Eurostat (Eurostat, 2023) since population density is associated with social cohesion and mental health (Hong et al., 2014).

The *global and climate context* was addressed by including the city samples as a dummy variable in the model as the cultural, societal, as well as climate conditions likely vary widely between the study areas and otherwise bias the results (Cardinali et al., 2023b). In addition, this allowed us to adjust for the differences in timing (pre- or post-pandemic) and the season when the survey was conducted. In contrast to a stratified analysis, the dummy variable approach allowed us to maintain the necessary statistical power. The PRIGSHARE reporting guidelines also prescribe to assess modifying variables, like differences in age groups (Cardinali et al., 2023b). This investigation was out of scope for this study because of the number of structural equation models to perform and compare (see 2.6). This limitation will be debated in the discussion.

2.6. Statistical analysis

Data handling and processing were done in Python. Missing data could be characterized as missing at random (MAR) since missingness was associated with other observed variables. Thus, a multiple imputation technique is considered the most appropriate to handle the missing data (Mirzaei et al., 2022). We used multiple imputation software package of miceforest 5.6.3 in Python (Wilson, Samuel, 2022), with 10 iterations to estimate the missing variables. The final step of data processing was to standardize the dataset by min-max scaling (0−1) since all our variables, but NDVI, can only be positive. The standardization ensured that all variables were on the same scale, thus allowing for meaningful comparisons and accurate model estimation (Kline, 2015).

Structural equation modelling (SEM) was performed in R with the lavaan package (Rosseel, 2023) on a single mediator model (Fig. 4) using the diagonal weighted least squares estimator. The full model including all control variables can be found in the supplementary material (Figure A1). Sensitivity analysis was done by exchanging the green space indicator 105 times (7 indicators, each for 15 distances). The rest of the model remained unchanged. As the Porto sample showed very distinct characteristics an additional sensitivity analysis was done to test if the results remained robust to the exclusion of this subgroup.

An example of the summary statistics for one green space indicator can be found in the supplementary material (Table A4). These single mediator models are just-identified (0 degrees of freedom) and serve the main goal of this research to compare green space indicators and the relative proximity of green spaces. However, this leads to the fact that the quality of the model can only be judged on theoretical grounds and not with model fit indices, which might be expected from SEM Models.

In the following results and discussion, we use the common phrases of partial effects (a or b), indirect effects (a*b), direct effects (c) and total effects (a*b+c) in SEM. However, we want to highlight that these are in fact associations, due to the cross-sectional study design. Since indirect effects and total effects are products and not linear, we used bootstrap-generated standard errors and confidence intervals for all regression paths (5000 samples for every structural equation model). The relationship was considered significant when the bootstrapped 95% confidence intervals did not include zero.

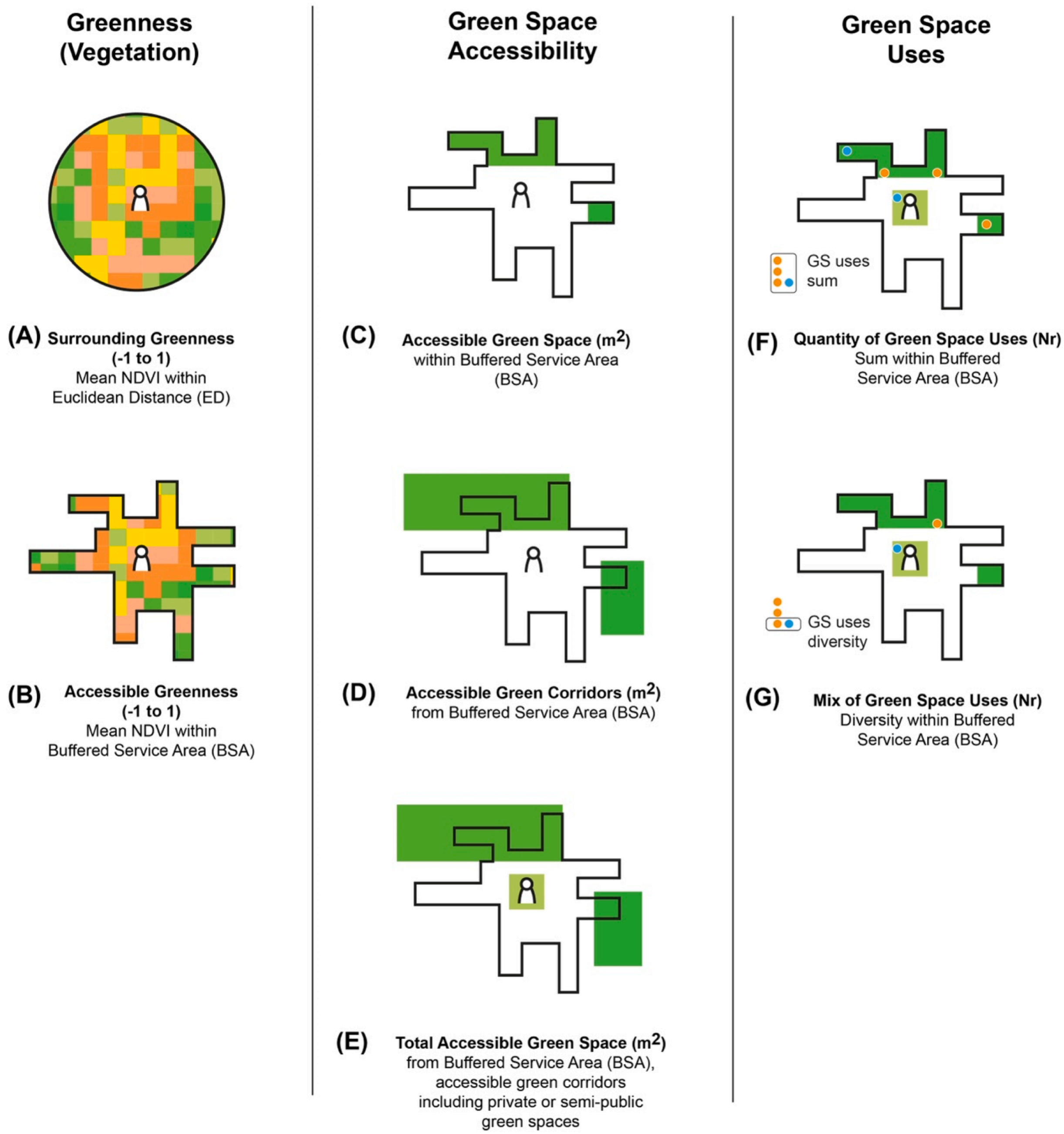

Fig. 3. Green space indicators: Indicators used in the sensitivity analysis. Notes: Network distances are measured as 25 m buffered service areas (walkable distance in m in every direction). Green Corridor and Total green space indicators (E, F, H, I) count every green space that intersects with the Euclidean buffer or network distances, while green space indicators (D, G) count only those green spaces that are within the buffer type (Cardinali et al., 2024).

3. Results

3.1. Characteristics of the sample

The total sample contained 201 individuals from Høje-Taastrup (Denmark), 293 from Nantes (France), 439 from Porto (Portugal), and 432 from Sofia (Bulgaria). The population density varied among the cities, with Sofia demonstrating the highest with 9021.14 (3689.54) residents/km^2 and Høje-Taastrup displaying the lowest at 4028.65 (1336.94) residents/km^2. The local context also showed significant differences in all included variables (Table 1). Self-rated social cohesion was rated best in Porto with 81.1% of respondents satisfied or very satisfied with the social cohesion, followed by Nantes (62.8%), Høje-Taastrup (60.7%), and Sofia (53.4%).

Personal indicators also differed between the study areas. The city samples are composed of roughly 50% of men and women in Høje-Taastrup, Nantes, and Sofia. In Porto, the sample was composed of nearly 64% men and 36% women. Porto also had the most people over 65 years with 41.0% compared to Nantes with only 17.1% and the highest proportion of people with disabilities (39.6%). The mean (SD) years of education were 12.49 (2.55) in Høje-Taastrup, 12.57 (3.37) in Nantes, 7.02 (3.70) in Porto, and 13.11 (2.68) in Sofia. Most of the participants were employed, with significant differences between cities. The mean income, harmonized as a percentage of minimum wage of the country, was roughly between 140–150% in Høje-Taastrup, Nantes, and Sofia, but only 40% in Porto. The mean reported mental health (SD) was similar across the city samples and rated at 55.23 (9.31) in Porto, 54.93 (10.82) in Høje-Taastrup, 52.75 (6.45) in Sofia and 50.13 (12.45) in

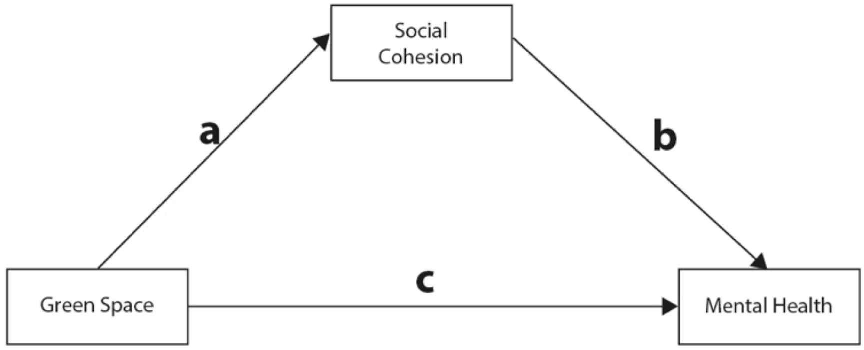

Fig. 4. Conceptual Model: Conceptual diagram showing theoretically indicated pathways linking green space to social cohesion and mental health. The green space indicator was exchanged 105 times for each structural equation model.

Nantes.

3.2. Partial effects – how green space indicators are associated with social cohesion

Greenness, green space and green space uses indicators were correlated differently to social cohesion. Surrounding greenness (Fig. 5A) showed an almost constant pattern of association to social cohesion regardless of the tested proximity, although none were significant. Accessible greenness (Fig. 5B) showed a more sensitive behaviour to the measured distance with a plateau of positive significant associations with social cohesion for a proximity between 700–900 m, with a peak at 700 m (ß: 0.745; CI: 0.031, 1.462). This pattern was even clearer for accessible green spaces (Fig. 5C), where the association increased continuously the larger the catchment area of the measurement and showed significant associations to social cohesion from 900–1500 m. The plots of accessible green corridors (Fig. 5D) and total green spaces (Fig. 5E) showed divergent patterns, peaking at the 800 m catchment area. After this, the coefficient declined continuously until a negative significant association with social cohesion when measured in a 1500 m catchment area. The quantity of green space uses (Fig. 5F) was not associated with social cohesion in our study. On the other hand, the mix of green space uses (Fig. 5G) showed a plateau of positive associations for uses measured at 700 m and above, not all of which were significant. For detailed results we refer to supplementary material Table A5. The sensitivity analysis without the Porto sample showed similar results in green space accessibility and green space uses indicator, but differences in greenness indicators (Table A9). Both surrounding greenness and accessible greenness showed overall higher estimates and patterns of significant associations.

3.3. Indirect effects – how green space indicators are indirectly associated with health via social cohesion

Social cohesion mediated the effect from green space to mental health but with clear differences between the type of green space indicator and catchment area. Basically, the slopes were very similar to the partial effects, including the behaviour of the subsample without Porto (Table A10), as the relation between social cohesion and mental health (b) was constant (ß: 0.03; CI: 0.02, 0.03). We found a statistically significant positive mediating effect of social cohesion for accessible greenness measured in 700–900 m (Fig. 6B), accessible green space measured in 900–1500 m (Fig. 6C), accessible green corridors and total green spaces measured in 300–800 m (Fig. 6D-E), and mix of green space uses measured in 700–900 m and 1100–1300 m (Fig. 6G). In addition, accessible green corridors and total green space also showed a significant negative indirect relationship at a 1500 m network distance. For detailed results we refer to supplementary material Table A6.

3.4. Direct effects – how green space indicators are associated with health

Green space indicators, factually adjusted for social cohesion, were not directly positively associated with mental health and even showed negative associations for accessible green corridors and accessible total green space in larger catchment areas. We observed no direct association between greenness indicators and mental health (Fig. 7A, B). The accessible green spaces also showed no significant direct relationship (Fig. 7C). However, accessible green corridors (Fig. 7D) and accessible total green space (Fig. 7E), showed a significant negative direct association with health, for distances of 1000 m and 1200–1500 m. We did not observe a direct association between the indicators on green space use (Fig. 7F, G) and mental health. For detailed results, we refer to supplementary material Table A7. The sensitivity analysis without the Porto sample showed similar results for all indicators (Table A11).

3.5. Total effects – how green space indicators, directly and indirectly, relate to health

For the total effects, we found no significant positive, but some negative, associations between green space and mental health. The direct effects appeared to dominate the relationship, as the demonstrated patterns were very similar to those of the direct effects (Fig. 8). None of the indirect effects carried over to a significant total effect. The only remaining significant effects were the negative associations between accessible green corridors (Fig. 8D) and total green areas (Fig. 8F) measured with network distances of 1000 m and 1200–1500 m. For detailed results, we refer to supplementary material Table A8. The sensitivity analysis without the Porto sample showed similar results for all indicators, but greenness variables (Table A12). Those showed higher estimates due to the strengthened relationship to partial and indirect effects in this subsample.

3.6. Collinearity between significant green space characteristics

To clarify whether the documented associations arise from separate mechanistic processes or merely function as alternative markers of the same underlying variable, we assessed the correlation matrix of all green space characteristics (Table A13). We evaluated the peak associations from the partial effects (path a).

As detailed in Section 3.2, the peak relations for the partial effect (path a) were between social cohesion and accessible greenness at 800 m (B), accessible green space at 1400 m (C), accessible green corridors at 800 m (D), accessible total green spaces at 800 m (E), mix of green space uses in 1100 m (G), as well as two negative associations for accessible green corridors (D) and accessible total green spaces (E) at 1500 m. The investigation of the correlation matrix indicated the expected strong collinearity between the nested green space characteristics when measured at similar distances (D & E). However, the

Table 1
Characteristics of the sample (unstandardized).

Context	Indicator	Høje-Taastrup	Nantes	Porto	Sofia	p
global	*city sample (n)*	201	293	439	432	
urbanicity	*Population density (residents/km^2 , mean (SD))*	4028.65 (1336.94)	5616.27 (2353.62)	4829.28 (1632.50)	9021.14 (3689.54)	< 0.001
local	***self-rated social cohesion (%)***					< 0.001
	very satisfied	28.4%	15.7%	49.4%	8.3%	
	satisfied	32.3%	47.1%	31.7%	45.1%	
	moderately satisfied	21.4%	22.2%	13.0%	39.4%	
	not satisfied	12.4%	6.5%	2.7%	7.2%	
	not at all satisfied	5.5%	8.5%	3.2%	0.0%	
	self-rated satisfaction with shops (%)					< 0.001
	very satisfied	39.3%	11.3%	28.0%	23.6%	
	satisfied	33.8%	51.5%	28.5%	40.5%	
	moderately satisfied	14.4%	19.1%	13.2%	30.1%	
	not satisfied	10.0%	10.6%	17.1%	5.8%	
	not at all satisfied	2.5%	7.5%	13.2%	0.0%	
	self-rated satisfaction with leisure facilities (%)					< 0.001
	very satisfied	31.3%	4.8%	22.6%	6.9%	
	satisfied	32.3%	29.7%	33.0%	35.2%	
	moderately satisfied	23.4%	27.3%	15.3%	37.3%	
	not satisfied	9.0%	21.8%	14.4%	20.1%	
	not at all satisfied	4.0%	16.4%	14.8%	0.5%	
	self-rated satisfaction with public transport (%)					< 0.001
	very satisfied	62.7%	50.2%	35.3%	12.3%	
	satisfied	26.9%	44.4%	29.6%	61.3%	
	moderately satisfied	6.0%	4.1%	9.6%	25.2%	
	not satisfied	1.5%	1.0%	10.3%	1.2%	
	not at all satisfied	3.0%	0.3%	15.3%	0.0%	
personal	***gender (%)***					< 0.001
	male	52.2%	44.0%	36.2%	47.2%	
	female	47.8%	55.3%	63.8%	52.8%	
	diverse	0.0%	0.7%	0.0%	0.0%	
	age group (%)*					< 0.001
	15-24	6.5%	10.9%	4.1%	10.6%	
	25-44	28.4%	42.7%	21.4%	39.6%	
	45-64	32.8%	29.4%	33.5%	29.6%	
	over 65	32.3%	17.1%	41.0%	20.1%	
	mean years lived in neighbourhood (SD)	16.60 (13.76)	14.53 (15.03)	28.90 (20.08)	22.41 (12.34)	< 0.001
	mean net income as % of minimum wage (SD)	141% (93%)	149% (63%)	40% (66%)	143% (73%)	< 0.001
	mean years of education (SD)	12.40 (2.51)	12.46 (3.38)	7.03 (3.72)	13.16 (2.67)	< 0.001
	has disabilities (%)	10.00%	15.70%	39.60%	15.50%	< 0.001
	employed (%)	57.20%	56.70%	28.70%	73.60%	< 0.001
	Mental Health, 14-70 (mean (SD))	54.93 (10.82)	50.13 (12.45)	55.23 (9.31)	52.75 (6.45)	< 0.001
green space characteristics	*surrounding greenness in 500 m Euclidean distance (−1 to 1, mean (SD))*	0.46 (0.05)	0.42 (0.03)	0.37 (0.08)	0.23 (0.04)	< 0.001
	accessible greenness in 500 m network distance (−1 to 1, mean (SD))	0.44 (0.04)	0.39 (0.03)	0.34 (0.06)	0.24 (0.04)	< 0.001
	accessible green space in 500 m network distance (0 - 16.32 hectare, mean (SD))	3.70 (1.45)	1.64 (1.56)	2.35 (2.11)	3.12 (3.68)	< 0.001
	accessible green corridors in 500 m network distance (0 – 154.30 hectare, mean (SD))	51.76 (17.59)	56.92 (66.64)	9.74 (9.81)	28.93 (37.99)	< 0.001
	accessible total green space in 500 m network distance (0 – 158.66 hectare, mean (SD))	56.77 (16.33)	60.18 (66.51)	12.16 (10.37)	32.99 (41.47)	< 0.001
	quantity of green space uses in 500 m network distance (0 - 34, mean (SD))	21.17 (7.49)	6.13 (4.04)	5.15 (4.39)	10.17 (6.70)	< 0.001
	mix of green space uses in 500 m network distance (0 - 5, mean (SD))	3.75 (0.65)	2.10 (0.82)	1.83 (1.01)	2.36 (1.13)	< 0.001

* age was used as a continuous variable in the analysis and is only shown here in groups to highlight the differences across samples.

correlation across the different sets of indicators (e.g. between A and D or between E and G), was weak to moderate for accessible greenness (−0.18–0.16), accessible green space (−0.06–0.51), green corridors (0.17–0.56), and green space uses (−0.16–0.59). We found a weak to moderate correlation for the negative association of accessible green corridors at 1500 m to other green space characteristics (0.14–0.56). This indicates partially unique mechanisms to social cohesion from accessible greenness, accessible green spaces, green corridors and green space uses.

4. Discussion

4.1. Main findings

We found that certain green space characteristics are linked with elevated levels of social cohesion, which in turn appear to favour mental health outcomes. Specifically, accessible greenness (including vegetation along streets) and accessible green spaces in a surrounding area of up to 1500 m, as well as green corridors in an intermediate surrounding

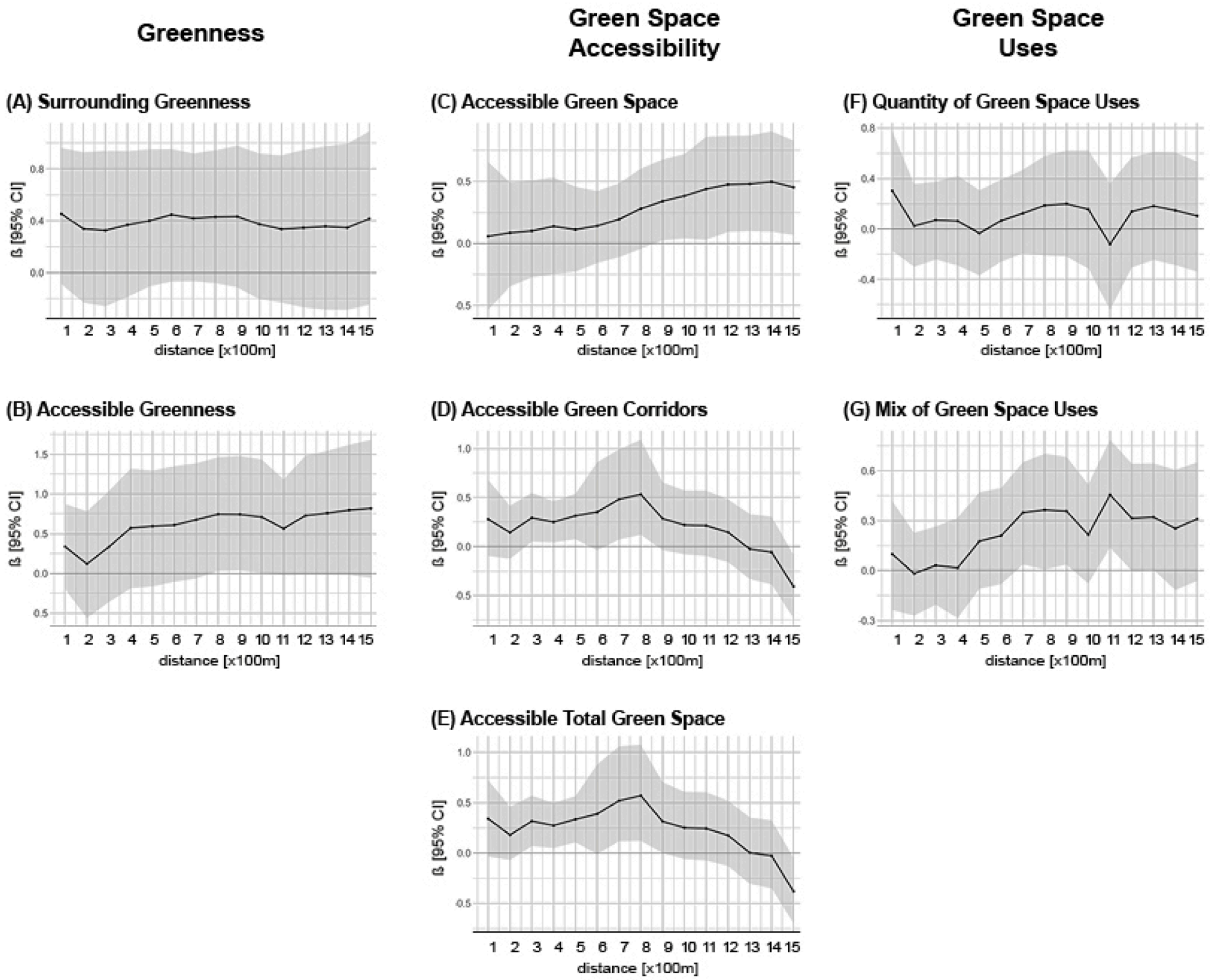

Fig. 5. Partial Effects (a). Green Space – Social cohesion Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, employment status, years lived in the neighbourhood, well-being, satisfaction with shops, leisure facilities, public transport, population density and city. 5000 Bootstrap Samples, shaded grey area show 95% confidence interval.

of up to 800 m, and mix of use in green spaces measured in 700 to 1300 m, showed significant indirect associations to mental health. Moreover, a sensitivity analysis without the Porto sample indicates cross-cultural differences in the relationship between greenness, social cohesion and indirect associations on mental health, but not for green space accessibility or green space uses. On the contrary, we did not find a direct positive effect between any neighbourhood green space characteristics in any of the 105 structural equation models to mental health, including the sensitivity analysis without the Porto sample. Our results shed light on the complex relationship between neighbourhood green spaces, social cohesion and mental health. They suggest a strong relationship between neighbourhood green space characteristics and social cohesion, as well as modest indirect but no direct effects on mental health.

4.2. Social cohesion as a mediator in the green space mental health pathway

We identified consistent patterns of indirect associations between accessible greenness, green space corridors and mix of use with mental health through the mediating role of social cohesion. This echoes the findings of several studies on the association between green space and social cohesion or related concepts. For instance, Rugel et al. (2019) discovered that accessible neighbourhood nature was positively associated with mental health through increased social cohesion in a large study of over 1,9 million individuals in Canada. Another study found that the use of green spaces influenced mental health indirectly through social support and collective restoration (Pasanen et al., 2023). Ricciardi and colleagues (2023) reported a mediating effect of social support on geriatric depression symptoms. Similarly, Li et al. (2022) found that green spaces indirectly contributed to reduced anxiety through social cohesion and van den Berg et al. (2019) reported small mental health benefits when visiting green spaces mediated by social cohesion, among other mediators like physical activity and loneliness. In line with our findings on accessible greenness, Liu and colleagues (2020) found an indirect effect of street greenness on mental health through community participation. Our results on green space uses corroborate recent reviews that conclude that green space amenities and utilities are able to foster social cohesion (Clarke et al., 2023) and that bigger green space areas might be better able to support social cohesion through more visitors and different activities (Wan et al., 2021), which might reflect the strong associations with green space corridors and their theorized relation to

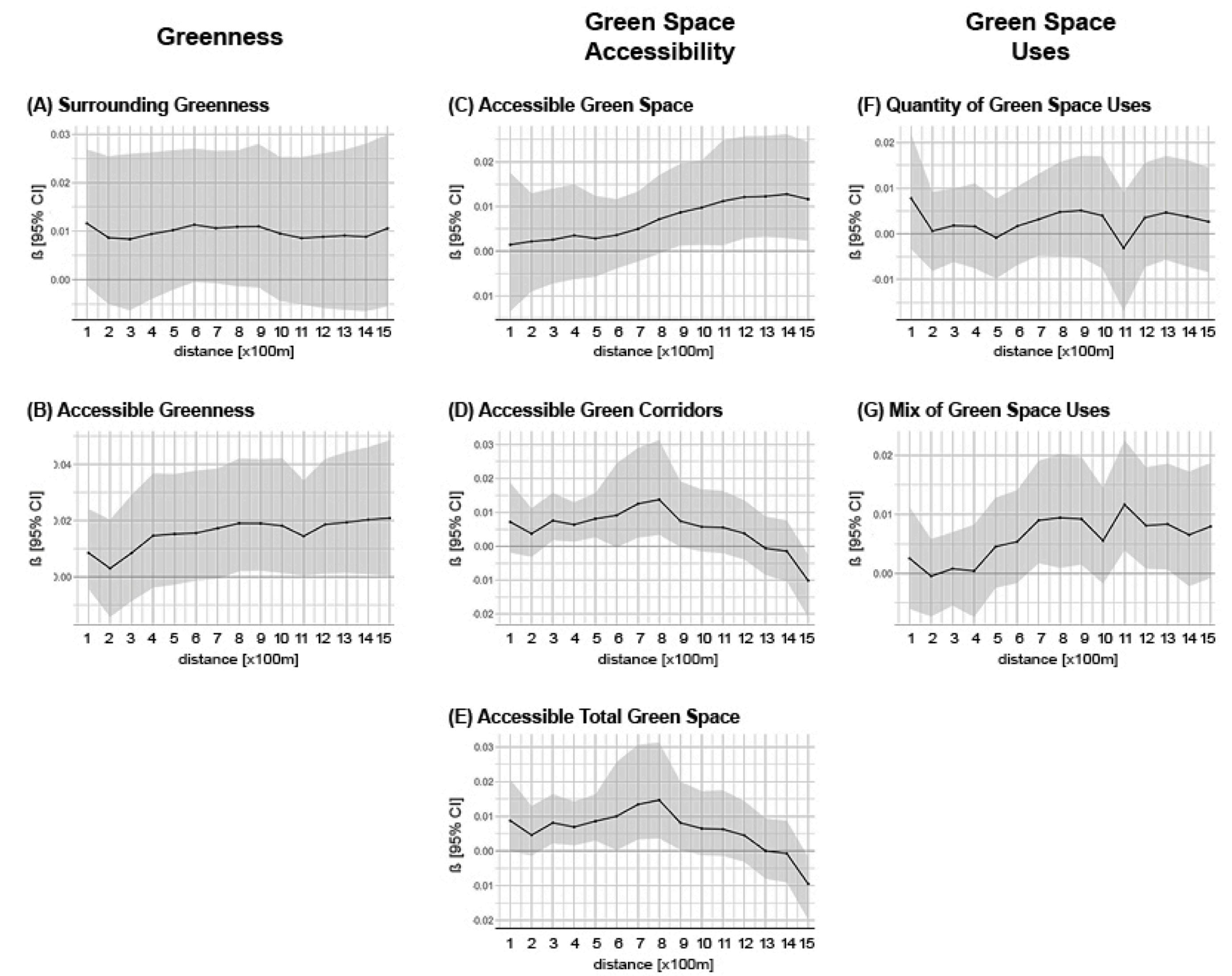

Fig. 6. Indirect Effects (a*b). Green Space – Social cohesion – Mental Health Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, employment status, years lived in the neighbourhood, well-being, satisfaction with shops, leisure facilities, public transport, population density and city. 5000 Bootstrap Samples, shaded grey area show 95% confidence interval.

physical activity (Cardinali et al., 2024).

On the contrary, some studies were not able to find evidence for a mediating effect and reported inconclusive evidence for social cohesion in the green space mental health pathway (Dzhambov et al., 2018). Our sensitivity analysis without the Porto subsample indicates differences in the relationship between greenness and social cohesion between population groups, which might be able to explain part of the remaining inconsistency across studies. Possible explanations include differences in social behavioural patterns across cultures or age groups that change the influence of greenness on social cohesion.

Despite these inconclusive findings and a general heterogeneity in green space, social cohesion and mental health indicators used, our findings are consistent with the majority of studies that suggest a small but consistent mediating role of social cohesion on the green space mental health pathway. Our results add to the body of knowledge, where these relationships might occur and which green space characteristics might be responsible for this relationship.

4.3. *Direct effects of neighbourhood green space on mental health*

We did not find any positive significant relationship between green space characteristics and mental health in any of our structural equation models. Moreover, all coefficients, except green space corridors measured at large distances, were not only not significant but also ranged around zero, indicating the absence of a direct relationship between the tested green space characteristics and mental health. This is in line with the study of Rugel and colleagues in Canada that also found no direct effect between any measure of the natural environment and mental health (Rugel et al., 2019). Similarly, Ricciardi et al. found no direct effect on geriatric depression (Ricciardi et al., 2023), while Zhang and colleagues concluded that green space is not a dominant factor contributing to adolescent well-being (Zhang et al., 2022). However, this is in contrast to earlier studies that were able to find a direct association between green space or greenness and mental health in direct proximity (Dzhambov et al., 2018; Liu et al., 2020; van Herzele & de Vries, 2012; Zijlema et al., 2017).

Several factors could explain this inconsistency. Firstly, differences in how green space exposure is measured might contribute to different findings, especially since direct contact with nature is considered to be one of the main drivers for the green space mental health relationship (Bratman et al., 2019; Cardinali et al., 2023b; Hartig et al., 2014; Markevych et al., 2017) which might not be captured by green space

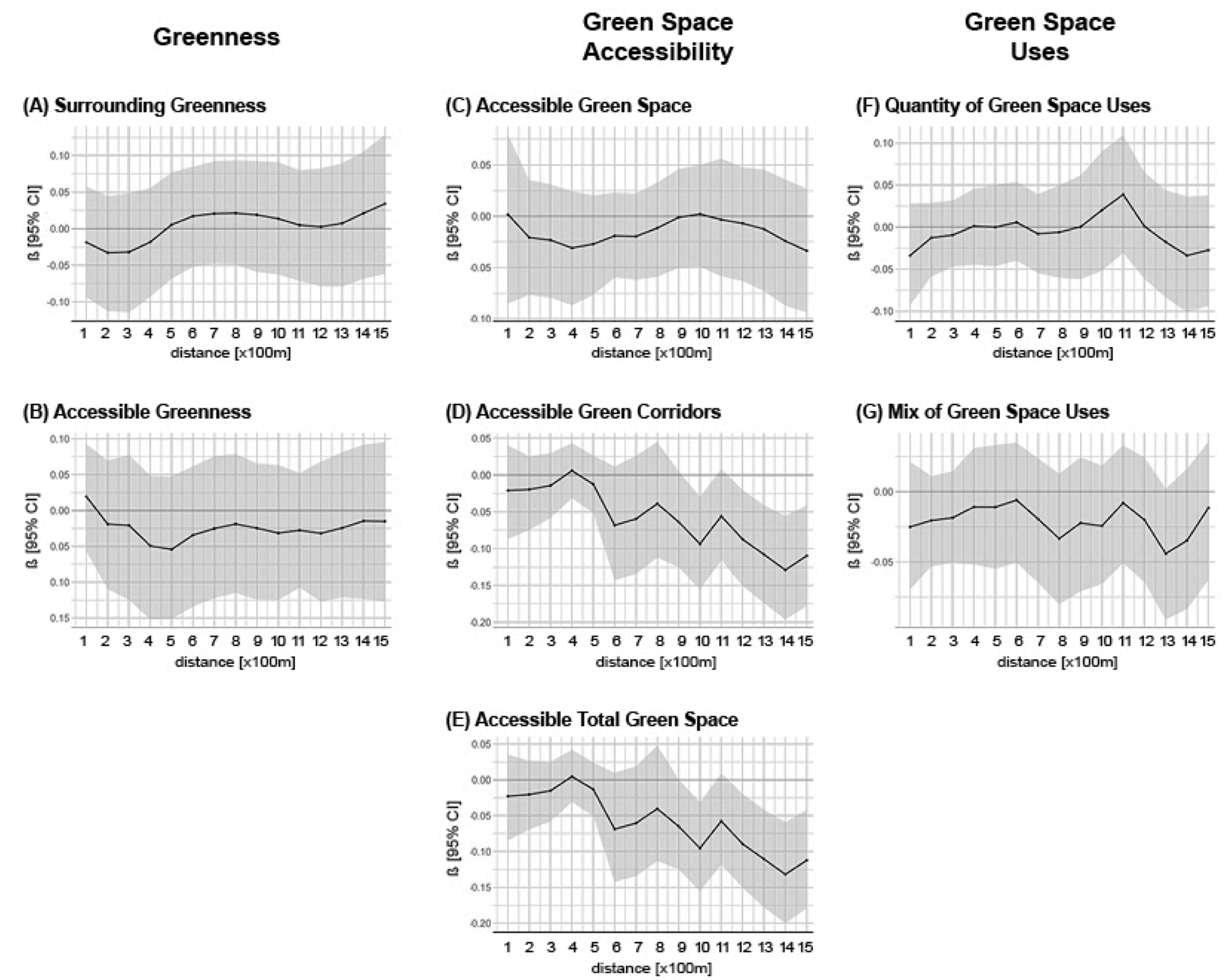

Fig. 7. Direct Effects (c). Green Space – Mental Health Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, employment status, years lived in the neighbourhood, well-being, satisfaction with shops, leisure facilities, public transport, population density and city. 5000 Bootstrap Samples, shaded grey area show 95% confidence interval.

characteristics around a residential address since it does not measure if there is an actual engagement with these green spaces. Secondly, the variation of the mental health indicator across studies might partly explain the differences since they capture different aspects or even subdomains of psychological well-being or mental illness (Bratman et al., 2019), which might be influenced differently by green spaces. Thirdly, differences in contextual variables included in the models may be partly responsible for some of the inconsistency in results.

Our results suggest negative associations between accessible green corridors or accessible total green space and mental health at distances of 1000–1500 m. This rather counterintuitive finding might be attributed to the null findings explained above since they additionally create a vulnerability to noise in the dataset, allowing spurious relations to dominate the measured relationship. Other research suggests that the composite socio-economic status (SES) of the neighbourhood might be negatively associated with mental health (Segrin & Amanda Cooper, 2023; Sui et al., 2022) in addition to the influence of individual SES. Our results might represent this effect since the studied satellite districts not only have a low composite socio-economic status but were also built according to the urban design principles of modernism with much more green space between the buildings compared to other parts of the city. This might explain our negative findings in larger distances, e.g. in the neighbourhood perspective. Therefore, we do not assume that there is an actual negative effect of the measured green space characteristics on mental health.

4.4. Strengths and limitations

The strengths of our study are based on the systematic investigation of green space characteristics and relative proximity to the residence in an elaborate investigation of 105 structural equation models. This allowed us to contribute new insights into how and where neighbourhood green spaces are related to social cohesion and mental health. Due to our mental health indicator, measured in terms of emotional, social, and psychological well-being, instead of the absence of a disease, our results also add a valuable different perspective in this research field compared to the frequent measures of mental illness scales like GHQ-12 or single illnesses like depression.

However, this study design is also associated with certain limitations. For instance, the complexity of the structural equation model was limited, as we chose to work with simple models for reasons of comparability and feasibility. Theoretically indicated dependencies and

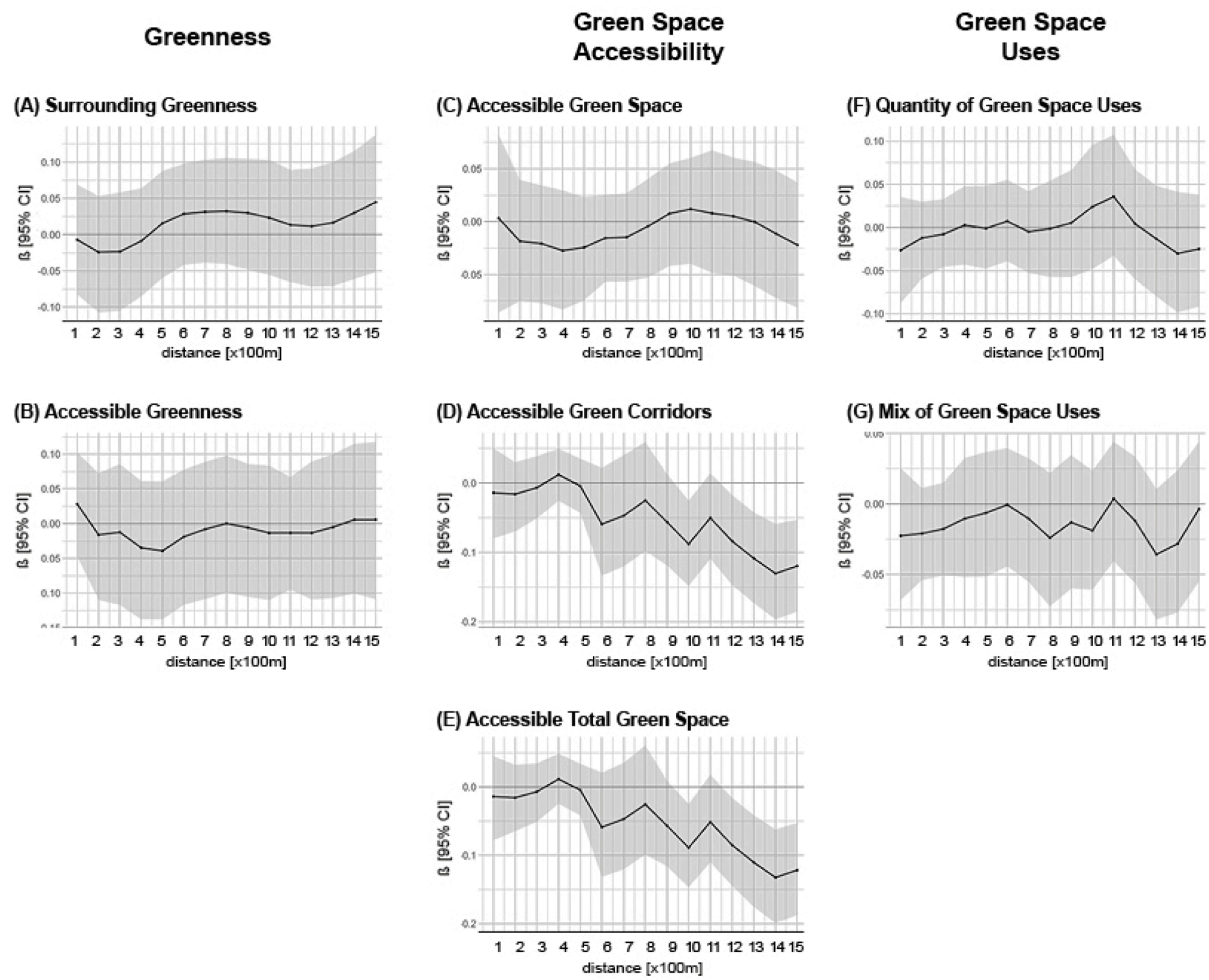

Fig. 8. Total Effects (a*b+c). Green Space – Social Cohesion – Mental Health Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, employment status, years lived in the neighbourhood, well-being, satisfaction with shops, leisure facilities, public transport, population density and city. 5000 Bootstrap Samples, shaded grey area show 95% confidence interval.

serial mediation have not been modelled (Dzhambov et al., 2018), as this would have caused variations in model fit across the structural equation models and work against the main aim of the study to compare green space characteristics. For the same reason, we only adjusted for confounders but not model theorized effect modifications due to differences in the life course and gender (Astell-Burt et al., 2014). Not accounting for these differences may have partly led to masked effects. Furthermore, as we used simple (just-identified) mediation models we can only assume that these models are correct, but not prove it through model fit indices. In addition, the clustering of survey participants in rather small geographical areas might have led to reduced variability in larger buffers. However, due to the four case studies included, we assume that the overall sample has enough variability to justify the inclusion and discussion of larger buffers. Lastly, while we adjusted for seasonal differences in the greenness indicator and the dummy city variable, there still might have been a variation in weather conditions within the weeks of the data collection, which might limit the precision of our results.

Furthermore, our data set is largely based on subjective self-assessments, which are associated with several biases like social desirability, recall or reporting bias. In addition, the ordinal variables in the model, limit the depth of information and make it more difficult to detect subtle correlations. Furthermore, our study design is cross-sectional, which does not allow any conclusions about causal relationships. We could not rule out reverse causation where respondents with lower mental health perceive social cohesion to be lower. Another limitation comes from the characterisation of green spaces. The study does not consider their quality (maintenance, quality of design, amenities, etc.). This quality criteria, which was identified during site visits, has a potential impact on the way green spaces are used, and therefore on their impact on social cohesion and health. Lastly, the recruitment of study participants in specific urban contexts, as well as the missing information on response rates in each city, also constrains the generalisability of our results.

4.5. Further research avenues and implications

Further research is needed to confirm and extend our findings. Firstly, further research is needed to better understand the inconsistency in neighbourhood green space associations to mental health, by exploring the differences between actual contact with nature and living near neighbourhood green, as the research results are still inconclusive. Secondly, while our results indicate which green space characteristics can foster social cohesion, the mediators on the pathway between green space characteristics and social cohesion remain of interest. These could potentially be physical activity and social interaction, which should be investigated in more complex serial mediation models, including moderation effects, building on our results about green space characteristics and relative proximity. Thirdly, our results showed a negative relationship between accessible green corridors and mental health, when measured with 1000–1500 m Euclidean buffers. The theorized reverse causation should be further investigated by trying to reproduce our results in longitudinal studies to analyse the causal pathway, preferably with more diverse urban characteristics, to rule out residual confounding. The sensitivity analysis indicated that cultural differences may be important to consider in future research when analysing the mediating role of social cohesion. Fourthly, by comparing our results to other studies, a potentially important difference is highlighted between the concepts of mental health, mental illness and well-being, which should be further explored in their relationship to green spaces and more precisely distinguished from one another in green space mental health studies. Lastly, more longitudinal study designs are warranted to better understand the causal relationships, and green space thresholds in these pathways (e.g. would adding more green actually lead to more social cohesion?) and also to feed policy analysis, planning and design processes.

5. Conclusion

Our study aimed to examine the role of green space characteristics and proximity to residents' homes for social cohesion and mental health. Our results suggest that specific green space characteristics are associated with higher social cohesion and in turn better mental health, namely green space corridors in intermediate surroundings up to 800 m, and mix of use in green spaces approximately in 700–1300 m surroundings. The association of surrounding greenness with social cohesion and indirectly with mental health was sensitive to the inclusion of the Porto subsample, indicating cross-cultural differences in this relationship, worth to be further investigated. Interestingly, we detected no direct positive association between any neighbourhood green space characteristics in any buffer distance to mental health. Although our study is limited due to its cross-sectional design, our findings provide valuable insights into the potential of green spaces to help promote local social cohesion and indirectly improve mental health. These insights into how and where these mechanisms may occur, provide important evidence for policymakers, urban and landscape planners, and public health decision-makers on how to design and regenerate neighbourhood green spaces to foster social cohesion and mental health.

CRediT authorship contribution statement

Cardinali Marcel: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Beenackers Mariëlle A.**: Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis. **Fleury-Bahi Ghozlane:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Bodénan Philippe:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Tasheva Petrova Milena:** Writing – review & editing, Validation, Investigation. **van Timmeren Arjan:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Pottgiesser Uta:** Writing – review & editing, Validation, Supervision, Resources, Methodology.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT 4.0 in order to proofread the text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128230.

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