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Green stormwater infrastructure and perception of the neighborhood social environment in Philadelphia 2010–2018

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ABSTRACT

Green stormwater infrastructure (GSI) is increasingly preferred to traditional stormwater management as it may confer environmental, social, or health co-benefits from its planted vegetation, although evidence for co-benefits remains sparse. Using the Southeastern Pennsylvania Household Health Survey, we conducted a study of the impact of GSI installations in Philadelphia neighborhoods from 2010 to 2018 on resident perceptions of the neighborhood social environment that reflect social cohesion. Exposure was estimated as the total area of GSI within 250 m and 1 km of participants' homes, limited to installations completed prior to the survey year, and was assessed separately for private- and publicly-owned GSI. Poisson regression with robust standard errors was used to estimate the association between GSI exposure and aspects of social cohesion, adjusting for potential confounders at the individual and neighborhood levels. Greater GSI density within 1000 m was associated with participants reporting that they trust their neighbors (highest tertile: RR = 1.22, 95% CI: 1.07 – 1.40) and that neighbors have worked together to improve the neighborhood (highest tertile: RR = 1.08, 95% CI: 1.01 – 1.16). Significant findings were found primarily for GSI within 1000 m, but not 250 m, suggesting that neighborhood perceptions may be influenced by the larger neighborhood environment. Positive findings were also largely driven by associations with privately-owned GSI. While these results suggest GSI's potential role in promoting social cohesion, future research should consider the timing of impacts and examine interactions with gentrification and neighborhood displacement.

1. Introduction

Green stormwater infrastructure (GSI) can be defined as infrastructure that uses vegetation or soil systems, permeable pavement, or other permeable substrates to reduce stormwater flow to the public storm drain systems or to surface waters (US EPA, 2024). There are both vegetated and non-vegetated types of GSI, with vegetated GSI being more common in cities with climates that support year-round vegetation, like Philadelphia. Types of vegetated GSI include stormwater basins, bumpouts, trees, planters and wetlands; green gutters and roofs; downspout planters; rain gardens; swales; and tree trenches (Green City clean waters, n.d.). Porous (permeable) pavement, blue roofs, cisterns, rain barrels, drainage wells, and subsurface trenches are types of non-vegetated GSI that are employed in some cities. GSI is often promoted over traditional grey stormwater infrastructure, in part because of environmental, socioeconomic, and health co-benefits that may stem from vegetated GSI as a form of neighborhood 'greening.' Studies have documented increases in property values and reductions in crime rates near GSI installations (Kondo, Low et al. 2015, Venkataramanan, Packman et al. 2019). A multitude of studies linking exposure to greenspace with lower mortality and enhanced mental well-being has largely focused on urban greenspace generally, rather than on GSI (Roe, Thompson et al. 2013, Heo, Desai et al. 2021). While neighborhood greenspace (i.e., vegetated landcover), is known to enhance community health through various mechanisms (Hartig, Mitchell et al. 2014), there is a paucity of research on similar health and social well-being impacts of GSI, specifically, as a type of greenspace.

A growing body of research has investigated how greenspace

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supports or hinders social cohesion (Clarke, Cadaval et al. 2023). Social cohesion encompasses many dimensions and definitions, but is generally understood as a sense of community belonging, attachment to neighborhood and place, and sense of trust in others (Jennings and Bamkole, 2019). Stated simply, social cohesion is what makes people want to remain part of their community. Furthermore, higher levels of social cohesion have been associated with more frequent interaction with neighbors, a more positive perception of the neighborhood, and feeling that the neighborhood is improving (Poortinga, 2006, Bateman, Fouad et al. 2017). Social cohesion is also intertwined with neighborhood development, which can lead to greater availability and quality of parks, grocery stores, and produce affordability and freshness (Moore et al., 2008).

Greenspace may enhance social cohesion via its role as a neighborhood amenity – providing communal spaces for recreation and social interactions (Kondo, Fluehr et al. 2018, Jennings and Bamkole, 2019, Addas, 2023). Such interactions can contribute to stronger social ties, greater trust among neighbors, and a heightened sense of belonging to the community (Cheng and Nicklett, 2022, Du, Jiang et al. 2023). New greenspace installations may enhance social cohesion by fostering a sense of neighborhood pride and collective investment in the area's improvement, as well as by improving safety (Jennings and Bamkole, 2019, Kruize et al., 2019, Javadi and Nasrollahi, 2021). The proximity and maintenance of greenspace, and perceptions of safety may also play a role in the impact of greenspace on social cohesion (Wan, Shen et al. 2021). A 2023 systematic review of research on social cohesion and greenspace identified 113 articles on the topic, yet none were specifically focused on GSI (Mendoza-Graf et al., 2023). Such studies examined overall urban greenspace/vegetation, parks, community gardens, urban forests, as well as school yards and memorial sites. The review found that greenspace contributes to social cohesion when it reduces crime, improves maintenance, and creates spaces for people to gather.

Given the rise of GSI implementation in urban neighborhoods around the world, there is a need for research on its neighborhood impacts. GSI as a specific type of greenspace may operate through similar mechanisms as overall greenspace to affect social cohesion, such as by serving as a place for social gatherings or recreation (e.g., for larger GSI installations like green roofs or raingardens). Beyond providing gathering spaces, GSI may also foster social cohesion by improving the conditions under which residents interact with one another in their everyday environments. For instance, investment in walkable infrastructure has been associated with increased community engagement, likely because they increase the frequency of social contact among neighbors, building familiarity, trust, and a sense of shared community (Hassen and Kaufman, 2016). While few studies have directly assessed GSI, some have assessed GSI along with other green infrastructure and the findings indicate that they potentially lead to similar outcomes on walking and cycling in urban areas (Lemieux, 2023). The way that GSI is implemented can impact how people use areas as well. For example, GSI can be used to reduce the length of crossing at an intersection, making it safer for people to walk in an area (Hub, 2025). Vegetated GSI also makes an area "greener," potentially improving the neighborhood aesthetics and maintenance (e.g., with multiple small GSI installations like tree trenches and bumpouts) and thereby fostering positive perceptions of the neighborhood and neighborhood pride (Chen et al., 2021).

The objective of this study was to investigate the impact of living near GSI on perceptions of the neighborhood social environment and resources among surveyed Philadelphia residents. For this study, we conceptualized social cohesion as a construct linked to community participation with notions of trust, shared emotional commitment and reciprocity (Peterson and Hughey, 2004; Wan, 2021). We hypothesized that people with a greater density of GSI installed near their homes would have more favorable perceptions of the neighborhood social environment and resources, compared to respondents living near less GSI. We also expected that people living within 250 m of GSI would report more favorable perceptions of the neighborhood than respondents with GSI at a greater distance, within 1000 m, due to a greater density of GSI. We further hypothesized that publicly owned GSI would be more strongly associated with favorable neighborhood perceptions than privately owned GSI, due to the accessibility of public GSI. Finally, we expected that vegetated GSI would be more strongly associated with favorable neighborhood perceptions than non-vegetated GSI, due to positive outcomes observed with other types of neighborhood greening. These hypotheses were tested by coupling survey data on neighborhood perceptions with detailed administrative records on GSI installations in Philadelphia. These data allowed examination of GSI footprints, as well as distinguishing between public- and private-funded GSI, and specific types of GSI such as rain gardens and green roofs. With adjustment for other types of greenspace (tree canopy coverage and distance to nearest park) in the analysis, we sought in our research to distinguish neighborhood impacts of GSI, as a particular type of greenspace.

2. Material and methods

We estimated the association between density of GSI near survey participant homes and perception of the neighborhood social environment and resources among residents of Philadelphia from 2010 to 2018. Philadelphia was chosen as the study location due to extensive GSI installations in the city resulting from the city's 25-year plan to reduce combined sewer overflows (CSO) (Green City clean waters n.d.). The Philadelphia Water Department partnered with many local organizations to install public and private GSI during this time frame.

2.1. Study population, time period, and region

The study population included adult (age $\geq$18 years) residents of the City of Philadelphia who participated in the Southeastern Pennsylvania Household Health Survey (SEPAHHS) in 2010, 2012, 2015, or 2018 (Public Health Management Corporation n.d.). The SEPAHHS survey, conducted by the Public Health Management Corporation (PHMC), was administered by telephone in English and Spanish to adults residing in five counties of the Philadelphia metropolitan area (Bucks, Chester, Delaware, Montgomery, and Philadelphia counties), in multiple waves. PHMC identified SEPAHHS participants via random digit dialing to obtain a representative, cross-sectional sample of the adult population in the study area. Survey participants were asked questions on a variety of topics, including their demographics, education, income, health behaviors, health status, and neighborhood.

This study of Philadelphia GSI included only Philadelphia County SEPAHHS respondents. The study was further restricted to the areas of Philadelphia with combined sewer systems, as GSI was predominantly installed in these areas, in line with the city's plan to reduce the volume of stormwater entering combined sewers in order to avoid sewer overflows (Green City clean waters n.d.). SEPAHHS respondents were included if they provided a valid address that was geocoded to indicate a residential location in a combined sewer system area of Philadelphia. The inclusion and exclusion criteria resulted in a sample of 8914 participants. The sample size was largest for the 2015 survey year ($n = 2777$) and smallest for 2018 ($n = 959$), when only a subset of respondents was asked questions about neighborhood perceptions.

2.2. Perceptions of the neighborhood

SEPAHHS participants responded to questionnaire items regarding neighborhood perceptions in the wave of the survey that they participated in: "Please rate how likely people in your neighborhood are willing to help their neighbors with routine activities such as picking up their trash cans, or helping to shovel snow."; "Have people in your neighborhood ever worked together to improve the neighborhood? For example, through a neighborhood watch, creating a community garden, building a community playground, or participating in a block party.";

"Please tell me if you strongly agree, agree, disagree or strongly disagree with the following statement: Most people in my neighborhood can be trusted."; "Please tell me if you strongly agree, agree, disagree, or strongly disagree with the following statement: I feel that I belong and am a part of my neighborhood."; "How many local groups or organizations in your neighborhood do you currently participate in such as social, political, religious, school-related, or athletic organizations?"; "Is there a park or other outdoor space in your neighborhood that you're comfortable visiting during the day?"; and, "How would you rate the overall quality of groceries available in the stores in your neighborhood?" All questionnaire items with multiple response options were recoded as binary responses for this study. The questions and response options for each of the questionnaire items, the survey years the questions were asked, and binary coding for this study are shown in Supplemental Table 1.

2.3. Green stormwater infrastructure (GSI)

The presence of GSI was defined as the density of GSI within specified land areas around participant homes. Data on GSI installations were obtained from Open Data Philly (Philadelphia, 2021), uploaded by the Philadelphia Water Department. Data included the status of the GSI installation (active or proposed), the year of installation, the geographic 'footprint' of the GSI feature, the type of GSI (trench; bumpout; rain garden; wetland; basin; tree trench; planter; pervious pavement; swale; green roof; cistern), and the owner (e.g., Philadelphia Water Department [PWD], private, etc.). For the purposes of this study of associations between GSI and neighborhood perceptions, the presence of GSI for each individual was coded from GSI installations that were completed before their survey year (2010, 2012, 2015, or 2018). The GSI shapefile was imported into ArcGISPro along with SEPAHHS participant residential geocodes. To assign GSI presence, the total area of GSI features located within 250 m and 1000 m buffers surrounding participants' residential addresses was summed, and the sum was used to calculate the proportion of the total buffer area. 250 m was chosen as the first buffer distance because it represents a roughly 3-to-4-minute walk which we assumed would correspond to walking up and down the block adjacent to a respondent's residence. 1000 m was chosen as the second buffer distance because we assumed that the walking time of 10–15 would equate to a walkable distance across a neighborhood. The GSI variables were calculated for all GSI and for public- and private-owned GSI, separately. GSI variables were also calculated for all vegetated GSI (including bumpouts, rain gardens, wetlands, tree trenches, planters, swales, and green roofs) and for rain gardens, tree trenches, and green roofs, separately. Each GSI density measure representing the proportion of the residential buffer area covered by GSI was coded in categories split by tertile values vs. none.

2.4. Covariates

Covariate selection was informed by literature on both GSI and broader urban greening initiatives, as we theorize that GSI operates in a similar mechanistic pathways with other forms of greenspace. Potential confounders were selected *a priori* based on a conceptual diagram informed by prior literature (Fig. 1) and were included in all models. These potential confounders included both individual-level and neighborhood-level factors.

Philadelphia's Green City, Clean Waters initiative targets areas with high impervious surface coverage as sites for GSI installations (Philadelphia, 2021). Impervious surface is also associated with reduced neighborhood greenness and elevated urban heat (Ziter, Pedersen et al. 2019), which may negatively impact outdoor physical activity (Lanza, Gohlke et al. 2022) and perceptions of neighborhood quality (Zhang et al., 2017). Population density is correlated with built environment characteristics such as high amounts of impervious surface and stormwater runoff (Shuster, Bonta et al. 2005), which drive GSI placement. Population density is also associated with characteristics of the built environment, including greenspace and walkability, which may influence residents' use of neighborhood environments and opportunities for social interaction (Sallis, Cerin et al. 2016). Additionally, neighborhood density is linked to perceptions of neighborhood safety and social cohesion, as more densely populated areas can shape the frequency of social interactions and collective engagement (Sampson, Raudenbush et al. 1997). Traffic density is disproportionately concentrated in lower-income and racially minoritized communities (Rowangould, 2013), which has been linked to GSI placement in Philadelphia (Shokry, Connolly et al. 2020). High traffic density has also been linked to reduced use of street spaces, decreased walkability and unfavorable perceptions of neighborhood safety (Sallis, Cerin et al. 2016, Anciaes, Stockton et al. 2019). Urban tree canopy and greening resources ae unequally distributed by income and race, with lower canopy coverage in low-income and residentially segregated neighborhoods (Locke, Hall et al. 2021, McDonald, Biswas et al. 2021, Zhou, Huang et al. 2021). Access to parks is similarly patterned to race and income (Rigolon, 2016). Living in greener areas and having access to greenspace has been associated with more favorable perceptions of the neighborhood and

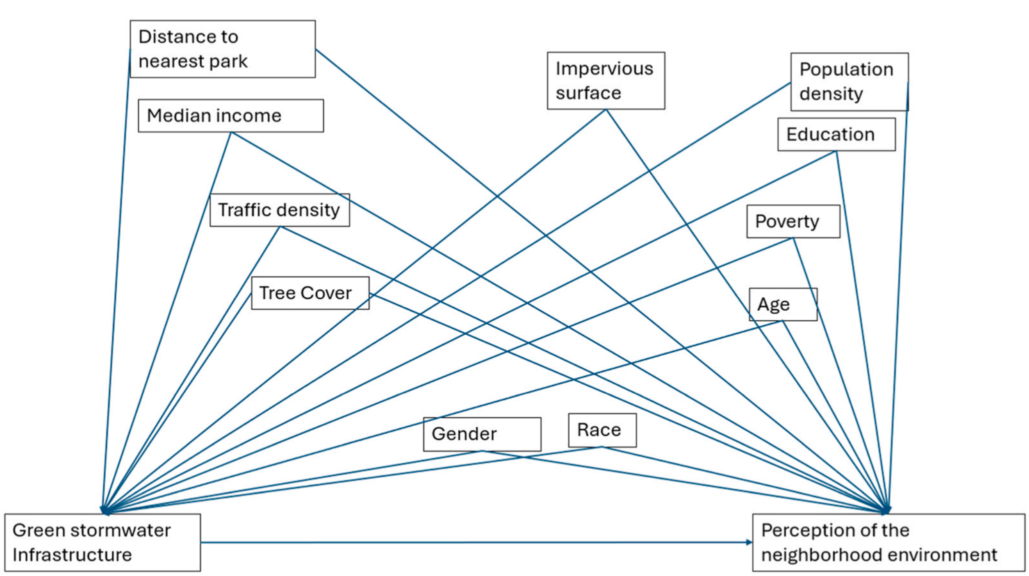

Fig. 1. Conceptual diagram showing the relationship between Green stormwater infrastrucutre, Perception of the neighborhood environment, and covariates.

social cohesion (Jennings and Bamkole, 2019).

The literature shows inequities in access to greenspaces in racial groups with White residents having greater exposure compared to Black, Hispanic, and Chinese American residents (Jenson et al., 2025). Race has been associated with displacement of residents after implementation of stormwater control measures, including GSI (Chan et al., 2021). These findings remained true across the intersection of education and neighborhood socioeconomic status. Race has also been associated with perceptions of neighborhood safety and social cohesion (Laméris, Hipp et al. 2018). Prior research has also shown disparities in access to greenspace across education, homeownership in comparison to renting, and income (Endalew Terefe and Hou, 2024). Homeownership is associated with social cohesion with homeowners generally perceiving higher levels of social cohesion (Uchida, Swatt et al. 2013, Akbar, Hartono et al. 2023). Educational attainment is associated with neighborhood social cohesion, with lower educational attainment linked to less favorable perceptions of community social cohesion (Huang, Uchida et al. 2025). Gender influences how people interact with their physical environment and perceive their safety (Ode Sang et al., 2016). As stated previously, perceptions of safety may contribute to the impact of GSI on social cohesion (Wan et al., 2021). Age has also been found to influence how people perceive and use neighborhood spaces, particularly greenspace and parks (Moore and Kestens, 2011). Research also indicates that greenspace is positively associated with greater physical activity among older adults (Wang, Song et al. 2025), and increased physical activity has also been linked to greater social cohesion (Quinn, Wu et al. 2019). Smoking was included as a covariate as the literature indicates that higher levels of social cohesion are associated with lower levels of smoking (Patterson et al., 2004) and smoking is patterned by socioeconomic characteristics such as education and income (Barbeau, Krieger et al. 2004) which have been shown to correlate with GSI placement.

Individual-level confounders were obtained from the SEPAHHS, harmonized over the four survey waves. These variables were categorized for the analysis as follows: age (18–34; 35–49; 50–64; 65 + years); gender (male; female); race (White, not Latino; Black, not Latino; Latino; Asian; biracial or multiracial; Native American; other); education (less than high school graduate; high school graduate or GED certificate; technical, trade, or vocational school after high school; some college but no four-year degree; college graduate; post-graduate or professional schooling after college); current smoking status (yes; no); rent or own home (rent; own; other); and, household income below federal poverty level (yes; no). The models were also adjusted for survey wave (2010; 2012; 2015; 2018). The neighborhood-level covariates included census-tract level population density, median household income, impervious surface within 500 m (proportion of area), tree canopy coverage within 500 m (proportion of area), distance to the nearest park (in meters), and traffic density within 500 m (vehicles per km squared); these were categorized by quartiles for the analysis. Categories for all covariates were included as indicator variables in regression analyses.

At the neighborhood level, census-tract level population density (per km^2) and median household income were obtained from the American Community Survey (ACS) (Census 2018). Land cover as tree canopy or impervious surface for 2008, 2013, and 2018 were obtained from Pennsylvania Spatial Data Access (Data Summary - Pennsylvania Spatial Data Access 2018). These high-resolution land cover data were developed using object-based image analysis techniques (OBIA) using the best available remotely sensed and vector GIS datasets (Multi-Resolution Land Characteristics (MRLC) Consortium 2024). Each pixel (1 ft resolution for 2008 and 1 m for 2013 and 2018) was assigned to 1 of 12 mutually exclusive landcover categories. The fraction of land cover as tree canopy and impervious surface were calculated separately for our study using 2008, 2013, and 2018 high resolution land cover data, within a buffer area of 500 m around participant homes. Distance from each participant's residence to the nearest park in meters was calculated using the 2020 ParkServe park boundary/location dataset from The Trust for Public Land (calculated using the 2018 population estimates) (Trust for Public Land 2020). Traffic density was calculated using average daily traffic for all vehicles on interstate, principal arterial, minor arterial, and major collector roadway types using data from the Highway Performance Monitoring System (HPMS) (DOT, 2022), based on the kernel density surface of daily traffic density per square kilometer within 500 m of participant homes (ESRI n.d.).

2.5. Statistical analysis

Participant and neighborhood characteristic distributions were summarized using frequencies and percentages for categorical variables and means with standard deviations (SD) for continuous variables, overall (for the entire study population), and according to the presence of GSI within 250 m and 1000m-buffer areas around participant homes. Next, the percentage of participants responding positively to each of the neighborhood perception variables was summarized by participant characteristics.

To assess the relationship between the presence of GSI and neighborhood perceptions, we fit generalized linear models (GLMs) of the Poisson family with robust standard error estimation to generate prevalence ratios (as estimates of relative risks [RR]) and 95% confidence intervals (CI) in SAS v. 9.4. Each combination of GSI (independent variable) and neighborhood perception outcome (dependent variable) was modeled separately. We used modified Poisson regression approach with a robust error variance because it is an accepted method of modeling binomial data, and the approach allowed us to overcome convergence issues when applying a log-binomial distribution (Zhao n. d.). The Poisson regression approach also allowed us to estimate prevalence ratios with unbiased confidence intervals. Models were further specified with stratification by PHMC-generated weights to account for the complex SEPAHHS sampling design with differential probabilities of selection for segments of the population in the survey sample.

3. Results

The study population of 8914 participants (Table 1) was majority female (66.7%), age 50 years or older (59.2%), non-Latino Black (50.0%) or non-Latino White (32.8%), homeowners (61.5%), and not classified as living in poverty (77.5%). Approximately half of the study population completed education beyond high school graduation (49.6%). The percentage of participants living within proximity of GSI increased substantially over time, between survey waves, from 13.3% in 2010–46.8% in 2018 for GSI within 250 m, and from 79.6% in 2010–99.3% in 2018 for GSI within 1000 m (Supplemental Table 2). Participants living within 250 m of GSI were more likely than those not living near GSI (Table 1) to be male, age 65 years or older, non-Latino White, renters, classified as living in poverty, and to have a college-level or postgraduate-level education. Smoking status (ever/never) did not differ substantially by living near GSI (250 m). With regards to area-level characteristics, participants living near GSI were more likely than those without GSI (within 250 m) to live in census tract areas with higher population density (Table 1) and higher median household income. In addition, those living near GSI had, on average, less tree canopy coverage within 500 m, greater traffic density within 500 m, and a shorter distance to the nearest park. Approximately twice as many participants lived within 1000 m of private GSI (N = 7726) than near public GSI (N = 3963). Compared to participants living near public GSI within 1000 m (Table 1), those living near private GSI skewed younger, more frequently Latino, and had less formal education; furthermore, those near private GSI lived in areas with lower population density, lower median household income, greater traffic density, and a greater distance to the nearest park.

Supplemental Table 3 presents the frequency of affirmative responses to the questionnaire items about neighborhood perceptions, stratified by participant characteristics. A majority of participants

Table 1
Study population characteristics, overall and by presence of GSI within proximity to residence. Number and percentage (n (%)) are indicated in the table below using data from the Philadelphia Water Department for GSI installations and individual information from the Southeastern Pennsylvania Household Survey. The p-values represent differences in the covariates across presence of any GSI within the buffer area. Continuous variables were tested with a *t*-test and categorical variables with chi square.

		Overall	Any GSI 250 m		p-value	Any Public GSI 1000 m	Any Private GSI 1000 m
		N = 8914	No (N = 6624)	Yes (N = 2290)		Yes (N = 3963)	Yes (N = 7726)
Individual Level Characteristics							
Gender (%)	Female	5943 (66.7)	4473 (67.5)	1470 (64.2)	0.004	2583 (65.2)	5115 (66.2)
	Male	2971 (33.3)	2151 (32.5)	820 (35.8)		1380 (34.8)	2611 (33.8)
Age (%)	13–34	1372 (15.4)	1022 (15.4)	350 (15.3)	0.002	563 (14.2)	1163 (15.1)
	35–49	2197 (24.6)	1679 (25.3)	518 (22.6)		900 (22.7)	1887 (24.4)
	50–64	3109 (34.9)	2328 (35.1)	781 (34.1)		1366 (34.5)	2673 (34.6)
	65 +	2168 (24.3)	1543 (23.3)	625 (27.3)		1107 (27.9)	1943 (25.1)
	Missing	68 (0.8)	52 (0.8)	16 (0.7)		27 (0.7)	60 (0.8)
Race (%)	Asian	145 (1.6)	106 (1.6)	39 (1.7)	< 0.001	61 (1.5)	118 (1.5)
	Biracial/Multi	266 (3.0)	189 (2.9)	77 (3.4)		127 (3.2)	220 (2.8)
	Black, not Latino	4459 (50.0)	3298 (49.8)	1161 (50.7)		1995 (50.3)	3790 (49.1)
	Latino (total)	872 (9.8)	710 (10.7)	162 (7.1)		314 (7.9)	710 (9.2)
	Native American	59 (0.7)	38 (0.6)	21 (0.9)		32 (0.8)	53 (0.7)
	Other	38 (0.4)	27 (0.4)	11 (0.5)		18 (0.5)	35 (0.5)
	White, not Latino	2927 (32.8)	2149 (32.4)	778 (34.0)		1342 (33.9)	2672 (34.6)
	Missing	148 (1.7)	107 (1.6)	41 (1.8)		74 (1.9)	128 (1.7)
Education (%)	Less than high school	1146 (12.9)	855 (12.9)	291 (12.7)	0.044	468 (11.8)	975 (12.6)
	High school graduate	3221 (36.1)	2449 (37.0)	772 (33.7)		1300 (32.8)	2763 (35.8)
	Technical/ Vocational/Trade School	204 (2.3)	144 (2.2)	60 (2.6)		115 (2.9)	181 (2.3)
	Some college, Associate Degree	1854 (20.8)	1373 (20.7)	481 (21.0)		771 (19.5)	1580 (20.5)
	College graduate	1396 (15.7)	1021 (15.4)	375 (16.4)		697 (17.6)	1239 (16.0)
	Post-graduate/ Professional degree	1050 (11.8)	754 (11.4)	296 (12.9)		591 (14.9)	947 (12.3)
	Missing	43 (0.5)	28 (0.4)	15 (0.7)		21 (0.5)	41 (0.5)
Rent or Own (%)	Other	372 (4.2)	273 (4.1)	99 (4.3)	< 0.001	164 (4.1)	323 (4.2)
	Own	5481 (61.5)	4204 (63.5)	1277 (55.8)		2375 (59.9)	4712 (61.0)
	Rent	2997 (33.6)	2100 (31.7)	897 (39.2)		1391 (35.1)	2638 (34.1)
	Missing	64 (0.7)	47 (0.7)	17 (0.7)		33 (0.8)	53 (0.7)
Below federal poverty guidelines (%)	No	6906 (77.5)	5170 (78.0)	1736 (75.8)	0.084	3023 (76.3)	5967 (77.2)
	Yes	2005 (22.5)	1452 (21.9)	553 (24.1)		939 (23.7)	1757 (22.7)
	Missing	3 (0.0)	2 (0.0)	1 (0.0)		1 (0.0)	2 (0.0)
Smoked at least 100 cigarettes (%)	No	4616 (51.8)	3435 (51.9)	1181 (51.6)	0.606	2026 (51.1)	3986 (51.6)
	Yes	4252 (47.7)	3152 (47.6)	1100 (48.0)		1918 (48.4)	3700 (47.9)
	Missing	46 (0.5)	37 (0.6)	9 (0.4)		19 (0.5)	40 (0.5)
Area Level Characteristics							
Population density (per km2) (mean (SD))		8623.55 (3867.57)	8538.53 (3694.24)	8869.49 (4321.53)	< 0.001	9011.90 (4153.93)	8666.38 (3953.78)
Median HH income in CT (dollars) (mean (SD))		36219 (17188)	35752 (15410)	37569 (21468)	< 0.001	38415 (20028)	36528 (17959)
Education high-school graduation or higher in CT (percent of population) (mean (SD))		36% (12%)	36% (11%)	33% (13%)	< 0.001	33% (13%)	35% (12%)
Impervious Surface within 500 m (percent area) (mean (SD))		77% (12%)	77% (12%)	77% (11%)	0.013	77% (12%)	77% (11%)
Tree canopy within 500 m (percent area) (mean (SD))		16% (9%)	16% (9%)	14% (8%)	< 0.001	15% (8%)	15% (9%)
Traffic density within 500 m (vehicles per km2) (mean (SD))		70890.11 (106344.33)	70633.92 (106919.44)	71631.17 (104682.57)	0.699	70722.29 (110693.61)	72582.67 (108784.36)
Distance to nearest park (m) (mean (SD))		243.25 (166.87)	255.67 (172.29)	207.32 (144.23)	< 0.001	218.87 (143.82)	234.52 (160.31)

reported working together to improve the neighborhood (70.0%) and perceiving a sense of belonging (80.2%), as well as availability of good quality groceries (66.3%). Males more frequently reported having a park/outdoor space they are comfortable visiting, compared to females, while females were more likely to report current participation in neighborhood groups. Compared to older age groups, participants aged 18–34 years were less likely to have affirmative responses to any of the neighborhood perception items, except to presence of a park/outdoor space they are comfortable visiting. Non-Latino White participants were more likely than the other race/ethnicity groups to report trust in neighbors, belonging in neighborhood, good quality groceries, and a park they are comfortable visiting, whereas non-Latino Black participants were most likely among the race/ethnicities to report that neighbors had ever worked together to improve the neighborhood. Participants with post-graduate/professional degrees were more likely than those with less education to respond affirmatively to all of the neighborhood perception items, except presence of a park.

Having any type of GSI located within 1000 m was positively associated with the perception that neighbors are willing to help, as participants within the second and third tertiles (indicating greater density of GSI within buffer area around their home) were 19% (RR=1.19, 95% CI: 1.03–1.36) and 12% (RR= 1.12, 95% CI: 0.95–1.31) more likely to report that neighbors are willing to help than were participants with no GSI within 1000 m (Fig. 2). This association for GSI within 1000 m was

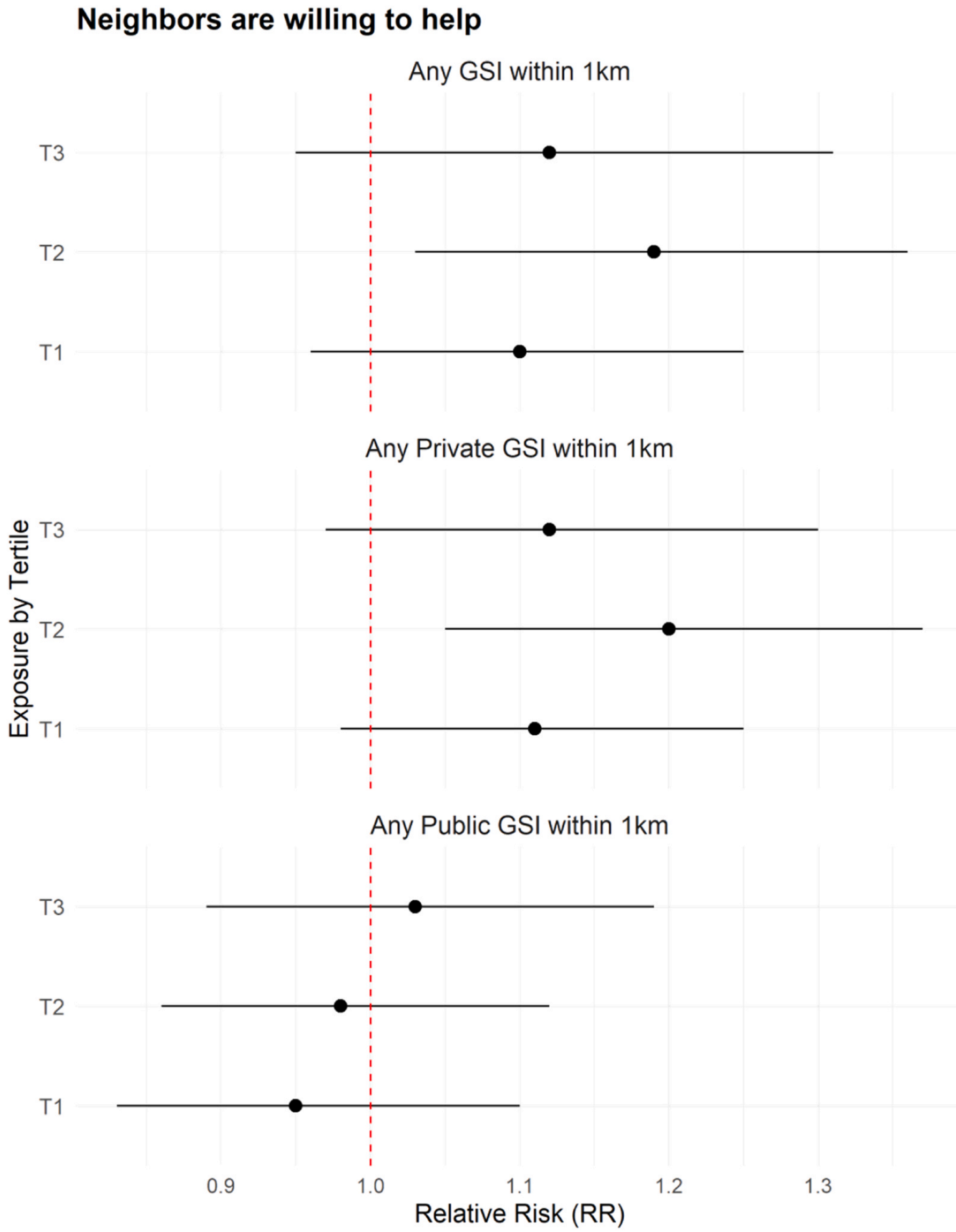

Fig. 2. Poisson regression analysis results for 'Neighbors are willing to help'. T1 represents the lowest level of GSI density compared to people with no GSI within the buffered distance. T2 is the middle density and T3 represents the highest density of exposure compared to people with no GSI within the buffered distance. Models were adjusted for age, gender, education, survey year, poverty, smoking status, homeownership status, race, median census tract income, population density, impervious surface, distance from nearest park, tree canopy coverage, and traffic density.

primarily due to a positive association with private GSI. Living within 250 m of GSI was not associated with the perception of neighbor willingness to help.

Vegetated GSI was positively associated with the perception that people work together to improve the neighborhood. Participants with the highest tertile category of vegetated GSI within 1000 m of their home were 8% (RR= 1.08, 95% CI: 1.01–1.16) more likely to report people working together to improve the neighborhood than were those with no vegetated GSI (Fig. 3). This positive association was limited to private vegetated GSI (RR= 1.10, 95% CI: 1.03–1.17), as there was no association with public vegetated GSI (RR=1.00, 95% CI: 0.92, 1.09). Private green roofs within 1000 m, in particular, were associated with the perception of people working together to improve the neighborhood, with positive associations observed for those with second-tertile (RR=1.15, 95% CI: 1.07, 1.23) and third-tertile (RR=1.14, 95% CI: 1.06, 1.23) categories. No consistent associations were observed for public GSI within 1000 m.

Participants with any type GSI within 1000 m were more likely to report that most people in their neighborhood can be trusted; specifically, 22% more likely at the third tertile category of GSI presence compared to those without any GSI (RR= 1.22, 95% CI: 1.07–1.40) (Fig. 4). However, having GSI within 250 m did not show a significant association with trust (third-tertile vs. none, RR= 1.04, 9%% CI: 0.93–1.17). As for other neighborhood perception outcome variables, the positive relationship of trust with GSI within 1000 m was limited to private GSI installations.

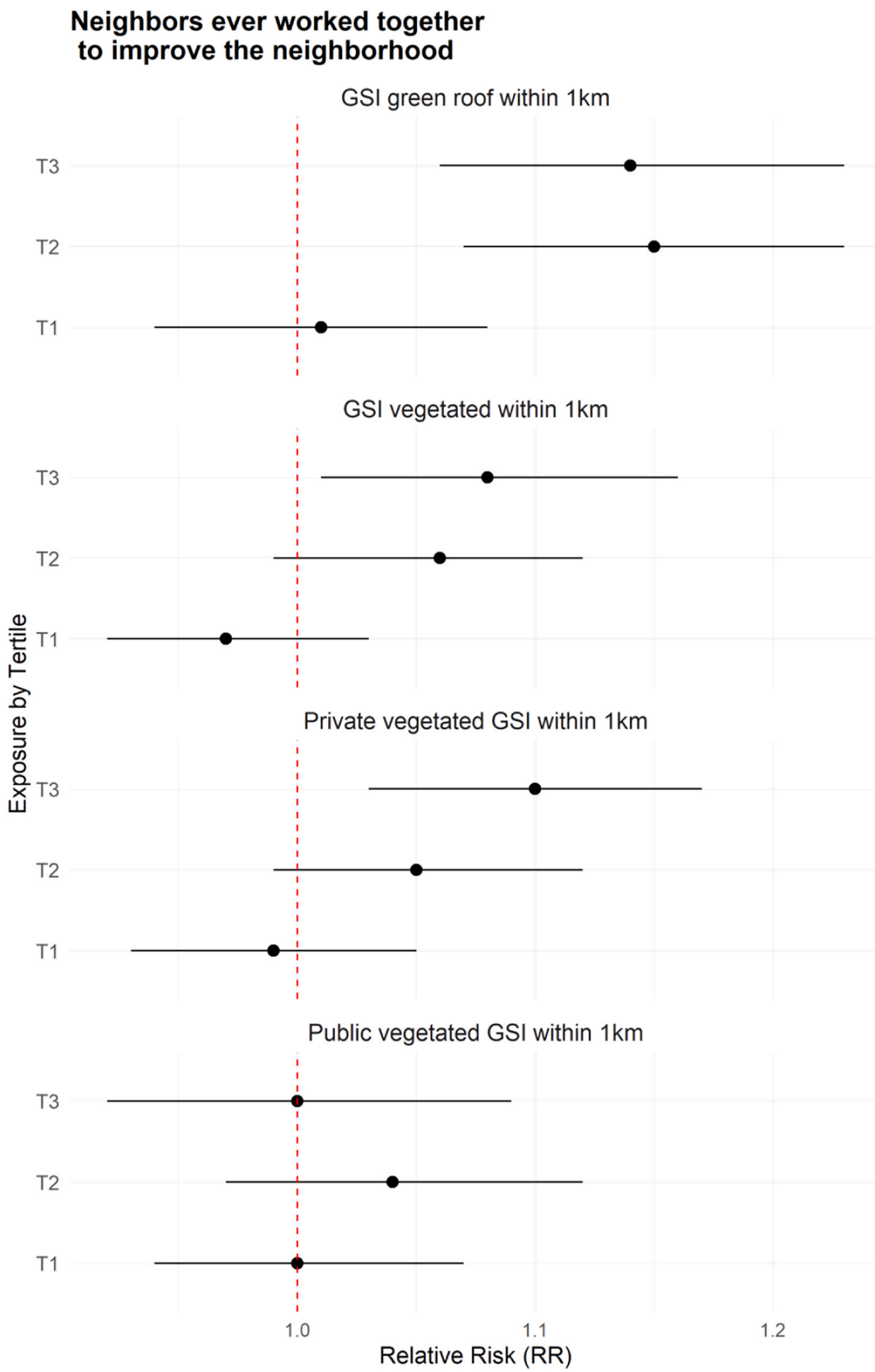

Fig. 3. Poisson regression analysis results for 'Neighbors ever worked together to improve the neighborhood'. T1 represents the lowest level of GSI density compared to people with no GSI within the buffered distance. T2 is the middle density and T3 represents the highest density of exposure compared to people with no GSI within the buffered distance. Models were adjusted for age, gender, education, survey year, poverty, smoking status, homeownership status, race, median census tract income, population density, impervious surface, distance from nearest park, tree canopy coverage, and traffic density.

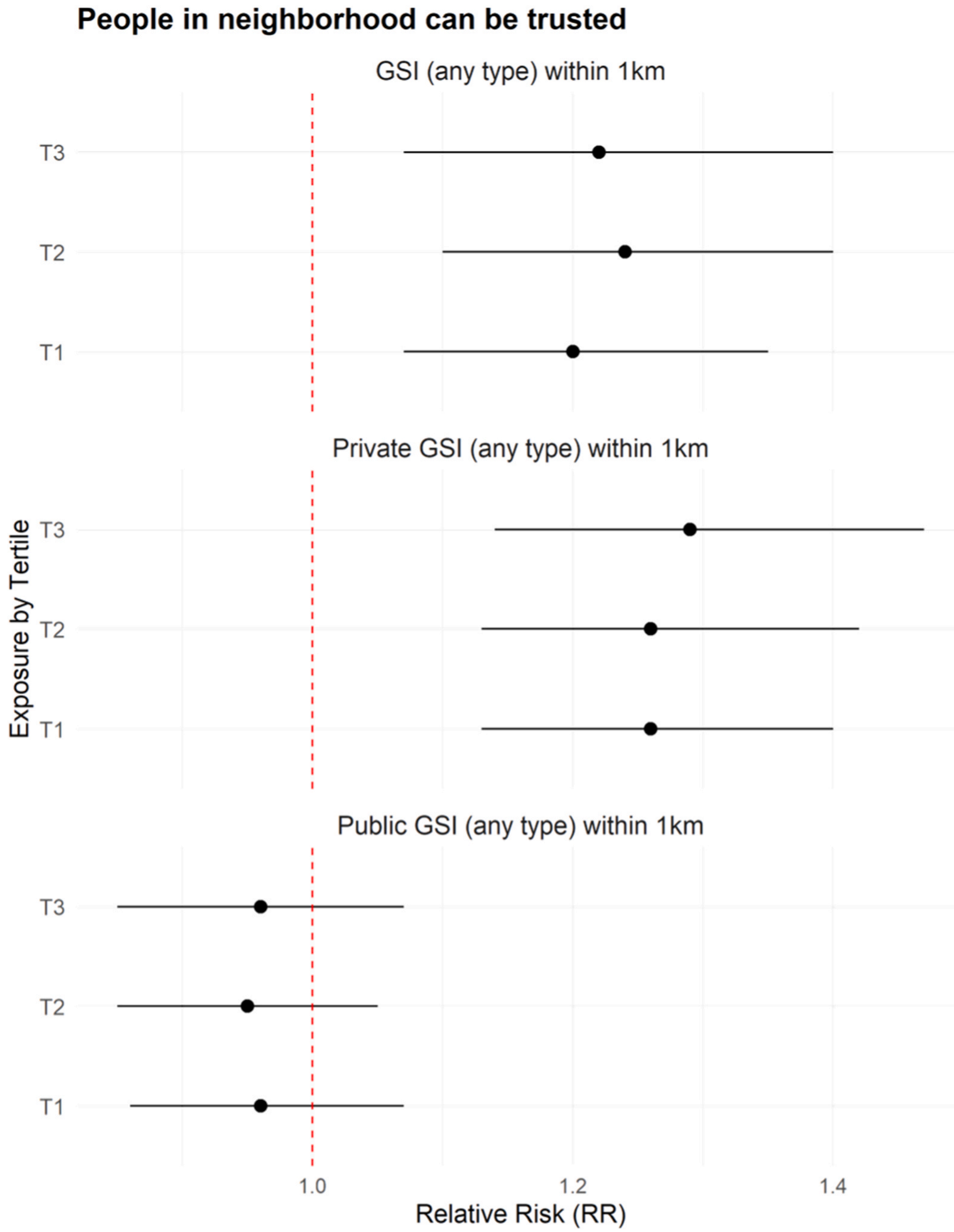

Fig. 4. Poisson regression analysis results for 'People in the neighborhood can be trusted'. T1 represents the lowest level of GSI density compared to people with no GSI within the buffered distance. T2 is the middle density and T3 represents the highest density of exposure compared to people with no GSI within the buffered distance. Models were adjusted for age, gender, education, survey year, poverty, smoking status, homeownership status, race, median census tract income, population density, impervious surface, distance from nearest park, tree canopy coverage, and traffic density.

Participants feeling that they belong in their neighborhood was associated with a greater density of green roofs GSI within 1000 m of their home. The presence of private green roofs within 1000 m was associated with 5% (1.05, 95% CI: 1.00–1.11) and 7% (RR=1.07, 95% CI: 1.01–1.14) greater likelihood of participants reporting that they belong, for the second and third tertiles, respectively, relative to no green roofs (Fig. 5).

GSI presence, overall, was not associated with participation in neighborhood groups. However, survey respondents with the highest level of tree trench GSI within 1000 m were 22% (Fig. 6) more likely to report that they participate in one or more neighborhood groups (RR=1.22, 95% CI: 1.06, 1.40). A similar association was observed for tree trench GSI within 250 m, but this association was stronger with the second tertile (RR=1.41, 95% CI: 1.14–1.74). These associations were similar for public tree trenches, as the vast majority of tree trench GSI was publicly owned.

Participant reports on the quality of groceries in their neighborhood was not associated in an exposure-dependent manner with any of the GSI tertiles in the 250 m or 1000 m buffer areas (Supplemental Table 4).

Living with a greater density of GSI of any type within 1000 m was positively associated with participants reporting they have a park or other outdoor space they are comfortable visiting during the day, with 21% higher likelihood of reporting a park for those in the highest tertile (RR=1.21, 95% CI: 1.07–1.38) (Fig. 7). The corresponding association was weak and not statistically significant for GSI within 250 m. The association between GSI within 1000 m and participants reporting a

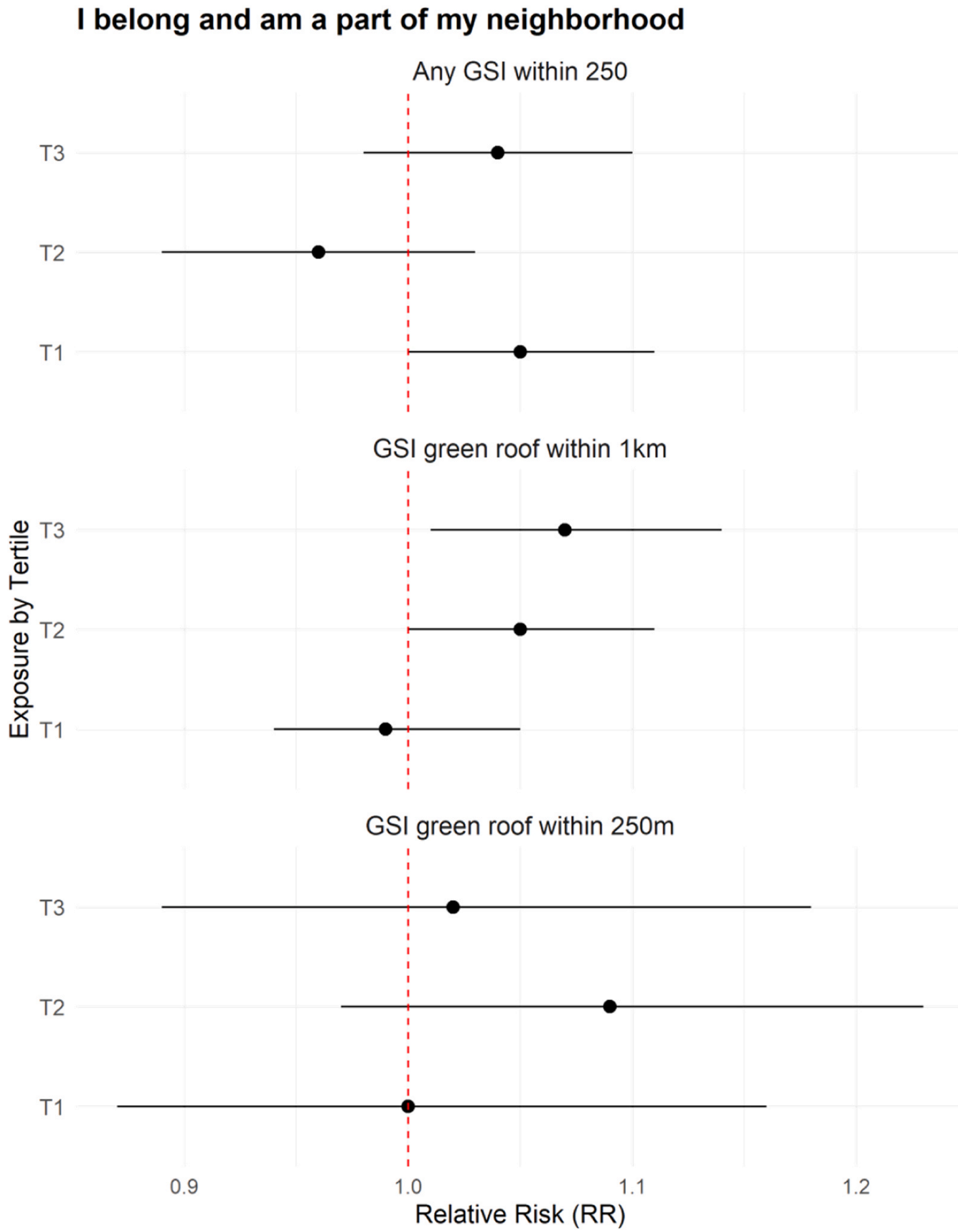

Fig. 5. Poisson regression analysis results for 'I belong and am a part of my neighborhood'. T1 represents the lowest level of GSI density compared to people with no GSI within the buffered distance. T2 is the middle density and T3 represents the highest density of exposure compared to people with no GSI within the buffered distance. Models were adjusted for age, gender, education, survey year, poverty, smoking status, homeownership status, race, median census tract income, population density, impervious surface, distance from nearest park, tree canopy coverage, and traffic density.

park they are comfortable visiting during the day was stronger for private GSI (highest level: RR=1.23, 95% CI: 1.10–1.37) than for public GSI (highest level: RR= 1.05, 95% CI: 0.98–1.12), and was notably associated in an exposure-dependent manner with private green roof GSI, with 10% (RR=1.10, 95% CI: 1.03–1.18), 11% (RR=1.11, 95% CI: 1.04–1.19), and 15% (RR=1.15, 95% CI: 1.08–1.24) higher likelihoods of participants reporting a comfortable park/outdoor space across the three tertile categories of increasing green roof presence. A similar association for green roof GSI within 250 m was observed for the second-tertile versus none (RR=1.15, 95% CI: 1.04, 1.26).

GSI within 250 m of participant homes was generally not associated with respondent perceptions of the neighborhood. However, several positive associations were observed for GSI within 250 m at the lowest tertile only. Specifically, such associations were observed for both private and public GSI with the outcomes of belonging in the neighborhood, people working together to improve the neighborhood, and trust in neighbors, and for any type of GSI with participation in neighborhood groups.

4. Discussion

We hypothesized that people with a greater density of GSI installed near their homes would have more favorable perceptions of the neighborhood social environment and resources compared to respondents living near less GSI, but we found varying associations. As one of the few studies on GSI and perceptions of the neighborhood social environment,

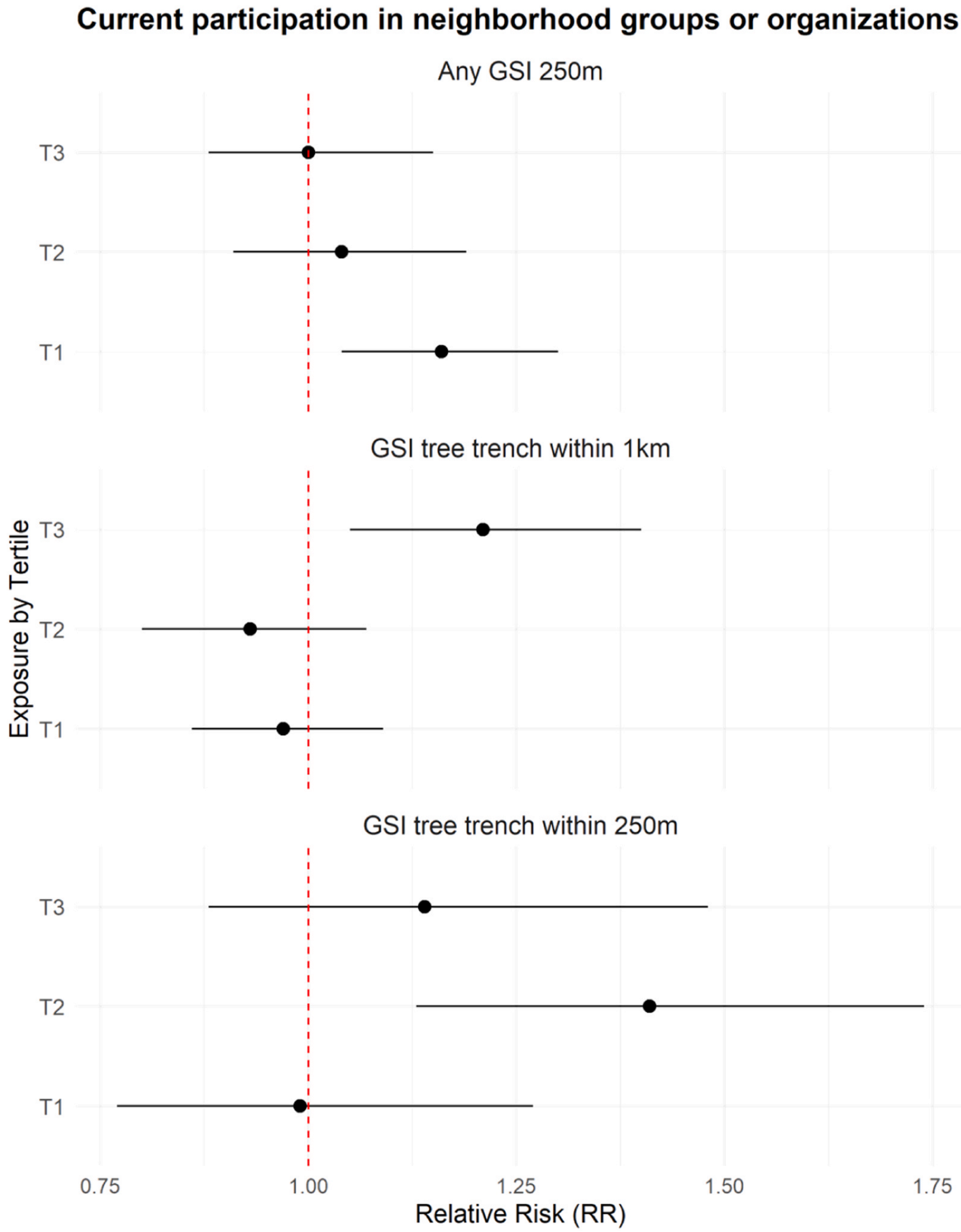

Fig. 6. Poisson regression analysis results for 'Current participation in neighborhood groups or organizations'. T1 represents the lowest level of GSI density compared to people with no GSI within the buffered distance. T2 is the middle density and T3 represents the highest density of exposure compared to people with no GSI within the buffered distance. Models were adjusted for age, gender, education, survey year, poverty, smoking status, homeownership status, race, median census tract income, population density, impervious surface, distance from nearest park, tree canopy coverage, and traffic density.

our study suggests that GSI has a similar relationship with social cohesion as other types of urban greenspace. For example, we found that individuals with higher densities of vegetated GSI and green roofs within 1000 m were more likely to report that neighbors had worked together to improve the neighborhood. This is consistent with prior work suggesting that visible environmental enhancements can foster a sense of collective responsibility and community action (Shandas, 2015). Similarly, our analysis revealed that proximity to green roofs within 1000 m was associated with a heightened sense of belonging in the neighborhood. This underscores the potential psychological benefits of living near greenspaces, which may contribute to people feeling more connected to their community (Roe, Thompson et al. 2013). Furthermore, we found an association between trust in neighbors and the presence of GSI that was consistent across types of GSI (any type within 1000 m and private GSI within 250 m) and across tertiles of GSI density. This may indicate the potentially stabilizing influence of GSI on social cohesion, suggesting that GSI can positively impact interpersonal trust within neighborhoods (Wolch, Byrne et al. 2014).

While we expected that people living within 250 m of GSI would report more favorable perceptions of the neighborhood than respondents with GSI at a greater distance (within 1000 m), due to a greater density of GSI within a smaller area near their home, this was not always the case. A possible explanation may be that the 1000 m buffer captures the scale at which GSI influences perception of the neighborhood. Trust and social cohesion are shaped by neighborhood-wide interactions which may extend beyond the immediate surroundings

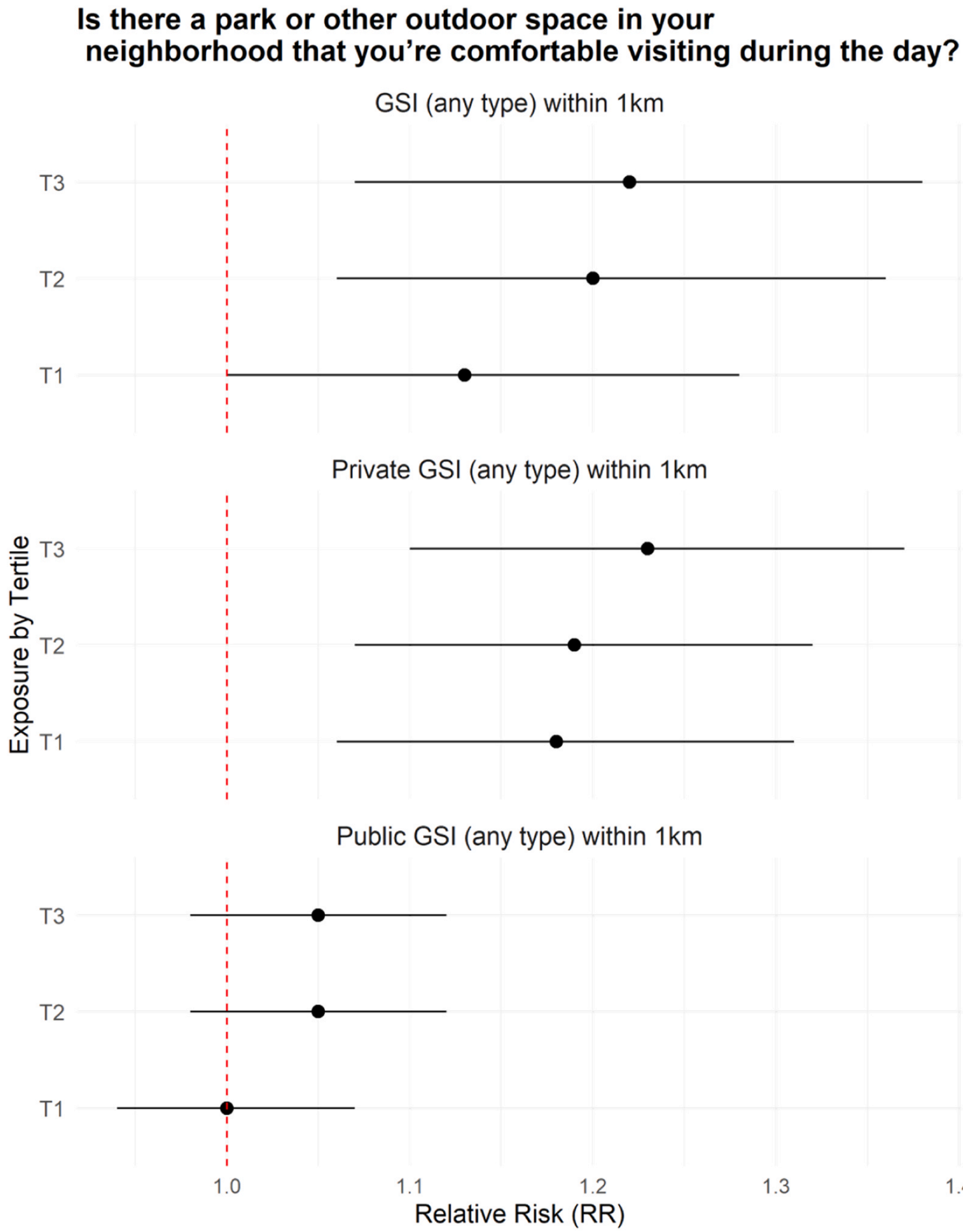

Fig. 7. Poisson regression analysis results for 'Is there a park or other outdoor space in your neighborhood that you're comfortable visiting during the day?'. T1 represents the lowest level of GSI density compared to people with no GSI within the buffered distance. T2 is the middle density and T3 represents the highest density of exposure compared to people with no GSI within the buffered distance. Models were adjusted for age, gender, education, survey year, poverty, smoking status, homeownership status, race, median census tract income, population density, impervious surface, distance from nearest park, tree canopy coverage, and traffic density.

captured by 250 m, reflecting the modifiable areal unit problem in how neighborhoods are spatially defined (Kwan, 2012). Significant exposure-response relationships emerging for GSI density within 1000 m may imply that neighborhood perceptions reflect broad neighborhood dynamics, which may be more influenced by neighborhood infrastructure at a larger scale, rather than within smaller areas that immediately surround an individual's home. This aligns with studies suggesting that people's sense of community and neighborhood cohesion is often shaped by broader environmental factors, including the frequency of contact, type, quality, and amount of green space(Hartig, Mitchell et al. 2014), which may not be fully captured by smaller buffers.

We further hypothesized that publicly owned GSI would be more strongly associated with favorable neighborhood perceptions than privately owned GSI, due to greater accessibility of public GSI, which is built on city-owned properties such as streets and sidewalks that are accessible to all (Sell, 2022). However, we found that private GSI was associated with aspects of social cohesion more than public GSI. Our unexpected results for private GSI may be due to the types of private and public GSI installations. Examples of GSI that may facilitate a space for social gatherings are green roofs and rain gardens, which were more frequently private, than public, installations in our study (in fact, roof gardens were exclusively private GSI). In contrast, public GSI are frequently tree trenches and bumpouts along roadways and sidewalks, which do not offer a designated space to gather. Another possible explanation for stronger results with private GSI may relate to gentrification. A prior study in Philadelphia found that green resilient infrastructure (GRI) sites were commissioned in more economically valued neighborhoods which saw whiter and wealthier residents increasingly move in, at the same time that the percentage of lower-income and minority residents increased in areas that were not prioritized for GRI (Shokry, Connolly et al. 2020). The authors concluded that GRI was installed in neighborhoods that were already gentrifying in the time period before installation, suggesting that GRI likely is integrated with and intensifies the process of gentrification. As related to our findings, renters may have been displaced by gentrification in neighborhoods with GSI installations, which would strain social cohesion (Jennings et al., 2017) and may have affected the relationships we observed with public GSI. On the other hand, greater private investment that included GSI installations, coupled with gentrification, may have positively affected neighborhood perceptions due to an accompanying boost in economic activity in the area. Teasing out these relationships requires a longitudinal examination of the timing of GSI and other neighborhood improvements, gentrification, and changes in neighborhood perceptions, and is beyond the scope of our current study.

Finally, our findings do not support our hypothesis that vegetated GSI would be associated with more favorable neighborhood perceptions, compared with any GSI. For example, any GSI within 1000 m of participants' homes was associated with participants reporting that neighbors could be trusted (RR= 1.22, 95% CI: 1.07–1.40) and having a park/outdoor space in the neighborhood that they were comfortable visiting (RR= 1.22, 95% CI: 1.07–1.38). In contrast, vegetated GSI within 1000 m was not associated, or less strongly associated, with these same outcomes (RR= 0.96, 95% CI: 0.86–1.08 and RR= 1.10, 95% CI: 1.03–1.19, respectively). Similar patterns were observed across other neighborhood perception measures, suggesting that the presence of GSI overall, rather than whether installations are vegetated, may be more relevant for positive neighborhood perceptions. When discussing neighborhood perceptions, it is essential to recognize that while vegetation such as trees can enhance the environment, vegetated elements can also evoke concerns about potential concealment of crime. Research suggests that greenspace can contribute positively to perceived safety by providing well-maintained, open areas that encourage social interaction and foster a sense of community ownership (Coleman, Ryan et al. 2021). One study on the health and safety effects of GSI installments in Philadelphia found reductions in burglaries and narcotics possession and manufacturing (Kondo, 2015). However, the presence of dense vegetation, excessive undergrowth, and trees can also create opportunities for concealment, potentially increasing fears of crime or some residents (Cozens, Hillier et al. 2001, Hur and Nasar, 2014, Maruthaveeran and van den Bosch, 2014). Philadelphia GSI installations typically do not have dense vegetation; rather, installations such as rain gardens and tree trenches have low-profile or sparsely planted vegetation that is well-maintained. Nevertheless, the lack of associations for vegetated GSI with positive neighborhood perceptions in our study may reflect concerns among some residents about visibility or upkeep. Community input and design features that address visibility and maintenance may be essential for actualizing co-benefits of GSI.

Survey respondents in our study were not asked questions about their awareness of GSI, so they may not have attributed any positive neighborhood perceptions to GSI. The impact of GSI might vary depending on whether residents were aware of these features and whether they valued them. In a study of residents knowledge of green infrastructure in Philadelphia and Toronto, 27% of survey respondents in Philadelphia had heard of the term (Conway, Ordóñez et al. 2021). Of respondents that provided a definition, 32% gave a definition that was coded as stormwater green infrastructure by the authors, indicating that respondents in Philadelphia were familiar with GSI. There were only 147 survey responses from Philadelphia, therefore, this is not representative of awareness of GSI across the city. Future studies examining how awareness impacts the association could better inform community communication and acceptance of GSI installations.

Reverse causality cannot be ruled out in this study as there was potential for bidirectional influence. While our study investigates whether living near previously installed GSI may impact perceptions of the neighborhood social environment and resources, it is important to consider that already-existing strong social cohesion in a neighborhood may have been a driver of neighborhood improvements including GSI installations. Future research should more clearly delineate social cohesion and neighborhood changes over time to clarify the causal directions of the relationships. In addition, future research should more closely examine the potentially concurrent impacts of gentrification and GSI on neighborhood outcomes. While there are various drivers of gentrification, new or improved environmental amenities may be one of them (Cole, Mehdipanah et al. 2021). "Green gentrification" refers to the process in which new residents displace long-term residents, who then do not benefit from the new greenspace (Gould, 2016, Mowen and Rung, 2016). The literature surrounding gentrification and social cohesion indicates that long-term residents do not experience greater social cohesion in their community after gentrification, and rather, may experience a breakdown of social cohesion (Shaw and Hagemans, 2015) (Betancur, 2011)(Gibbons, Barton et al. 2020) (Mendoza-Graf, MacCarthy et al. 2023). In contrast, studies have found that new individuals moving into gentrifying neighborhoods reported higher collective efficacy compared to residents living in a neighborhood that did not gentrify (Steinmetz-Wood, Wasfi et al. 2017). Enhanced understanding of potentially positive impacts of GSI or other greenspace on neighborhood perceptions in the context of gentrification may provide clues for infrastructural improvements with net benefits for residents.

Our study combined multiple waves of the Southeastern Pennsylvania Household Health Survey, spanning the years of 2010, 2012, 2015, and 2018, resulting in a substantial sample size of 8719 observations. In addition, we adjusted for both individual and area-level potential confounders, enabling strong inferences about the observed associations. A limitation of our study is that because each survey wave contained a different group of respondents, it was not possible to conduct a longitudinal study of changes in perception for the same people over time. In addition, the study's focus on Philadelphia County may limit generalizability. Philadelphia is an urban area; therefore, results would not be applicable to suburban and rural areas. Furthermore, local policies, governance and public awareness regarding GSI initiatives in Philadelphia may vary significantly from those in other cities.

Our study provides valuable insights into potential positive impacts of GSI on resident perceptions of the neighborhood. Evidence for co-benefits of GSI may be useful in fostering support for incorporation of these relatively small greenspaces (small, compared to parks) into communities, with the primary goal of stormwater control. Further understanding of the relationship between GSI and neighborhood impacts such as perceptions of the social environment may help inform planning on how GSI is distributed across communities. Our study found that a greater density of GSI within 1000 m was associated with positive perceptions of the neighborhood social environment, whereas GSI within 250 m was not. This may indicate the importance of planning GSI installations across a widespread area when aiming to maximize co-benefits. If these installations also provide space to rest or gather such as benches or tables, improved social cohesion is another potential co-benefit that may be seen. By strategically integrating GSI into urban landscapes, cities may not only enhance environmental sustainability, but also potentially foster social cohesion.

CRediT authorship contribution statement

Russel K McIntire: Writing – review & editing. **Hamil Pearsall:** Writing – review & editing. **Anneclaire J De Roos:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Amber Palmer-McCabe:** Writing – original draft, Formal analysis. **Michelle C**

Kondo: Writing – review & editing, Methodology, Formal analysis.

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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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2026.129437.

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