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Measures of Greenspace Exposure and Their Association to Health-Related Outcomes for the Periods before and during the 2020 Lockdown: A Cross-Sectional Study in the West of England

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Abstract: Greenspaces are argued to be one of the important features in the urban environment that impact the health of the population. Previous research suggested either positive, negative, or no associations between greenspaces and health-related outcomes. This paper takes a step backward to, first, explore different quantitative spatial measures of evaluating greenspace exposure, before attempting to investigate the relationship between those measures and health-related outcomes. The study uses self-reported health data from an online cross-sectional survey conducted for residents in the West of England. This yielded data of greenspace use, physical activity, wellbeing (ICECAP-A score), and connectedness to nature for 617 participants, divided into two sets: health outcomes for the period before versus during the 2020 lockdown. The study uses the participants' postcodes (provided in the survey) to calculate eleven spatial measures of greenspace exposure using the software ArcGIS Pro 2.9.5. A total of 88 multivariate regression models were run while controlling for eleven confounders of the participants' characteristics. Results inferred 57 significant associations such that six spatial measures of greenspace exposure (NDVI R200m, NDVI R300m, NDVI R500m, Network Distance to nearest greenspace access, Euclidean Distance to nearest greenspace access, and Euclidean Distance to nearest 0.5 ha doorstep greenspace access) have significant association to at least one of the four health-related outcomes, suggesting a positive impact on population health when living in greener areas or being closer to greenspaces. Moreover, there are further significant associations between the frequency of use of greenspaces and increasing physical activity or feeling more connected to nature. Still, the residents' patterns of using greenspaces significantly changed during versus before lockdown and has impacted the relationships between health outcomes and the greenspace exposure measures.

Keywords: parks; greenspace exposure measures; population health; NDVI; greenspace proximity; physical activity; wellbeing

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1. Introduction

Urban environments are an important determinant of the populations' health. Given that over half of the world's population (80% to 90% of people in high income countries) are already living in urban areas, and this is expected to rise to 7 in 10 people by 2050 [1], it is essential that urban environments support health and healthy lifestyles. However, urban development is associated with a higher prevalence of some non-communicable diseases including mental ill-health and obesity [2], while also being associated with a detachment of the population from nature and greenspaces. Therefore, a crucial question for researchers recently has been to understand whether this detachment from greenspaces has an impact on health and wellbeing of urban populations and to answer this question the research first needs to define and investigate how to measure the population's exposure to greenspaces.

The health impacts of urban greenspaces have been studied through both observational and experimental designs [3]. Since the 1990s, there has been a concerted effort to relate access, exposure, and/or use of greenspace to a range of health outcomes. This research field is diversified in terms of findings, suggesting a mix of beneficial and detrimental impacts or no relationship [4–7]. Nevertheless, most publications do not explicitly define what is meant by the term 'greenspace', meaning that the evidence is not currently sufficient or specific enough to guide planning decisions [8]. A systematic review in 2018 found that the wide range of measures of greenspace and dearth of definitions made it difficult to synthesise results and may be responsible for inconsistent findings in epidemiological studies on greenspace and health outcomes [9]. This lack of clarity in terminology and greenspace 'exposure' measures has been highlighted as one of the most pressing issues for the evidence base on greenspace and health [10]. Another issue contributing to heterogeneous findings is the wide range of health and health-related outcomes studied, including health-related behaviours, mental health, and physical health [11].

Considering the inconsistency in research findings on greenspaces and health outcomes, this paper, using data from the West of England, investigates the efficacy of different methods for defining the access and exposure to greenspaces. This is pursued using a systematic approach to assess relationships between various measures of greenspace exposure and a range of health-related outcomes of interest. The paper also considers health-related outcomes of two different periods: before and during the first English lockdown, implemented upon the spread of COVID-19 which had implications for urban residents in terms of their environments [12] and public health [13,14]. The lockdown took place from 26 March to 23 June 2020 (although some restrictions remained in place beyond this) when non-essential businesses were closed, and greenspaces were one of few spaces still accessible during this period and are argued to have been a main destination during that time. This paper examines three research questions: how can exposure to greenspaces be measured; which measure(s) of greenspace exposure better explain the relationship between greenspace exposure and population health in terms of physical activity, nature connectedness, and wellbeing; and how did the efficacy of the exposure measures change between the period before versus during lockdown? To answer these questions, the paper provides a brief overview of the literature, followed by a description of the methods of data collection and analyses, results and discussion, and conclusions.

2. Measures of Greenspace Exposure

Greenspaces encompass areas in our environment with natural vegetation, as well as different elements added to the built environment, such as parks, smaller areas of greenery, or even street trees [9]. Objective measures are important when assessing relationships between the elements in the built environment, such as greenspaces, and the population's health [15]. Geographic Information Systems (GIS) offer the potential to generate quantitative measures of greenspace exposure and are commonly used in studies examining the relationship with health. Often, the greenspace data used within the GIS depends on the definition of greenspace being adopted by a particular study. Studies interpreting the term greenspace to mean a discrete space, with a boundary (e.g., a park, allotment, woodland) often use polygon data depicting the spatial extent of individual greenspaces. These studies tend to measure the distance from the residential address to the nearest greenspace, either as a Euclidian straight-line distance between the address and the greenspace or as a realistic network travel distance of a pedestrian from their address to the greenspace [16,17].

Alternatively, studies use a measure of neighbourhood greenspace, for example, the proportion of land cover that is greenspace or the neighbourhood 'greenness' to estimate exposure to greenspaces within a given distance (or buffer) around the residential address [7,18]. This buffer varies among studies and ranges from 30 to 3000 m [19,20]. Within this buffer, the degree of greenness is determined as the total area from national land-use databases or as the Normalized Difference Vegetation Index (NDVI) [16]. NDVI quantifies vegetation by measuring the difference between the near-infrared light reflected by vegetation and red light which is absorbed by vegetation [21].

3. Materials and Methods

The objective of this paper is to compare greenspace exposure measures and their association to health outcomes. To do this, the study makes use of several quantitative datasets. An online survey was used to collect residents' demographic, social, and health data, in addition to the residents' postcodes (which equate to around 15 dwellings). These postcodes are used to link the survey data, using ArcGIS Pro 2.9.5, to different spatial measures of greenspace exposure which were calculated also using ArcGIS Pro 2.9.5. Further information about the sample and the datasets is given in the sections below.

3.1. Study Design and Participants

The sample comprised respondents to an online cross-sectional survey which was administered via Qualtrics from 22 May to 14 July 2020. The project was approved by the Faculty Research Ethics Committee at the University of the West of England. To be eligible for the study, participants needed to be a resident in West of England (which includes the local authorities of North Somerset, City of Bristol, Bath and North East Somerset, and South Gloucestershire—see Figure 1). Participants were invited through a combination of two of the local authorities' Citizens Panels (which are chosen to be representative of the local populations, in terms of age and other demographics, and include 'boost' samples of groups with lower participation rates), general invitations on social media platforms, and targeted invitations via the West of England Combined Authority's (WECA) networks. It is important to note that although the West of England includes all four local authorities; the combined authority does not include North Somerset. Before taking part in the study, respondents were directed to a participant information sheet outlining the purpose of the study and were required to indicate their consent before completing the survey. All survey responses were anonymous, and the survey took 20–30 min to complete. The survey yielded 617 participants who answered 49 questions divided into six sections. Data were stored on OneDrive for Business and analysed using Microsoft Excel (version 16.66.1) and IBM SPSS Statistics (Version 27). Participants were asked questions about health-related behaviours, including greenspace use, and wellbeing (described in the next section) for two different periods: before and during the first UK lockdown (which took place in the year 2020 amid the spread of COVID-19). Participants were also asked to provide their postcode to enable spatial analysis.

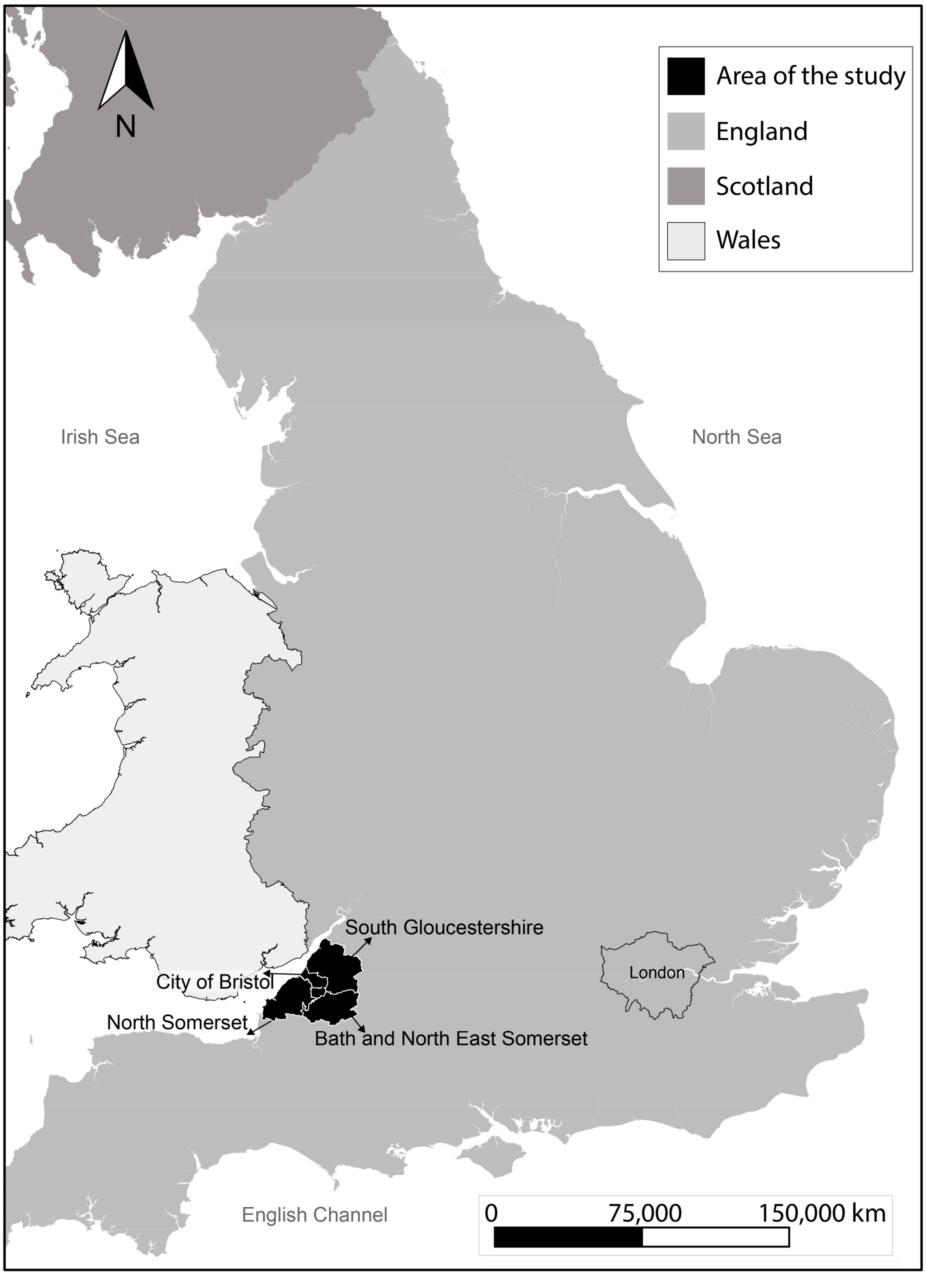

Figure 1. Map of England, reproduced with permission from Office for National Statistics licensed under the Open Government Licence v.3.0 [22] with areas (in black) from which participants were invited for the survey.

3.2. Measures of Health-Related Behaviour and Wellbeing

The survey provided self-reported data on health-related behaviours and wellbeing, which are considered as dependent variables for the purposes of this study. The measures were (1) frequency of visits to greenspaces, (2) level of physical activity (measured using GPAQ, (3) scales for connectedness to nature, and (4) wellbeing (measure using ICECAP-A). These measures were chosen to reflect different stages on the causal pathway between exposure to green space, and health and wellbeing outcomes (see, for example, Ref. [3] adapted from Ref. [23]; Figure 2).

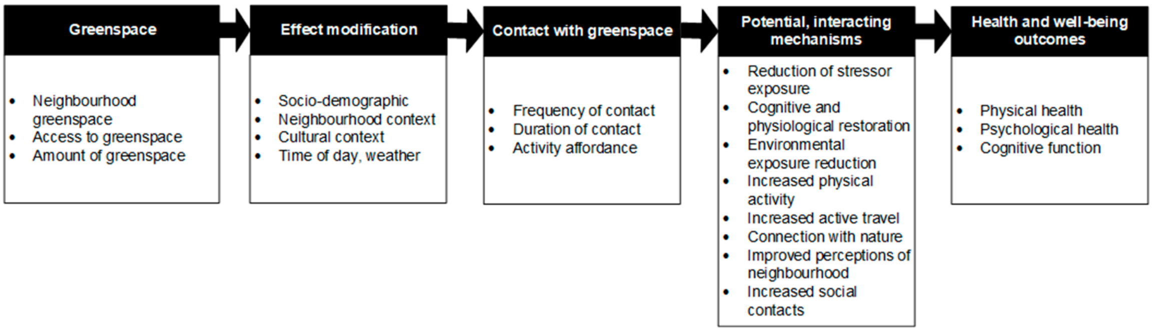

Figure 2. Socio-ecological framework for the relationship between greenspace and health and wellbeing [Ref. [3]; adapted from Ref. [23]].

To measure greenspace use, participants were asked to provide the frequency of visiting any greenspace (for up to three most frequently visited greenspaces). We provided a broad definition of greenspace as follows 'By green spaces we mean any natural or semi-natural areas partially or completely covered by vegetation that occur in or near urban areas. They include parks, trails, woodlands and allotments, which provide habitat for wildlife and can be used for recreation'. Their answers were extrapolated to estimate a yearly number of visits, for (1) visits before lockdown and (2) visits during lockdown. Greenspace use is considered as both a dependent and independent variable. It is a health-related behaviour on the causal pathway to other health outcomes (Figure 2; [3]) and therefore is a dependent variable related to greenspace exposure, and independent variable were related to other health outcomes, such as physical activity.

Physical activity is a mechanism related to both greenspace exposure and health and wellbeing outcomes (Figure 2) [23] and was measured using the Global Physical Activity Questionnaire (GPAQ) as the duration (minutes/week) of all types of physical activity (e.g., cycling and sports) of any intensity (moderate or vigorous) excluding physical activity related to the participant's work/job. This was also calculated for both time periods (before and during lockdown) and aggregated into a weekly total in minutes for physical activity. The GPAQ [24] was modified slightly to enable online responses and to use examples of physical activity that were permitted during the lockdowns.

Participants' connectedness to nature was measured using the Nature Connection Index [25,26] and was included as a potential interacting mechanism with particular relevance to access to greenspace [27]. The questionnaire is composed of six affective statements whereby participants are required to respond using a 7-point response scale ('strongly agree' to 'strongly disagree') about how they felt before lockdown. The six statements were: 'I find beauty in nature', 'It's important to me to treat nature with respect', 'Being in nature makes me happy', 'Spending time in nature is important to me', 'I find being in nature amazing', and 'I feel part of nature'. Responses were converted into ratings (e.g., strongly agree = 7, strongly disagree = 1) which were weighted to calculate an overall Nature Connection Index score [25] for before lockdown. For scores during lockdown, the same statements were used, but responses were changed to measure change since lockdown, e.g., 'I agree with this more since lockdown' or 'I disagree with this more since the lockdown'. Wellbeing was quantified through the ICECAP-A [28], a questionnaire which assesses five individual attributes: feeling settled and secure; love, friendship, and support; being independent; achievement and progress; and enjoyment and pleasure. Each attribute is coded from 'full capability for the attribute' to 'no capability' and converted into a tariff value. Tariff values are then summed together across attributes to give an overall score for each participant [29]. An ICECAP-A score was calculated for the two different periods of before and during lockdown.

3.3. Spatial Measures of Greenspace Exposure

The measures of greenspace exposure are the independent variable in this study. In addition to greenspace use, this study considered objective measures of greenspace exposure. These are not solely quantified through studying greenspaces as an isolated variable but primarily through studying greenspaces as an element within urban spaces and their association to members of the society that inhabit urban spaces. All spatial analyses were conducted using QGIS 3.6 and ArcGIS Pro 2.9.5. We constructed a spatial dataset composed of different methods to quantify (1) the proximity of participants' residential postcode to different sizes of greenspaces and (2) the degree of greenness of an urban space at different radii from participant postcodes. Participant postcodes were converted into longitude and latitude point data based on the centroid of each postcode, using Code-Point Open data [30].

Exposure to greenspaces for each participant was calculated using several measures reported in the literature or set by English policy. These are:

- Network distance to nearest greenspace: Distance to the greenspace access point closest to the postcode centroid using the street network. This is calculated using network analysis in ArcGIS Pro 2.9.5 (shortest path—point-to-point), from Ordnance Survey Open Greenspace data [31] and street network data [32]. OS Open Greenspace includes polygons of greenspaces, including parks, playing fields, play areas, cemeteries, sport facilities, and allotments, and point data of access points to each space.
- Euclidean distance to nearest greenspace. Euclidean (i.e., straight line) distance to the greenspace access point closest to the postcode centroid.
- Euclidean distance to nearest greenspace of 0.5 ha, 2 ha, 10 ha, and 20 ha. As above, but focusing on the sizes of greenspace specific in Natural England's Accessible Greenspace Standards (AGS) [33] which recommends that residents should be no more than 200 m away from a doorstep greenspace (0.5 ha), 300 m away from a local greenspace (2 ha), 1000 m away from a neighbourhood greenspace (10 ha), and 2000 m away from a wider neighbourhood greenspace (20 ha), all measured as straight-line Euclidean distances [33].
- Normalised Difference Vegetation Index (NDVI) within 500 m network distance: NDVI quantifies vegetation by computing the difference between near-infrared (NIR) which is reflected by vegetation and red light (RED) which is absorbed by vegetation, then dividing the outcome by their summation [34]. It results in a value between -1 and 1 for a defined area; the higher the value, the greener the space is. NDVI was calculated using ArcGIS Pro 2.9.5 using satellite images of Sentinel-2 [35]. NDVI within a network distance of 500 m from the postcode centroid was calculated as the NDVI of the polygon covering a service area of 500 m in the street network [32].
- NDVI within 200 m, 300 m, 1000 m, and 2000 m radius: NDVI of the catchment areas of different radial distances from the postcode centroid chosen to align with AGS.

To summarise the datasets in this study, there are 617 participants who answered questions on their greenspace use (processed as a yearly number of visits before and during lockdown), their physical activity (aggregated as a yearly duration in minutes before and during lockdown), their connectedness to nature (processed as a score before lockdown), and their wellbeing (processed as an ICECAP-A score before and during lockdown). The participants also provided their postcodes which enabled the calculation of eleven measures of greenspace exposure based on their proximity to greenspaces (network distance to the closest greenspace; Euclidean Distance to the closest greenspace; Euclidean distance to the closest 0.5 ha, 2 ha, 10 ha, and 20 ha greenspace) and the degree of greenness of their location (NDVI within 200 m, 300 m, 1000 m, and 2000 m radii and a network distance of 500 m).

3.4. Statistical Analysis

The sample is described using counts and percentages. The health-related behaviours and wellbeing variables are described using mean and standard deviation (both before and during lockdown). Paired sample *t*-tests are used to test for a change in these variables between the two time points of before versus during the lockdown period. Bivariate relationships between the eleven greenspace exposure variables (independent variables) and the four health outcome variables (dependent variables) were then assessed using scatter plots and correlation coefficients. The next step was to run linear multiple regression models to estimate the strength and statistical significance of these associations while controlling for eleven socio-demographic confounders (participants' characteristics) for which data were available. Out of the eleven greenspace exposure measures (independent variables), six measures of distances went through log-transformation before running their regression models against the four health-related outcomes (dependent variables). In total, there are 88 possible relationships (eleven exposure variables X four outcome variables X two periods of before versus during lockdown). All statistical analysis was carried out in SPSS 28.0.1.1.

4. Results

The sociodemographic characteristics of participants are displayed in Table 1. The sample is 62% female, predominantly white (94%), and highly educated (73% had a degree), and the most common age groups were 55–64 and 65–74 years; 85% of the respondents owned their own home; 95% had access or private or shared outdoor space; 61% were in employment; and 21% reported having a limiting long-term illness.

Table 1. Characteristics of the survey participants.

Characteristics	Category	N (%)
Sex	Female	383 (62)
	Male	224 (36)
	Prefer not to say	10 (2)
Age in years	18–24	16 (3)
	25–34	64 (10)
	35–44	109 (18)
	45–54	103 (17)
	55–64	141 (23)
	65–74	142 (23)
	75–84	33 (5)
	Prefer not to say	9 (1)
Ethnicity	White	578 (94)
	Mixed	13 (2)
	Other	12 (2)
	Black/African/Caribbean	10 (2)
	Asian	4 (0)
Education	Degree or Higher	450 (73)
	GCSE only	85 (14)
	A-levels or equivalent	68 (11)
	No qualifications	14 (2)
Housing tenure	Owner-occupied	522 (85)
	Rented	63 (10)
	Socially Rented	30 (5)
	Other	2 (0)
Car ownership	No	90 (15)
	Yes	524 (85)
Dog ownership	No	490 (79)
	Yes	127 (21)
Private/shared outdoor space	No	33 (5)
	Yes	584 (95)

Table 1. *Cont.*

Characteristics	Category	N (%)
Having children	No	452 (73)
	Yes	165 (27)
Having limiting long-term illness	No	489 (79)
	Yes	127 (21)
Employment	Employed	376 (61)
	Retired	142 (23)
	Other	68 (11)
	Unemployed	19 (3)
	Student	11 (2)

Mean NDVI (from the participants' postcodes) increases slightly as the radius increases (Table 2). In other words, a greater level of greenspace exposure is found as the analysis captures a bigger buffer area from the resident address, as one might expect as more land uses, including parks and other greenspaces, are included. The mean network distance to the nearest greenspace is 333 m, and the mean Euclidean distance is 190 m. The former distance is higher because the way the streets are designed results in greater traveling distances along a network. The mean distance to the nearest greenspace increases as the size of the greenspace increases (Table 2). Again, this is to be expected at larger greenspaces are less frequent in the urban environment, and this is accounted for in the minimum distances set out in the AGS. Nevertheless, the mean distances for the participants of this survey are greater than the expectations for the doorstep greenspace (275 m mean > 200 m standard) and the local greenspace (374 m mean > 300 m standard) but meet those for the neighbourhood greenspace (774 m mean < 1000 m standard) and the wider neighbourhood greenspace (1100 m mean < 2000 m standard).

Table 2. Greenspace exposure characteristics.

Greenspace Exposure Measure	Mean (SD)
NDVI within 200 M Radius	0.46 (0.11)
NDVI within 300 M Radius	0.47 (0.11)
NDVI within 1000 M Radius	0.49 (0.10)
NDVI within 2000 M Radius	0.51 (0.09)
NDVI within 500 M Network	0.45 (0.1)
Network distance (m) to nearest greenspace access	333 (213)
Euclidean distance (m) to nearest greenspace access	190 (125)
Euclidean distance (m) to nearest 0.5 ha doorstep greenspace access	275 (195)
Euclidean distance (m) to nearest 2 ha local greenspace access	374 (270)
Euclidean distance (m) to nearest 10 ha neighbourhood greenspace access	774 (659)
Euclidean distance (m) to nearest 20 ha wider neighbourhood greenspace access	1100 (870)

Table 3 summarises the participants' health-related behaviours and wellbeing outcomes before and during the 2020 COVID-19 lockdown. Firstly, the participants' mean frequency of visiting greenspaces (per month) increased by 38% to a mean of 29 visits per month during lockdown. A Paired Sample *T*-test shows that the difference in means (8.14 visits/month) is statistically significant (t = 10.19, $p < 0.001$). Moreover, the amount physical activity has also increase by 9%. The difference in means (90.76 min/week) is statistically significant (t = 2.02, $p = 0.04$). At the same time, the residents' wellbeing was lower during lockdown than before (difference in mean ICECAP score −0.13), and this difference is also statistically significant (t = −20.13, $p < 0.001$).

Table 3. Descriptive statistics of visits to greenspace, physical activity, wellbeing, and connectedness to nature before and during the 2020 COVID-19 lockdown.

Health Outcome	Mean (SD)	
	Before Lockdown	During Lockdown
Visits to greenspaces (month)	21 (17)	29 (19)
Physical activity (minutes/week)	794 (862)	885 (1165)
Icecap score	0.87 (0.12)	0.73 (0.19)
Connectedness to nature score	74 (22)	2.52 (2.34) [1]

[1] Connectedness to nature score is calculated from data that represent the period before lockdown and the change since lockdown.

Multivariate Analysis

Turning to the multivariate analysis, the study ran 88 models for eleven spatial measure of exposure variables (log-transformed for the six distance measures of the eleven variables) and four health-related outcome variables, before and/or during lockdown (see Table 4). For each model the paper presents an overall significance test (p-value) and an R^2 and an adjusted R^2 value. There are 57 significant models (p-value < 0.05), suggesting that in these cases the model reliably predicts the dependent outcome variable. R^2 ranges from 0.069 to 0.208, and adjusted R^2 ranges from 0.012 to 0.149 (Table 4).

Nevertheless, this study is more focused on reporting and discussing the statistical significance of the greenspace exposure measures within each model, rather than the overall model's ability to predict the dependent variable. There are 13 relationships inferred to be statistically significant for the measure of greenspace exposure (Table 5). Six spatial measures of green space exposure (NDVI R200m, NDVI R300m, NDVI R500m in Network, Network Distance to nearest greenspace access, Euclidean Distance to nearest greenspace access, and Euclidean Distance to nearest 0.5 ha doorstep greenspace access) have a significant association with at least one of the four health-related outcomes. In total, nine relationships coincide with hypotheses that greenspace exposure has a positive impact on population health, as discussed in next section.

Alongside testing the health-related outcomes (as the dependent variables) against the spatial measures of greenspace exposure (as the independent variables), the study explored the relationships between greenspace use and the health-related outcomes of physical activity, wellbeing (ICECAP), and connectedness to nature, while also controlling for the same eleven confounders (participants' characteristics) (Table 6). While all the six relationships portray a significant model for their overall goodness-of-fit (R^2 0.078–0.183 and adjusted R^2 0.025–0.135), results indicate that only four associations (of the six tested relationships) are significant for the particular health-related outcome of interest. This includes a significant relationship between the increase in number of visits to greenspaces and the increase in duration of physical activity or the increase in connectedness to nature, both for the periods before and during the lockdown. There was no association between visiting greenspaces and the measure of wellbeing (ICECAP).

Table 4. *p*-value for overall significance test, R^2 and adjusted R^2, for 88 multivariate regression models of exposure to greenspace and health-related outcomes, controlling for sex, age in years, ethnicity, education, housing tenure, car ownership, dog ownership, private/shared outdoor space, having children, having limiting long-term illness, and employment.

Measure of Exposure to Greenspace	**Health-Related Outcome**							
	Visits to Greenspaces/Month		**Physical Activity in Minutes**		**ICECAP Score**		**Connectedness to Nature** [1]	
	Before Lockdown	**During Lockdown**	**Before Lockdown**	**During Lockdown**	**Before Lockdown**	**During Lockdown**	**Before Lockdown**	**During Lockdown**
	Overall Fit R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2	**Overall Fit** R^2 **Adjust** R^2
NDVI radius 200 m (Euclidean)	<0.001 *** 0.168 0.122	<0.001 *** 0.125 0.074	0.071 0.071 0.021	0.592 0.047 −0.004	<0.001 *** 0.137 0.092	<0.001 *** 0.154 0.110	0.002 ** 0.091 0.044	0.056 0.071 0.022
NDVI radius 300 m (Euclidean)	<0.001 *** 0.168 0.122	<0.001 *** 0.129 0.079	0.071 0.071 0.021	0.592 0.047 −0.004	<0.001 *** 0.136 0.091	<0.001 *** 0.154 0.109	0.002 ** 0.092 0.045	0.072 0.069 0.020
NDVI radius 1000 m (Euclidean)	<0.001 *** 0.169 0.123	<0.001 *** 0.117 0.066	0.048 * 0.074 0.024	0.587 0.047 −0.004	<0.001 *** 0.136 0.090	<0.001 *** 0.154 0.109	0.003 ** 0.09 0.043	0.098 0.066 0.018
NDVI radius 2000 m (Euclidean)	<0.001 *** 0.17 0.124	<0.001 *** 0.116 0.065	0.041 * 0.075 0.026	0.577 0.048 −0.004	<0.001 0.136 0.090	<0.001 *** 0.154 0.109	0.003 ** 0.089 0.042	0.090 0.067 0.018
NDVI radius 500 m (Network)	<0.001 *** 0.168 0.122	<0.001 *** 0.12 0.069	0.074 0.070 0.021	0.592 0.047 −0.004	<0.001 *** 0.138 0.092	<0.001 *** 0.156 0.111	0.002 ** 0.091 0.044	0.078 0.068 0.020
Network Distance (m) to nearest greenspace access [2]	<0.001 *** 0.208 0.149	<0.001 *** 0.157 0.091	0.286 0.074 0.008	0.770 0.055 −0.012	<0.001 *** 0.145 0.084	<0.001 *** 0.167 0.107	0.003 ** 0.111 0.049	0.100 0.085 0.020
Euclidean Distance (m) to nearest greenspace access [2]	<0.001 *** 0.207 0.148	<0.001 *** 0.153 0.087	0.276 0.074 0.008	0.777 0.055 −0.012	<0.001 *** 0.146 0.085	<0.001 *** 0.166 0.106	0.002 ** 0.112 0.049	0.099 0.085 0.020
Euclidean Distance (m) to nearest 0.5 ha doorstep greenspace access [2]	<0.001 *** 0.207 0.148	<0.001 *** 0.160 0.094	0.281 0.074 0.008	0.734 0.057 −0.010	<0.001 *** 0.146 0.084	<0.001 *** 0.164 0.104	0.002 ** 0.114 0.051	0.099 0.085 0.020
Euclidean Distance (m) to nearest 2 ha local greenspace access [2]	<0.001 *** 0.198 0.138	<0.001 *** 0.153 0.087	0.291 0.073 0.008	0.697 0.058 −0.009	<0.001 *** 0.145 0.084	<0.001 *** 0.163 0.103	<0.001 *** 0.163 0.103	0.100 0.085 0.020

Table 4. *Cont.*

Measure of Exposure to Greenspace	Health-Related Outcome							
	Visits to Greenspaces/Month		Physical Activity in Minutes		ICECAP Score		Connectedness to Nature [1]	
	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown
	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2	Overall Fit R^2 Adjust R^2
Euclidean Distance (m) to nearest 10 ha neighbourhood greenspace access [2]	<0.001 *** 0.197 0.137	<0.001 *** 0.153 0.087	0.272 0.074 0.009	0.393 0.069 0.003	<0.001 *** 0.145 0.084	<0.001 *** 0.164 0.104	0.003 ** 0.089 0.042	0.079 0.087 0.022
Euclidean Distance (m) to nearest 20 ha wider neighbourhood greenspace access [2]	<0.001 *** 0.197 0.137	<0.001 *** 0.153 0.087	0.291 0.077 0.012	0.653 0.060 −0.007	<0.001 *** 0.145 0.084	<0.001 *** 0.165 0.105	<0.001 *** 0.065 0.017	0.086 0.086 0.022

* p-value < 0.05; ** p-value < 0.01; *** p-value < 0.001. [1] Connectedness to nature score is calculated from data that represent the period before lockdown and the change since lockdown. [2] The six distance measures of greenspace exposure went through log-transformation prior to their testing against the health-related outcomes.

Table 5. Multivariate regression coefficients, standard errors and *p*-values, for the associations between measures of exposure to greenspace and health-related outcomes, controlling for sex, age in years, ethnicity, education, housing tenure, car ownership, dog ownership, private/shared outdoor space, having children, having limiting long-term illness, and employment.

Measure of Exposure to Greenspace	Health-Related Outcome							
	Visits to Greenspaces/Month		Physical Activity in Minutes		ICECAP Score		Connectedness to Nature [1]	
	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown
	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value
NDVI radius 200 m (Euclidean)	5.5 (6.07) 0.37	18 (6.83) 0.009 ***	−231 (328) 0.48	13 (433) 0.98	0.046 (0.043) 0.284	0.05 (0.065) 0.442	13.5 (7.9) 0.088 *	1.57 (0.84) 0.063 *
NDVI radius 300 m (Euclidean)	4.75 (6.20) 0.44	21.5 (6.95) 0.002 ***	−238 (335) 0.48	38.5 (442) 0.931	0.033 (0.044) 0.45	0.038 (0.066) 0.57	14.2 (8.06) 0.079 *	1.28 (0.86) 0.14
NDVI radius 1000 m (Euclidean)	11.6 (7.74) 0.134	0.006 (0.048) 0.909	−570 (369) 0.12	−155 (487) 0.75	−7.91 (6.80) 0.25	0.028 (0.073) 0.70	12.4 (8.92) 0.17	0.79 (0.95) 0.41

Table 5. *Cont.*

Measure of Exposure to Greenspace	Health-Related Outcome							
	Visits to Greenspaces/Month		Physical Activity in Minutes		ICECAP Score		Connectedness to Nature [1]	
	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown
	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value
NDVI radius 2000 m (Euclidean)	−11.2 (7.78) 0.15	11.9 (8.87) 0.18	−751 (423) 0.076	290 (558) 0.60	−0.002 (0.055) 0.97	0.033 (0.083) 0.70	13.1 (10.2) 0.20	1.14 (1.08) 0.30
NDVI radius 500 m (Network)	5.03 (7.16) 0.48	16.13 (8.06) 0.046 **	−204 (387) 0.60	−14.6 (511) 0.977	0.060 (0.051) 0.233	0.096 (0.076) 0.21	15.5 (9.31) 0.097	1.36 (0.990) 0.17
Network Distance (m) to nearest greenspace access [2]	−6.857 (2.508) 0.006 **	−5.813 (2.873) 0.044	−49.7 (139.5) 0.72	124 (182.411) 0.497	0.005 (0.018) 0.781	0.041 (0.027) 0.132	3.422 (3.302) 0.301	−0.047 (0.354) 0.895
Euclidean Distance (m) to nearest greenspace access [2]	−6.538 (2.471) 0.008 **	−3.647 (2.843) 0.200	−88.4 (138.2) 0.525	98.68 (181.65) 0.587	−0.016 (0.018) 0.387	0.035 (0.027) 0.200	3.945 (0.007) 0.230	0.101 (0.352) 0.774
Euclidean Distance (m) to nearest 0.5 ha doorstep greenspace access [2]	−2.591 (0.974) 0.008 **	−7.732 (1.122) 0.015 **	27.42 (54.6) 0.616	82.568 (71.75) 0.250	−0.005 (0.007) 0.462	0.007 (0.011) 0.530	2.095 (1.294) 0.100 *	0.00 (0.00) 0.81
Euclidean Distance (m) to nearest 2 ha local greenspace access [2]	−4.896 (2.136) 0.022 *	−4.138 (2.440) 0.091	−3.199 (118.53) 0.978	229 (155.182) 0.140	−0.005 (0.015) 0.75	0.001 (0.023) 0.954	0.001 (0.023) 0.954	−0.039 (0.302) 0.897
Euclidean Distance (m) to nearest 10 ha neighbourhood greenspace access [2]	−1.714 (1.911) 0.370	−2.643 (2.147) 0.219	−74.53 (104.095) 0.474	402.58 (135.82) 0.003	0.007 (0.014) 0.600	0.017 (0.020) 0.414	0.017 (0.020) 0.414	−0.313 (0.265) 0.238
Euclidean Distance (m) to nearest 20 ha wider neighbourhood greenspace access [2]	−0.059 (2.163) 0.978	−3.171 (2.430) 0.192	−170.915 (117.911) 0.148	275.24 (155.295) 0.077	0.009 (0.015) 0.551	0.027 (0.023) 0.242	0.027 (0.231) 0.242	−0.288 (0.302) 0.340

* p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01. [1] Connectedness to nature score is calculated from data that represent the period before lockdown and the change since lockdown. [2] The six distance measures of greenspace exposure went through log-transformation prior to their testing against the health-related outcomes.

Table 6. Multivariate regression coefficients, standard errors and *p*-values, for the associations between visits to greenspace and health-related outcomes, controlling for sex, age in years, ethnicity, education, housing tenure, car ownership, dog ownership, private/shared outdoor space, having children, having limiting long-term illness, and employment.

	Physical Activity in Minutes		ICECAP Score		Connectedness to Nature [1]	
	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown	Before Lockdown	During Lockdown
	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value	B (SE), *p*-Value
Visits to greenspace	5.41 2.26 0.017 *	14.6 2.76 <0.001 ***	0.0 0.0 0.164	0.0 0.0 0.78	0.155 0.057 0.007 **	0.12 0.005 0.026 *

* *p*-value < 0.05; ** *p*-value < 0.01; *** *p*-value < 0.001. [1] Connectedness to nature score is calculated from data that represent the period before lockdown and the change since lockdown.

5. Discussion

5.1. Measures of Greenspace Exposure

This study has used different greenspace exposure measures to be tested for their association with health-related outcome measures. NDVI, as a measure of the degree of greenness and one of the greenspace exposure measures, was calculated at different catchment area radii (200 m, 300 m, 1000 m, and 2000 m as Euclidean distances and 500 m as network distance), which match the walking distances set by Natural England's AGS to different sizes of greenspaces (Natural England, 2023). These radii are different than the set chosen by [18] for their NDVI calculations (100 m, 300 m, 500 m, 1000 m, and 3000 m as Euclidean distances). Still, both studies, despite being conducted in different places (West of England and Utrecht, Netherlands), show an increase in the mean NDVI as the radius increases. In other words, more greenspaces are found as the analysis captures a bigger buffer area from the resident address. That is why future research needs to be critically aware of defining the catchment areas of the study, as well as the logic of choosing these buffers in relation to the residents and the chosen health-related outcomes, because the degree of zooming in on (or out of) an area impacts the output measures of proximity to greenspaces or degree of vegetation which in return would show (or not) associations to health measures.

A major strength of this study is the use of the precise distances from the residents' addresses to the greenspace access points, as a measure of greenspace exposure, similar to the method adopted by [36] but conducted in this study on a larger urban scale and with a larger sample size. This method is chosen for its accurate representation of travel distances covered by residents from their home addresses to enter a greenspace, unlike [37] who measured green space distances toward the population weighted centroid (not addresses). This study's method also further improves on [17] (that was chosen due to computational limitations), which created service areas of accessible streets within a network distance from the greenspace access points, thus, being limited to defined categories for greenspace proximity (≤100 m, 101–200 m, 201–300 m, 301–400 m, 401–500 m, 501–1000 m, and >1000 m), whereas this study yields precise distance figures (a continuous variable) for each residential address. The high attention given to the calculated distances is meant to minimise the margin of error for greenspace proximity measures, to match the highly accurate calculations of NDVI (degree of greenness measures), thus enabling a fair comparison of the different measures of greenspace exposure.

5.2. Efficacy of Different Measures of Greenspace Exposure

In common with other studies carried out over the COVID-19 lockdowns we found that wellbeing was lower during lockdown [38,39], but physical activity and greenspace visitations increased [38,40].

The first major finding in this study is that the relationship between exposure to greenspaces and the measured health outcomes changes for the periods before and during the first 2020 COVID-19 lockdown, shown by the differences in the results of the regression models for both periods and more importantly the significant differences in the Paired Sample *T*-tests of the outcome health variables. Given that the greenspaces exposure measures did not change between those periods (i.e., no extensive work on creating or removing greenspaces), it is argued that what has changed is the participants patterns of increased visits to greenspaces and increased physical activity yet decreased wellbeing, in relation to the changes in the lifestyle during the lockdown when most activities (other than exercising and visiting greenspaces) were heavily restricted to limit the spread of COVID-19 [41]. Thus, the proximity to greenspaces or the greenness of neighbourhoods, as measures of greenspace exposure, could be argued as one of the factors that impacted those changes in residents' behaviours during lockdown. This corresponds to studies that have previously discussed the change in people's behaviours during the COVID-19 pandemic [42], with several studies reporting changes in greenspace use, as being related to health outcomes during the lockdowns, including anxiety and depression in China [40] and Denver [39] and wellbeing in England [38].

Regarding the period before lockdown and considering the regression models, there are certain findings that reflect the positive relationship between exposure to greenspaces and health outcomes. First, the multivariate analyses of four regression models suggest a statistically significant relationship between the increase in the number of residents' visits to greenspaces in respect to the decrease in Euclidean or network distance to the nearest greenspace or the decrease in distance toward the smaller greenspaces (0.5 ha and 2 ha). This is complemented with the results from another regression model that illustrates the significant increase in physical activity in relation to the increase in number of visits to greenspaces. In simple words, the closer the greenspace, the more often the resident visits that space which in return could enable more physical activity; thus, a spatial measure of greenspace exposure is positively related to a health-related outcome.

Moreover, despite the calculated NDVI of all radii (as a measure of greenness of the neighbourhood) not showing any relation to the number of visits to greenspaces, the NDVI of smaller radii (200 m and 300 m) has been significantly and positively related to the residents' connectedness to nature before lockdown. In other words, the greener the immediate context of the home (NDVI radii 200 m and 300 m), the more the residents feel connected to nature. However, larger radii NDVI (1 km and 2 km—indicating the greenness of the larger context) appears to have no relationship to the residents' connectedness to nature nor with frequency of visits to greenspaces. This could suggest that residents are more aware of their immediate smaller context and how green it is, which impacts their connection to nature and their use of close-by greenspaces. This is similar to findings reported for England, where the immediate neighbourhood greenspace exposure was found to be associated with wellbeing during the lockdown [38].

During the period of lockdown, there is a change in the residents' behaviours in terms of visits to greenspaces and physical activity (as shown in the paired *T*-tests), which accordingly affected the relationships between greenspace exposure measures and the health outcomes. For instance, there is a significant relationship between the number of visits to greenspaces and the greenness of the local area around the participants address (smaller NDVIs 200 m, 300 m and 500 m). This is further supported by another significant relationship between increasing the number of visits to greenspaces and decreasing the distance towards the doorstep green space (minimum of 0.5 ha), as well as another significant relationship between the more frequent visits to greenspaces and the increase in physical activity during lockdown. These findings, when seen together as a chain of inter-related decisions and daily choices, could reflect how residents of areas with locally high greenery were more likely to leave their home and either visit local greenspaces (one of few places they are allowed to go to) to engage in physical activity or to walk in their neighbourhood. This is suggestive of a causal pathway from proximity to greenery to greenspace use to health outcomes reported elsewhere (e.g., Refs. [3,23]).

From the above discussions, it could be recognised that, in this study, visits to greenspaces, physical activity, and connectedness to nature are the three health-related outcomes that showed a significant relationship to any of the greenspace exposure measures, and those relationships were in the expected direction; i.e., being within greener areas or being closer to greenspaces positively impact visits, physical activity, and nature connectedness. In contrast, wellbeing (measured through the ICECAP score) is one health-related outcome that did not show significant association to greenspace exposure except in an opposite to expected manner where wellbeing was shown to increase proportionally to the distance from a greenspace during the lockdown period (i.e., wellbeing is worse with more exposure to greenspace). Wellbeing (ICECAP) is also the only health-related outcome that is not significantly related to visits to greenspaces. It is not uncommon for a non-significant relationship between wellbeing and greenspace exposure to be reported in the literature once the modifying effect of sociodemographic variables are accounted for [38]. It may be that during the COVID-19 pandemic wellbeing was so severely affected that greenspace exposure did not have a positive impact or even that going outdoors reduced wellbeing due to the risk of contact with others.

Finally, from all the significant regression models in this study, either for the period before or during the lockdown, it is noticed that the studied health-related outcomes are mostly associated to measures of greenspace exposure that capture the immediate context, whether expressed as (1) the smaller NDVI radii (200 m, 300 m and 500 m), (2) the proximity to smaller greenspaces (0.5 ha) which are commonly close-by, or (3) the nearest greenspaces (which are commonly of smaller areas). However, heath-related outcomes in this study do not relate to the larger context in terms of the larger NDVI radii (1000 m and 2000 m) nor the proximity to larger greenspaces (10 ha and 20 ha). This happens despite the mean distance to the smaller greenspaces not meeting Natural England's AGS, i.e., being farther away than where they are expected to be.

This study demonstrates that it is important to use an appropriate measure of greenspace exposure. The findings here may go some way to explaining the inconsistent findings reported in systematic reviews examining the relationship between greenspace access and health outcomes (e.g., Refs. [4–7,43]). Here we report that a measure of greenspace use appears to have a closer relationship to greenspace access and neighbourhood greenness as well as physical activity and nature connectedness, perhaps indicative of a causal pathway. It is therefore important that those examining the impact of greenspace on health and wellbeing consider including a measure of greenspace use in addition to, or instead of, greenspace access or neighbourhood greenness.

5.3. Limitations

There are a number of limitations to the study. First, this is a cross-sectional study in which we relied on the ability of respondents to recall their pre-lockdown greenspace behaviours, physical activity, nature connectedness, and wellbeing. Recall bias has been reported to be a limitation of self-reported wellbeing [44] and physical activity questionnaires, such as GPAQ, leading to an overestimation of physical activity [45]. Given that the before lockdown measure was further in past when the survey was completed, it is possible that this timepoint is subject to greater recall bias than the measure during lockdown. In common with all cross-sectional studies, we cannot attribute causality as those exhibiting greater levels of greenspace use may have chosen to live in areas with greater opportunity to visit local greenspaces, which they benefitted from during the lockdown. Second, although we considered Nature Connectedness during lockdown, this was recorded as a change from the before lockdown condition, so the two measures cannot be compared across the two timepoints. Third, our sample was not representative of the West of England, tending to be biased towards those who are white, female, more highly educated, affluent, and older. Those in more socially disadvantaged groups tend to have lower levels of wellbeing, physical activity, and/or greenspace use than the general population in the UK [46], so our findings might not be representative of the population of the West of England.

6. Conclusions

This paper has examined different methods of measuring greenspace exposure, before proceeding to investigate the association of those measures to health-related outcomes. It has been inferred that certain measures of greenspace exposure, such as the degree of greenness (NDVI) or the proximity to greenspace (as a network or Euclidean distances), are significantly associated with health-related outcomes, quantified through the number of visits to greenspaces and connectedness to nature. At the same time, the frequency of visits to greenspace is significantly associated with physical activity, thus suggesting that greenspace use is on the causal pathway between greenspace access/neighbourhood greenness and physical activity and nature connectedness. Still, some measures of greenspace exposure have shown significant negative correspondences to the same health outcomes, suggesting the existence of other factors (not considered in this study) which play a role in formulating the health outcomes.

This study has taken into account a very critical period of time, i.e., the lockdown which happened in 2020 upon the spread of COVID-19, while attempting to understand the change in residents' behaviours and health outcomes during versus before that period. Results of the statistical models suggest that greenspace use, physical activity, wellbeing, and connectedness to nature all changed during lockdown, in comparison to the period before that. This could set the scene for a future broader investigation to understand how national decisions in response to health hazards (e.g., the decision of imposing a country lockdown) has significant implications on individuals' behaviours and possibly their physical and mental wellbeing.

Finally, it is worth mentioning that not a single measure of greenspace exposure (from eleven quantitative measures described in this paper) has shown association with all the four health-related outcomes. This suggests the need for further investigation into how to quantify measures of exposure to greenspace and the measures of population health.

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