Residential greenness and prevalence of major depressive disorders: a cross-sectional, observational, associational study of 94 879 adult UK Biobank participants

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Summary

Background Increased urbanisation and the associated reduced contact of individuals with natural environments have led to a rise in mental disorders, including depression. Residential greenness, a fundamental component of urban design, has been shown to reduce the public health burden of mental disorders. The present study investigates the association between residential green exposure and prevalence of major depressive disorders using a large and diverse cross-sectional dataset from the UK Biobank.

Methods In this cross-sectional, observational, associational study, we used baseline data from the UK Biobank cohort of participants aged 37–73 years from across the UK. Environmental exposure data were derived from a modelled and linked built environment database. Residential greenness was assessed with a 0·5 m resolution Normalised Difference Vegetation Index, which is derived from spectral reflectance measurements in remotely sensed colour infrared data and measured within geocoded dwelling catchments. Other environment metrics included street-level movement density, terrain, and fine particulate exposures. A series of logistic models examined associations between residential greenness and odds of major depressive disorder after adjusting for activity-influencing environments and individual covariates.

Findings Of 122 993 participants with data on major depressive disorder, the study analytical sample comprised 94 879 (77·1%) participants recruited across ten UK Biobank assessment centres between April 29, 2009, and Oct 1, 2010. A protective effect of greenness on depression was consistently observed, with 4·0% lower odds of major depressive disorder per interquartile increment in Normalised Difference Vegetation Index greenness (odds ratio 0·960, 95% CI 0·93–0·99; p=0·0044). Interaction analyses indicated that the beneficial effects of greenness were more pronounced among women, participants younger than 60 years, and participants residing in areas with low neighbourhood socioeconomic status or high urbanicity.

Interpretation The results point to the benefits of well designed green environments on mental health. Further longitudinal studies are needed to decipher causal pathways. In the UK, policies aimed at optimising allocation and design of green spaces might help preserve psychological ecosystem services, thereby, improving the mental wellbeing of populations and enhancing the mental capital of cities.

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Introduction

Given the present unprecedented rate of urbanisation, about 60% of the global population are predicted to reside in cities by 2030, with one in every three people living in cities with at least half a million inhabitants.[1] Typically, cities are characterised by highly dense, impervious, built-up spaces and a scarcity of natural environments, with the associated potential effects on mental health. Dynamic stress vulnerability models have reported links between reduced exposure to green environments and enhanced vulnerability to the negative health effects of stressful life events, which can result in increments in the proportion of the population with mental disorders and an overall reduction in the mental capital of cities.[2–4] In recent years, mental disorders, including mood disorders, have emerged as a leading cause of global disease burden. They also act as risk factors for the development of communicable and non-communicable diseases, and contribute to accidental and non-accidental injuries.[5–7] The UK's total annual expenditure on brain disorders was estimated to be approximately €134 billion in 2010, of which €19·24 billion was incurred on mood disorders, accounting for approximately 3·9 million annual cases or 8·73% of all brain disorders.[8]

The causes of mental health disorders are complex, with a long latency between exposures and subsequent incidence and progression. A systems-based life course approach towards enhancing the mental capital of cities and wellbeing of their populations has been proposed.[9]

Research in context

Evidence before this study

We searched online databases, including PubMed, MEDLINE, EBSCO, Scopus, and Google/Google Scholar databases, for studies and reports published in English between Jan 1, 1984, and Feb 10, 2018, using a combination of search terms, including "residential greenness", "green space", "NDVI", or "built environment", and "mental health", "depression", or "major depressive disorder".

Mental health disorders have emerged as a leading cause of the global burden of disease. At the same time, the present unprecedented pace of urbanisation and an increasing proportion of impervious built-up spaces in our cities have resulted in reduced exposures to salutogenic green environments. Several studies have examined the links between exposure to green environments and mental health, with most studies suggesting beneficial effects. Green exposure has been measured in terms of access to green spaces (proportion of green spaces within a residential neighbourhood) as well as the general salutogenic potential of green environments. The protective effects of residential green have been hypothesised to originate from one or more of its functional roles: as restorative stress-relieving spaces; supportive social interaction spaces promoting a sense of community; active living spaces facilitating physical activity; and natural filters ameliorating the adverse effects of negative exposures such as air, noise, and thermal pollution.

Notwithstanding the evidence generated so far, the links between residential green exposure and mental health still remain equivocal in adults. Many of the studies linking residential green exposure with mental health have used coarse measures of green exposure, whereas a few studies have used the Normalised Difference Vegetation Index as an index of salutogenic green, although of low-to-moderate spatial resolution. Most studies so far have been small scale and done in homogeneous environmental settings, resulting in limited statistical power and generalisability.

Added value of this study

The present study is the first of its kind to use the UK Biobank data to investigate links between green exposure and mental health. The study used a large and diverse analytical sample across ten UK cities of 94 879 middle-aged and older adults, a crucial life stage for the onset and progression of incipient mental disorders. A large spatially diverse sample also enabled sufficient statistical power for the examination of interactions. The study used structured and validated diagnostic criteria to assess lifetime probable major depressive disorders and was able to comprehensively adjust for sources of confounding. To our knowledge, this is the first mental health-related study to use a very high-resolution metric of residential greenness (0·5 m resolution index of salutogenic green derived from colour infrared imageries) that is adjusted for other objectively measured physical environment exposures, which are all measured within functional catchments of participants' dwellings.

The study consistently found a protective association between greenness and lifetime depression status, reporting a 4% lower odds of major depressive disorder with every interquartile increment in residential greenness after adjusting for all other factors. The beneficial effects of greenness were more pronounced among women, participants younger than 60 years, and participants residing in areas with low neighbourhood socioeconomic status or high urbanicity.

Implications of all the available evidence

The results of our study point to the protective effects of well designed green environments on mental health. These findings have notable policy implications with respect to optimising allocation and design of green spaces to preserve psychological ecosystem services and thereby improve the mental wellbeing of a population and enhance the mental capital of cities.

The importance of such a holistic approach has been emphasised by the inclusion of mental health within the Sustainable Development Goals.[10,11] Relatedly, exposure to residential green environment has also been regarded as an effective upstream-level urban intervention with an aim to reduce the public health burden of mental disorders.[12]

Some studies report a beneficial effect of contact with green environments on health, in general,[13–15] and more specifically, with regard to stress, mood, and mental health.[16,17] Several studies have established a protective independent association between various indicators of mental health and the percentage of green space within a residential neighbourhood,[18–21] the amount of tree cover in an urban area,[22] and the overall exposure of individuals to salutogenic green environments.[23–25] These protective effects of residential green spaces have been explained in terms of four mechanisms related to their specific functional roles: restorative, stress-relieving spaces;[4,26–28] supportive, social interaction spaces that promote a sense of community;[29] active living spaces that facilitate physical activity;[30–32] and natural filters that ameliorate the adverse effects of air, noise, and thermal pollution.[33–35]

Despite the substantial body of evidence, the links between residential green exposure and mental health still remain far from conclusive in adults.[17] Many of the studies have used coarse measures of green exposure, expressed as a proportion of greenness based on land cover maps within a specific catchment or census geography, thereby neglecting to include private gardens, street trees, and green spaces that do not meet a specific criterion, such as a size threshold, and hindering the study's replicability and comparability. A few studies have used the Normalised Difference Vegetation Index (NDVI), an index of greenery derived from Landsat satellite data, as an overall measure of green exposure (although at a low-to-moderate resolution). Most studies so far have been small scale and done in homogeneous environmental settings, resulting in limited statistical power and generalisability. Furthermore, most studies do not adjust for other aspects of activity-influencing built environment and individual-level confounding effects, or consider interaction effects.

The present study analyses a UK-wide population health dataset of unprecedented size and diversity for greenspace mental health research. It uses highly characterised metrics of green exposure to investigate cross-sectional associations between residential greenness and major depressive disorders, after adjusting for pertinent built environment (ie, walkability, terrain, and air pollution) and individual confounders. Because exposure to greenness and its relation to health is often stratified by underlying factors such as socioeconomic status and urbanicity,[18,36,37] this study also did analyses stratified by age, sex, neighbourhood socioeconomic status, and urbanicity, and analysed their interactions.

Methods

Analytical sample

This cross-sectional, observational, associational study analysed the UK Biobank baseline data on health and environment exposures. The National Health Service Register randomly sent out around 9·2 million invitation letters to potential participants who resided within a 25 mile radius of a UK Biobank collection centre, each of which are located in 22 cities across the UK. 502 649 adult participants aged 37–73 years were eventually recruited in the UK Biobank study, achieving a response rate of 5·5%.[38,39] The participants provided electronically signed consent. The range and scale of the UK Biobank study enables accumulation of an adequate number of cases of particular diseases within a reasonable follow-up period for clinically reliable effect detection. The baseline examination collected a wide range of information, including information on sociodemographics, lifestyle, and medical history through a series of touch-screen questionnaires; anthropometric measurements; biological sampling (blood, urine, and saliva); and imaging, and involved linkage with hospital-related outcomes. Individual-level, health-influencing, environment exposures were modelled within functional neighbourhoods for each participant.

The mental health component of the UK Biobank was an enhancement to the baseline data collection, and questions on depressive symptoms were added to the assessment protocol during the last 2 years of recruitment. These psychological inventories were available to participants who visited the remaining ten collection centres in the last 2 years of the baseline phase and fulfilled the diagnostic criteria of mood disorder.[38] The analytical sample excluded participants who subsequently dropped out or who did not meet the diagnostic criteria for a mood disorder. We also excluded from the analyses participants with missing data on residential green exposure and other individual confounders. The participants of our analytical sample attended the assessment centres between April 29, 2009, and Oct 1, 2010.

UK Biobank received ethical approvals from the North West Multi-centre Research Ethics Committee, the Community Health Index Advisory Group, the Patient Information Advisory Group, and the National Health Service National Research Ethics Service. The detailed cohort protocol, scientific rationale, and study design are described elsewhere.

For the **cohort protocol, scientific rationale, and study design** see http://www.ukbiobank.ac.uk/wp-content/uploads/2011/11/UK-Biobank-Protocol.pdf

Measurement of major depressive disorder

Depression was defined as per UK Biobank's assessment protocol for lifetime experience of probable major depressive disorder. The classification and definition of lifetime history of mood disorders in UK Biobank was based on structured and validated diagnostic criteria reported previously.[40,41] Briefly, the assessment of major depressive disorder comprised items relating to lifetime experience of minor or major depression, items from the Patient Health Questionnaire, and items related to social support for mental health.[40,42] As such, the binary outcome variable comprised participants with no lifetime experience of major depressive disorder (0 or "no case") and participants who had experienced a major depressive disorder (1 or "case"). The criteria for participants who had experienced a major depressive disorder included those who had experienced a single probable lifetime episode of major depression, probable recurrent major depression (moderate), or probable recurrent major depression (severe), or any combination thereof (panel).

Measurement of residential environment exposures

Residential environment exposure data were derived from the UK Biobank Urban Morphometric Platform (UKBUMP). UKBUMP is a high-resolution spatial database of health-influencing environment exposures modelled within multiscale residential neighbourhoods of each UK Biobank participant's geocoded dwelling. Environmental exposure metrics were developed through spatial and network analyses of data from multiple UK-wide spatial databases, resulting in multiple exposure variables related to greenness, urban density, destination accessibility, street-level accessibility, terrain, and deprivation.[43,44] Briefly, UKBUMP was developed by geocoding participants' dwelling addresses to the level of building footprints, delineating multiscale dwelling neighbourhoods by defining street network buffers centred on the geocoded dwelling locations in ArcGIS12 Network Analyst, and measuring environmental exposures within these functional neighbourhoods. After linking the exposure metrics to the participants' dwelling locations, the data were reanonymised. Accurate data on building-level land uses and street networks were sourced from UK Ordnance Survey AddressBase Premium and MasterMap Integrated Transport Network databases, whereas residential greenness was modelled from high-resolution (50×50 cm^2)

Panel: UK Biobank study's diagnostic criteria for classification of lifetime experience of probable major depressive disorders[40,41]

Single probable episode of major depressive disorder
Ever depressed or down for a whole week; plus at least 2 weeks' duration; plus only one episode; plus ever seen a general practitioner or a psychiatrist for "nerves, anxiety, depression" OR ever anhedonic (unenthusiasm or uninterest) for a whole week; plus at least 2 weeks' duration; plus only one episode; plus ever seen a general practitioner or a psychiatrist for "nerves, anxiety, depression"

Probable recurrent major depressive disorder (moderate)
Ever depressed or down for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a general practitioner (but not a psychiatrist) for "nerves, anxiety, depression" OR ever anhedonic (unenthusiasm or uninterest) for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a general practitioner (but not a psychiatrist) for "nerves, anxiety, depression"

Probable recurrent major depressive disorder (severe)
Ever depressed or down for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a psychiatrist for "nerves, anxiety, depression" OR ever anhedonic (unenthusiasm or uninterest) for a whole week; plus at least 2 weeks' duration; plus at least two episodes; plus ever seen a psychiatrist for "nerves, anxiety, depression"

colour infrared data captured during aerial photography with the Vexcel UltraCamD and the Leica ADS4.[43]

Residential greenness

Residential exposure to salutogenic green environment was measured in terms of mean NDVI within a 500 m catchment radius of geocoded UK Biobank participants' dwellings. NDVI is a unit-less index of relative overall vegetation density and quality, and is derived from differential surface reflectance in the red and near infrared regions,[45] which is measured with a remote sensing device. Chlorophyll in healthy vegetation absorbs radiation in the visible red region (630–690 nm) of the electromagnetic spectrum and reflects radiation in the near-infrared region (760–900 nm). This differential in the absorbance and reflectance of wavelengths by chlorophyll is used as a proxy for green quality and intensity. The differential is measured using the following formula:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}$$

The formula includes the spectral reflectance measurements acquired in the visible (RED) and near-infrared regions (NIR) of the electromagnetic spectrum. Index scores range between –1 and 1, with higher values indicating higher densities of green vegetation.

In the present study, NDVI greenness was derived from a series of 0·5 m resolution, colour-infrared imagery collected by Bluesky (Ashby-De-La-Zouch, UK) with the help of specially developed sensors mounted underneath a survey aircraft. Summer-time images of the study areas collected over similar temporal scales (across the baseline phase of the UK Biobank study) were stitched together to avoid temporal mismatch. After excluding large water bodies, we modelled mean NDVI within a 500 m residential buffer of each UK Biobank participant. Selection of a 500 m catchment area for measuring residential green exposures was based on our previous studies[46,47] and on other previous reports[48,49] that used a quarter mile (400–500 m) neighbourhood for measuring NDVI greenness.

Physical environment

Among the physical environment exposures, terrain was modelled in ArcGIS12 Spatial Analyst from a 5 m resolution Bluesky digital terrain model and expressed as variability (SD) of slope, in degrees, within a 0·5 km residential catchment of UK Biobank participants' dwellings. As such, the metric is able to differentiate between flat and hilly surface within the residential catchment.

Exposure to $PM_{2·5}$ obtained from UK Biobank's linked air pollution exposure data was used as a proxy for traffic-related air pollution. The measurement was based on monitoring on three occasions over a 14 day period during the cold, warm, and intermediate seasons of the year. Individual annual exposure to particulate matter concentrations around geocoded residential addresses was derived from land-use regression models.[50]

Built environment

Built-environment metrics from UKBUMP were assessed within a 1 km street catchment of participants' dwellings. Street-level movement density was modelled in terms of through-movement potential of the street segments, also termed as betweenness centrality in graph theoretic terminology. The method has been used in active living research and described elsewhere.[51,52] The UK-wide street network data for the study area comprised approximately 4 million street segments, which were extracted from the OS MasterMap Integrated Transport Network database, transcribed into an access graph model, and subjected to network analysis in sDNA[53] to model street-level movement density. Movement density is expressed as the simulated counts of movement through each link in the network, given its relative position and topological connectivity with other segments within the network. The measure also acts as a proxy for relative accessibility and centrality of a place. Betweenness centrality of x in a graph of N links might be defined as:

$$BtWl(x) = \sum_{y \in N} \sum_{z \in R_y} L(y) L(z) P(z) \mathrm{OD}(y,z,x)$$

In the formula, y and z are the geodesic endpoints; R_y is the set of links within a defined neighbourhood catchment from y; $L(y)$ is the length of link y and $L(z)$ is the length of link z; and $P(z)$ is the proportion of link z within the defined radius.

The origin-destination function (OD) is defined as:

$$\mathrm{OD} = \begin{cases} 1, \text{ if } x \text{ is on the geodesics from } y \text{ to } z \\ \frac{1}{2}, \text{ if } x \equiv y \not\equiv z \\ \frac{1}{2}, \text{ if } x \equiv z \not\equiv y \\ \frac{1}{2}, \text{ if } x \equiv z \equiv y \\ 0, \text{ otherwise} \end{cases}$$

An objective index of urbanicity within a 1 km residential catchment was developed from the UKBUMP built-environment variables to investigate associations between residential greenness and major depressive disorder, stratified by urbanicity quartiles. Urbanicity was defined as:

$$\text{Urbanicity} = zscore_{resid} + zscore_{retail} + zscore_{PT} + zscore_{street\ movement}$$

The formula includes the density of residential housing (*resid*), retail (*retail*), and public transport (*PT*) in units per km^2 street catchment, in addition to street-level movement density (*street movement*).

Individual-level covariates

On the basis of previous scientific literature, the study adjusted for demographic covariates (age, sex, highest educational qualification, and employment status), smoking status, and prevalent comorbidities (body-mass index [BMI] status, doctor-diagnosed cardiometabolic disease, and diabetes).

Socioeconomic status was assessed at household and neighbourhood levels in terms of mean annual household income before tax and Townsend deprivation index scores,[54] which is a composite index of four postcode-level socioeconomic status variables (household overcrowding, unemployment, non-home ownership, and non-car ownership), with a higher score indicative of lower neighbourhood socioeconomic status.

We used participation in leisure and social activities as a proxy for social interaction and support. Level of participation was based on response to the questionnaire: "Which of the following do you attend once a week or more often? (You can select more than one)"; with available responses being none; pub or social club; religious group; sports club or gym; and adult education class or other group activity. Responses were converted into a six-factor variable: none, pub or social club, religious group, sports club or gym, adult education class and other, and combination of two or more activities.

Statistical analyses

The prevalence of lifetime experience of probable major depressive disorder was modelled as a two factor variable (case or non-case) as per UK Biobank's assessment protocol. Age was coded as a three-factor variable (38–50 years, 51–60 years, or 61–73 years) and sex as a two-factor variable (female or male). Highest educational attainment was defined as a five-factor variable (none; O levels, GCSEs, or CSEs; A levels or AS levels; NVQ, HND, HNC, or other professional qualification; or college or university degree) and employment as a three-factor variable (employed; retired; or unemployed, home maker, or other). Mean annual household income before tax was expressed as a four-factor variable (<£18 000, £18 000–£30 999, £31 000–£51 999, or ≥£52 000). The household income data were available for 82 839 participants in the analytical sample. Townsend scores were categorised into quintiles and used as a five-factor variable. Smoking status was coded as non-smoker, previous smoker, and current smoker. Doctor-diagnosed cardiometabolic disease was transformed into a four-factor variable (none; high blood pressure; heart attack, angina, or stroke; or both high blood pressure and heart attack, angina, or stroke) and diabetes was coded as a two-factor variables (yes or no). Measured BMI status was expressed as a three-factor variable (<25 kg/m^2; ≥25 kg/m^2 and <30 kg/m^2; or ≥30 kg/m^2). Terrain variability and walkability (expressed as movement density) were transformed into quartiles.

The study followed a multi-layered analyses strategy. Logistic regression models investigated the association between residential greenness and odds of major depressive disorder. Odds ratios (OR) and two-tailed 95% CIs estimated by bootstrapping have been presented for each IQR increment in NDVI. In model 1, we modelled initial crude estimates adjusted for age. Model 2 further adjusted for sex, educational qualification, employment status, smoking status, prevalent obesity, cardiometabolic disease, and diabetes status; model 3 additionally adjusted for physical and built environment variables of terrain, exposure to fine particulates, and activity-influencing movement density; and model 4 additionally adjusted for household and neighbourhood socioeconomic status and leisure and social activity. Multicollinearity among predictor variables was assessed through Pearson's correlation coefficients and variance inflation factors to ensure parsimonious fit.

Stratified analyses were done by age, sex, urbanicity, and neighbourhood socioeconomic status to investigate potential changes in point estimates and level of significance across each stratum. As a further step, the study analysed the interaction effects of age and urbanicity, sex and urbanicity, age and neighbourhood socioeconomic status, and sex and neighbourhood socioeconomic status on the relation between residential greenness and prevalence of major depressive disorder.

All analyses were done in statistical software Stata 14.

	Depression status		Analytical sample (n=94 879)
	No major depressive disorders (n=70 531)	Major depressive disorders (n=24 348)	
Age (years)	57·38 (8·1)	55·73 (8·0)	56·96 (8·1)
Residential greenness	0·213 (0·1)	0·209 (0·1)	0·211 (0·1)
Socioeconomic status (Townsend index)	−1·44 (2·8)	−1·16 (2·9)	−1·37 (2·8)
Sex			
Female	35 409 (50·2%)	15 854 (65·1%)	51 263 (54·0%)
Male	35 122 (49·8%)	8494 (34·9%)	43 616 (46·0%)
Highest educational qualification			
None	10 918 (15·5%)	2975 (12·2%)	13 893 (14·6%)
College or university degree	23 912 (33·9%)	8833 (36·3%)	32 745 (34·5%)
O levels, GCSEs, or CSEs	19 126 (27·1%)	6739 (27·7%)	25 865 (27·3%)
A levels or AS levels	7991 (11·3%)	3015 (12·4%)	11 006 (11·6%)
NVQ, HND, HNC, or other professional	8584 (12·2%)	2786 (11·4%)	11 370 (12·0%)
Employment status			
Employed	39 519 (56·0%)	13 927 (57·2%)	53 446 (56·3%)
Retired	26 079 (37·0%)	7710 (31·7%)	33 789 (35·6%)
Unemployed, home maker, or other	4933 (7·0%)	2711 (11·1%)	7644 (8·1%)
Household income*			
<£18 000	11 693 (19·2%)	5269 (23·9%)	16 962 (20·5%)
£18 000–£30 999	15 375 (25·3%)	5522 (25·1%)	20 897 (25·2%)
£31 000–£51 999	15 984 (26·3%)	5759 (26·1%)	21 743 (26·2%)
≥£52 000	17 764 (29·2%)	5473 (24·9%)	23 237 (28·1%)
Smoking status			
Non-smoker	40 709 (57·7%)	12 292 (50·5%)	53 001 (55·9%)
Previous smoker	24 035 (34·1%)	9034 (37·1%)	33 069 (34·9%)
Current smoker	5787 (8·2%)	3022 (12·4%)	8809 (9·3%)
Leisure or social activities			
None	21 133 (30·0%)	7674 (31·5%)	28 807 (30·4%)
Pub or social club	9010 (12·8%)	2645 (10·9%)	11 655 (12·3%)
Religious group	4581 (6·5%)	1415 (5·8%)	5996 (6·3%)
Sports club or gym	10 108 (14·3%)	3088 (12·7%)	13 196 (13·9%)
Adult education or others	7682 (10·9%)	3019 (12·4%)	10 701 (11·3%)
Two or more of above activities	18 017 (25·5%)	6507 (26·7%)	24 524 (25·8%)
Body-mass index status			
Normal weight	24 046 (34·1%)	7906 (32·5%)	31 952 (33·7%)
Overweight	30 334 (43%)	9834 (40·4%)	40 168 (42·3%)
Obese	16 151 (22·9%)	6608 (27·1%)	22 759 (24·0%)
Vascular problems			
None	49 902 (70·8%)	16 946 (69·6%)	66 848 (70·5%)
High blood pressure	16 931 (24%)	5973 (24·5%)	22 904 (24·1%)
Heart attack, angina, or stroke	1826 (2·6%)	615 (2·5%)	2441 (2·6%)
High blood pressure and heart attack, angina, or stroke	1872 (2·7%)	814 (3·3%)	2686 (2·8%)
Diabetes			
None	66 779 (94·7%)	22 981 (94·4%)	89 760 (94·6%)
Yes	3752 (5·3%)	1367 (5·6%)	5119 (5·4%)

Data are mean (SD) or n (%). *Data on household income were available for 82 839 participants of the analytical sample (60 816 in the no major depressive disorder category and 22 023 in the major depressive disorders category).

Table 1: **Characteristics of UK Biobank analytical sample**

Role of the funding source

The funders and UK Biobank participants did not participate in developing the research questions, outcome measures, and environmental measures of the present study. They had no role in study design, modelling, data collection, data analysis, data interpretation, or writing of the report. CS, CW, and JG had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

172 751 participants visited the remaining ten UK Biobank collection centres in the last 2 years of the baseline phase and completed the mental health component of the UK Biobank assessment protocol. After excluding participants who subsequently dropped out and participants who did not meet the diagnostic criteria for a mood disorder, valid data were available for 122 993 participants. After excluding missing data on residential green exposure for 23 945 (19·5%) participants and other individual confounders for 4169 (3·4%) participants, an analytical sample of 94 879 (77·1%) participants was available for analyses.

The analytical sample remained representative of the full UK Biobank cohort (table 1; appendix). Overall, 24 348 (25·7%) patients in the sample had major depressive disorders. In all our models, the Pearson's correlation coefficients remained less than 0·23 and the variance inflation factors remained less than 1·08, indicating low levels of collinearity.

Exposure to residential greenness remained significantly associated with major depressive disorder, with 4·0–4·9% lower odds of major depressive disorder reported across models 1–4 (table 2). Adjusting for individual-level covariates, physical and built environment variables (model 3), an interquartile increment in NDVI greenness within a 500 m catchment was associated with 4·3% lower odds of major depressive disorder (OR 0·957, 95% CI 0·93–0·98; p=0·0008; table 2; see appendix for full table). After further adjustments for socioeconomic status and social activities (in the fully adjusted model 4), an interquartile increment in NDVI was associated with 4·0% lower odds of major depressive disorder (OR 0·960, 0·93–0·99; p=0·0044; table 2).

Among the other significant environment exposure variables in our fully adjusted model 4, terrain variability (ie, more hilly terrain) was associated with higher odds of major depressive disorder, with the third (p=0·026) and fourth (p<0·0001) quartiles of terrain variability having higher odds of major depressive disorder than the first quartile. Street-level movement density, measured as betweenness centrality, was associated with lower odds of major depressive disorder, with the second (p=0·013) and third (p=0·0030) quartiles (ie, areas of greater street-level movement density) having lower odds of major depressive disorder than the first quartile. Higher mean annual household income was consistently associated with lower odds of major depressive disorder (p<0·0001 for those earning £18 000–£30 999, p<0·0001 for those earning £31 000–£51 999, and p<0·0001 for those earning ≥£52 000, in reference to the lower income group earning <£18 000). Lower neighbourhood socioeconomic status (expressed in terms of Townsend's deprivation score) was associated with higher odds of major depressive disorder, with the results being significant for the fifth quintile only (p=0·048 in reference to the first quintile). In reference to participants not engaged in any social activities, participants attending pubs or participating in social club-based activities (p<0·0001), engaging in religious group activities (p<0·0001), and attending a sports club or gym (p<0·0001) reported significantly lower odds of major depressive disorder.

Rerunning the analysis with the residential greenness as a factor variable categorised into quartiles indicated a beneficial effect for the third (OR 0·933, 95% CI 0·89–0·98; p=0·0029) and fourth (OR 0·947, 0·90–0·99; p=0·023) quartiles but not the second quartile (OR 1·039, 0·99–1·09; p=0·090) in reference to the first quartile and subsequent to all adjustments.

In the stratified models (figure 1), the association between residential greenness and odds of major depressive disorder remained significant only in female participants (OR 0·96, 95% CI 0·92–0·99; p=0·022); participants younger than 60 years (OR 0·96, 0·92–0·99; p=0·017); participants in the third (OR 0·92, 0·87–0·98; p=0·0085) and fourth (OR 0·91, 0·85–0·97; p=0·0070) urbanicity quartiles; and participants in the lower neighbourhood socioeconomic status quintiles, namely the fourth (OR 0·89, 0·83–0·96; p=0·0037) and fifth (0·85, 0·78–0·93; p=0·0003) quintiles of the Townsend index.

Consistent with the results of the stratified analyses, interactions between age and urbanicity and between sex and urbanicity found a slightly stronger protective association of residential greenness on major depressive disorder for women and participants younger than 60 years, with the effects being significant only in urban areas (ie, the third and fourth urbanicity quartiles; figure 2). Similarly, interaction models of age and neighbourhood socioeconomic status and of sex and neighbourhood socioeconomic status reported slightly stronger protective effects in women and participants younger than 60 years, with the effects being significant among lower neighbourhood socioeconomic status groups (ie, the fourth and fifth quintiles of the Townsend index; figure 2).

	Model 3, OR (95% CI)	Model 4, OR (95% CI)
Residential greenness (500 m:NDVI)*	0·957 (0·93–0·98)	0·960 (0·93–0·99)
Physical environment		
Terrain variabiliy†		
Low (Q1)	1 (ref)	1 (ref)
Low–medium (Q2)	1·035 (0·99–1·08)	1·017 (0·97–1·06)
High–medium (Q3)	1·050 (1·01–1·09)	1·052 (1·01–1·10)
High (Q4)	1·133 (1·09–1·18)	1·104 (1·06–1·16)
$PM_{2.5}$ (per 1 μg/m³)	1·024 (1·01–1·04)	0·996 (0·98–1·02)
Built environment (street-level movement density)†		
Low (Q1)	1 (ref)	1 (ref)
Low–medium (Q2)	0·930 (0·89–0·97)	0·942 (0·90–0·99)
High–medium (Q3)	0·908 (0·87–0·95)	0·934 (0·89–0·98)
High (Q4)	0·938 (0·90–0·98)	0·955 (0·91–1·00)
Socioeconomic status and social environment		
Individual socioeconomic status (household income)‡		
<£18 000	NA	1 (ref)
£18 000–£30 999	NA	0·800 (0·76–0·84)
£31 000–£51 999	NA	0·743 (0·71–0·78)
≥£52 000	NA	0·595 (0·56–0·63)
Neighbourhood socioeconomic status (Townsend index)§		
Low (Qn1)	NA	1 (ref)
Qn2	NA	1·025 (0·98–1·08)
Medium (Qn3)	NA	1·042 (0·99–1·10)
Qn4	NA	1·019 (0·97–1·07)
High (Qn5)	NA	1·057 (1·00–1·12)
Activities		
None	NA	1 (ref)
Pub or social club	NA	0·889 (0·84–0·94)
Religious group	NA	0·847 (0·79–0·91)
Sports club or gym	NA	0·894 (0·85–0·94)
Adult education class or other	NA	1·076 (1·02–1·14)
Two or more activities	NA	1·025 (0·98–1·07)

Analysis includes data for 94 879 UK Biobank participants. Model 3 is adjusted for age, individual-level covariates, and physical environment (terrain, street-level movement density, and exposure to $PM_{2.5}$). Model 4 is a fully adjusted model, additionally adjusting for household income, neighbourhood-level socioeconomic status, and social activities for 82 839 participants. OR=odds ratio. NDVI=Normalised Difference Vegetation Index. NA=not applicable. *The OR for residential greenness was 0·954 (95% CI 0·93–0·98) for model 1, which is adjusted for age, and 0·951 (0·93–0·98) for model 2, which is adjusted for age and individual-level covariates (sex, highest educational qualification, employment, smoking status, body-mass index status, doctor-diagnosed cerebrovascular disease, and diabetes status). †Q1, Q2, Q3, and Q4 represent the first, second, third, and fourth quartiles, respectively. ‡Data on household income were available for 82 839 participants of the analytical sample. §Qn1, Qn2, Qn3, Qn4, and Qn5 represent first, second, third, fourth, and fifth quintiles, respectively.

Table 2: **Association between residential greenness and odds of major depressive disorders**

Discussion

In this large, UK-wide, cross-sectional study, residential greenness was consistently associated with lower odds of depression, with the results remaining robust to adjustments for other physical, built, and social environment variables. This is one of the largest studies to use very high-resolution metrics of residential greenness (0·5 m on the ground measured from an aircraft) and to have adjusted for other objectively measured physical environment exposures.

See Online for appendix

This study reported a protective association of greenness on lifetime depression status, with effect sizes being moderate at 4% lower odds of major depressive disorder with every interquartile increment in residential greenness after adjusting for all other factors. This finding lends support to previous studies reporting protective effects of residential green exposure on depression.[18–21,23,24] One large-scale study[19] has reported that having 10% more greenness than average within 1 km

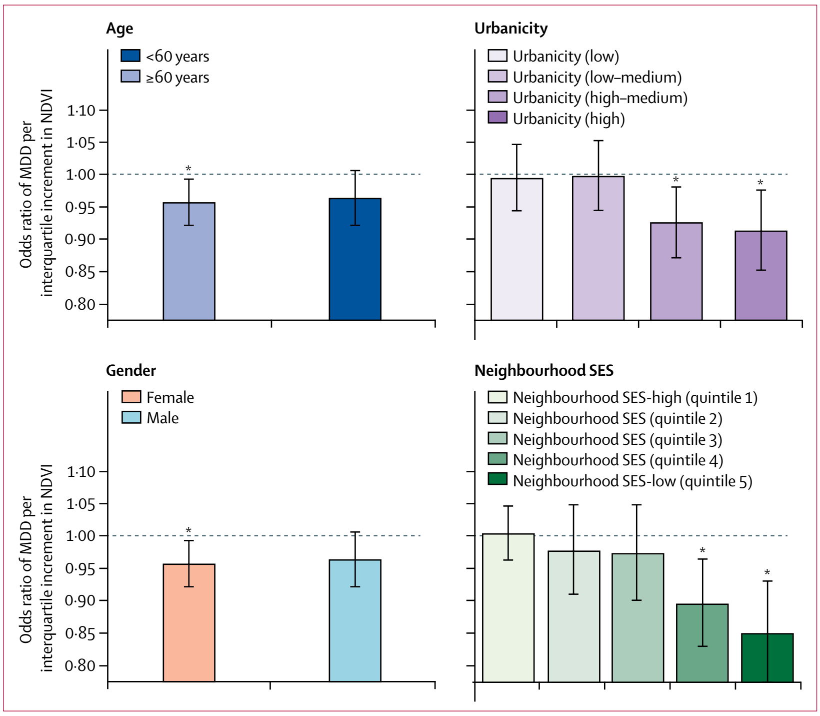

***Figure 1:* Association between residential greenness and odds of major depressive disorders stratified by age, gender, urbanicity, and neighbourhood socioeconomic status**

Each model is adjusted for age, sex, highest educational qualification, employment status, social activities, household income, neighbourhood socioeconomic status, body-mass index status, cardiometabolic disease, diabetes, terrain, street-movement density, and $PM_{2.5}$. Urbanicity was measured as an aggregated index of residential, retail, public transport, and street-movement density, and expressed in quartiles. Neighbourhood socioeconomic status was defined in terms of Townsend's index of deprivation and expressed as quintiles, with higher quintiles indicating higher levels of deprivation. MDD=major depressive disorder. NDVI=Normalised Difference Vegetation Index. SES=socioeconomic status. *p<0·05.

was associated with 4% lower odds of depression, and within 3 km was associated with 2% lower odds of depression. A US study[23] involving 2479 residents of Wisconsin reported that a 25% increment in NDVI greenness was associated with a 1·4 unit reduction in a depression anxiety and stress scale. Another study[24] of 8793 participants in Catalonia, Spain, reported that each interquartile increment in NDVI greenness was associated with a 21% lower perceived risk of poor mental health and a 19% lower risk of perceived depression or anxiety. In both the later studies,[23,24] NDVI greenness was derived from 30 m resolution Landsat satellite data and our study improves on these findings in terms of both spatial accuracy and confounders.

Green spaces and wellbeing are intrinsically linked.[55] The observed overall protective effects of residential green on depression status might be interpreted in terms of mechanisms oriented around biology, physiology, and lifestyle. The biophilia hypothesis suggests that biologically, human beings have an innate affinity towards natural environments, life forms, and life-like processes as a consequence of evolution and natural selection, and such environments are inherently associated with lower stress levels than more urban environments.[15,56] According to the stress reduction hypothesis, residential green can provide restorative stress-relieving environments that are capable of instilling a positive psychological state.[26–28,57] Green environments might also provide stimuli for attention restoration and associated cognitive benefits.[58,59] At a physiological level, evidence has been established for beneficial, stress-relieving effects of green exposure in urban settings, assessed through biological markers, including salivary cortisol,[60] amylase,[61] telomere length,[62] and improved cardiometabolic health.[63] At a neuro-biological level, rumination and associated neural activity in the subgenual prefrontal cortex have been linked to elevated levels of depression and psychological disorders.[64] The place-cells within the hippocampus also help encode attributes of real-world places, enabling the formation of cognitive maps of places, which again affects an individual's sense of attachment and route choice.[65] A 2015 study[66] reported that a 90 min walk in a green environment decreases both self-reported rumination and subgenual prefrontal cortex activity, whereas the same duration of walk in an urban setting had no effect. Rumination is a maladaptive attentional focus and has been linked to onset of depressive episodes and mental disorders. Neurological evidence has shown that the subgenual prefrontal cortex in the brain is particularly active during rumination. At a lifestyle level, residential greenness provides spaces for people to interact and support one another and facilitates a positive perception of neighbourhood and sense of community.[29,67] Furthermore, green spaces act as activity spaces, facilitating participation in physical and social activities.[31,68] The protective effects[69] of physical activity on depression can plausibly be attributed to elevated levels of brain neurotransmitters, such as monoamines and endorphins, and to enhanced self-esteem.[70]

Unlike previous reports, our study also adjusted for activity-influencing environment metrics. As per previous findings,[71] terrain variability was associated with higher odds of major depressive disorder. Terrain variability acts as a proxy for the degree of impediments to physical mobility, with its negative association with major depressive disorder possibly attributable to the effects of reduced functional capacity among participants residing in variable terrain. Furthermore, in a varied terrain, people might not be able to make as much use of available green spaces. Built environment metrics of density and form capture variations in the configuration of urban spaces in a city and these might directly affect mental health independently of green effects. In addition to green exposure, an optimised neighbourhood design might act as buffers against stressful environments. A 2018 study[72] reported more pronounced beneficial effects of walkability on hypertension in the high-green quartiles than in the low-green quartiles. Built-environment design and configuration determines accessibility to green spaces and, as such, actual usage

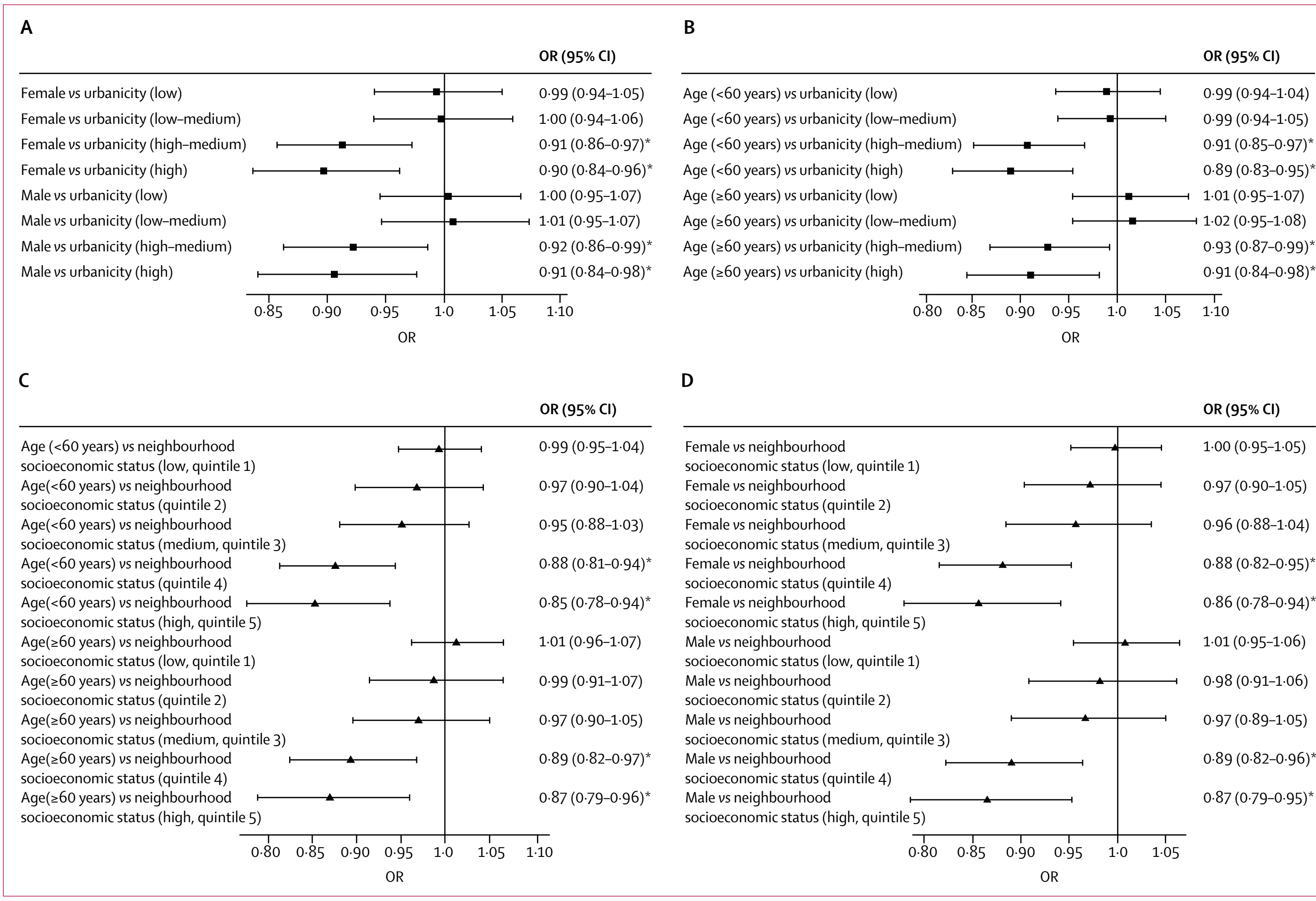

***Figure 2:* Models of interaction effects in the association between residential greenness and odds of major depressive disorder**
Each model is adjusted for age, sex, highest educational qualification, employment status, social activities, household income, neighbourhood socioeconomic status, body-mass index status, cardiometabolic disease, diabetes, terrain, street-movement density, and $PM_{2·5}$. Urbanicity was measured as an aggregated index of residential, retail, public transport, and street-movement density, and expressed in quartiles. Neighbourhood socioeconomic status was defined in terms of Townsend's index of deprivation and expressed as quintiles, with higher quintiles indicating higher levels of deprivation. OR=odds ratio. *p<0·01.

and levels of physical activity. In the present study, street-level movement density, captured by the index of betweenness centrality, was consistently associated with reduced odds of major depressive disorder. This finding points to the protective effects of well designed and connected neighbourhoods and greater activity and walking,[46] and hence, improved mental health.[71] Furthermore, a walkable, well designed community is associated with increased neighbourhood cohesion and social support. The beneficial effects of participation in leisure and social activities on major depressive disorder might point to the community social capital-based mechanism.[73] Corroborating previous studies,[18,37] this study reported that higher socioeconomic deprivation, measured by Townsend's score, was associated with higher odds of major depressive disorder.

In the subgroup analyses, the significant beneficial effects of residential green on major depressive disorders in women is attributable to increased daily exposure to functional neighbourhood environment and corresponds with previous findings.[18,24,74] The reduced effects in participants aged older than 60 years might be related to the reduced functional capacity in these population clusters.[75] The significantly higher protective effects of residential greenness reported in low neighbourhood socioeconomic status and high urbanicity groups than reported in their opposite counterparts has been reported previously.[18,37,76] The pronounced protective effects reported in the deprived and high urbanicity areas might originate from the restorative potential of green environments in exposure subgroups, which are generally associated with increased levels of stress.[77] Furthermore, in this study, urbanicity is a composite index of density, which is synonymous with compactness. The protective effects of green allocated in these areas stem from an increased density of exposed population, an increased degree of accessibility, and potentially increased usage.

The results of this study have important implications for public health and urban policies. Of specific interest is the use of green exposures as an upstream-level intervention to manage and minimise the burden of mental health disorders. Our findings will support public health and urban planning professionals in arguing for optimisation of residential green space exposure and related built environment attributes, in terms of allocation (size and shape), quality, density, and accessibility, with an aim to improve psychological ecosystem services[78] to yield benefits for individuals' mental health. Our findings also give guidance for more targeted interventions; in addition to urban environmental stressors, the characteristics of the resident population, especially their intrinsic sociodemographic and vulnerability profiles, need to be considered.

The study has several strengths. It used a high-quality, UK Biobank cohort dataset of unprecedented size and with substantial population-level and spatial diversity. Such a large analytical sample also meant the study had sufficient statistical power to investigate interactions. The study used clinically meaningful and validated instruments to define lifetime prevalence of major depressive disorders.[40] It also used highly characterised metrics of residential greenness and physical and built environment that were measured within neighbourhoods of an individual's dwelling. The NDVI has been previously validated as a measure of greenness in epidemiological research.[79] In the present study, it acted as an objective measure of green exposure (both density and quality) and as a proxy for capturing the intangible salutogenic potential within a residential environment. The use of very high resolution (50×50 cm²) colour infrared data captured during aerial photography with the Vexcel UltraCamD and the Leica ADS4 enabled extreme precision in green measurements. Previous studies have used conventional satellite remote-sensing data, for which the quality is often limited by low resolution, cloud cover, and atmospheric distortions.[46] In view of the established links between active living and depression,[69] the study also adjusted for other influencing environment features, which it operationalised through objective measures of terrain variability, street-level walkability, and exposure to fine particulate matter, in addition to adjusting for socioeconomic status, social activities, and other individual-level confounders.

This study also has some limitations. A cross-sectional study design limits confidence in the establishment of causal associations. Depressed participants might have migrated to greener areas and the resulting self-selection could potentially lead to underestimation of the effects of greenness on major depressive disorder. The study did not have data on the spatial mobility of participants over the baseline phase (2006–10) or on changes in exposures owing to migration from one address to another. Nonetheless, the mean duration of residence across the non-major depressive disorder and major depressive disorder groups was similar at 18 years and 16 years, respectively, and the introduction of duration of residence in the fully adjusted model did not produce any material effects on the point estimates and level of significance. As repeat-assessment data from the UK Biobank subsample become available, future studies should investigate the longitudinal associations of green exposure with major depressive disorder. The major depressive disorder outcome, being derived from a self-reported instrument, is prone to recall bias, leading to potential under-reporting of mood symptoms, especially severe depressive disorders.[80] Representativeness is another factor; individuals with a lifetime history of psychiatric disorders might have been less likely to participate in the UK Biobank study, potentially limiting the generalisability of the findings. Nevertheless, in view of the large sample size, diverse population characteristics, and heterogeneity in the environmental exposures, the effects on generalisability of the reported findings would have been minimal. The reported ORs of major depressive disorder might be further affected by finer design parameters of public green spaces, including size, shape, degree of landscaping, park facilities, and recreational programmes, which our study could not adjust for. Although the study included objectively measured metrics of residential green and physical environment, it could not individually adjust for perceptions of neighbourhood environment, including proxies of aesthetics and safety, which might influence usage of public green space.[81]

With rapid urbanisation and progressive urban densification, optimisation of individual-level exposures to green can be one of the most enduring public health interventions achieved by urban design and planning. Adding to previous evidence, our large-scale study concludes that exposure to green environments in an urban setting is associated with accrued psychological benefits in the form of reduced odds of major depressive disorders. This has substantial public health implications. As an upstream-level intervention, green environments, when optimally allocated, designed, and configured in relation to the existing matrix of land uses and the characteristics of the resident population, have the potential to enhance psychological ecosystem services and, subsequently, enhance the mental capital of cities.

Contributors

CS, CW, and JG conceived and designed the study. CS developed the built environment metrics, did the statistical analysis, and drafted the report. CS, CW, and JG contributed to redrafting and interpretations. All the authors read and approved the final manuscript.

Declaration of interests

We declare no competing interests.

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