Residential greenness and adiposity: findings from the UK Biobank

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Abstract

Background:

With the rapid urbanization and prevailing obesity pandemic, the role of residential green exposures in obesity prevention has gained renewed focus. The study investigated the effects of residential green exposures on adiposity using a large and diverse population sample drawn from the UK Biobank.

Materials and methods:

This was a population based cross-sectional study of 333 183 participants aged 38-73 years with individual-level data on residential greenness and built environment exposures. Residential greenness was assessed through 0.50-metre resolution normalized difference vegetation index (NDVI) derived from spectral reflectance measurements in remotely sensed colour infrared data and measured around geocoded participants' dwelling. A series of continuous and binary outcome models examined the associations between residential greenness and markers of adiposity, expressed as body-mass index (BMI) in Kg/m^2, waist circumference (WC) in cm, whole body fat (WBF) in Kg and obesity (BMI≥30 Kg/m^2) after adjusting for other activity-influencing built environment and confounders. Sensitivity analyses involved studying effect modification by gender, age, urbanicity and SES as well as examining relationships between residential greenness and active travel behaviour.

Results:

Residential greenness was independently and consistently associated with lower adiposity, the association being robust to adjustments. An interquartile increment in NDVI greenness was associated with lower BMI (β_{BMI}=-0.123 Kg/m^2, 95% CI: -0.14,-0.10 Kg/m^2), WC (β_{WC}=-0.551 cm, 95% CI: -0.61,-0.50 cm), and WBF (β_{WBF}=-0.138 Kg, 95% CI: -0.18,-0.10 Kg) as well as a reduced relative risk of obesity (RR=0.968, 95% CI: 0.96, 0.98). Residential greenness was beneficially related with active travel, being associated with higher odds of using active mode for non-work travel (OR=1.093, 95% CI: 1.08,1.11) as well as doing more than 30 minutes walking (OR=1.039, 95% CI: 1.03,1.05).

Conclusion:

Residing in greener areas was associated with healthy weight outcomes possibly through a physical activity-related mechanism. Green allocation and design may act as upstream-level public health interventions ameliorating the negative health externalities of obesogenic urban environments. Further prospective studies are needed to identify potential causal pathways and thereby effectively guide such interventions. `

Keywords: adiposity, body mass index, UK Biobank, NDVI, residential greenness, UKBUMP, active travel.

1. Introduction

Obesity is a global pandemic (Swinburn et al. 2011). Excessive adiposity is an important risk factor for morbidity and mortality from type 2 diabetes, cardiovascular disease and cancer (Flegal et al. 2007; Bhaskaran et al. 2014; Tobias et al. 2014). The role of built environment has long been established, especially in shaping daily lifestyles, walking, activity behaviours and adiposity outcomes (Brownson et al. 2009; Leal and Chaix 2011; Sallis et al. 2012; Sarkar et al. 2014). Residential green spaces, in particular, constitute a key health-promoting component of built environment (Depledge et al. 2011; Hartig et al. 2014). Exposures to residential green has been independently associated with higher levels of recreational and utilitarian walking and physical activity (Bedimo-Rung et al. 2005), lower odds of obesity (Lachowycz and Jones 2011), higher levels of social contacts and sense of community (Kweon et al. 1998). It has also been established to ameliorate adverse effects originating from exposures to air pollution (Nowak et al. 2006) and urban heat island effects (Loughner et al. 2012).

There is nonetheless some ambiguity in the relationships between residential greenness and physical activity and obesity and research evidence has been far from consistent. A recent systematic review (James et al. 2015) of twenty five cross sectional studies have reported intermediate-level evidence on the beneficial effects of residential greenness upon obesity. However, a few null (Potestio et al. 2009; Mowafi et al. 2012; Ord et al. 2013) and counterintuitive (Maas et al. 2008; Prince et al. 2011; Cummins and Fagg 2012) findings were also noted. Additionally, it is often difficult to establish the exact functional causality as most studies have focused on the protective effects of residential greenness outcomes accrued from their functional role as recreational spaces, often measured in terms of size, density and accessibility to residential park space. There has thus far been very few studies on the links between the functional role of residential green as *salutogenic environmental spaces* and adiposity (Sarkar et al. 2015b). Furthermore, many of the studies measure residential green space at an aggregate level of analysis such as census-defined units or through satellite-derived metrics of lower spatial resolution, while most have been small scale studies within homogeneous environmental settings, thereby limiting accuracy, statistical reliability and generalizability.

The present study examines the links between adiposity and residential greenness in a diverse UK-wide adult population employing data from the UK Biobank cohort and high resolution metrics of salutogenic green exposures after adjusting for other pertinent activity-influencing built environment, socio-demographics, lifestyle and co-morbidities. Effect modification by gender, age, urbanicity and SES was also tested.

2. Materials and methods

2.1 Study sample

The UK Biobank is a prospective population-based cohort of 502 649 adults aged 37-73 years (99.5% aged between 40-69 years) established to study the lifestyle, environment and genetic determinants of a various adult diseases. The participants recruited at baseline (2006-2010) attended one of the 22 collection centres across UK for detailed assessment providing a range of information through extensive questionnaires on socio-demographics, lifestyle and medical history; anthropometric measurements; biological samples (blood, urine and saliva); imaging and hospital-related outcomes. Details of the study can be found elsewhere (Allen et al. 2014; Sudlow et al. 2015). The recruited participants resided within 25 miles of the collection centres and included participants residing in urban areas as well as some beyond the urban fringes (Figure 1). Built environment exposures within multi-scale residential neighbourhoods were modelled for the cohort participants. The cross sectional study employed N=353 670 (70.4%) participants of the UK Biobank with valid data on residential green exposures. After exclusions on account of incomplete data on adiposity and individual-level confounders for 18 438 (3.7%), and built environment and air pollution exposure variables for 2 049 (0.4%) participants, an analytic sample of N=333 183 was available for analyses.

[Insert Figure 1]

2.2 Adiposity measures

Body mass index (BMI), waist circumference (WC), whole body fat (WBF) and obesity constituted the primary measures of adiposity. Standing height (cm) was measured using a Seca 202 device and waist circumference (cm) was enumerated using a Wessex non-stretchable sprung tape. Weight and whole body fat mass was measured using electrical bio-impedance with the Tanita BC-418 MA body composition analyser.

Body Mass Index (BMI) was derived by dividing weight (kilograms) by square of standing height (square metres). Obesity was expressed as per as the World Health Organization's definition (cut-offs for BMI≥30 Kg/m^2). Anthropometrics were assessed by trained technicians at the collection centres as the participants wore light clothes and no shoes.

2.3 Active travel behaviour

Using active travel mode and doing more than 30 minutes walking were employed as secondary outcome variables of active travel behaviour. The UK Biobank participants were asked "In the last 4 weeks, which forms of transport have you used most often to get about? (Not including any journeys to and from work)" with the option of selecting one or more of the following: car/motor vehicle; walk; public transport; cycle. This was subsequently dichotomized into a binary variable; using active travel mode (walk, cycle, public transport) versus motorized transport (car/motor vehicle). The questionnaire on "average number of minutes spent walking on a typical day" was transformed in to a binary variable (doing more than 30 minutes walking versus doing less than 30 minutes).

2.4 Environmental exposures

Data on residential environment exposures were obtained from the UK Biobank Urban Morphometric Platform (UKBUMP). The UKBUMP is a linked database of objectively measured urban morphological metrics measuring health-influencing environmental exposures within functional neighbourhoods around UK Biobank participants' geocoded dwelling locations (Sarkar et al. 2015a; Sarkar and Webster 2017). Spatial and network analyses were performed upon diverse national-level spatial databases resulting in the automation of multiple health-specific neighbourhood metrics categorized as density, destination accessibility, street-level physical accessibility, food outlets accessibility, building class, greenness, terrain and neighbourhood deprivation. These exposure metrics have been subsequent linked back to the anonymized UK Biobank participant ids. Briefly, participant's dwelling addresses were first geocoded to the level of building footprints and dwelling neighbourhoods was defined within street network buffers centred on the geocoded locations in ArcGIS12 Network Analyst. Accurate data on building-level land uses and street networks were sourced from UK Ordnance Survey AddressBase Premium and MasterMap Integrated Transport Network databases. The UK-wide AddressBase Premium data of Ordnance Survey comprised approximately 36 million valid address point features with approximately 550 land use classifications. UKBUMP employed standard land-use classification scheme of the Ordnance Survey AddressBase Premium database and has land-use intensities of more than 200 health promoting/inhibiting land-use destinations within the defined dwelling neighbourhoods as well as measures of street distance to nearest, street network based measures of walkability. Residential greenness was modelled from a 0.50-metre color infrared imagery.

Residential greenness

Residential exposure to salutogenic green environment was measured with the help of Normalized Difference Vegetation Index (NDVI). The NDVI is an objective measure of overall salutogenic green exposure showing a strong correlation with expert's ratings in epidemiological research setting (Rhew et al. 2011) and has been employed in previous studies on links between green exposure and walkability (Sarkar et al. 2015b), physical activity (Almanza et al. 2012; Gong et al. 2014; McMorris et al. 2015) and adiposity (Bell et al. 2008; Pereira et al. 2013; Dadvand et al. 2014). It is a unit-less index of relative overall green vegetation or biomass derived from pixel values of spectral reflectance in remotely sensed data. The underlying principle employed in the NDVI calculation is that chlorophyll in healthy vegetation absorb radiation in the visible red region (630–690 nm) of the electromagnetic spectrum and reflect radiation in the near-infrared region (760–900 nm). This differential absorbance and reflectance wavelengths by chlorophyll is employed as a proxy for green quality and intensity, as illustrated by the following formulae:

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

where RED and NIR stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions of the electromagnetic spectrum. Index scores range between -1 to +1 with high negative values indicating water, those in the range 0-0.1 representing barren rock, sand or snow, 0.2-0.3 corresponding to shrub and grassland, while higher values indicating dense green vegetation.

A series of 0.50 cm by 0.50 cm resolution Colour Infrared (CIR) imagery collected by Bluesky through specially developed sensors mounted underneath a survey aircraft was employed in the present study. Summer-time images of the study areas collected over similar temporal scales (across the baseline phase of UK Biobank study) were employed to calculate mean NDVI values, thereby avoiding potential temporal mismatch and the resulting influence on account of seasonal variability in greenness. Large water bodies were excluded from the analyses. Residential greenness was measured as mean and standard deviation in the NDVI values within 500-metre catchment radius of geocoded UKB participants' dwellings. The criteria of 500-metre catchment for measuring residential green exposures in UKBUMP was informed by prior research piloted in Caerphilly (Sarkar et al. 2014; Sarkar et al. 2013b) and Greater London (Sarkar et al. 2015). Previously, approximately a quarter mile (400-500 metres) distance corresponding to 10-15 minutes travel time have been employed for measuring greenness (Villeneuve et al. 2012; Wolch et al. 2011; Gong et al. 2014).

Neighbourhood urban environment

The study adjusted for potential activity-influencing residential environment through variables derived from UKBUMP. Street-level neighbourhood walkability was modelled in terms of betweenness centrality or through-movement potential of the street segments. The method has been employed in active living research and described elsewhere (Sarkar et al. 2013a; Sarkar et al. 2015b). The street network data of the study areas comprising approximately 4 million street segments were extracted from the OS MasterMap Integrated Transport Network database, transcribed in to an access graph model and subjected to network analysis in sDNA (Chiaradia et al. 2012) to model the street-level walkability within an 800 metres street catchment of UKB participants' residence. It is expressed as the simulated counts of movement through each link in the network, given its relative position and the topological connectivity with other segments within the network. sDNA betweenness of x in a graph of N links may be defined as:

$$Bt\,Wl(x) = \sum_{y\varepsilon N}\sum_{z\varepsilon \boldsymbol{R}_{\boldsymbol{y}}} L(y)L(z)P(z)OD(y,z,x)$$

where:

y and z are the geodesic end points;

R_y is the set of links within a defined radius (800m in this case) from y;

L(y) and L(z) are length of links y and z respectively;

P_z is the proportion of link z within the defined radius

OD is a function defined as:

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

Density of retail outlets was sourced from expressed as the Ordnance Survey AddressBase Premium database and expressed as the number/Km^2 of outlets within 1 Km residential street catchment. Other density measures employed in the study included residential and public transport density within I Km street catchment.

Terrain was modelled from a 5-metre resolution Bluesky digital terrain model and expresses as variability (standard deviation) of slope in degrees within a 0.5 kilometer residential catchment.

Air pollution exposure

The study employed exposure to particulate matter as a proxy of traffic-related air pollution. Residential exposures to particulate matter ($PM_{2.5}$ and PM_{10}) was obtained from UK Biobank's linked air pollution exposure data. PM was monitored three times for 14 days, in the cold, warm and intermediate seasons of the year. Land use regression models were employed to estimate individual annual exposure to PM concentrations around residential addresses (Eeftens et al. 2012).

Covariates

Socio-demographic covariates comprised age in years, gender, ethnicity, education, and employment status. SES was assessed through census-based Townsend deprivation scores which is a composite index of four variables (household overcrowding, unemployment, non-home ownership and non-car ownership) with low values representing high SES status and linked to the postcode of residence of UK Biobank participants. Smoking status was included as three-factor lifestyle level variable. The models also adjusted for prevalence of two pre-existing comorbidities; namely doctor diagnosed vascular disease and diabetes.

2.5 Statistical analyses

A series of linear regression models were employed to examine the associations between residential greenness and BMI, WC and WBF. Poisson regression with robust estimator assessed the relative risk (RR) ratios for obesity in relation to residential greenness. Risk ratios provide a more accurate and unbiased estimation as compared to the odds ratios when the clinical outcome under investigation is common; i.e. a prevalence higher than 10% (Cummings 2009).

Both continuous and categorical NDVI models were developed. In the continuous models, the association between residential green exposures and adiposity were expressed in terms of an interquartile increment in NDVI index. NDVI was also categorized in to quartiles and used as a four-factor variable. Initial data quality checks performed on all predictor variables included assessment of multicollinearity and model fit to ensure a parsimonious fit. First set of models (Model 1) adjusted for potential confounding by age (coded as 38-50, 51-60 and 61-73 years), gender (coded as female; male), ethnicity (coded as British; others), education (five-factor variable coded as none; O levels/GCSEs/CSEs; A levels/AS levels; NVQ/HND/HNC/Other professional; and College or University degree), and employment (three-factor variable coded as employed; retired; and unemployed, home maker, others), smoking status (coded as non-smoker, previous smoker and current smoker), vascular disease (none;

high blood pressure; and heart attack/ angina/ stroke) and diabetes (yes versus no). Second set of models (Model 2) adjusted additionally for SES. Townsend scores were categorized in to quintiles and used as a 5-factor variable. Fully adjusted models (Model 3) further adjusted for built environment exposures (walkability, retail density and terrain variability) as well as air pollution exposures ($PM_{2.5}$ and PM_{10}). Walkability and retail density were categorized in to quartiles and employed as 4-factor variables.

As further sensitivity analyses, effect modification by gender, age, urbanicity and SES after adjusting for all other factors were examined. A composite index of urbanicity was developed from the UKBUMP built environment variables and expressed as:

$$Urbanicity = zscore_{resid} + zscore_{retail} + zscore_{PT} + zscore_{walkability}$$

where 'resid', 'retail' and 'PT' represent the density of residential housing units, retail and public transport in units per square kilometer street catchment, while 'walkability' is expressed in terms of street movement potential.

Post-hoc analyses further aimed to understand the behavioural mechanism behind the observed associations between residential greenness and adiposity. Logistic regression models explored the relationship between residential greenness and odds of using active travel mode and doing more than 30 minutes walking for physical activity, adjusting for all other factors.

Statistical analyses was performed with statistical software package Stata 11.4. Point estimates (β, risk ratio and odds ratio) and two-tailed 95% confidence intervals have been presented. Confidence intervals were estimated by bootstrapping except in Poisson regression where robust estimator was employed.

3. Results

The characteristics of eligible study population (N=333 183) have been presented in Table 1, while Supplementary Table 1 compared the characteristics of the full UK Biobank cohort and those included in the present study. The analytic sample remained representative of the UK Biobank cohort. Overall, the mean BMI, WC and WBF was 27.47 Kg/m^2 (SD=4.8 Kg/m^2), 90.35 cm (SD=13.4 cm) and 24.93 Kg (9.6 Kg) respectively, while 24.6% (N=82 024) of the participants were classified as obese.

21.3% of the participants used active transport mode for non-work travel trips and 46.3% did more than 30 minutes of walking. The study participants had a mean age of 56.5 years (SD=8.1 years), while 54.6% were female. Current smokers accounted for 10.3% of the participants, while 24.1%, 5.6% and 5.2% had high blood pressure, cardiac disease and diabetes respectively.

[Insert Table 1]

Table 2 summarizes the distribution of residential greenness and other built environmental exposure variables. The mean residential greenness expressed in terms of NDVI index was 0.16 (SD=0.17) with an interquartile range of 0.24. Pearson's correlation coefficients between residential greenness and built environment exposure measures ranged from 0.03 to 0.23. The variance inflation factors for all the association models were between 1.06 and 1.54 indicating a low level of collinearity.

[Insert Table 2]

Table 3 presents the characteristics of the analytic sample by distribution of residential greenness. The mean BMI in the first, second, third and fourth greenness quartiles were 27.62, 27.46, 27.38 and 27.40 Kg/m^2 respectively. The corresponding proportion of obese participants were 25.8%, 24.2%, 24.3% and 24.1% respectively.

[Insert Table 3]

Table 4 presents the results of regression models of association between residential green exposure and adiposity for N=333 183 participants with valid data across all variables. Residential greenness remained consistently significantly associated in all the three models (Model 1, 2, and 3) for BMI, WC, WBF and obesity with the beneficial effects of greenness being slightly strengthened across the minimally adjusted models (Model 1) to fully-adjusted models (Model 3). After adjusting for all other variables, an interquartile increment in NDVI greenness within a 500 metres catchment was associated with reduction of 0.123 Kg/m^2 (95% CI: -0.14, -0.10 Kg/m^2) in BMI, 0.551 cm (95% CI: -0.61, -0.50 cm) in WC, and 0.138 Kg in WBF (95% CI: -0.18, -0.10 Kg) as well as a lower relative risk of obesity (RR=0.968, 95% CI: 0.96, 0.98). The protective effects of greenness upon adiposity outcomes remained consistent in the categorical NDVI models (see Table 4).

[Insert Table 4]

Sub-group level analyses identified significant effect modification (p-value for interaction<0.01) by age, gender, degree of urbanicity and SES (measured as Townsend index quintiles) was observed between exposure to NDVI green and all the four markers of adiposity after adjusting for all other factors (presented in Figure 2).

[Insert Figure 2]

To test a physical activity-related mechanism, a set of models associating residential green exposure and travel behaviour were developed (Table 5). Valid data on non-work travel mode and duration of walking was available for a subset of 336 682 and 281 061 participants respectively. Subsequent to all adjustments, an interquartile increment in NDVI greenness within 500m dwelling catchment was significantly associated with higher odds of using active travel mode (OR=1.093, 95% CI: 1.08,1.11) for non-work trips and higher odds of doing more than 30 minutes walking (OR=1.039, 95% CI: 1.03,1.05). The results remained consistent in the categorical NDVI models.

[Insert Table 5]

Rerunning the models of adiposity and non-work travel with adjustments for duration of walk in minutes (as a marker of physical activity) slightly modified the regression point estimates and their corresponding confidence intervals (Supplementary Table 2). Restricting analyses to only employed participants and further adjusting for work travel mode attenuated the effects of residential green exposure (Supplementary Table 3).

Restricting analyses to a subset of healthy weight and overweight participants (N=251 159; by excluding obese participants) attenuated the beneficial effects of green exposures on weight outcomes pointing to the higher beneficial effects experienced by participants in the more vulnerable weight categories (obese as compared to overweight). An interquartile increment in NDVI greenness was associated with lower relative risk of being overweight (RR=0.990, 95% CI: 0.98,0.99).

4. Discussion

In a very large and diverse UK-wide sample of adult population, residential greenness was independently associated with adiposity. The study is to the best of knowledge the largest of its kind and residential greenness, built environment and PM exposures were objectively modelled within catchments of individual participant's dwelling addresses, enabling substantial statistical power to detect effects.

The study reported an overall decrement of 0.123 Kg/m^2, 0.551 cm and 0.138 Kg in BMI, WC and WBF respectively as well as a 3.2% lower risks of obesity accrued per interquartile increment in NDVI greenness. These corroborate findings from a few previous smaller scale studies on association between NDVI greenness and obesity (Bell et al. 2008; Pereira et al. 2013; Dadvand et al. 2014). This study focused on an UK-wide adult population sample (age spanning across 38-73 years with a mean of 56.5 years), given that this is a critical life stage for weight gain and development of obesity and related chronic disease. The results remained consistent across all the three markers of adiposity (BMI, WC and WBF) and remained robust subsequent to adjustments for SES, built environment and air pollution exposures. That the models remained sensitive to the inclusion of SES (Townsend's score) and wider built environment (terrain, retail, walkability, PM) underscores the necessity of a holistic approach that accounts for pertinent activity-influencing environmental exposures. The observed beneficial effects upon odds of using active travel mode for non-work trips and walking more than 30 minutes may point to a physical activity-related mechanism. These findings are consistent with prior studies largely small scale studies on the association between greenness and active travel; specifically walking (Sarkar et al. 2015b), cycling (Cole-Hunter et al. 2015) and physical activity (Almanza et al. 2012; Gong et al. 2014; McMorris et al. 2015).

Stratified models indicated differences in effects of green exposure across age-, gender-, urbanicity- and SES-subgroups. The gender differences in the association between green exposure and adiposity, especially the pronounced beneficial effects observed in female participants with respect to BMI, WBF and obesity outcomes correspond with previous reports and may be attributed to gender differences in perception, exposure and usage of green space within functional neighbourhoods (Roe et al. 2013; Astell-Burt et al. 2014a). However, in the case of waist circumference, the effects were more pronounced in male participants than female. The mean BMI and WBF was 27.1 Kg/m^2 (SD=5.2 Kg/m^2) and 27.0 Kg (SD=10.1 Kg) for female and 27.9 Kg/m^2 (SD=4.2 Kg/m^2) and 22.4 Kg (SD=8.2 Kg) respectively for male. The mean waist circumference was 97.1cm (SD=11.2 cm) for male and 84.8 cm (SD=12.5 cm) for female participants. That the beneficial effects of greenness were more pronounced and significant in the medium high and high quartiles of urbanicity points to their significant activity-promoting potential in high density city environments (Liu et al. 2007). Similarly, the beneficial effects of greenness were more pronounced in the higher quintiles of deprivation corresponding to lower SES groups. These point to the higher stress-releasing protective effects of residential greenness in deprived neighbourhoods and corroborate previous findings (de Vries et al., 2003; Mitchell and Popham, 2007, 2008). These results point to the need for more targeted policies for green space allocation and design that gives due credence spatial density profiles as well as the population-level characteristics of the residents.

4.1 Interpretation

The observed associations point to three potential underlying mechanisms; namely, physical, physiologic and psycho-social all corresponding to specific functional capacity of green. Firstly, a physical activity related mechanisms is plausible. Models of travel behaviour consistently indicated a significant beneficial association between residential green exposure and odds of using active transport for non-work trips as well as walking for more than 30 minutes. Any residential green space has an intrinsic activity-promoting potential associated with it. Natural forest and green spaces, parks, sports facilities and tree-lined streets may thus directly act as recreational and physical activity facilities with associated increments in physical activity accrued (Bedimo-Rung et al. 2005; Kaczynski and Henderson 2007; Björk et al. 2008; White et al. 2016). However, physical activity is not the only pathway linking green exposure and adiposity. Physiologically, the stress-releasing pathway is very important (Halonen et al. 2014). In an urban setting, residential green constitute therapeutic stress-releasing environments (Grahn and Stigsdotter 2003; Hartig et al. 2003). Reductions in stress levels associated with green exposures (Nielsen and Hansen 2007) and have been measured through biomarkers such as salivary cortisol, amylase (Ward Thompson et al. 2012; Beil and Hanes 2013) and telomere length (Woo et al. 2009). Such stress-releasing exposures promote healthy weight maintenance by facilitating active travel in the form of walking and exercise as well as recreation. Previously, studies have already established the positive associations between stress and weight gain (Block et al. 2009; Harding et al. 2014). Other physiologic benefits include better health outcomes including longevity (Takano et al. 2002), and cardio-metabolic health (Mitchell and Popham 2008; Pereira et al. 2012; Bodicoat et al. 2014). Lastly, the intangible salutogenic potential associated with a residential green may help constitute a better perception of residential environment. It can thus act as spaces for social interaction facilitating neighbourhood cohesion and sense of community (Kweon et al. 1998; Maas et al. 2009; Arnberger and Eder 2012; Kaźmierczak 2013) and improved mental health (Barton and Pretty 2010; Alcock et al. 2014; Astell-Burt et al. 2014b). All these factors together promote active travel and walking behaviour and corresponding increments in physical activity.

4.2 Strengths and limitations

The strengths of the study include high quality data of unprecedented size (>300k); geographical coverage and diversity; sub-group level analyses; application of objective measures of urban greenness; extensive adjustments for activity-influencing exposure metrics of built environment, air pollution and other confounding. The UK Biobank cohort health data underwent considerable central quality control. The NDVI index employed in the present study represent a highly characterized measure of residential green exposure. Conventional measures of urban green such park access derived from land use database are often coarse and fail to capture small scale variability in vegetation, private gardens and street trees. In contrast, the NDVI vegetation index not only constitutes a more objective measure of green exposure (both density and quality) but can also act as metrics capturing the intangible salutogenic potential of residential environment and therefore it’s influence on behaviour and weight outcomes. The NDVI index was generated from a multispectral Bluesky colour infrared imagery of 0.50-metre resolution captured during aerial photography with the Vexcel UltraCamD and the Leica ADS4 (having a spatial accuracy of 1 m). Such a precise data capture method implied that the study was able to overcome the limitations inherent in most prior studies using satellite remote sensing data, whose quality is often limited by low resolution (approximately 30 m resolution), cloud cover and atmospheric distortions (Sarkar et al. 2015b). Adjustments for activity-influencing built environment measured around individual residential catchments enhanced the reliability of the models. A highly detailed metrics of walkability expressed in terms of betweenness (through-movement potential) measured at the level of street network segments meant intuitive linkages urban morphology and design, walking and health could be practically established. Similarly, adjustments for a wide array of individual-level variables pertaining to socio-demographics, lifestyle and comorbidities ensured extensive adjustments for confounding. Most residential green – health studies tended to employ body mass index as the outcome measure with virtually no studies focusing on other biomarkers of body adiposity (distribution and mass), especially waist circumference and whole body fat. The present analyses employs a more holistic and objective definition of adiposity (Flegal et al. 2009) and the effects of residential green upon the three measures showed a near similar trend.

The study is however limited by its cross sectional design. Causal inferences can't be made with confidence. The role of geographic life environments and effects of cumulative exposures to green environment upon weight outcomes require further exploration. Neighbourhood self-selection may have influenced the reported results. Obese participants may have selectively migrated to greener areas leading to under-estimation of the effects of residential green on obesity prevalence. Nonetheless, the effects of migration were less likely as mean length of stay in the current dwelling address was 17.5 years indicating considerable degree of residential stability. It was similar for both non-obese (17.3 years) and obese (17.8 years) participants and addition of duration of stay in the models didn't produce any material effects upon the observed associations. Temporal mismatch is another issue associated with cross-sectional cohort studies when data are collected at different time points (Buzzelli and Su 2006). Adiposity measures and most of the individual-level confounders were assessed over the baseline phase of UK biobank (2006-2010) for the established cohort participants already residing in specific dwelling locations. The green exposure measures of

UKBUMP were modelled over the same period to avoid temporal mismatch as much as possible; however the study lacked detailed information on the dates of adiposity measurements at an individual participant-level to establish if the adiposity outcome measurements preceded or followed exposure measurements. Future investigations upon accumulated follow-up data of full UK Biobank cohort should focus on longitudinal analyses to isolate potential causal pathways. As prospective data gets accumulated over time, further studies focusing on natural experiments can be feasible through analyses of a sub-set of cohort participants moving to new addresses, thereby associating changes in adiposity with changes green exposures prior and subsequent to such moves. The use of self-reported data on travel mode and duration of walking is subject to individual bias. Future studies employing accelerometry sub-sample data from UK Biobank would enable a more objective method for quantifying walking and physical activity. Response bias may have affected the degree of generalizability of the observed association; the UK Biobank study could attain a response rate of 5.5%. Nonetheless, it doesn’t imply significant loss of generalizability of these findings, given the sufficiently large sample size, existing diversity in the sample characteristics as well as the heterogeneity of environmental exposures as discussed earlier (Collins 2012). Most of the built environment measures showed significant variability across space and population groups.

4.3 Conclusion

In conclusion, residential green exposure was beneficially associated with markers of adiposity in a cross sectional UK Biobank population sample of unprecedented size and diversity. Effect modification models identified underlying sensitivities in the associations to population characteristics, urbanicity and SES. With the rapid urban expansion, more research is needed to understand optimal parameters for green allocation and design (in terms of its design, size and distribution, connectivity characteristics) for it to act as upstream-level public health intervention ameliorating the negative health externalities of obesogenic urban environments. The effectiveness of such public health interventions will also entail an empirical understanding of specific causal pathways linking exposure to green, adiposity and health through further research based on a prospective data.

Ethics statement

UK Biobank has received ethical approvals from the North West Multi-centre Research Ethics Committee (MREC), the Community Health Index Advisory Group (CHIAG), the Patient Information Advisory Group (PIAG) and National Health Service National Research Ethics Service. Permission to use the UK Biobank resource for the research was approved by UK Biobank Access sub-committee (approved research application no. 11730).

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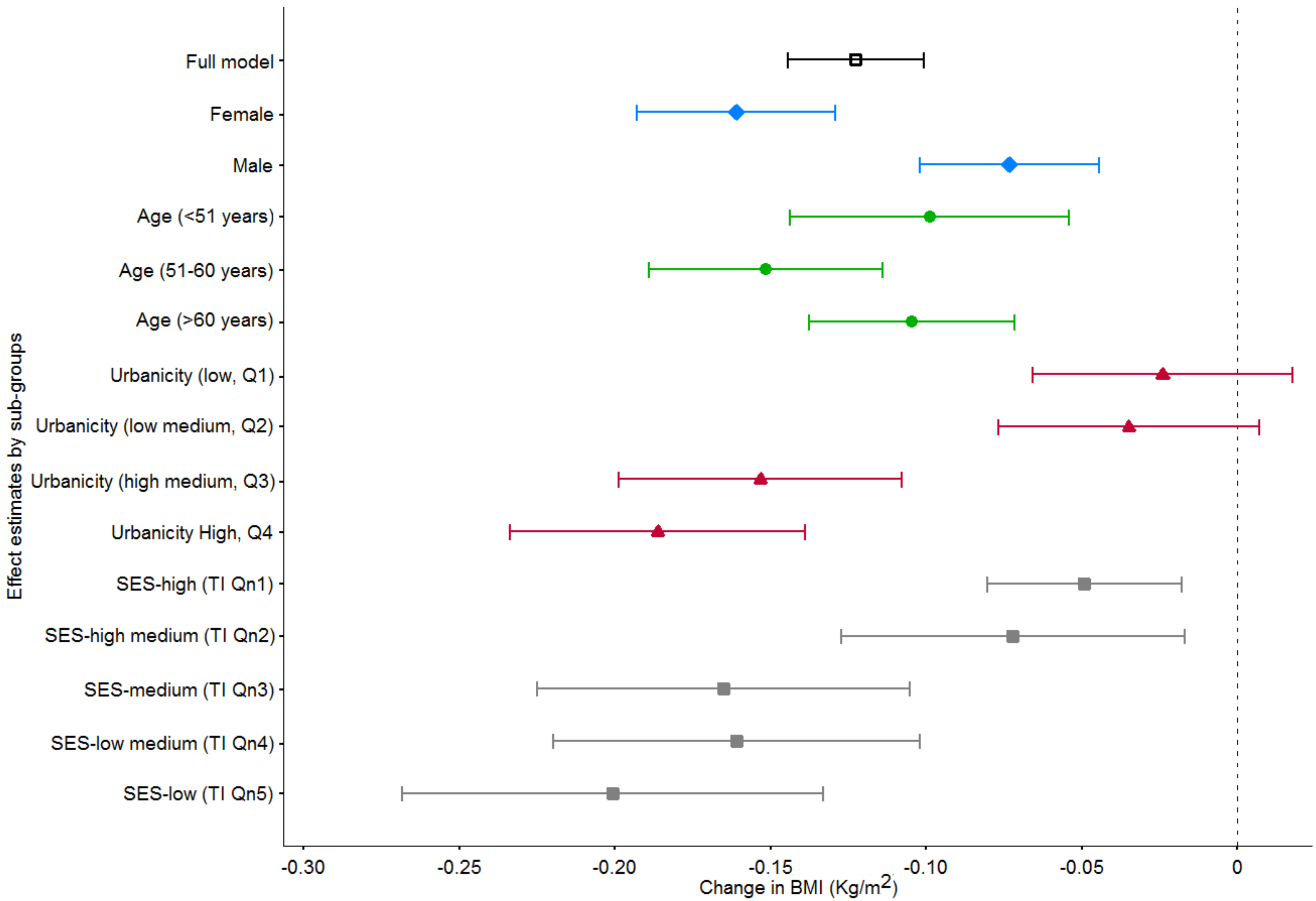
Figure 1. Location of UK Biobank collection centres with the number of participants.



Full model
Female
Male
Age (<51 years)
Age (51-60 years)
Age (>60 years)
Urbanicity (low, Q1)
Urbanicity (low medium, Q2)
Urbanicity (high medium, Q3)
Urbanicity High, Q4
SES-high (TI Qn1)
SES-high medium (TI Qn2)
SES-medium (TI Qn3)
SES-low medium (TI Qn4)
SES-low (TI Qn5)
Effect estimates by sub-groups
-0.30
-0.25
-0.20
-0.15
-0.10
-0.05
0
Change in BMI (Kg/m2)

Figure 2a

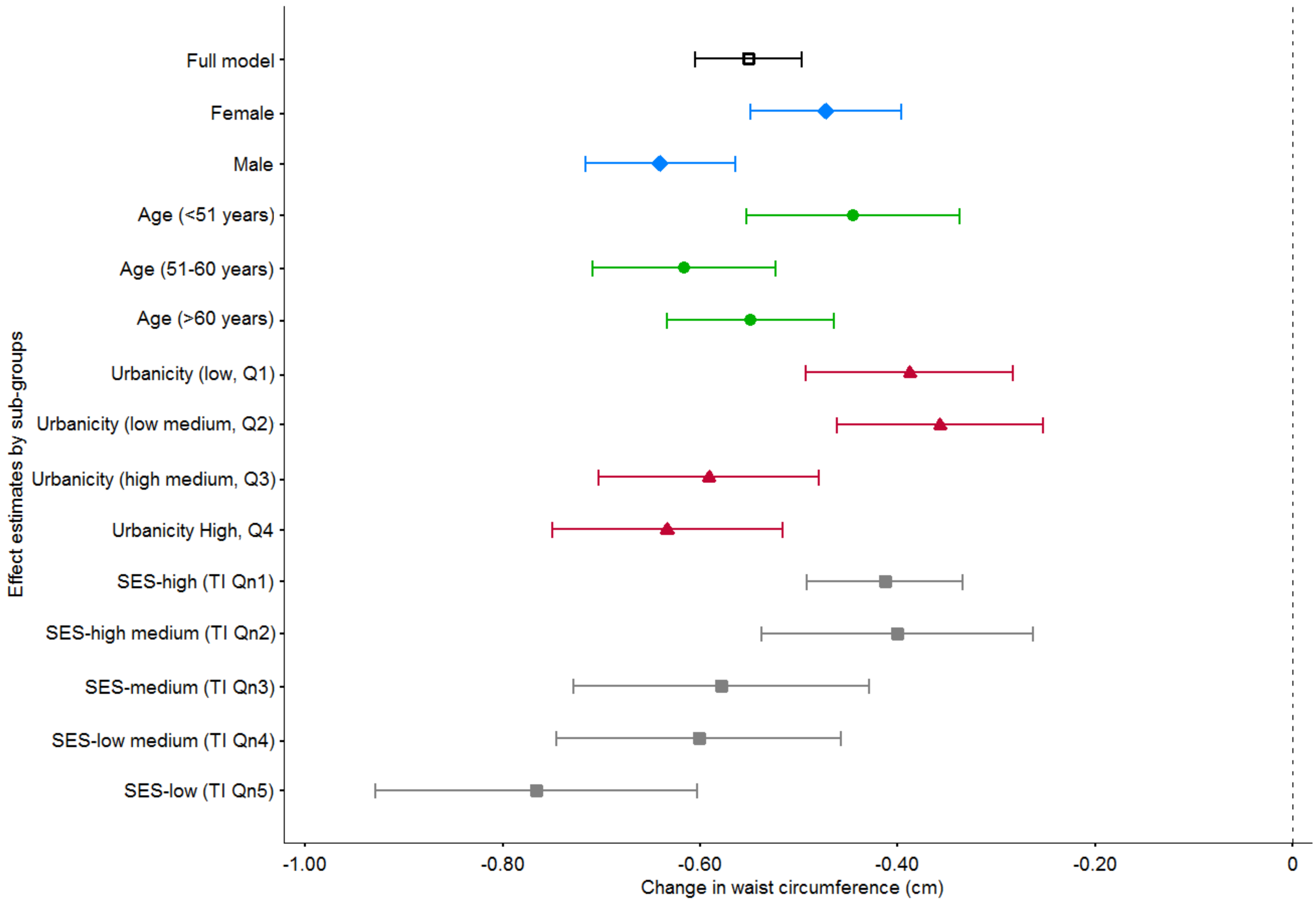

Full model
Female
Male
Age (<51 years)
Age (51-60 years)
Age (>60 years)
Urbanicity (low, Q1)
Urbanicity (low medium, Q2)
Urbanicity (high medium, Q3)
Urbanicity High, Q4
SES-high (TI Qn1)
SES-high medium (TI Qn2)
SES-medium (TI Qn3)
SES-low medium (TI Qn4)
SES-low (TI Qn5)
Effect estimates by sub-groups
-1.00
-0.80
-0.60
-0.40
-0.20
0
Change in waist circumference (cm)

Figure 2b

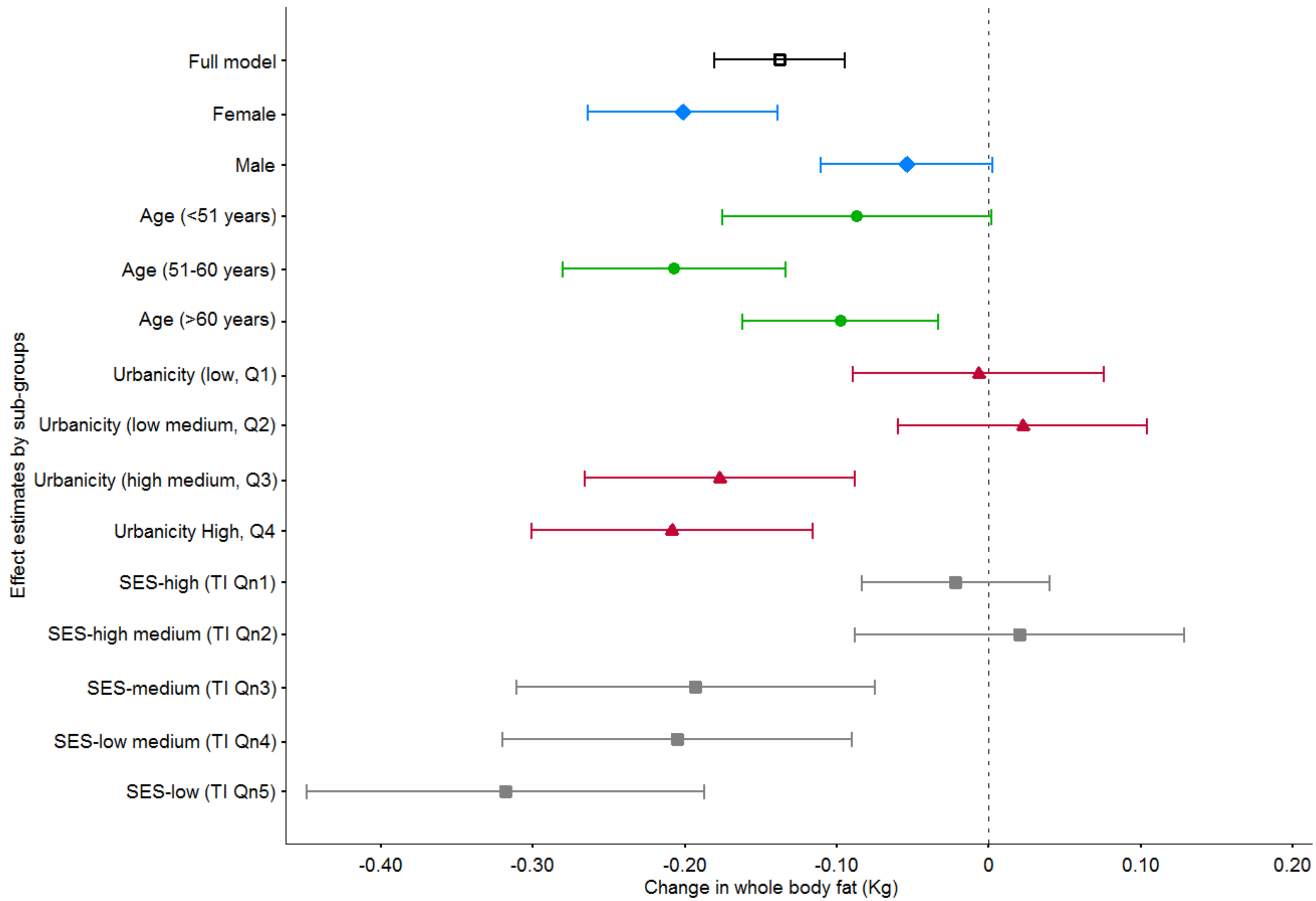
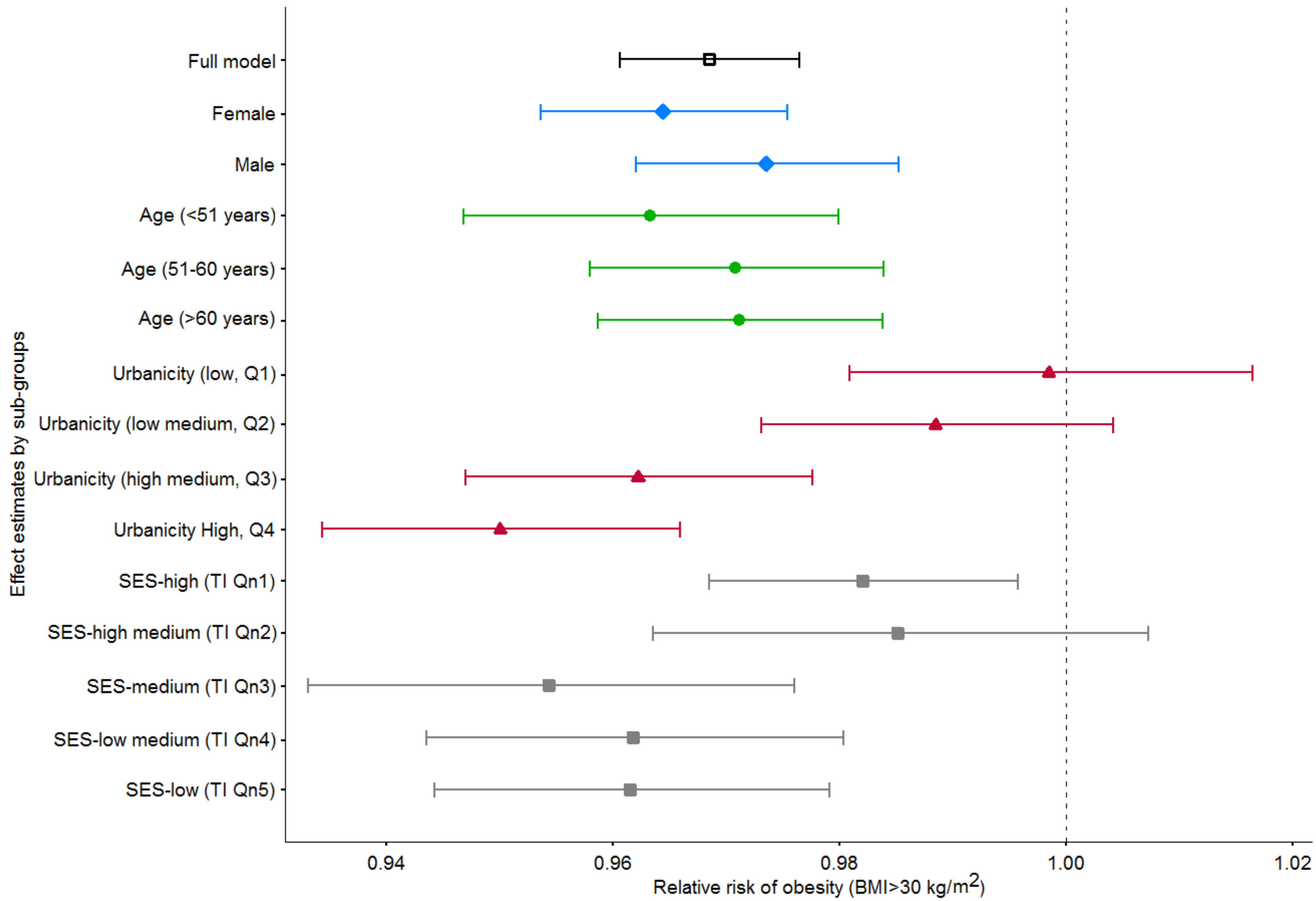

Full model
Female
Male
Age (<51 years)
Age (51-60 years)
Age (>60 years)
Urbanicity (low, Q1)
Urbanicity (low medium, Q2)
Urbanicity (high medium, Q3)
Urbanicity High, Q4
SES-high (TI Qn1)
SES-high medium (TI Qn2)
SES-medium (TI Qn3)
SES-low medium (TI Qn4)
SES-low (TI Qn5)
Effect estimates by sub-groups
-0.40
-0.30
-0.20
-0.10
0
0.10
0.20
Change in whole body fat (Kg)

Figure 2c



Full model
Female
Male
Age (<51 years)
Age (51-60 years)
Age (>60 years)
Urbanicity (low, Q1)
Urbanicity (low medium, Q2)
Urbanicity (high medium, Q3)
Urbanicity High, Q4
SES-high (TI Qn1)
SES-high medium (TI Qn2)
SES-medium (TI Qn3)
SES-low medium (TI Qn4)
SES-low (TI Qn5)
Effect estimates by sub-groups
0.94
0.96
0.98
1.00
1.02
Relative risk of obesity (BMI>30 kg/m2)

Figure 2d

Figure 2a-d. Association between residential green and adiposity; effect modification by gender, age, urbanicity and SES adjusting for all other factors.

Bars show 95% confidence intervals.

Q1, Q2, Q3 and Q4 represent 1st, 2nd, 3rd, 4th quartiles of index of urbanicity; Qn1, Qn2, Qn3, Qn4 and Qn5 represent 1st, 2nd, 3rd, 4th, 5th quintiles of Townsend Index (TI) respectively.

Tables

Table 1. Characteristics of UK Biobank participants (N=333 183).

Participant characteristics	Not obese (BMI<30 Kg/m^2)	Obese (BMI≥30 kg/m^2)	Overall
N	251 159	82 024	333 183
Mean (SD)			
BMI (Kg/m^2)	25.35 (2.6)	33.94 (3.9)	27.47 (4.8)
Waist circumference (cm)	85.57 (10.3)	105.0 (11.0)	90.35 (13.4)
Whole body fat mass (Kg)	21.12 (6.0)	36.57 (9.1)	24.93 (9.6)
Duration of walk (minutes)*	52.03 (48.5)	49.71 (48.7)	51.48 (48.5)
Age (years)	56.43 (8.2)	56.86 (7.9)	56.5 (8.1)
SES (Townsend index)	-1.47 (2.9)	-0.91 (3.2)	-1.33 (3.0)
N (%)			
Gender: Female	138 824 (55.3)	43 262 (52.7)	182 086 (54.6)
Male	112 335 (44.7)	38 762 (47.3)	151 097 (45.4)
Ethnicity: British	225 025 (89.6)	73 148 (89.2)	298 173 (89.5)
Others	26 134 (10.4)	8 876 (10.8)	35 010 (10.5)
Education: None	39 225 (15.6)	18 385 (22.4)	57 610 (17.3)
College or University degree	85 628 (34.1)	19 707 (24)	105 335 (31.6)
O levels/GCSEs/CSEs	69 287 (27.6)	24 277 (29.6)	93 564 (28.1)
A levels/AS levels	28 369 (11.3)	8 335 (10.2)	36 704 (11)
NVQ/HND/HNC/Other professional	28 650 (11.4)	11 320 (13.8)	39 970 (12)
Employment status: Employed	147 436 (58.7)	45 367 (55.3)	192 803 (57.9)
Retired	84 885 (33.8)	27 997 (34.1)	112 882 (33.9)
Unemployed, home maker, others	18 838 (7.5)	8 660 (10.6)	27 498 (8.2)
Smoking status: Nonsmoker	140 273 (55.8)	41 882 (51.1)	182 155 (54.7)
Previous smoker	84 303 (33.6)	32 461 (39.6)	116 764 (35)
Current smoker	26 583 (10.6)	7 681(9.4)	34 264 (10.3)
Non-work transport mode**:			
Walk/ cycle/ public transport	55 349 (21.8)	16 192 (19.6)	71 541 (21.3)
Car/ motor vehicle	198 756 (78.2)	66 385 (80.4)	265 141 (78.7)
Vascular problems: None	190 014 (75.7)	44 335 (54.1)	234 349 (70.3)
High blood pressure	49 684 (19.8)	30 436 (37.1)	80 120 (24.1)
Heart attack/ angina/ stroke	11 461 (4.6)	7 253 (8.8)	18 714 (5.6)
Diabetes: None	243 221 (96.8)	72 728 (88.7)	315 949 (94.8)
Yes	7 938 (3.2)	9 296 (11.3)	17 234 (5.2)

*N=281 061; **N= 336 682

Table 2. Summary of environmental exposure variables

Environmental exposure	Mean ± SD	Minimum	P25	P50	P75	Maximum
Residential greenness (mean NDVI, 500m)	0.16 ± 0.17	-0.26	0.04	0.17	0.28	0.70
Terrain variability (1 SD)	2.96 ± 1.62	0.14	1.74	2.71	3.85	15.05
Walkability (betweeness R800)	4.70×10^6 ± 5.59×10^6	5076.2	8.8×10^5	2.7×10^6	6.5×10^6	8.59×10^7
Density retail (units/Km^2)	46.89 ± 68.80	0	8.23	23.45	58.59	1752.07
Urbanicity	0.12 ± 2.94	-5.27	-1.76	-0.35	1.41	42.57
$PM_{2.5}$ ($\mu g.m^{-3}$)	10.05 ± 1.05	8.17	9.34	10.0	10.63	21.31
PM_{10} ($\mu g.m^{-3}$)	16.24 ± 1.87	11.78	15.27	16.04	17.02	31.39

P25, P50 and P75 represent the 25th, 50th and 75th percentiles.

Table 3. Characteristics of UK Biobank participants by residential green exposure (N=333 183).

Participant characteristics	Residential greenness (NDVI) distribution Q1	Q2	Q3	Q4
Mean (SD)				
BMI (Kg/m^2)	27.62 (4.8)	27.46 (4.7)	27.38 (4.8)	27.40 (4.7)
Waist circumference (cm)	90.86 (13.6)	90.37 (13.5)	90.35 (13.4)	89.82 (13.1)
Whole body fat mass (Kg)	25.05 (9.6)	24.95 (9.5)	24.91 (9.7)	24.80 (9.4)
Duration of walk (minutes)*	51.32 (48.7)	51.66 (48.9)	50.87 (48.0)	52.08 (48.6)
Age (years)	56.31 (8.1)	56.79 (8.0)	56.39 (8.2)	56.67 (8.1)
SES (Townsend index)	-1.48 (2.8)	-1.97 (2.6)	-0.99 (3.1)	-0.86 (3.2)
N (%)				
Gender: Female	45 791 (54.7)	45 439 (54.3)	45 185 (54.5)	45 671 (55.1)
Male	37 918 (45.3)	38 193 (45.7)	37 696 (45.5)	37 290 (44.9)
Ethnicity: British	76 845 (91.8)	77 409 (92.6)	70 389 (84.9)	73 530 (88.6)
Others	6 864 (8.2)	6 223 (7.4)	12 492 (15.1)	9 431 (11.4)
Education: None	15 576 (18.6)	14 405 (17.2)	13 438 (16.2)	14 191 (17.1)
College or University degree	24 483 (29.2)	24 629 (29.4)	28 537 (34.4)	27 686 (33.4)
O levels/GCSEs/CSEs	24 677 (29.5)	24 675 (29.5)	22 034 (26.6)	22 178 (26.7)
A levels/AS levels	8 909 (10.6)	9 599 (11.5)	9 260 (11.2)	8 936 (10.8)
NVQ/HND/HNC/Other professional	10 064 (12)	10 324 (12.3)	9 612 (11.6)	9 970 (12)
Employment status: Employed	49 096 (58.7)	47 746 (57.1)	48 895 (59)	47 066 (56.7)
Retired	27 822 (33.2)	29 596 (35.4)	26 877 (32.4)	28 587 (34.5)
Unemployed, home maker, others	6 791 (8.1)	6 290 (7.5)	7 109 (8.6)	7 308 (8.8)
Smoking status: Nonsmoker	44 995 (53.8)	46 178 (55.2)	45 260 (54.6)	45 722 (55.1)
Previous smoker	29 323 (35)	29 490 (35.3)	28 822 (34.8)	29 129 (35.1)
Current smoker	9 391 (11.2)	7 964 (9.5)	8 799 (10.6)	8 110 (9.8)
Non-work transport mode**:				
Walk/ cycle/ public transport	16 589 (19.6)	14 532 (17.2)	20 064 (24.0)	20 356 (24.2)
Car/ motor vehicle	67 854 (80.4)	70 069 (82.8)	63 587 (76.0)	63 631 (75.8)
Obesity: None	62 147 (74.2)	63 367 (75.8)	62 718 (75.7)	62 927 (75.9)
Yes	21 562 (25.8)	20 265 (24.2)	20 163 (24.3)	20 034 (24.1)
Vascular problems: None	58 646 (70.1)	59 010 (70.6)	58 386 (70.4)	58 307 (70.3)
High blood pressure	20 237 (24.2)	19 961 (23.9)	19 924 (24)	19 998 (24.1)
Heart attack/ angina/ stroke	4 826 (5.8)	4 661 (5.6)	4 571 (5.5)	4 656 (5.6)
Diabetes: None	79 402 (94.9)	79 389 (94.9)	78 314 (94.5)	78 844 (95)
Yes	4 307 (5.1)	4 243 (5.1)	4 567 (5.5)	4 117 (5)

*N=281 061; **N= 336 682

Table 4. Association between residential green exposure and adiposity for N=333 183 participants of UK Biobank with valid individual-level and built environment data.

Residential green (NDVI, 500 m catchment)	Body mass index (kg/m^2) β (95% CI)	Waist circumference (cm) β (95% CI)	Whole body fat (Kg) β (95% CI)	Obesity (BMI > kg/m^2) RR (95% CI)
Model 1[a]				
Mean greenness (per IQR)	-0.077 (-0.10,-0.06)*	-0.465 (-0.52,-0.41)*	-0.060 (-0.10,-0.02)**	0.981 (0.97,0.99)*
Mean greenness categories				
Low (Q1) – Ref				
Q2	-0.135 (-0.18,-0.09)*	-0.477 (-0.59,-0.37)*	-0.041 (-0.13,0.05)	0.953 (0.94,0.97)*
Q3	-0.183 (-0.23,-0.14)*	-0.404 (-0.51,-0.30)*	-0.004 (-0.09,0.08)	0.961 (0.95,0.98)*
High (Q4)	-0.159 (-0.20,-0.12)*	-0.893 (-1.00,-0.79)*	-0.172 (-0.26,-0.09)*	0.955 (0.94,0.97)*
Model 2[b]				
Mean greenness (per IQR)	-0.099 (-0.12,-0.08)*	-0.524 (-0.58,-0.47)*	-0.096 (-0.14,-0.05)*	0.974 (0.96,0.98)*
Mean greenness categories				
Low (Q1) – Ref				
Q2	-0.097 (-0.14,-0.05)*	-0.373 (-0.48,-0.26)*	0.020 (-0.07,0.11)	0.966 (0.95,0.98)*
Q3	-0.221 (-0.27,-0.18)*	-0.506 (-0.61,-0.40)*	-0.067 (-0.15,0.02)	0.949 (0.93,0.96)*
High (Q4)	-0.213 (-0.26,-0.17)*	-1.033 (-1.14,-0.93)*	-0.259 (-0.35,-0.17)*	0.939 (0.92,0.95)*
Model 3[c]				
Mean greenness (per IQR)	-0.123 (-0.14,-0.10)*	-0.551 (-0.61,-0.50)*	-0.138 (-0.18,-0.10)*	0.968 (0.96,0.98)*
Mean greenness categories				

Low (Q1) - Ref				
Q2	-0.109 (-0.15,-0.07)*	-0.385 (-0.50,-0.27)*	0.001 (-0.08,0.09)	0.964 (0.95,0.98)*
Q3	-0.232 (-0.28,-0.19)*	-0.527 (-0.64,-0.42)*	-0.083 (-0.17,0.00)	0.947 (0.93,0.96)*
High (Q4)	-0.252 (-0.30,-0.21)*	-1.074 (-1.19,-0.96)*	-0.332 (-0.42,-0.25)*	0.929 (0.91,0.94)*

[a] models adjusted for individual-level covariates (age, gender, ethnicity, education, employment, smoking status, doctor-diagnosed cerebrovascular disease status and diabetes status).
[b] models adjusted for individual-level covariates and SES.
[C] Models adjusted for individual-level covariates, SES and built environment exposures (retail density, street walkability, terrain, and PM_{10} and $PM_{2.5}$).
IQR: Interquartile range; Q1, Q2, Q3 and Q4: 1st, 2nd, 3rd, 4th quartiles of greenness respectively.
* p<0.001; ** p<0.01.

Table 5. Association between residential green exposure and travel behaviour

Residential green (NDVI, 500 m catchment)	Non-work travel mode; N=336 682 (walk, cycle or public transport) OR (95% CI)[a]	Walking for PA; N=281 061 (> 30 min/day) OR (95% CI)[a]
Mean greenness (per IQR)	1.093 (1.08,1.11)*	1.039 (1.03,1.05)
Mean greenness categories		
Low (Q1) - Ref		
Q2	1.023 (1.00,1.05)	1.019 (1.00,1.04)
Q3	1.164 (1.14,1.19)*	1.026 (1.00,1.05)**
High (Q4)	1.211 (1.18,1.24)*	1.075 (1.05,1.10)*

[a] Models adjusted for age, gender, ethnicity, education, employment, SES, smoking status, obesity status, doctor-diagnosed cerebrovascular disease status and diabetes status; retail density, street walkability, terrain, PM_{10} and $PM_{2.5}$.
IQR: Interquartile range; Q1, Q2, Q3 and Q4: 1st, 2nd, 3rd, 4th quartiles of greenness respectively.
* p<0.001; ** p<0.01.

Supplementary Tables

Supplementary Table 1. Demographic comparison of study analytic sample and UK Biobank full cohort.

Participant characteristics	Study analytic sample	Full UK Biobank Sample
N	333 183	502 649
	Mean (SD) or %	
BMI (Kg/m^2)	27.47 (4.8)	27.43 (4.8)
Waist circumference (cm)	90.35 (13.4)	90.31 (13.5)
Whole body fat mass (Kg)	24.93 (9.6)	24.86 (9.6)
Duration of walk (minutes)	51.4 (48.5)	51.0 (48.1)
Age (years)	56.5 (8.1)	56.53 (8.1)
SES (Townsend index)	-1.33 (3.0)	-1.29 (3.1)
Gender: Female	54.6	54.4
Male	45.4	45.6
Ethnicity: British	89.5	88.6
Others	10.5	11.4
Education: None	17.3	17.3
A levels/AS levels	11.0	11.2
NVQ/HND/HNC/Other professional	12.0	11.9
Employment status: Employed	57.9	57.8
Retired	33.9	33.6
Unemployed, home maker, others	8.2	8.6
Smoking status: Nonsmoker	54.7	54.8
Previous smoker	35	34.6
Current smoker	10.3	10.6
Non-work transport mode: Walk/ cycle/ public transport	21.3	21.8
Car/ motor vehicle	78.7	78.2
Vascular problems: None	70.3	70.2
High blood pressure	24.1	24.0
Heart attack/ angina/ stroke	5.6	5.8
Diabetes: None	94.8	94.7
Yes	5.2	5.3

Supplementary Table 2. Association between residential green exposure, adiposity and odds of active non-work travel among participants of UK Biobank after adjusting for duration of walk (in minutes).

Residential green (NDVI, 500 m catchment) N	Body mass index (kg/m^2) 276 895 β (95% CI)	Waist circumference (cm) 276 895 β (95% CI)	Whole body fat (Kg) 276 895 β (95% CI)	Obesity (BMI > kg/m^2) 276 895 RR (95% CI)	Non-work travel mode (walk, cycle or public transport)† 280 523 OR (95% CI)
Mean greenness (per IQR)	-0.115 (-0.14,-0.09)*	-0.521 (-0.58,-0.46)*	-0.120 (-0.16,-0.07)*	0.967 (0.96,0.98)*	1.089 (1.07,1.10)*
Mean greenness categories					
Low (Q1) - Ref					
Q2	-0.091 (-0.14,-0.04)*	-0.328 (-0.45,-0.21)*	0.025 (-0.07,0.12)	0.969 (0.95,0.99)*	1.019 (0.99,1.05)
Q3	-0.210 (-0.26,-0.16)*	-0.463 (-0.58,-0.34)*	-0.053 (-0.15,0.04)	0.946 (0.93,0.96)*	1.161 (1.13,1.19)*
High (Q4)	-0.243 (-0.29,-0.19)*	-1.021 (-1.14,-0.91)*	-0.308 (-0.40,-0.22)*	0.926 (0.91,0.94)*	1.202 (1.17,1.24)*

Models adjusted for age, gender, ethnicity, education, employment, SES, minutes walked, smoking status, doctor-diagnosed cerebrovascular disease status and diabetes status; retail density, street walkability, terrain, PM_{10} and $PM_{2.5}$.
† Additionally adjusted for obesity.
IQR: Interquartile range; Q1, Q2, Q3 and Q4: 1st, 2nd, 3rd, 4th quartiles of greenness respectively.
* p<0.001; ** p<0.01.

Supplementary Table 3. Association between residential green exposure, adiposity and odds of active non-work travel among participants of UK Biobank after adjusting for work travel mode.

Residential green (NDVI, 500 m catchment) N	Body mass index (kg/m^2) 148 133 β (95% CI)	Waist circumference (cm) 148 133 β (95% CI)	Whole body fat (Kg) 148 133 β (95% CI)	Obesity (BMI > kg/m^2) 148 133 RR (95% CI)	Non-work travel mode (walk, cycle or public transport)† 149 597 OR (95% CI)
Mean greenness (per IQR)	-0.096 (-0.13,-0.06)*	-0.480 (-0.56,-0.40)*	-0.087 (-0.15,-0.02)**	0.974 (0.96,0.99)*	1.053 (1.03,1.08)*
Mean greenness categories					
Low (Q1) - Ref					
Q2	-0.089 (-0.15,-0.03)**	-0.354 (-0.52,-0.19)*	0.011 (-0.11,0.13)	0.980 (0.95,1.01)	1.000 (0.96,1.04)
Q3	-0.189 (-0.25,-0.12)*	-0.481 (-0.64,-0.32)*	-0.011 (-0.14,0.12)	0.960 (0.94,0.99)*	1.037 (0.99,1.08)
High (Q4)	-0.199 (-0.27,-0.13)*	-0.935 (-1.10,-0.77)*	-0.248 (-0.37,-0.12)*	0.941 (0.92,0.97)*	1.122 (1.07,1.17)*

Models adjusted for age, gender, ethnicity, education, employment, SES, work travel mode, minutes walked, smoking status, doctor-diagnosed cerebrovascular disease status and diabetes status; retail density, street walkability, terrain, PM_{10} and $PM_{2.5}$.
† Additionally adjusted for obesity.
IQR: Interquartile range; Q1, Q2, Q3 and Q4: 1st, 2nd, 3rd, 4th quartiles of greenness respectively.
* p<0.001; ** p<0.01.