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1 Abstract

2 Background: One cause of childhood obesity is a reduction in the amount of unstructured
3 time spent outdoors, resulting in less physical activity. Greenspaces have the potential to
4 increase children's physical activity levels, so it is desirable to understand how to create
5 spaces that promote visitation and activity.

6 Objectives: We investigate the relationship between rates of obesity at ages 4-5 and 10-11
7 in small-area census geographies, and indicators of the neighbourhood greenspace
8 environment, in the northern English city of Sheffield.

9 Methods: To capture the environment at scales relevant to children, we test the importance
10 of overall green cover; garden size; tree density around residential addresses; and
11 accessibility within 300m of any greenspace, greenspaces that meet quality criteria, and
12 greenspaces with play facilities. We use a multi-model inference approach to improve
13 robustness.

14 Results: The density of trees around addresses is significant at both ages, indicating the
15 importance of the greenspace environment in the immediate vicinity of houses. For 10-11
16 year olds, accessibility of greenspaces meeting quality criteria is also significant, highlighting
17 that the wider environment becomes important with age and independence.

18 Conclusions: More attention should be given to children's requirements of greenspace when
19 considering interventions to increase physical activity or planning new residential areas.

20 Keywords

21 childhood obesity; urban greenspace; neighbourhood environment; greenspace
22 accessibility; Sheffield, UK; health inequalities

23 1. Introduction

24 Childhood obesity is a major global public health concern affecting over 40 million children
25 worldwide ^{1,2}. In the UK in 2014/15, 22% were overweight by school entry age (4-5 years),
26 rising to 33% by age 10-11 ¹. Children who are overweight or obese are more likely to suffer
27 from overweight and obesity as adults, and to suffer physical and psychological ill-health
28 and a reduced quality of life both in childhood and as adults ^{2,3}.

29 The causes of this obesity epidemic are varied and complex, but many are determined early
30 in life, before the age of five. The earliest risk factors arise in the parents before conception,
31 for example from parental body mass index (BMI) and diabetes status ^{2,4,5}. Maternal
32 smoking, exposure to environmental pollutions, excess weight gain during gestation, and
33 method of delivery, are also important risk factors ^{1,2,5}. Infancy is a critical time in the
34 development of risk factors for obesity: both metabolic functioning and behavioural habits
35 are set and modified most easily at this age ^{1,2,4}. Dietary factors – breastfeeding vs. formula
36 feeding, age at introduction of solid foods, and food choices – are important, but so are
37 parenting styles and quality of relationships with parents, physical activity, sleep, and use of
38 antibiotics ¹⁻⁵. As the child ages, exposure to easy availability and marketing of high-energy

39 foods also becomes a concern ^{1,3}. Stressful events in childhood may also increase the risk of
40 obesity ⁶. Some of these risk factors are more modifiable than others.

41 One of the wider behavioural factors that has been linked with obesity is a lack of
42 unstructured time spent outdoors and in nature, leading to what has been termed “nature
43 deficit disorder” ^{7,8}. Children use free, unstructured time to play, which contributes to
44 creative and social development and emotional health as well as to physical health via
45 physical activity ⁸. However, there have been recent decreases in outdoor unstructured play
46 time accompanied by increases in indoor, sedentary activities ^{2-4,6}. There are a number of
47 reasons for this decrease, including a perceived lack of safety outdoors, a lack of parental
48 time to supervise outdoor activity, and the absence of suitable and age-appropriate spaces
49 ^{3,9}.

50 In this study, we focus on factors relating to the green aspects of the urban environment
51 and relate these to incidence rates of childhood obesity. A number of studies have reported
52 associations between the amount of greenspace near children’s houses, or distance to a
53 greenspace, and obesity rates ¹⁰⁻¹². However, not all greenspace has the same capacity to
54 contribute to health and well-being ^{13,14}. Children have requirements of greenspace that are
55 different to those of adults, and these requirements vary by age and gender ^{15,16}.

56 One of the key interventions to prevent childhood obesity is encouraging higher levels of
57 physical activity ⁴. Given the potential of greenspaces to increase physical activity levels
58 amongst children ^{4,8}, it is important to understand which aspects of the neighbourhood
59 greenspace environment contribute most. In addition to reducing obesity risk via promoting
60 physical activity, providing a suitable greenspace environment for children may benefit their
61 health via stress reduction and other emotional benefits ^{7,8}, which may also reduce obesity
62 risk ⁶. There is therefore a need for population-level studies of associations between
63 detailed indicators of the greenspace environment and obesity rates. Children generally
64 experience a relatively limited spatial area on a day-to-day basis due to parental limits on
65 independent travel, although this area may increase with age as the child’s level of
66 independence increases ^{9,17,18}. For this reason, indicators of the greenspace environment
67 should focus on the areas closest to homes.

68 The aim of this study is to examine associations between small-area population rates of
69 childhood obesity and several specific indicators of the local greenspace environment. Our
70 data are captured at Lower-layer Super Output Areas (LSOA), a census geography used for
71 reporting small area statistics. LSOAs have an average population of 1600, with an average
72 of approximately 14-17 children per school year group. LSOAs are commonly used in
73 research into relationships between health and greenspace ^{14,19}. They provide a suitable
74 scale for investigating spatial patterns within cities while having an adequate population to
75 reduce the risk of random statistical fluctuations and preserve anonymity for most types of
76 health data. Sheffield’s 345 LSOAs have an average area of 107ha; if they were circular, this
77 would correspond to a radius of 329m. Whilst examining at the level of the individual would
78 be preferable to avoid the potential issues of ecological studies, due to confidentiality
79 concerns individual-level data pertaining to childhood obesity across an entire city are not

80 usually available. We have obtained data at this relatively low level of aggregation through
81 partnership with Sheffield City Council.

82 2. Methods

83 2.1. Study area

84 Sheffield is an ex-industrial northern English city located near the Peak District (53°23'N,
85 1°28'W). The city covers an area of 368km² and had a population in 2011 of 552,000. There
86 is a substantial area of moorland and agricultural land within the western half of the city:
87 only 50% of Sheffield's land area is classified as urban, although 98% of the population lives
88 in these areas. Within the urbanised area, there is a strong west-east gradient of income
89 and health deprivation. This has existed since the Victorian era, when the east end was
90 heavily industrialised and housed working class neighbourhoods, while wealthier citizens
91 lived in the cleaner west ²⁰.

92 2.2. Obesity data

93 Our obesity data were supplied by Sheffield City Council. The data are LSOA counts of
94 childhood overweight (BMI \geq 85th centile of the British 1990 growth reference, UK90 ²¹,
95 according to age and sex) and very overweight (BMI \geq 95th centile; together termed
96 obesity) for children in the first and final years of primary school, i.e. Reception year
97 (abbreviated to YR, age 4-5) and Year Six (Y6; age 10-11). The data, collected as part of the
98 National Child Measurement Programme, relate to the years 2013-2017 (aggregated to
99 provide sufficient numbers for robust analysis). Children attending all state-run schools
100 were included, excluding those not consenting or withdrawn by parents and children with
101 growth disorders or Down syndrome. Weight was assessed using Class III scales, and height
102 using a stand-on height measure, by staff trained by a medical professional. Children were
103 asked to remove shoes and wear normal, light indoor clothing ²². Table 1 shows details of
104 population size and composition, deprivation levels and ethnicity for LSOAs divided into
105 tertiles of obesity. Maps of obesity rates are shown in the Supplementary Material, Figure
106 S1.

107 2.3. Greenspace variables

108 We use six greenspace indicators, selected on the basis of theory or previous studies
109 suggesting an association with health, and also on the availability of suitable data.

110 Green cover, our simplest and broadest indicator of LSOA greenspace is green cover,
111 quantifies the percentage of the LSOA that is under natural land covers (excluding that in
112 private domestic gardens, which is captured separately). This follows other studies that have
113 found a broad measure of local greenness to be important for childhood obesity ¹⁰⁻¹². This
114 variable was derived from Ordnance Survey (OS) MasterMap (November 2017 issue), which
115 maps all physical features in the environment that are considered to be important in the
116 landscape. The indicator is the percentage of the LSOA under natural land covers, including
117 water but excluding domestic gardens.

118 Garden size, our second indicator, is the mean size of private gardens averaged across
119 residential properties within LSOAs, measured in m². Previous work has found that the

120 availability of gardens is related to childhood obesity¹¹. Moreover, a substantial proportion
121 of children's physical activity takes place in private gardens²³. Gardens were identified from
122 OS MasterMap. The total area of these within LSOAs was divided by the number of
123 residential addresses, identified from OS AddressBase Plus (December 2017 data).

124 Tree density around homes is our third indicator. Studies have shown that trees in the local
125 environment have positive effects on children's BMI/rates of obesity by promoting physical
126 activity. In Houston, Texas, 9- to 11-year-old Hispanic children living in areas with more trees
127 and larger areas of trees had lower BMI and a higher health-related quality of life²⁴.
128 Similarly, greater street tree density has been associated with lower obesity rates amongst
129 3- to 5-year-old children in New York City²⁵. We measured tree density around individual
130 residential addresses and then averaged across LSOAs. We used Bluesky's National Tree
131 Map, which maps trees and shrubs over 3m in height. We calculated the density of trees
132 within 100m of each address in GIS by creating a raster of the number of trees within a
133 100m circular radius of each 5m grid cell, and extracting the value of this raster at each
134 address point. The radius of 100m was used as humans can readily grasp the scene around
135 them at this scale²⁶, and 5m grid cells were used as the smallest houses in the study area
136 are approximately 5m². We also tested 50m and 200m radii and these were strongly
137 correlated with values at 100m (Pearson's $r = 0.98$ and 0.97 respectively). Using 50m made
138 no qualitative difference to model results but using 200m resulted in a poorer model fit due
139 to failure to capture adequately fine scale variation.

140 The final three indicators relate to the accessibility of greenspaces from residential
141 properties. Public greenspace accessibility is assessed as the proportion of addresses that
142 are within 300m of at least one publicly accessible greenspace. 300m equates to
143 approximately a five minute walk; this is the distance recommended by a recent literature
144 review²⁷ and is also similar to the distances that most parents will allow children to travel
145 independently^{17,18}. This indicator is also measured at the level of individual addresses and
146 averaged across LSOAs. This variable is the proportion of residential addresses that are
147 within 300m by the transport network of an access point to a greenspace that is considered
148 to have recreational or leisure value. Data on these 936 greenspaces were obtained from
149 Sheffield City Council's 2008 green and open space assessment, and includes sports pitches,
150 parks and gardens, (semi-)natural greenspaces, cemeteries/churchyards, allotments and
151 community gardens, children's play facilities, and amenity greenspaces such as central
152 greens in residential areas. However, it does not include rural open space. Full details of the
153 calculation of all three accessibility measures are given in Mears et al.²⁰.

154 Good public greenspace accessibility is a similar measure that includes only greenspaces
155 meeting three quality-related criteria that increase the likelihood of contributing to health
156 ²⁰: size of at least 2ha, having a predominantly natural feeling, and received a 'good' or
157 better quality rating in the 2008 assessment. These criteria indicate the ability of
158 greenspaces to convey health benefits and also correlate with how well greenspaces are
159 actually used²⁰.

160 Public greenspace with provision for children and young people accessibility, hereafter
161 shortened to play facility accessibility, is the final accessibility measure. This is calculated

162 using the same method as the previous two indicators, but includes only green and open
163 spaces designed at least partly for children and young people's play and social interaction,
164 as identified from the 2008 assessment. Such facilities, including playgrounds, games areas,
165 and skate or bike parks, can increase visitation rates and physical activity levels amongst
166 these age groups ^{15,16}.

167 Descriptive statistics for the greenspace variables are shown in Table 2. None of the
168 greenspace variables were highly correlated (maximum absolute Spearman's $\rho = 0.48$),
169 although garden size was strongly correlated with some controlling variables, especially
170 address density ($\rho = -0.92$). The full correlation matrix is shown in the Supplementary
171 Material, Table S1.

172 2.4. Controlling variables

173 In order to minimise confounding in our models, we included two socioeconomic factors
174 (income deprivation and air pollution) that influence health of children and are likely to
175 correlate with aspects of the greenspace environment, and which have been included in
176 other analyses of relationships between greenspace and health ^{13,19,28}. We also added an
177 indicator of urbanicity (address density) following observations that the results of earlier
178 versions of the model were confounded with levels of urbanisation. Descriptive statistics of
179 controlling variables are shown in Table 2. The controlling variables are also shown in the
180 correlation matrix in Table S1.

181 Income deprivation is used to control for socioeconomic deprivation. For this variable we
182 used the income deprivation domain of the English Indices of Deprivation 2015, which is
183 based on the number of individuals receiving various forms of state support. Note that this
184 domain was used instead of the Index of Multiple Deprivation as it also includes a health
185 domain, and so is likely to be confounded with obesity. We also did not use the income
186 deprivation affecting children index as this has only been calculated at two time points, so
187 its longer-term stability is less clear.

188 Air pollution is controlled for using the proxy variable of average modelled PM₁₀
189 concentrations for 2010. These were derived from the Department for Environment, Food
190 and Rural Affairs 1km grid model, with LSOA values calculated using unit postcode level
191 population weighted averages.

192 Address density is the average density of residential addresses within 100m of each
193 residential address. This was calculated using the same method used for tree density
194 (Section 2.3) but using residential address points (from OS AddressBase Plus) instead of
195 trees. Other distances (50m and 200m) were again highly correlated (Pearson's $r \geq 0.97$)
196 and their use did not result in substantially different model results.

197 2.5. Statistical modelling

198 One LSOA, which contains mostly student housing and has the highest address density but
199 lowest income deprivation of all LSOAs, was excluded from analysis due to exerting a large
200 influence on results. This left a sample size of 344. Following similar work by other authors
201 ¹⁹, we used negative binomial regression to model the effects of the greenspace and
202 controlling variables on obesity rates at YR and Y6. Poisson regression was rejected due to

203 overdispersion. Expected rates of obesity, calculated using indirect standardisation for sex
204 distribution, were included in models as an offset term (a term with an assumed coefficient
205 of 1).

206 Given the large number of predictor variables, we used a multi-model inference approach
207 following Symonds & Moussalli²⁹ and Richards et al.³⁰ to reduce the risk of overfitting. We
208 first constructed a base model including only the offset term and linear terms for the
209 controlling variables. We then tested all possible combinations of greenspace variables
210 (linear and quadratic terms) plus quadratic terms for the controlling variables, following
211 marginality rules (i.e. quadratic terms only included where linear terms are present).
212 Quadratic terms were included because, although we hypothesised that each of the
213 included variables would influence obesity rates, we did not have specific hypotheses for
214 the shapes of the relationships. The multi-model inference approach facilitated inclusion of
215 the quadratic terms where there was evidence from AICc (Akaike Information Criterion
216 corrected for small sample size) values for curvilinear relationships, while preventing
217 overfitting where evidence was lacking.

218 Orthogonal transformation was used to aid stability and ensure that the significance of
219 linear and quadratic terms was independent. Due to the difficulty of interpreting
220 coefficients from orthogonally transformed data (as they are not on 'real' scales), to aid
221 interpretation we used coefficients from a version of the averaged model using
222 untransformed data to draw plots of the marginal effects of each greenspace and
223 controlling variable. Both averaged models used the same plausible set of models; data
224 (non)transformation was the only difference. It should be noted that fitted values are
225 identical regardless of whether untransformed or orthogonally transformed data are used.

226 From this full set of possible models we constructed a plausible subset of models within six
227 AICc units of the model with the lowest AICc score, and excluding models that were more
228 complex versions of models with a lower AICc score. Finally, the plausible set was averaged,
229 imputing zero for coefficients not appearing in individual models in order to prevent
230 inflation of relatively unimportant variables that appear in few models. As a simple indicator
231 of model fit, we show the range of Nagelkerke's pseudo-R² for the models comprising the
232 plausible set. (There is no accepted way to calculate a pseudo-R² for averaged models at
233 present.)

234 Variance inflation factors (VIFs) were used to check for potential influence of
235 multicollinearity on model results. Garden size and address density were found to have VIFs
236 greater than 5, due to their high correlation ($\rho = -0.92$; Table S1). We therefore re-ran
237 models excluding garden size (all VIFs < 3). The results of the averaged models were very
238 similar to those of the models including garden size (results not shown), so we do not
239 consider collinearity to have influenced our results.

240 3. Results

241 The results of the averaged plausible set models (using orthogonally transformed data) are
242 shown in Table 3. The marginal effects of each variable are plotted in Figure 1. These plots
243 indicate the shape of the relationships between individual variables and obesity, and for

244 interpretability are constructed from coefficients of averaged models using untransformed
245 data; the results of the model using untransformed data are shown in the Supplementary
246 Material, Table S2. When interpreting the marginal effects plots it is important to note the
247 variable's distribution; this is indicated in the box-and-whisker plots below each plot.

248 3.1. Reception Year obesity

249 The averaged model fits the data well, with models in the plausible set having pseudo-R²
250 values between 0.79 and 0.81. Only two greenspace variables appear in the final model for
251 YR: tree density, which is highly statistically significant, with an association between higher
252 densities of trees and lower rates of obesity; and play facility accessibility, which is not
253 significant.

254 All three controlling variables are significant. Greater income deprivation, high levels of air
255 pollution and lower address density are associated with higher rates of obesity. Income
256 deprivation shows a curvilinear relationship: when income deprivation is low, increases are
257 associated with increasing obesity rates; but when income deprivation is already high,
258 further increases appear to be associated with lower obesity rates. However, across the
259 numerical range where most of the data points lie, the relationship is positive (greater
260 income deprivation = higher obesity rates), and given the small number of data points with
261 very high deprivation levels the relationship in reality likely slows or saturates, i.e. further
262 increases in deprivation are not related to obesity rates.

263 3.2. Year Six obesity

264 There is again a good fit between the models in the plausible set and the observed data
265 (pseudo-R² = 0.87 for all models). Tree density is again statistically significant, with lower
266 densities associated with higher rates of obesity. However, in this case the relationship is
267 curvilinear. While increases in tree density are associated with lower obesity rates across
268 the range where most of the data points lie, this saturates at low densities, i.e. further
269 reductions in density are not associated with changes in obesity rates. Good greenspace
270 accessibility is also significant, with better accessibility linearly associated with lower rates
271 of obesity. Any greenspace accessibility, garden size and green cover appear in the plausible
272 set, but do not approach statistical significance.

273 Greater income deprivation and lower address density are also associated with higher rates
274 of obesity, showing similar relationships to those at YR. Air pollution is also approaching
275 significance ($p = 0.061$). Income deprivation and air pollution show curvilinear relationships
276 that saturate at the high ends of the numerical ranges, i.e. when income deprivation or air
277 pollution is already high, further increases are not associated with changes in obesity rates.

278 4. Discussion

279 4.1. Associations between greenspace and childhood obesity

280 Our analysis found more and stronger relationships between controlling variables and
281 obesity rates than between greenspace variables and obesity rates. The relationship with
282 income deprivation is particularly strong. This is not surprising, as it is well known to have a
283 large effect on population level health³¹. A number of other studies have found positive

284 relationships between socioeconomic deprivation and childhood obesity in England and
285 elsewhere^{32–35}. Many of these studies found increasing obesity inequalities with deprivation
286 with increasing age^{33–35}. There are suggestions in our data that this is also the case in
287 Sheffield: the marginal effect of income deprivation is greater across the range of
288 deprivation where most LSOAs lie at Y6 than at YR (Figure 1h), and the differences in mean
289 deprivation levels between LSOAs with the lowest and highest obesity rates are also greater
290 at Y6 (Table 1).

291 Our measure of urbanicity is also significant at both ages, with lower rates of obesity at
292 higher address densities even after accounting for income deprivation levels. The same
293 relationship between childhood obesity and urbanicity has also been found in a study from
294 Australia³², as well as between population obesity and urbanicity in Montreal and the
295 United States^{36,37}. The direction of this relationship may arise from greater connectivity of
296 destinations for children in more densely urbanised areas (e.g. friends' houses, parks)
297 leading to higher levels of physical activity. Such neighbourhoods can also promote walking
298 and cycling, with additional health benefits³⁸.

299 Air pollution is significantly associated with obesity rates at YR. The association is almost
300 significant at Y6; the slightly weaker relationship at this age may arise from the greater
301 mobility of older children leading to more opportunities for respite from high pollution
302 levels. Our finding supports the body of evidence showing relationships between exposure
303 to high levels of air pollution (PM₁₀ and other pollutants) *in utero* and in early life and higher
304 BMI throughout childhood^{39,40}. Possible mechanisms for this effect are limitation of ability
305 to be physically active e.g. due to asthma; direct physiological effects (e.g. endocrine
306 disruption or mitochondria dysfunction) of pollutants, and the physiological and
307 psychological consequences of inflammation caused by exposure^{39,40}.

308 After controlling for these socioeconomic and built environment factors, we find that higher
309 tree density in the 100m radius around houses is associated with lower rates of obesity at
310 both YR and Y6. Similar results have been observed in other cities. Zip codes in New York
311 City with a greater density of street trees (within and in the 400m buffer around zip code
312 boundaries) have lower rates of obesity in 3-5 year old children²⁵. In inner-city Houston,
313 Texas, 9-11 year old children with a greater area of trees and forest within 800m of their
314 homes are also less likely to be obese²⁴. This effect is likely to be mediated by higher levels
315 of physical activity occurring in such areas⁴¹. Physical activity may be promoted by a more
316 attractive environment for socialising and play^{16,25}, and also due to parents viewing such
317 areas as safer for play and therefore permitting more independent outdoor activity²⁵.
318 However, there may also be residual confounding related to socioeconomic status, as more
319 affluent residential areas often have greater tree cover^{19,42} and lower levels of air pollution
320⁴³. Diet quality (including amongst children), which contributes to obesity prevention, is also
321 associated with socioeconomic status due to financial and time barriers⁴⁴.

322 Additionally at Y6, high rates of access to a good quality greenspace within 300m from home
323 are associated with lower rates of obesity. The accessibility of parks and playgrounds is
324 found to be related to rates of obesity amongst children and adolescents^{45,46}. A longitudinal
325 study following children from age 9-10 to 18 also found that a greater area of parks within

326 500m of homes was associated with less of an increase in BMI, especially for boys⁴⁷. This is
327 not always the case, however²⁵, and may in some cases be influenced by factors such as
328 ethnicity; for example, Alexander et al.⁴⁶ found that Non-Hispanic Black children but not
329 Non-Hispanic White children in the US had lower rates of obesity in areas with access to a
330 park.

331 It has been postulated that where no relationship between park access and obesity is
332 observed, this is due to reliance on car transportation instead of walking/cycling, meaning
333 that children are not dependent on park resources so close to home⁴⁸. Another study from
334 the UK also found no relationship between obesity rates and park access at YR⁴⁸. The
335 authors suggest that children of this age in the UK predominantly play elsewhere, such as in
336 private gardens⁴⁸.

337 Some studies have shown that access to a park is associated with higher levels of physical
338 activity⁴⁹. It is not always clear that physical activity is necessarily the causal mechanism
339 reducing obesity rates, however. A mediation analysis in a US-wide study of 40,000 children
340 did not find evidence to support the hypothesis that physical activity mediates the
341 relationship between park access and obesity⁴⁶.

342 In our study, rates of access to *any* greenspace do not show any relationship to obesity,
343 suggesting that children have quality-related requirements of greenspaces in order either to
344 use them or to obtain health benefits from their use. One explanation for this would be that
345 larger parks may be more likely to include playgrounds and other play facilities, which
346 promote physical activity; however, play facilities accessibility was not significant for either
347 age group, suggesting that presence of play facilities alone is inadequate to explain health
348 benefits. Larger parks may also include a variety of landscape features (e.g. trees and other
349 plants, water features) that are preferred by children and promote physical activity⁵⁰.
350 Children's requirements may vary by demographic group: for example, physical activity in
351 parks amongst girls in the US was promoted by paths and running tracks, playgrounds,
352 basketball courts and good lighting¹⁶. Conversely, the presence of skateboard parks
353 reduced physical activity levels amongst these girls¹⁶. Interestingly, a study of adults in
354 Rotherham – a town adjacent to Sheffield – found that neither park access nor quality was
355 related to adult obesity⁵¹, again highlighting the importance of considering children's needs
356 separately to those of adults.

357 4.2. Limitations

358 A major limitation of cross-sectional studies is that causality cannot be inferred. Observed
359 relationships may be due to reverse causation or residual confounding. This is a problem in
360 many studies of the relationship between greenspace and health, as they are primarily
361 observational and therefore cannot provide strong evidence for causation, especially where
362 relationships are complex⁵².

363 We chose LSOAs as our spatial unit of analysis. While LSOA boundaries are drawn to be
364 socially homogeneous, the average LSOA population is 1600, making socioeconomic and
365 demographic variation inevitable. Analyses of LSOAs may therefore be subject to the
366 ecological fallacy, where population-level associations do not hold at individual-level⁵³.

367 Similarly, analysis at alternative levels or areas of aggregation may not find the same results
368 ⁵³. A particularly relevant point to note is that any spatial aggregation unit is unlikely to
369 capture the spatial environment experienced by residents on a day to day basis ⁵⁴. We have
370 attempted to address this issue by designing indicators at different scales, e.g. some
371 aggregated to LSOA boundaries and others calculated on the environment around individual
372 houses.

373 There are nevertheless some limitations associated with our greenspace indicators. We
374 were only able to capture the greenspace that is present in the environment, and not its
375 use, which is likely to provide the majority of health benefits ⁵². Data on greenspace usage is
376 rarely available, and costly to collect at the scales required for epidemiological studies. Our
377 selected indicators may have failed to capture the aspects of greenspace that are most
378 relevant for health. Also, we have not tested for interactions between indicators (doing so
379 would have proved computationally unfeasible using our multi-model inference approach);
380 this is important as, for example, socioeconomic status can alter the relationship between
381 availability of resources for physical activity and obesity ⁵⁵.

382 Further limitations of the greenspace indicators are that the accessibility indicators only
383 capture greenspaces up to 300m from homes. While greenspace use tends to fall rapidly
384 with distance from home ⁵⁶, it is implausible that there is no use of greenspaces more than
385 300m from home. Also, the green cover and accessibility indicators treat all greenspace as a
386 single category, while it is likely that certain greenspaces have a greater influence on obesity
387 rates than others. Garden size and tree density do capture two types of greenspace that we
388 considered particularly likely to be important, but it is possible that other types have strong
389 influences as well. Additionally, the accessibility indicators only include greenspaces
390 identified as part of Sheffield's green and open spaces assessment.

391 A final limitation is that we were unable to stratify our analysis by demographic factors such
392 as gender or ethnic background. Previous studies have found that both of these factors
393 influence the relationship between greenspace and physical activity/obesity ^{46,47}.

394 4.3. Conclusions

395 Using a small-area population analysis, we have found a relationship between lower obesity
396 rates amongst children in Reception Year (ages 4-5) and Year Six (ages 10-11) and higher
397 density of trees in a 100m buffer around homes, after controlling for several socioeconomic
398 and built environment factors. This indicates that the greenspace environment immediately
399 around young children's homes has an impact on their chance of becoming obese. In Year
400 Six, obesity rates are lower where more homes have access within 300m (approximately a
401 five-minute walk) of a greenspace that is large, natural-feeling and of high quality,
402 suggesting that older children also benefit from suitable greenspace resources located
403 slightly further from home. It seems likely that these associations are due to the promotion
404 by greenspace of physical activity, and that the absence of a relationship between access to
405 parks amongst younger children is due to reliance on other areas, such as private gardens,
406 for active play – although we did not find garden *size* to be a significant predictor of obesity.

407 Given the importance of childhood obesity as a public health issue, we recommend that
408 attention be given to the local greenspace environment when considering interventions or
409 planning new residential areas. Specifically, we recommend that high-quality greenspace be
410 provided both in the immediate surroundings of housing, as well as slightly further afield.
411 Greenspaces near to homes could, for example, be provided by designing residential streets
412 around central greens with a variety of planting, including trees. Local parks should also be
413 provided, with consideration to the specific needs of children in terms of quality and
414 accessibility. While not understating the primary importance of alleviating deprivation for
415 reducing the prevalence of obesity, ensuring that children have access to age-appropriate
416 greenspace resources could make an important contribution to reducing childhood obesity.

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587

588 Tables and figure legends

589 Table 1. Demographic statistics of Sheffield LSOAs divided into tertiles of obesity (ratio of
 590 observed to expected rates) at Reception Year and Years Six. Tertile 1 = lowest obesity ratio.
 591 ICADI = Income Deprivation Affecting Children Index; measures proportion of children living
 592 in income deprived families. All data from 2011 census.

Variable	Reception Year			Year Six		
	1	2	3	1	2	3
Index of Multiple Deprivation						
Mean	15.94	28.85	37.59	13.56	27.90	41.04
SD	13.65	18.48	19.83	11.69	17.52	18.31
IDACI						
Mean	0.11	0.22	0.28	0.09	0.22	0.31
SD	0.11	0.15	0.16	0.08	0.15	0.15
Population						
Mean	1622.29	1597.92	1563.38	1549.39	1581.64	1652.70
SD	303.07	248.34	223.27	180.95	243.85	327.87
Child population (0-15 years)						
Mean	266.78	307.16	302.61	234.84	287.24	354.75
SD	99.30	120.00	110.31	88.56	87.70	120.41
Mean % of population	16.66	19.03	19.33	15.26	18.19	21.59
Children in poor health						
Mean	1.72	2.40	3.03	2.24	2.30	2.61
SD	2.50	2.09	2.86	2.25	2.68	2.72
Mean % of children	0.58	0.76	0.98	0.78	0.71	0.82
Mean ethnic composition (%)						
White	76.95	73.02	76.65	80.87	76.70	69.05
Mixed/multiple ethnic group	5.80	5.97	6.28	5.65	5.61	6.79
Asian/Asian British	10.32	11.46	7.70	7.32	9.62	12.54
Black/African/Caribbean/Black British	3.70	5.25	5.88	2.59	5.11	7.16
Other ethnic group	3.22	4.30	3.49	3.57	2.97	4.46

594 Table 2. Descriptive statistics of greenspace metrics.

Variable	Min	Q1	Median	Q3	Max	Range	Mean	St. Dev.
Income deprivation	0.01	0.06	0.13	0.29	0.55	0.55	0.17	0.13
Air pollution	13.00	14.90	15.70	16.40	19.80	6.82	15.70	1.20
Address density	30.90	74.40	89.50	116.00	415.00	384.00	104.00	52.30
Green cover	0.01	0.16	0.28	0.48	0.98	0.98	0.34	0.22
Tree density	12.80	78.00	99.90	129.00	223.00	211.00	105.00	38.90
Garden size	0.73	110.00	175.00	217.00	768.00	767.00	178.00	106.00
Any greenspace accessibility	0.04	0.57	0.81	0.95	1.00	0.97	0.74	0.25
Good greenspace accessibility	0.00	0.00	0.06	0.37	1.00	1.00	0.20	0.27
Play facility accessibility	0.00	0.00	0.20	0.45	1.00	1.00	0.26	0.26

595

596 Table 3. Averaged models for rates of obesity at Reception Year and Year Six in Sheffield LSOAs. Empty lines indicate that the variable did not
 597 appear in the plausible set (quadratic terms that did not appear in any plausible set are not shown). Significant terms are shown in bold.

	Reception Year					Year Six				
	Estimate	SE (adj.)	z value	p value		Estimate	SE (adj.)	z value	p value	
(Intercept)	0.314	0.016	20.119	<0.001	**	-0.069	0.013	5.351	<0.001	***
Income deprivation	1.889	0.327	5.787	<0.001	***	3.101	0.295	10.528	<0.001	***
Income deprivation ^2	-1.721	0.278	6.198	<0.001	***	-1.026	0.227	4.510	<0.001	***
Air pollution	0.889	0.330	2.689	0.007	**	0.593	0.317	1.871	0.061	
Air pollution ^2						-0.234	0.289	0.809	0.419	
Address density	-2.432	0.434	5.602	<0.001	***	-1.298	0.596	2.178	0.029	*
Green cover						0.327	0.328	0.996	0.319	
Tree density	-1.070	0.363	2.951	0.003	**	-0.862	0.325	2.655	0.008	**
Tree density ^2	0.000	0.000	0.000	1.000		-0.453	0.376	1.207	0.227	
Garden size						-0.550	0.574	0.958	0.338	
Any greenspace accessibility						0.021	0.108	0.196	0.845	
Good greenspace accessibility						-0.565	0.269	2.098	0.036	*
Play facility accessibility	0.004	0.106	0.038	0.970						
Play facility accessibility ^2	-0.027	0.122	0.221	0.825						

598

599 Figure 1. Marginal effects of greenspace and controlling variables on obesity at Reception
600 Year (dashed lines) and Year Six (solid lines) in Sheffield LSOAs. Marginal effects are shown
601 on log scale (as per negative binomial GML link function). Missing lines indicate the variable
602 did not appear in the plausible set for the age. Box and whisker plots indicate variable
603 distribution, with the box encompassing the interquartile range and whiskers indicating a
604 further 1.5x the interquartile range. Units: (a) proportion cover, (b) count of trees within
605 100m of addresses, (c) m², (d-f) proportion of addresses with access, (g) index, (h) µg m⁻², (i)
606 count of addresses within 100m of addresses.