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Urban biodiversity and adolescent mental health and well-being☆

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ABSTRACT

Biodiversity may play a role in the mental health and well-being of people living in urban areas, but there is limited research on this. We investigated the association between proximity to Sites of Importance for Nature Conservation (SINCs) and mental health and well-being in 10- to 15-year-old adolescents living in London. SINCs are a key component of London's biodiversity and designated for their importance for the local habitat. We hypothesised that close proximity to a SINC (i.e., living within 1000 m from a SINC) would be a proxy for good access to it, which, in turn, would be associated with lower levels of mental health problems, and higher levels of self-esteem and happiness. In linear regression models, adjusted for individual and neighbourhood confounders, we did not find evidence to support our hypothesis. We discuss possible explanations for our null findings (e.g., definitions of biodiversity and access, and low statistical power) and highlight that, from our findings, we cannot infer that there is no association and that further research is needed.

1. Introduction

There is growing evidence for an association between nature and health (Hartig et al., 2014). In recent years, there has also been much interest in the association between greenspace and mental health and well-being, especially among young people (Tillmann et al., 2018; Vanaken & Danckaerts, 2018; Zhang et al., 2020). In adolescents, for example, exposure to greenspace has been linked to better mood (Li et al., 2018); lower levels of stress (Feda et al., 2015), psychological distress (Wang et al., 2019), and aggression (Younan et al., 2016); and better mental health (Bloemsma et al., 2022; Mavoa et al., 2019). This suggests that greenspace could be a promising factor for prevention and intervention, especially considering that adolescence is a critical period in the development of mental health problems. For example, 50% of lifetime cases of mental disorders start before the age of 14 years, and 75% start before the age of 24 years (de Girolamo et al., 2012; Kessler et al., 2005). Therefore, if there is a causal association between greenspace and adolescent mental health and well-being, provision, maintenance, and development of high-quality green spaces could be an important target for public health policy.

Despite the growing evidence for an association between greenspace and mental health, there also are inconsistencies, and our understanding of the specifics of the association remains limited. For example, we do not know much about the characteristics of green spaces that are essential, or most beneficial, for adolescent mental health and well-being. There are different characteristics that may be relevant, including access, safety, amenities, surroundings, and biodiversity (Knobel et al., 2019, 2021). In the present study, we focused on biodiversity. Biodiversity is an interesting and important quality because it may not only amplify the benefits of greenspace for human health and well-being, but also has much wider relevance, providing ecosystem services and having important environmental benefits (Cardinale et al., 2012). Although promising, the potential importance of biodiversity for mental health and well-being needs to be shown more consistently (Marselle et al., 2019).

1.1. Theoretical pathways underlying greenspace and health associations

Exposure to greenspace may be associated with adolescent mental health and well-being via several mechanisms that can be categorised into 'mitigation', 'restoration', and 'instoration' (Markevych et al., 2017). For example, high levels of greenspace around the home can

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reduce levels of environmental stressors, such as air pollution and noise, that may otherwise have negative effects on adolescent mental health and well-being (mitigation). Green spaces have also been proposed to be restorative environments (Kaplan & Kaplan, 1989; Kaplan, 1995; Ulrich, 1981; Ulrich et al., 1991), so adolescents may visit green spaces to recover from stress or to restore cognitive resources (restoration). Studies on potentially restorative effects of green spaces in children and adolescents are characterised by great heterogeneity regarding measures of exposures and outcomes, and methodology, and findings are mixed. Nonetheless, several studies suggest associations between greenspace and attention restoration, stress recovery, and/or perceived restorativeness (for a review, see Barger et al., 2021). Finally, green spaces may invite adolescents to play, spend time with their friends, and engage in physical activities (instoration). In fact, adolescents have reported that the main reason for visiting green spaces is to engage in physical and social activities (Bloemsma et al., 2018).

1.2. Biodiversity and mental health: evidence and theoretical considerations

The term 'greenspace' covers a wide range of types of spaces that differ in their qualities and, therefore, are likely to have different effects on health and well-being (Taylor & Hochuli, 2017). It is plausible that more biodiverse green spaces would have greater positive effects on health and well-being than less biodiverse green spaces; however, the evidence for this is limited, partly because the association between biodiversity and (mental) health has been understudied (Aerts et al., 2018; Houlden et al., 2021; Lovell et al., 2014). In adults, biodiversity may be associated with psychological restoration and perceived restorativeness (Meyer-Grandbastien et al., 2020; Wood et al., 2018; Young et al., 2020), and psychological and subjective well-being (Fuller et al., 2007; Knight et al., 2022; Schebella et al., 2019). However, importantly, some studies did not find an association, and Houlden et al. (2021) suggest that more research is needed to be able to draw conclusions about potential health benefits.

An important study to highlight is Knight et al.'s (2022) investigation of the role of access to Sites of Importance for Nature Conservation (SINCs) - green spaces with high levels of biodiversity - in adult mental health and well-being in London. The researchers found that poor access to SINCs was associated with lower levels of life satisfaction (but not mental health). This study is important to point out because it used the same exposure used in the present study. It also distinguished between mental health and well-being. However, the study focused on adults aged 16 years or older, not adolescents. As age is likely to play a role in the association between greenspace and mental health and well-being (e.g., in usage of and preferences for green spaces), we cannot simply generalise findings from adult populations to adolescent populations. As there is a lack of evidence on the role of biodiversity in adolescent mental health and well-being, as we will discuss in the next two paragraphs, a study similar to Knight et al.'s (2022) but with a focus on adolescents aged 10–15 years is an important contribution to the literature.

In adolescents, the evidence for the biodiversity-mental health association is even more limited than in adults. To the best of our knowledge, only one study has directly addressed the role of biodiversity in adolescent mental health and well-being. Mavoa et al. (2019) investigated the association between the neighbourhood's natural environment and mental health and well-being in 12- to 19-year-old adolescents in urban New Zealand. They found that greenness, presence of native vegetation, and general availability of nature in the neighbourhood were negatively associated with depressive symptoms. However, they also found that vegetation diversity, used as an indicator of biodiversity, was negatively associated with emotional well-being.

Other studies, not directly investigating biodiversity but related exposures, provide mixed evidence. For example, Maes et al. (2021) found that higher levels of woodland were associated with lower levels of mental health problems in adolescents in London. They did not find the same for grassland which suggests that the potentially higher ecological quality of woodlands may be especially beneficial. Gubbels et al. (2016), on the other hand, did not find evidence for a beneficial effect of improving neighbourhood greenery on adolescent mental health in the Netherlands. These are two exemplary studies that illustrate the generally mixed evidence for associations between greenspace and adolescent mental health and well-being, and the need for more studies into the nuances of the association.

Despite the limited empirical evidence, it is theoretically plausible that biodiverse green spaces would be beneficial for mental health and well-being. Although it is not yet clear how exactly biodiversity may impact mental health and well-being, psychological effects (e.g., via fascination), biological effects (e.g., via changes of the microbiome), and other, more indirect effects (e.g., via promotion of healthy behaviour) are all plausible (Aerts et al., 2018; Houlden et al., 2021; Lovell et al., 2014; Marselle et al., 2021; Wong & Osborne, 2022). It is thus likely that high levels of biodiversity support all three general functions of greenspace (described earlier): mitigation, restoration, and instoration. For example, a biodiverse green area may be particularly attractive and may encourage or facilitate physical and social activities. Increased interest could be another mechanism that encourages people's use of green spaces and, in this case, may facilitate restoration via fascination. For example, an experimental study found that higher levels of animal biodiversity were associated with higher interest of participants in tide pool communities (Fairchild et al., 2018).

An important complication in biodiversity and health research is that there is no agreement on the definition of biodiversity (Marselle et al., 2021; Swingland, 2013). Researchers use a range of measures to capture biodiversity or dimensions of biodiversity. Common measures of biodiversity are species richness (number of species) and species abundance (number of individuals in and/or across species; Marselle et al., 2019). Several studies suggest there may be an association between species richness (or perceived species richness) and mental health and well-being in adults (Dallimer et al., 2012; Fuller et al., 2007; Methorst, Bonn, et al., 2021; Methorst, Rehdanz, et al., 2021; Wolf et al., 2017). In our Methods section below, we describe in detail how we defined and measured biodiversity in the present study.

1.3. The present study

In our study, in Greater London, we used data on Sites of Importance for Nature Conservation (SINCs), also referred to as Local Wildlife Sites. SINCs are recognised for their importance for the local habitat and designated as such by ecological professionals. They are a core component of London's biodiversity. We hypothesised that good access to SINCs would be associated with better mental health and well-being in adolescents living in London. To test our hypothesis, we used data on 10- to 15-year-old adolescents from Understanding Society, a longitudinal study of households in the UK, and linked data on access to SINCs, provided by Greenspace Information for Greater London. In particular, we tested whether living beyond 1000 m walking distance from a SINC (i.e., having poor access to SINCs) would be negatively associated with mental health, self-esteem, and happiness.

2. Methods

2.1. Study sample

We used data from Understanding Society (University of Essex Institute for Social and Economic Research, 2020, 2021, 2022). Understanding Society is the UK Household Longitudinal Study (UKHLS) and includes data on the members of around 40,000 UK households at wave 1 (2009–2011). Up to this day, households have been followed for 12 waves. More information about the UKHLS data and study design is provided in the UKHLS user guide (Institute for Social and Economic

Research, 2020). In the present study, we used data from waves 1 to 8 (2009–2018). We used data from the Understanding Society youth dataset which includes self-reports from 10- to 15-year-olds. To these, we linked data on parents, families, and neighbourhoods. Mental health and well-being outcomes considered in this study—mental health as assessed by the Strengths and Difficulties Questionnaire (SDQ), self-esteem, and happiness—were measured at waves 1, 3, 5, and 7 (SDQ); waves 2, 4, 6, and 8 (self-esteem); and waves 1 to 8 (happiness). Across the eight waves, there were 32,404 observations clustered in 12, 675 adolescents. Our analytic sample included only those adolescents who lived in London (because the exposure variable was only available for London), had data on at least one of the three study outcomes for at least one wave, and had a non-zero study weight ($n = 1879$). Differences between analytic and non-analytic samples on study variables are summarised in Table 1. Note that some of the 1879 adolescents had data for more than one wave, so a total of 4217 observations were included in our study.

2.2. Study variables

2.2.1. Mental health and well-being

Mental health was measured with the self-reported Strengths and Difficulties Questionnaire (SDQ) at waves 1, 3, 5, and 7. The SDQ is a validated, widely used measure of emotional symptoms, conduct problems, hyperactivity and inattention, and peer relationship problems (Goodman, 1997; Goodman et al., 1998). Each subscale includes five items which are rated on a scale ranging from 0 ('not true') to 2 ('certainly true'). Example items for emotional symptoms are, 'I worry a lot', and, 'I have many fears'; for conduct problems, 'I get very angry and often lose my temper', and, 'I fight a lot'; for hyperactivity and inattention, 'I am restless', and, 'I am easily distracted'; and for peer relationship problems, 'I am usually on my own', and, 'I get on better with adults than with people my age'. The scores for each subscale range between 0 and 10. The 20 items of the four subscales can be combined to a total difficulties score ranging from 0 to 40. Cronbach's alphas were .65 (emotional symptoms), 0.61 (conduct problems), 0.64 (hyperactivity and inattention), 0.53 (peer relationship problems), and 0.76 (total difficulties) at wave 1.

Well-being was measured with two scales: self-esteem and happiness. Self-esteem was measured with eight items based on the Rosenberg self-esteem scale (Rosenberg, 1965) at waves 2, 4, 6, and 8. Example items are, 'I feel I have a number of good qualities', and, 'I am a likeable person'. Each item was rated on a scale ranging from 1 ('strongly disagree') to 4 ('strongly agree'). The self-esteem scale score was the mean of the eight items. The Cronbach's alpha for the self-esteem scale was 0.76 at wave 2.

Happiness was measured with six items at waves 1 to 8: 'How do you feel about (a) your schoolwork, (b) your appearance, (c) your family, (d) your friends, (e) your school, and (f) your life as a whole?' This scale has been used previously as a measure of mental well-being (Bannink et al., 2016; Kelly et al., 2016, 2018; Mueller and Flouri, 2021). Each item was rated on a scale ranging from 1 ('not at all happy') to 7 ('completely happy'). The happiness scale score was the mean of the six items. The Cronbach's alpha was .76 at wave 1. Note that we labeled this outcome 'happiness', but we recognise that the items reflect evaluative domains of subjective well-being/life satisfaction.

2.2.2. Access to Sites of Importance for Nature Conservation

Access to Sites of Importance for Nature Conservation (SINCs) was assessed with a binary variable. This was based on Areas of Deficiency (AoDs) in Access to SINCs, provided by Greenspace Information for Greater London (GiGL; *Greenspace Information for Greater London CIC - GIGL*, n.d.). A SINC is a greenspace that is recognised for the important habitat it supports and is defined by a panel of local ecological professionals. Sites designated as SINCs are sites with high levels of biodiversity, measured as wealth of wildlife (*Greenspace Information for Greater London CIC - GIGL*, n.d.). AoDs are areas where people have to walk more than 1000 m to reach a SINC of Metropolitan or Borough importance (*Greenspace Information for Greater London CIC - GIGL*, n.d.). GiGL calculated these areas, running spatial analyses using walking distances to SINCs. Around 21% of London's area are AoDs. Using postcode grid references provided by Understanding Society and spatially joining them with AoDs (in R, using the sf package; Pebesma, 2018), we assessed whether an adolescent lived in an AoD (no/yes). Living in an AoD was an indicator of having poor access to green spaces

Table 1
Bias analysis between analytic and non-analytic samples.

	Analytic sample ($n = 4217$)		Non-analytic sample ($n = 28{,}187$)		Test
Continuous variables	*n*	*M (SD)*	*n*	*M (SD)*	*F*
SDQ CP (0–10)	2281	2.13 (1.73)	14,119	2.21 (1.81)	1.54
SDQ ES (0–10)	2281	2.64 (2.14)	14,118	2.88 (2.26)	7.28 **
SDQ HA (0–10)	2279	3.70 (2.18)	14,115	4.06 (2.34)	22.18 ***
SDQ PP (0–10)	2279	1.61 (1.54)	14,120	1.82 (1.70)	16.01 ***
SDQ TD (0–40)	2276	10.09 (5.29)	14,106	10.97 (5.80)	17.79 ***
Self-esteem (1–4)	1881	3.17 (0.44)	13,819	3.11 (0.44)	8.65 **
Happiness (1–7)	4202	5.89 (0.87)	28,072	5.81 (0.85)	6.61 *
Area greenness [%] [1]	4123	38.54 (11.79)	–	–	–
Area air pollution [mean NO_2] [1]	4123	35.32 (5.65)	–	–	–
Area deprivation [Carstairs sum of z-scores]	4217	1.90 (3.49)	23,358	−0.32 (3.04)	135.32 ***
Maternal psychological distress (0–36)	3203	11.76 (5.96)	24,613	11.96 (5.90)	0.75
Age [years]	4217	12.42 (1.69)	28,187	12.54 (1.69)	9.59 **
Categorical variables	*n*	*%*	*n*	*%*	*F* [2]
University education (mother)	1560	41.42	10,308	40.05	0.29
Family owns its home	1805	48.38	19,498	66.45	35.44 ***
Intact family structure	2826	64.18	18,073	62.77	0.26
Ethnicity White	1182	53.58	23,262	90.65	359.93 ***
Ethnicity Mixed	534	10.23	1031	2.85	82.07 ***
Ethnicity Indian	310	6.29	824	1.76	54.23 ***
Ethnicity Pakistani and Bangladeshi	824	7.64	1980	2.75	47.27 ***
Ethnicity Black or Black British	1097	17.49	692	1.03	567.74 ***
Ethnicity Other	270	4.77	340	0.96	61.23 ***
Female	2120	50.75	14,025	49.50	0.36
Lives in an AoD	1184	27.66	–	–	–

Note. CP = conduct problems; ES = emotional symptoms; HA = hyperactivity/inattention; PP = peer problems; TD = total difficulties; AoD = Area of Deficiency. Data are taken from waves 1 to 8. Sample sizes refer to observations (not individuals). Some individuals have multiple observations across waves, and these multiple observations are included in the descriptive statistics. Descriptive statistics by wave and by age group differ slightly, but the overall descriptive statistics in this table give an appropriate overview of the sample characteristics. *Ns* are unweighted. *Ms*, *SDs*, and *%s* are weighted. [1] Values are for 500 m buffers around postcodes. [2] Design-based *F* statistic (i.e., corrected weighted Chi^2 statistic). $*p < .05$, $**p < .01$, $***p < .001$.

with high levels of biodiversity. Fig. 1 shows a map of AoDs in Access to SINCs.

We chose AoDs in Access to SINCs as our exposure for three main reasons. First, SINCs are an important element of London's biodiversity, identified by ecological professionals and recognised in local planning decisions. Considering that SINCs are already recognised as green spaces in London that deserve special consideration (i.e., protection) in local planning, it is important to investigate whether access to SINCs benefits people's health and well-being. Second, GiGL created a high-quality dataset, AoDs in Access to SINCs, using sophisticated spatial modelling (by defining AoDs using network distances to access points of green spaces). Using AoDs as the exposure has the advantage that findings are related to clearly identified and delineated areas in London, providing a good and practical basis for policy and planning. Third, the measure has already been used by Knight et al. (2022) to investigate a similar question. They found an association with well-being, but not mental health, in adults (where poor access to SINCs was associated with lower life satisfaction).

2.2.3. Neighbourhood-level confounders

We included three neighbourhood-level confounders: area greenness, air pollution, and deprivation. To measure area greenness, we used London Green and Blue Cover data, provided by the Greater London Authority (*London Green and Blue Cover - London Datastore*, n.d.). Green and blue cover data combine 2016 Normalized Difference Vegetation Index (NDVI) and land use data, providing information on how much of London is covered with green and blue spaces (including all areas of public and private green and blue space). For more information about the dataset, please visit the London Datastore. For this study, we used data on green cover. The data capture even small areas of vegetation (such as trees, private gardens, and green roofs) and can be used as an indicator of the greenness of an area. To account for area greenness in our study, we calculated the proportion of green cover in 500 m around adolescents' postcodes.

Area air pollution was measured with nitrogen dioxide (NO_2) data provided by the GLA and Transport for London (TfL) for the years 2010, 2013, and 2016 (*Air Quality Data – London Datastore*, n.d.). NO_2 data are provided as annual mean concentrations (μg/m^3), modelled using the London Air Quality Toolkit (LAQT) model. The LAQT model uses a kernel modelling technique to describe the dispersion from emission sources (i.e., road transport; aviation; river; rail; industry; gas heating; domestic and commercial fuels; biomass burning; cooking emissions; and other sources). The contributions were summed and mapped on a 20 m by 20 m grid. Model results were validated by evaluating modelled data against fixed site measurements. To account for area air pollution in our study, we calculated the average annual mean NO_2 concentration in 500 m around adolescents' postcodes. Depending on when Understanding Society data were collected, we linked air pollution data from 2010 (waves 1 and 2), 2013 (wave 3, 4, and 5), or 2016 (waves 6, 7, and 8).

Area deprivation was measured with the 2011 Carstairs Deprivation Index at Lower Layer Super Output Area (LSOA) level (Carstairs et al., 1989; Wheeler, 2019). The Carstairs Index is the sum of the z-scores of four unweighted Census variables: proportions of low social class households; households with no car or van; overcrowded households; and male unemployment. The Carstairs Deprivation Index reflects the level of socio-economic deprivation at LSOA level, with higher scores indicating higher levels of deprivation. Note that an LSOA is a unit of UK geography with an average population of around 1500.

2.2.4. Family- and child-level confounders

Family-level confounders were maternal mental health, maternal education, home ownership, and family structure. Maternal mental health was measured with the 12-item General Health Questionnaire (GHQ). The GHQ scale score ranges from 0 to 36, with higher scores indicating higher psychological distress. Maternal education was measured with a binary variable (whether the mother had a University education). Home ownership (whether the family owned their home) and family structure (whether the child lived with two natural parents) were also measured with binary variables. Child-level variables were sex

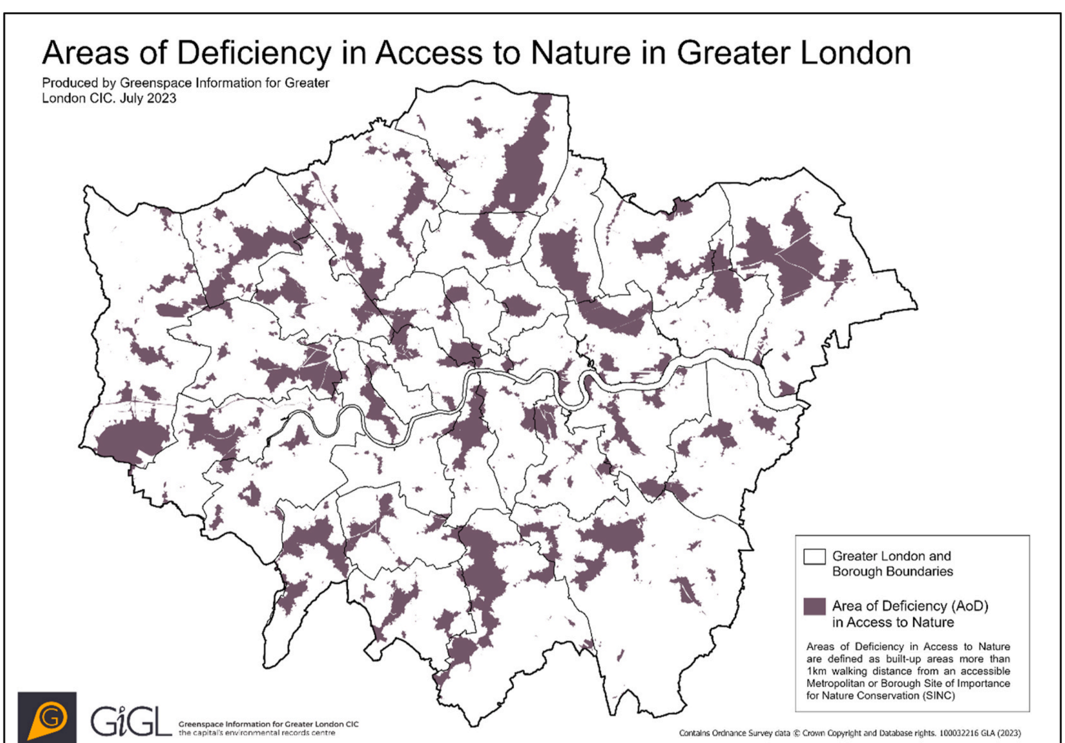

Fig. 1. Areas of Deficiency (AoDs) in Access to Nature. Living in an AoD is a proxy for living in poor proximity to an accessible SINC of Metropolitan or Borough importance. Note that this map is based on data from 2023 (whereas analyses presented in this paper are based on data from 2021).

(male/female) and ethnicity (White, Mixed, Indian, Pakistani and Bangladeshi, Black, and Other). As we were using data of multiple waves in one analysis, we included a dummy variable for wave.

2.3. Statistical analysis

All analyses were run in Stata 16. We fitted a multiple linear regression model for each outcome (i.e., five SDQ scales, self-esteem, and happiness), with access to SINCs (i.e., whether one lived in an AoD; no/yes) as the exposure. Each model was adjusted for area greenness, area air pollution, area deprivation, maternal mental health, maternal education, home ownership, family structure, sex, ethnicity, and wave. We accounted for Understanding Society's complex sampling design, using survey design variables (i.e., primary sampling unit, strata, and study weight).

We stratified each model by age. This is because Understanding Society does not provide longitudinal weights for youth data. To avoid using cross-sectional data of only one wave, it is possible to pool data of several waves into one cross-sectional analysis. However, because some individuals were a youth at multiple waves and contributed more than one observation to the analysis, observations were not independent. To address this, we pooled the data of eight waves and ran separate models for each age. This ensured that each model included only one observation per individual and also allowed us to assess age-specific associations. Note that pooling data of eight waves into one analysis means that we included data from several waves in each analysis. To account for that, we included a dummy variable for wave. Also note that it was not possible to run a multilevel model (with multiple observations clustered in individuals) because we used cross-sectional weights (which means that individuals have different weights at different waves).

Around 74% of adolescents had complete data. The highest proportion of missingness was for maternal psychological distress (around 24%). The exact amount of missingness differed depending on the age investigated in a given analysis. Under the assumption that missing data were missing at random (MAR), we imputed missing data using multiple imputation by chained equations (Raghunathan et al., 2001; Sterne et al., 2009). For each analysis (i.e., outcome-age combination), we generated 25 imputed datasets and used Rubin's combination rules to pool the individual estimates into a single set of multiply imputed estimates (Rubin, 1987). It should be noted that the assumption that missing data were MAR is probably not true for maternal psychological distress. However, because a complete-case analysis would make our sample very selective, and because sample sizes for individual analyses were already small, we decided to use MICE to retain cases with missing data in our analysis and to increase statistical power.

3. Results

3.1. Descriptive statistics and bias analysis

Descriptive statistics and a bias analysis are shown in Table 1. Note that, for reasons of parsimony, we did not stratify descriptive statistics by age, and that sample sizes refer to observations across waves (not individuals). Also note that Ns are unweighted, whereas means, SDs, and %s are weighted. Compared to adolescents in the non-analytic sample, adolescents in the analytic sample had lower scores on the SDQ, and higher scores on self-esteem and happiness. They lived in more deprived areas and their families were less likely to own their homes. Also, adolescents in the analytic sample were less likely to be 'White' (54%) than adolescents in the non-analytic sample (91%). Around 28% of the analytic sample lived in an AoD (i.e., had poor access to SINCs). Table 2 shows correlations between outcomes and exposure. SDQ scores were positively correlated with each other and negatively correlated with self-esteem and happiness. Except for a negative correlation with hyperactivity and inattention, living in an AoD did not seem to be correlated with mental health and well-being.

3.2. Linear regression models

Linear regression model results are shown in Tables 3–9. All estimates shown in tables are from fully adjusted models. However, due to the relatively large number of models, we only show estimates for our main exposure of interest (not for covariates). As can be seen, across age groups and outcomes, we did not find an association of living in an AoD (i.e., having poor access to SINCs) with mental health and well-being (except for emotional symptoms in 13-year-olds, and peer relationship problems in 10-year-olds).

4. Discussion

In this study, we investigated the association between access to Sites of Importance for Nature Conservation (SINCs; green spaces with high levels of biodiversity) and mental health, self-esteem, and happiness in adolescents living in London. Across outcomes and ages, we did not find

Table 3
Regression results (fully adjusted models) for conduct problems.

	b	*SE*	95% *CI*	*p*
15 years (n = 365)				
Lives in an AoD	0.119	0.215	[-0.309, 0.547]	0.582
14 years (n = 349)				
Lives in an AoD	0.048	0.294	[-0.537, 0.632]	0.872
13 years (n = 378)				
Lives in an AoD	0.114	0.220	[-0.324, 0.553]	0.605
12 years (n = 392)				
Lives in an AoD	0.024	0.221	[-0.415, 0.462]	0.915
11 years (n = 368)				
Lives in an AoD	−0.074	0.319	[-0.709, 0.560]	0.817
10 years (n = 375)				
Lives in an AoD	−0.118	0.295	[-0.706, 0.470]	0.691

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

Table 2
Correlations between outcomes and exposure (n = 4217).

	SDQ CP	SDQ ES	SDQ HA	SDQ PP	SDQ TD	Self-esteem	Happiness
SDQ ES	0.260 ***						
SDQ HA	0.513 ***	0.303 ***					
SDQ PP	0.200 ***	0.355 ***	0.179 ***				
SDQ TD	0.707 ***	0.717 ***	0.754 ***	0.574 ***			
Self-esteem	–	–	–	–	–		
Happiness	−0.374 ***	−0.397 ***	−0.367 ***	−0.293 ***	−0.521 ***	0.538 ***	
Lives in an AoD	0.017	−0.034	−0.044 *	−0.017	−0.032	0.019	0.026

Note. CP = conduct problems; ES = emotional symptoms; HA = hyperactivity/inattention; PP = peer problems; TD = total difficulties; AoD = Area of Deficiency. Data are taken from waves 1 to 8. The sample size refers to observations (not individuals). Some individuals have multiple observations across waves, and these multiple observations were included in the correlation analysis. There are no correlations between self-esteem and SDQ scales because these variables were measured at different waves. *p < .05, **p < .01, ***p < .001.

Table 4
Regression results (fully adjusted models) for emotional symptoms.

	b	*SE*	95% *CI*	*p*
15 years (*n* = 365)				
Lives in an AoD	−0.518	0.261	[-1.038, 0.002]	0.051
14 years (*n* = 349)				
Lives in an AoD	−0.501	0.463	[-1.423, 0.420]	0.282
13 years (*n* = 378)				
Lives in an AoD	−0.473	0.202	[-0.875, −0.071]	0.022
12 years (*n* = 392)				
Lives in an AoD	−0.109	0.321	[-0.747, 0.528]	0.734
11 years (*n* = 368)				
Lives in an AoD	0.043	0.396	[-0.746, 0.831]	0.914
10 years (*n* = 375)				
Lives in an AoD	−0.466	0.382	[-1.227, 0.295]	0.227

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

Table 5
Regression results (fully adjusted models) for hyperactivity and inattention.

	b	*SE*	95% *CI*	*p*
15 years (*n* = 365)				
Lives in an AoD	−0.085	0.315	[-0.711, 0.541]	0.788
14 years (*n* = 349)				
Lives in an AoD	−0.495	0.367	[-1.224, 0.235]	0.181
13 years (*n* = 378)				
Lives in an AoD	−0.362	0.268	[-0.895, 0.172]	0.181
12 years (*n* = 392)				
Lives in an AoD	−0.151	0.257	[-0.661, 0.359]	0.559
11 years (*n* = 368)				
Lives in an AoD	−0.111	0.492	[-1.090, 0.868]	0.822
10 years (*n* = 375)				
Lives in an AoD	−0.192	0.281	[-0.752, 0.369]	0.498

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

Table 6
Regression results (fully adjusted models) for peer relationship problems.

	b	*SE*	95% *CI*	*p*
15 years (*n* = 365)				
Lives in an AoD	−0.062	0.200	[-0.459, 0.336]	0.759
14 years (*n* = 349)				
Lives in an AoD	0.233	0.261	[-0.285, 0.752]	0.374
13 years (*n* = 378)				
Lives in an AoD	−0.150	0.180	[-0.507, 0.208]	0.408
12 years (*n* = 392)				
Lives in an AoD	−0.057	0.230	[-0.515, 0.401]	0.805
11 years (*n* = 368)				
Lives in an AoD	−0.254	0.276	[-0.803, 0.294]	0.359
10 years (*n* = 375)				
Lives in an AoD	−0.436	0.194	[-0.822, −0.049]	0.028

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

Table 7
Regression results (fully adjusted models) for total difficulties.

	b	*SE*	95% *CI*	*p*
15 years (*n* = 365)				
Lives in an AoD	−0.545	0.632	[-1.802, 0.712]	0.391
14 years (*n* = 349)				
Lives in an AoD	−0.715	1.027	[-2.757, 1.327]	0.488
13 years (*n* = 378)				
Lives in an AoD	−0.870	0.615	[-2.095, 0.356]	0.161
12 years (*n* = 392)				
Lives in an AoD	−0.294	0.735	[-1.754, 1.167]	0.690
11 years (*n* = 368)				
Lives in an AoD	−0.397	0.769	[-1.927, 1.133]	0.607
10 years (*n* = 375)				
Lives in an AoD	−1.211	0.876	[-2.956, 0.534]	0.171

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

Table 8
Regression results (fully adjusted models) for self-esteem.

	b	*SE*	95% *CI*	*p*
15 years (*n* = 293)				
Lives in an AoD	0.111	0.075	[-0.039, 0.261]	0.144
14 years (*n* = 306)				
Lives in an AoD	0.021	0.048	[-0.074, 0.117]	0.653
13 years (*n* = 338)				
Lives in an AoD	0.063	0.078	[-0.092, 0.218]	0.419
12 years (*n* = 298)				
Lives in an AoD	−0.029	0.085	[-0.200, 0.142]	0.734
11 years (*n* = 336)				
Lives in an AoD	−0.040	0.061	[-0.162, 0.083]	0.520
10 years (*n* = 264)				
Lives in an AoD	−0.022	0.108	[-0.239, 0.194]	0.836

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

Table 9
Regression results (fully adjusted models) for happiness.

	b	*SE*	95% *CI*	*p*
15 years (*n* = 663)				
Lives in an AoD	0.086	0.105	[-0.121, 0.292]	0.413
14 years (*n* = 663)				
Lives in an AoD	0.065	0.134	[-0.200, 0.330]	0.630
13 years (*n* = 725)				
Lives in an AoD	0.083	0.097	[-0.107, 0.274]	0.391
12 years (*n* = 699)				
Lives in an AoD	−0.018	0.102	[-0.219, 0.183]	0.857
11 years (*n* = 710)				
Lives in an AoD	−0.018	0.085	[-0.187, 0.150]	0.832
10 years (*n* = 644)				
Lives in an AoD	0.131	0.114	[-0.095, 0.356]	0.254

Note. AoD = Area of Deficiency. Estimates are taken from separate models (i.e., one model for each age). Estimates are pooled estimates of 25 imputed datasets.

evidence for a role of biodiversity in the mental health and well-being of young urban adolescents.

In our study, in order to investigate the association between access to SINCs and mental health and well-being, we created a binary variable measuring whether adolescents lived in an Area of Deficiency in Access to SINCs (defined as living beyond 1000 m walking distance from a SINC). Living in an AoD, therefore, was an indicator of poor access to green spaces with high levels of biodiversity. We did not find an association between living in an AoD and adolescent mental health and well-being in our sample. This is interesting considering that Knight et al. (2022) did find an association of the same exposure with life satisfaction (but not mental health) in adults living in London. We suggest two main explanations for our findings. First, it is possible that there is no association between biodiversity and mental health and well-being in young, urban adolescents (although this cannot be inferred directly from our null findings). Second, our measure of exposure had important limitations, so our null findings may be due to exposure misclassification bias. Below we discuss both explanations in turn as well as highlighting other limitations that may have contributed to our null findings (e.g., low statistical power).

With respect to the first explanation, only few studies to date have investigated the association of biodiversity with mental health and well-being, and almost all of these studies used data on adults. Reviews of the literature suggest that findings are inconsistent and the evidence is inconclusive (Houlden et al., 2021). However, some studies did find positive associations with perceived restoration and well-being, as described earlier. In consideration of these positive findings in adults and potential theoretical mechanisms, an association between biodiversity and adolescent mental health and well-being is certainly plausible. However, it is important to highlight that adolescence is a period in life that is vastly different from adulthood, and there are plausible explanations too for why biodiversity may *not* play a (big) role in the adolescent outcomes we considered.

Adolescence is a period of biological and social change. In adolescence, children gain more and more independence from their parents and are oriented towards their peers. They move around independently, spend less time with their parents and more time with their peers, and start taking more risks (Andrews et al., 2021; Brown & Larson, 2009; Christie & Viner, 2005). There also seems to be a decrease in nature connectedness (i.e., emotional connection with nature) in adolescence, with adolescents tending to have lower levels of nature connectedness than children and adults (Kahn & Kellert, 2002; Krettenauer, 2017; Krettenauer et al., 2020). The increasing focus on peers and the decreasing level of nature connectedness, together, suggest that biodiversity may not be an important factor in adolescent mental health and well-being, at least not compared to other factors, such as peer relationships. In other words, even if there were a benefit of having good access to biodiversity, this may be comparatively small.

Public open spaces, including green spaces, can offer adolescents the opportunity to spend time away from home and their parents, and to spend time with their friends unsupervised. This is important because it suggests that, even if adolescents were not interested in nature and biodiversity *primarily,* they may still use and benefit from green spaces. Indeed, adolescents report that they use green spaces mainly for physical and social activities, not so much to experience nature (Bloemsma et al., 2018). This suggests that, for adolescents, high levels of biodiversity may not be a main driver for a visit to a green space. Therefore, adolescents living beyond 1000 m walking distance from a SINC may not necessarily experience a disadvantage from this 'poorer access' because they may have access to other green spaces that meet their needs. This is also suggested by adolescents' preferences for certain characteristics of green spaces. Adolescents report that they value characteristics such as playgrounds, sports and picnic areas, and trails (Rivera et al., 2021; Van Hecke et al., 2016), which may not necessarily be provided by SINCs. Therefore, it is important to consider that high levels of biodiversity may not be the most important factor for adolescents to visit green spaces. Unfortunately, we did not have data on adolescents' actual use of green spaces or their preferences. These data would have helped us to understand better whether adolescents actually visit SINCs (and/or what other green spaces they visit), and whether this could explain our null findings. It would have allowed us to ask a range of interesting questions. For example, we could have tested whether visits of SINCs moderate the association between access to SINCs and mental health and well-being. Further, we could have investigated whether living within 1000 m of a SINC actually means 'good access' for adolescents and whether there may be other barriers that may prevent adolescents from visiting SINCs. Future studies would benefit from using a range of data to investigate these (and more) questions and add to our understanding of the association between biodiversity and adolescent mental health and well-being.

However, as discussed earlier, even though adolescents may not actively seek or use green spaces with high levels of biodiversity, they may still benefit due to passive or incidental exposure, for example, by walking past or through a green space, by simply viewing green space, or by breathing cleaner air. In fact, incidental (rather than intentional) exposure to green spaces may be one of the most important types of everyday exposure (Mears et al., 2021). Under the assumption that more biodiverse green spaces provide greater benefits, especially via mitigation and restoration, one could argue that, even if adolescents do not intentionally visit more biodiverse green spaces, they still benefit, simply by living in close proximity to them. In other words, one could expect a positive association between access to SINCs and mental health and well-being. However, it is plausible that other factors play a greater role in adolescent mental health and well-being, so biodiversity likely has very small effects on our outcomes and for our age range. Moreover, our measure of biodiversity may not have been sensitive enough because it did not assess the extent of biodiversity or adolescents' actual incidental or passive exposure to SINCs (or biodiversity more generally).

This leads to the second possible explanation for our null findings, related to limitations of our measure of exposure and potential exposure misclassification bias. In our study, poor access to SINCs was defined as living beyond 1000 m walking distance from a SINC, following GiGL's definition of AoDs. Although GiGL used a sophisticated measure to calculate walking distances to SINCs (arguably a more accurate assessment of exposure than, for example, Euclidean distances), whether 1000 m is a meaningful walking distance for adolescents is an open question. If an adolescent lives within 1000 m of a SINC, they may still need to make an intentional visit to the SINC to benefit from it. As discussed earlier, it is unclear whether the average adolescent would make this decision because they may prefer other green spaces nearby.

An additional limitation associated with our exposure variable is the definition of biodiversity. SINCs are an important component of London's biodiversity, however, the designation does not quantify the level of biodiversity or distinguish between types of biodiversity (e.g., floral, animal, and bird biodiversity). Although SINCs are designated for their importance for the local habitat, it is unclear what exactly a SINC looks like and how biodiverse a SINC is. In fact, two SINCs may have very different characteristics, both in terms of biodiversity and other qualities. Therefore, it would be worth investigating further whether certain types and levels of biodiversity may be associated with adolescent mental health and well-being in London (and beyond). This could be achieved by using measures of species richness and/or abundance, considering different taxa and species within taxa. In fact, as described earlier, most studies that found positive associations between biodiversity and adult mental health and well-being used species richness as a measure of biodiversity, and it would be interesting to investigate whether species richness may play a role in adolescent mental health and well-being too.

Another limitation of our binary exposure variable is loss of variance. For example, two adolescents living on the edge of an AoD, one on the inside, the other on the outside, essentially have the same real-world exposure, but their value on the binary exposure variable would be different. Furthermore, two adolescents living outside an AoD may have very different exposures: one of them may live right next to a SINC, whereas the other may live further away. However, both would have the same value on the binary exposure variable. Similarly, two adolescents living inside an AoD may also have very different exposures: one of them may live just over 1000 m away from a SINC, whereas the other may live much further away. Again, they would have the same value on the binary exposure variable. Ultimately, a binary exposure variable does not capture these nuances and, therefore, may add significantly to exposure misclassification bias. Future studies could compare exposures on categorical and continuous scales. Also, in addition to assessing exposure around the home, one could assess actual exposure to biodiversity (e.g., by tracking where adolescents go and for how long).

Before we draw final conclusions, we would like to highlight some additional study limitations. First, our analysis used observational data and was cross-sectional. Future studies would benefit from a longitudinal analysis into the association between access to biodiverse green spaces and mental health and well-being. Second, our study focused on London, a large, urban area in the southeast of England. Our null findings may not generalise to other urban or rural areas in the UK or beyond. Future studies that investigate associations in different geographies and cultures are needed. Third, our findings may be biased, especially due to exposure misclassification bias, as discussed earlier. Future studies would benefit from the investigation of more specific types of biodiversity and other measures of exposure. Fourth, due to our focus on London, we had to accept a decrease in sample size, in turn reducing statistical power to detect potentially small associations. For example, Knight et al. (2022), who found an association between AoDs and life satisfaction in adults, had a larger sample of over 1500 adults followed longitudinally (which increased the number of included observations to over 9000). Future studies should investigate associations in larger samples. Finally, due to our use of quantitative data, we had to make certain assumptions and could only speculate about some of the potential reasons for our null findings. Qualitative data (e.g., from interviews with adolescents in London) would complement our quantitative data and would allow for a more nuanced understanding of adolescents' views on, and use of, green spaces and biodiversity in London. Future studies would, therefore, benefit from using both quantitative and qualitative data.

5. Conclusion

In the present study, we investigated the association between access to green spaces with high levels of biodiversity and mental health, self-esteem, and happiness in young adolescents living in London. Across outcomes and ages, we did not find a robust association. This may be because other factors play a more important role in adolescent mental health and well-being (e.g., peer relationships) or because adolescents prefer, or benefit from, other types of green spaces. Our findings may also be explained by our definitions of biodiversity and access, or by potentially low statistical power due to small sample sizes. It is important to highlight that, from our findings, we cannot infer that biodiversity does not play a role in adolescent mental health and well-being. Future studies are needed to investigate the association between urban biodiversity and adolescent mental health and well-being, using a more comprehensive measure of exposure to biodiversity and larger samples not limited to London. A better understanding of the association between urban biodiversity and adolescent mental health and well-being could have implications for urban policy, planning, and design. For example, a better understanding of the barriers and facilitators for adolescents' use of biodiversity (and associations with their mental health and well-being) could inform inclusive design of urban green spaces that would allow adolescents to benefit from urban biodiversity.

Author statement

Marie A. E. Mueller: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing. Eirini Flouri: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

Declarations of competing interest

None.

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