A cross-sectional analysis of biodiversity, publicly accessible green space and mental well-being in Wales using routinely collected data

Oliver Thwaites [a,*], Amy Mizen [a], Richard Fry [a]

[a] Environment and Health (ENVHE) Research Centre, Population Data Science, Swansea University, Wales, UK

HIGHLIGHTS

- Investigated associations between publicly accessible green space, biodiversity and mental well-being in Wales.
- Bird species richness displayed a non-linear relationship with well-being in adjusted models.
- Bird, plant and total species richness were associated with well-being in urban LSOAs.
- Bird species richness results were robust to changing LSOA size and the recorded sighting within them.

ARTICLE INFO

ABSTRACT

There is a lack of studies investigating the effects of green space and biodiversity on mental well-being, across a large study area. Generally, exposure to natural environments promotes better physical health, mental health and well-being. This study investigated associations between publicly accessible green space, biodiversity and mental well-being for individuals living in Wales using routinely collected survey and biodiversity data. This study used the Warwick-Edinburgh Mental Well-Being Scale (WEMWBS) to measure mental well-being. The 2018–19 National Survey for Wales responses containing the WEMWBS scores and socio-demographic factors were linked to green space and biodiversity data in census areas. By utilising Generalised Additive Models this study found that all environmental metrics were associated with mental well-being. However, after adjustment for socio-demographic factors, only bird species richness remained associated with mental well-being, with a highly non-linear relationship. There was little to no evidence of associations between green space or biodiversity when stratifying by income group. When stratified by rural and urban areas, we found bird, plant and total species richness to be associated with mental well-being.

Environmental interventions should consider promoting bird species richness in urban areas which may benefit mental well-being. Future areas of research could include longitudinal studies to explore causal links between green spaces, biodiversity and mental well-being, utilising individual-level exposure.

1. Introduction

Urban environments have a lack of natural space compared to rural towns and villages and reduce the opportunity for people to interact with nature (Copenhagen: WHO Regional Office for Europe, 2021). Urban green space environments are often a reduced size and fragmented which in turn affects the number and variety of species that depend on them (McKinney, 2008). Access to green space is not homogenous, it can vary across rural and urban areas and by deprivation (Natural England, 2020), leading to an imbalance in the accessibility and health-promotion potential of green spaces across different socio-economic groups (Copenhagen: WHO Regional Office for Europe, 2021; Public Health England, 2020).

These trends may have a detrimental effect for humans, as there is a growing body of evidence that interacting with natural environments is beneficial for health and mental well-being (Aerts et al., 2018; Houlden et al., 2021; Lovell et al., 2014; Reyes-Riveros et al., 2021). For example, activities such as walks in natural environments can have more positive effects than walks in urban or synthetic environments (e.g. gyms) (Bowler et al., 2010). Interacting with nature has been shown to have cognitive (e.g. attention restoration), physiological (e.g. stress reduction, reduced blood pressure) and mental well-being benefits (e.g.
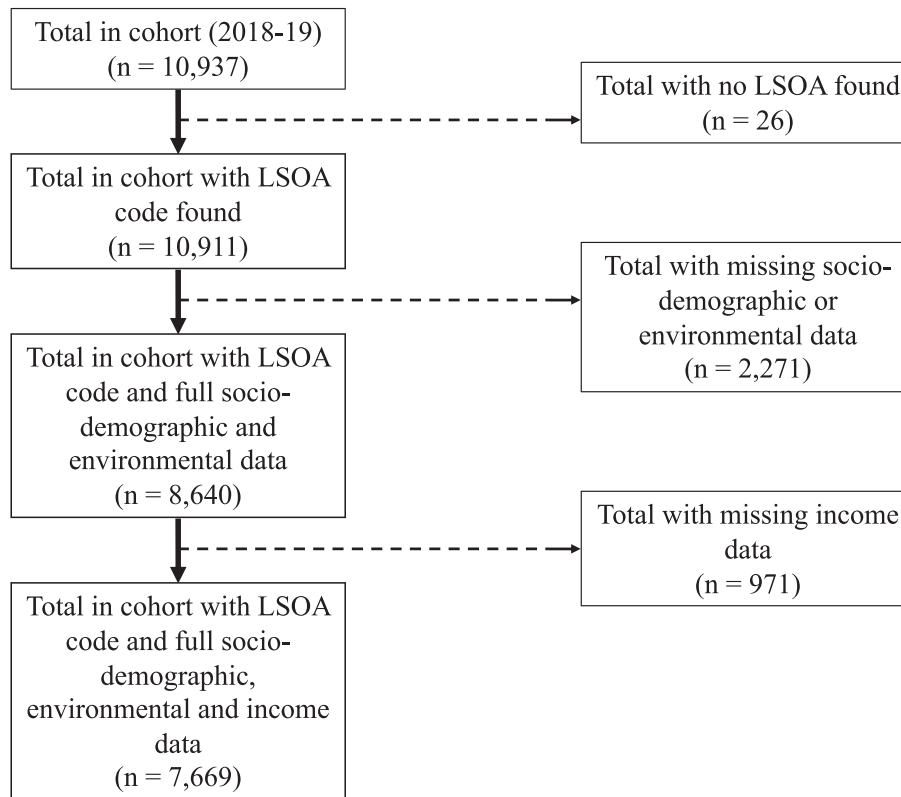

Fig. 1. Flow diagram of cohort preparation. LSOA = Lower layer Super Output Area.
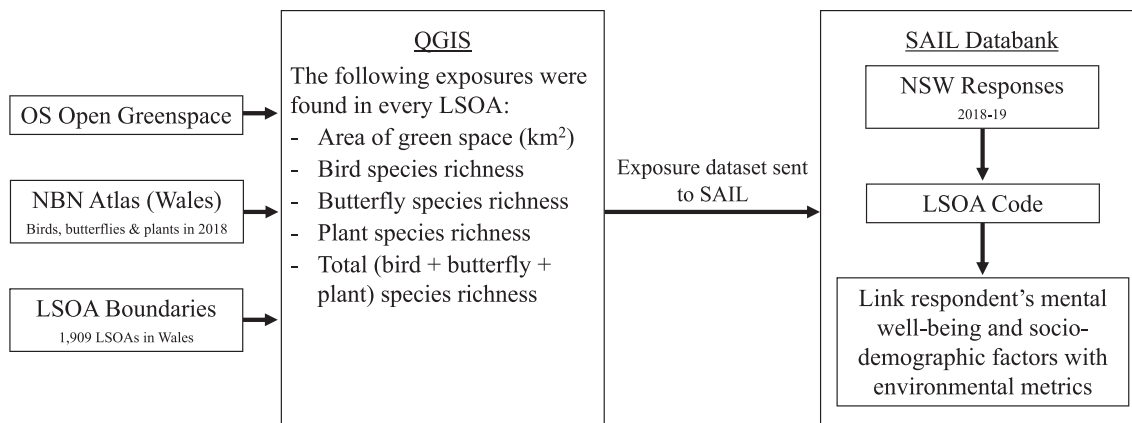

Fig. 2. The process to create the linked dataset between the five exposure variables and the National Survey for Wales (NSW) responses. OS = Ordnance Survey; NBN = National Biodiversity Network; LSOA = Lower layer Super Output Area; SAIL = Secure Anonymised Information Linkage.

improved self-esteem and mood) (Keniger et al., 2013). In terms of the economic benefits, access to green space has been estimated to provide savings to the National Health Service in the hundreds of millions of pounds sterling, with the potential of billions of pounds worth of savings if everyone had good access to green space (Public Health England, 2020).

However, the effects of exposure to or direct contact with biodiversity on well-being is less well understood (Houlden et al., 2021; Marselle, Lindley, et al., 2021). In the UK, several studies investigated the effects of biodiversity on well-being in small areas in England (Cameron et al., 2020; Cox et al., 2017; Dallimer et al., 2012; Fuller et al., 2007; Southon et al., 2018; Wood et al., 2018) and Wales (Adjei & Agyei, 2015). These studies typically investigated one or more of bird, butterfly or plant species richness. Bird or plant species richness are commonly

associated with improved mental well-being (Cameron et al., 2020; Cox et al., 2017; Dallimer et al., 2012; Southon et al., 2018), however butterfly species richness has repeatedly been found to have no association with mental well-being (Dallimer et al., 2012; Fuller et al., 2007; Southon et al., 2018).

There are several proposed mechanisms through which mental well-being can be improved by exposure to biodiversity. Mental well-being is multidimensional, concerned with emotions and psychological functioning (Linton et al., 2016). Alongside indices of psychological well-being (Dallimer et al., 2012; Fuller et al., 2007; Luck et al., 2011) and life satisfaction (Methorst et al., 2021), previous research indicates that biodiversity is associated with increases in positive emotions/affects (Cameron et al., 2020; Marselle et al., 2016; Wolf et al., 2017). Such findings are not limited to terrestrial biodiversity, as positive affect and

Table 1

Full socio-demographic breakdown of the cohort ($n = 8,640$). Note that percentages may not equal to 100, as exact proportions of groups with less than one percent of the total cohort size are masked to preserve anonymity.

Variable	Proportion of Cohort (%)
Female	55.52
Male	44.48
White - Welsh/English/Scottish/Northern Irish/British	94.86
White - Irish	< 1 %
White - Gypsy or Irish Traveller	< 1 %
White - Polish	< 1 %
White - Other	1.32
Mixed - White and Black Caribbean	< 1 %
Mixed - White and Black African	< 1 %
Mixed - White and Asian	< 1 %
Mixed - Other	< 1 %
Asian - Indian	< 1 %
Asian - Pakistani	< 1 %
Asian - Bangladeshi	< 1 %
Asian - Chinese	< 1 %
Asian - Other	< 1 %
Black - African	< 1 %
Black - Caribbean	< 1 %
Black - Other	< 1 %
Other - Arab	< 1 %
Other - Any other ethnic group	< 1 %
Full-time student (including on holiday)	3.54
In any paid employment or self-employment (or away temporarily)	49.06
On a government sponsored training scheme	< 1 %
Doing unpaid work for a business that you or a relative owns	< 1 %
Waiting to take up work already obtained	< 1 %
Unemployed and looking for work	2.07
Intending to look for work but prevented by a temporary sickness or injury (28 days or less)	< 1 %
Unable to work because of a long-term sickness or disability	4.73
Retired	34.76
Looking after home or family	4.86
Doing something else	< 1 %

Table 3

Means and standard deviations for publicly accessible green space and species richness.

Variable	Mean	Standard Deviation
Area of Publicly Accessible Green Space (km^2)	0.12	0.29
Bird Species Richness	26.58	32.70
Butterfly Species Richness	0.79	3.46
Plant Species Richness	10.68	41.22
Total Species Richness	38.06	61.44

(Korpela et al., 2018; Markevych et al., 2017), were used in our adjusted models. We also stratified our cohort by income and whether they live in a rural or urban area. This allowed us to explore the confounding effects of where and how people are able to live given their socio-economic status. Therefore, our research questions are:

1. Is green space or biodiversity associated with mental well-being?
2. Are these relationships affected by socio-demographic factors?
3. Do these relationships persist across different income groups?
4. Do these relationships persist across rural and urban areas?

Well-being is a key indicator for the Welsh Government, outlined through seven goals in the Well-being of Future Generations (Wales) Act 2015 (Welsh Government, 2015). One of these goals is 'A resilient Wales', focussing on maintaining and enhancing a biodiverse natural environment (Welsh Government, 2015). The Future Generations Commissioner recommended that the Welsh Government should adopt a policy to ensure accessible biodiverse green space within 300 m for everyone in Wales (Future Generations Commissioner for Wales, 2020).

2. Methods

2.1. Data sources

Previous studies have identified a wide variety of definitions of mental well-being (Hedin et al., 2022; Linton et al., 2016) and occasionally definitions are not given at all (Lovell et al., 2014). This can lead to difficulties in assessing how natural environments affect mental well-being. Improving well-being is a worthwhile goal in its own right, but well-being is also linked with physical health, which in turn has a beneficial impact on reducing the healthcare burden (Department of Health, 2014).

Therefore, following recommendations from the literature (e.g. Marselle et al., 2019) this study used a validated subjective instrument to record mental well-being in the Warwick-Edinburgh Mental Well-Being Scale (WEMWBS) (Tennant et al., 2007). The WEMWBS covers eudaimonic (i.e. meaning, autonomy, vitality and transcendence (Capaldi et al., 2015)) and hedonic (i.e. subjective or emotional (Capaldi et al., 2015)) well-being, as well as psychological functioning (Tennant et al., 2007). The WEMWBS is included in the National Survey for Wales (NSW), an annual survey involving approximately 10,000 respondents. This information is housed in the Secure Anonymised Information Linkage databank (Jones et al., 2019). To preserve the anonymity of the

arousal have been shown to be associated with marine diversity in an experimental study (White et al., 2017). Interactions with nature can also result in transcendent experiences (Marselle et al., 2021), with feelings of awe, humility and reflection all contributing to well-being (Capaldi et al., 2015; Pritchard & Richardson, 2022).

Most of the previous research has occurred on small spatial scales, often investigating green spaces within a single city, therefore what is particularly lacking is studies across large spatial scales (Houlden et al., 2021; Methorst et al., 2021). A European study of 32 countries included bird, mammal and tree species richness but found that only bird species richness was positively associated with life satisfaction (Methorst et al., 2021). That study calculated exposure at a regional level within countries, with nine regions in England, and one each in Wales, Scotland and Northern Ireland. This study explores the feasibility of using green space data and routinely-collected survey and biodiversity data at population scale to investigate associations between green space, species richness and mental-being in small areas across Wales. Socio-demographic variables, which have been highlighted as lacking in previous research

Table 2

A correlation matrix between publicly accessible green space and species richness.

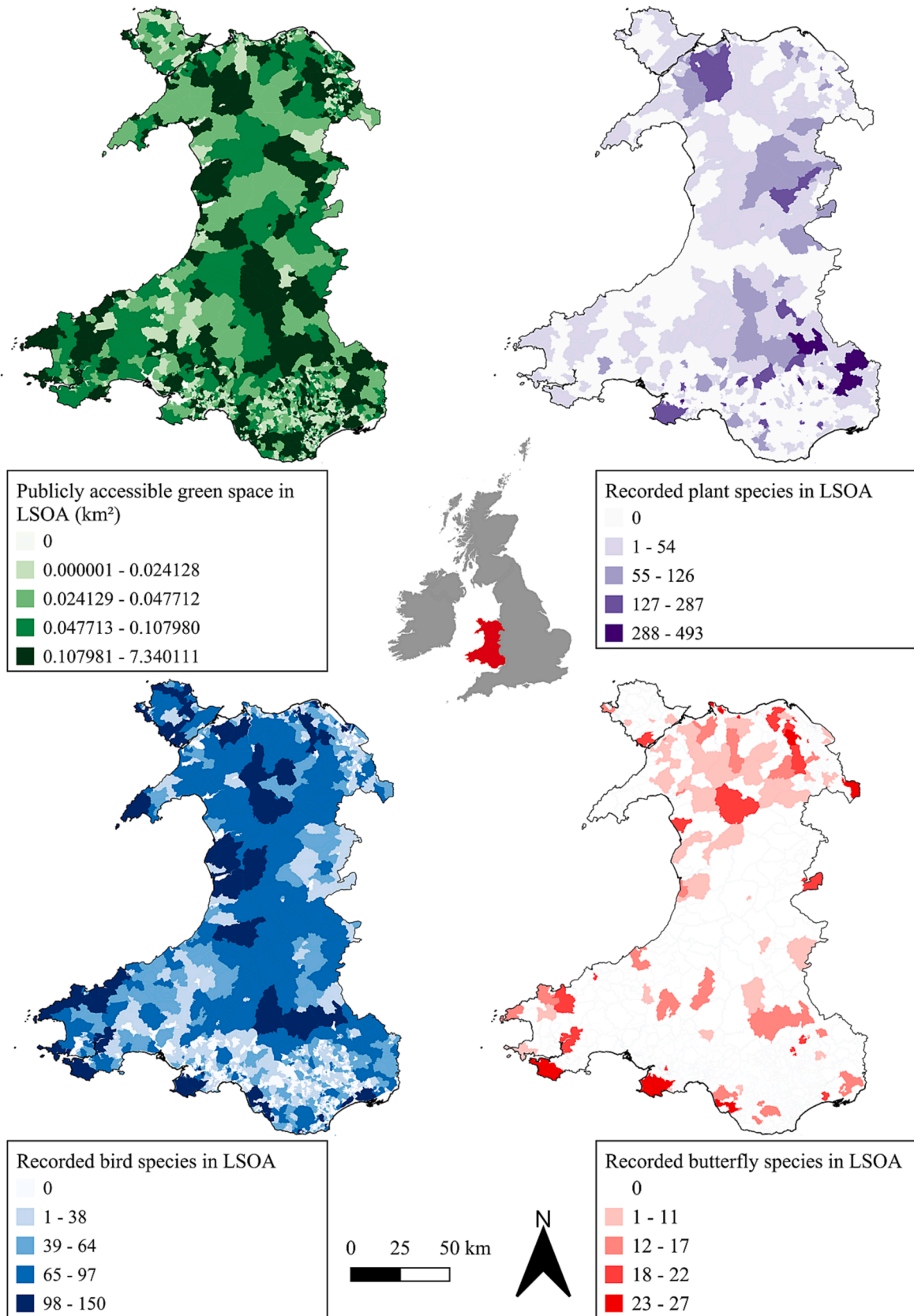|	Area of Publicly Accessible Green Space (km^2)	Bird Species Richness	Butterfly Species Richness	Plant Species Richness	Total Species Richness
Area of Publicly Accessible Green Space (km^2)	1.00	0.25	0.11	0.13	0.23
Bird Species Richness	0.25	1.00	0.38	0.32	0.77
Butterfly Species Richness	0.11	0.38	1.00	0.18	0.38
Plant Species Richness	0.13	0.32	0.18	1.00	0.85
Total Species Richness	0.23	0.77	0.38	0.85	1.00
Note: All p-values < 0.001					

Fig. 3. The prevalence of publicly accessible green space and the recorded number of plant, butterfly and bird species at Lower layer Super Output Area (LSOA) level across Wales, using data from the National Biodiversity Network Atlas Wales and Ordnance Survey for 2018.

Table 4
Generalized Additive Model outputs for each of the unadjusted and adjusted models.

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score									
	Green Space Univariate	Green Space Multivariate	Bird Species Univariate	Bird Species Multivariate	Butterfly Species Univariate	Butterfly Species Multivariate	Plant Species Univariate	Plant Species Multivariate	Total Species Univariate	Total Species Multivariate
Area of Publicly Accessible Green Space	edf: 1.83*	edf: 3.875								
Bird Species Richness			edf: 5.708***	edf: 6.056***						
Butterfly Species Richness					0.068* (0.029)	0.026 (0.028)				
Plant Species Richness							edf: 3.688**	edf: 1.775		
Total Species Richness									edf: 2.261***	edf: 1.576
Gender (Male)		–		–		–		–		–
Gender (Female)		−0.403* (0.197)		−0.410* (0.197)		−0.396* (0.197)		−0.395* (0.197)		−0.396* (0.197)
White (Welsh/ English/Scottish/ Northern Irish/ British)		–		–		–		–		–
White (Irish)		−0.662 (1.392)		−0.549 (1.390)		−0.559 (1.392)		−0.594 (1.392)		−0.571 (1.391)
White (Gypsy or Irish Traveller)		−3.028 (5.199)		−2.992 (5.193)		−3.050 (5.200)		−3.023 (5.199)		−3.047 (5.198)
White (Polish)		2.220 (1.269)		2.284 (1.268)		2.192 (1.270)		2.222 (1.270)		2.220 (1.269)
White (Other)		2.577** (0.851)		2.650** (0.850)		2.615** (0.851)		2.625** (0.850)		2.616** (0.850)
Mixed (White and Black Caribbean)		1.969 (2.212)		1.977 (2.210)		1.959 (2.213)		1.980 (2.212)		2.011 (2.212)
Mixed (White and Black African)		0.818 (2.845)		0.624 (2.843)		0.783 (2.846)		0.806 (2.845)		0.740 (2.845)
Mixed (White and Asian)		1.493 (3.181)		1.461 (3.178)		1.434 (3.182)		1.498 (3.182)		1.481 (3.181)
Mixed (Other)		5.169 (3.183)		5.239 (3.180)		5.177 (3.184)		5.196 (3.184)		5.167 (3.183)
Asian (Indian)		4.102* (1.651)		4.153* (1.645)		4.052* (1.647)		4.066* (1.646)		4.080* (1.646)
Asian (Pakistani)		0.346 (2.331)		0.475 (2.328)		0.478 (2.331)		0.457 (2.331)		0.496 (2.331)
Asian (Bangladeshi)		2.946 (2.124)		2.789 (2.122)		2.897 (2.124)		2.969 (2.124)		2.978 (2.124)
Asian (Chinese)		4.788 (2.599)		4.983 (2.596)		4.817 (2.599)		4.851 (2.599)		4.899 (2.599)
Asian (Other)		4.729** (1.738)		4.659** (1.736)		4.739** (1.738)		4.734** (1.738)		4.737** (1.738)
Black (African)		2.148 (1.778)		2.349 (1.777)		2.116 (1.779)		2.148 (1.779)		2.195 (1.779)
Black (Caribbean)		5.298 (5.204)		6.400 (5.187)		6.062 (5.194)		6.090 (5.193)		6.111 (5.193)
Black (Other)		−0.695 (3.001)		−0.671 (2.998)		−0.707 (3.001)		−0.675 (3.001)		−0.601 (3.001)
Other (Arab)		0.628 (2.851)		0.663 (2.848)		0.616 (2.851)		0.646 (2.851)		0.665 (2.851)
Other (Any Other Ethnic Group)		3.284* (1.410)		3.299* (1.408)		3.267* (1.410)		3.280* (1.410)		3.312* (1.410)
Full Time Student		–		–		–		–		–
Paid Employment or Self-Employment		0.685 (0.641)		0.610 (0.640)		0.663 (0.642)		0.641 (0.641)		0.638 (0.642)
Government Sponsored Training Scheme		3.396 (5.271)		3.402 (5.266)		3.277 (5.273)		3.359 (5.271)		3.323 (5.271)
Unpaid Work for Own or Relative-Owned Business		3.618 (2.672)		3.557 (2.670)		3.539 (2.674)		3.554 (2.672)		3.523 (2.672)
Waiting to Start Obtained Job		−1.999 (2.773)		−1.998 (2.770)		−2.043 (2.774)		−2.138 (2.773)		−2.106 (2.773)
Unemployed and Looking for Work		−5.784*** (0.899)		−5.784*** (0.898)		−5.809*** (0.899)		−5.813*** (0.899)		−5.787*** (0.899)

Table 4 (*continued*)

	Green Space Univariate	Green Space Multivariate	Bird Species Univariate	Bird Species Multivariate	Butterfly Species Univariate	Butterfly Species Multivariate	Plant Species Univariate	Plant Species Multivariate	Total Species Univariate	Total Species Multivariate
Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score										
Not Working Due to Temporary Sickness or Injury		−7.252** (2.211)		−7.336*** (2.208)		−7.289*** (2.211)		−7.295*** (2.211)		−7.257** (2.211)
Unable to Work Due to Long-Term Sickness or Injury		−10.904*** (0.778)		−10.929*** (0.777)		−10.929*** (0.778)		−10.937*** (0.778)		−10.907*** (0.778)
Retired		0.365 (0.733)		0.311 (0.731)		0.329 (0.733)		0.325 (0.733)		0.318 (0.733)
Looking After Home or Family		−1.786* (0.759)		−1.815* (0.755)		−1.826* (0.757)		−1.837* (0.757)		−1.826* (0.757)
Doing Something Else		−0.994 (1.541)		−0.991 (1.539)		−0.988 (1.541)		−1.028 (1.541)		−1.028 (1.541)
Age		edf: 5.028***		edf: 4.997***		edf: 5.062***		edf: 5.038***		edf: 5.050***
Intercept	51.195*** (0.102)	51.575*** (0.643)	51.195*** (0.104)	51.634*** (0.642)	51.141*** (0.104)	51.577*** (0.644)	51.195*** (0.102)	51.610*** (0.643)	51.195*** (0.102)	51.610*** (0.644)
Observations	8,640	8,640	8,640	8,640	8,640	8,640	8,640	8,640	8,640	8,640
Adjusted R²	0.001	0.097	0.005	0.099	0.001	0.096	0.002	0.096	0.003	0.097
Log Likelihood	−31,669.6	−31,251.59	−31,653.64	−31,242.56	−31,670.1	−31,252.26	−31,667.07	−31,251.31	−31,660.7	−31,250.58

Note: $p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; edf = effective degrees of freedom

respondents, this research took place at the Lower layer Super Output Area (LSOA) level – a statistical disclosure control geography used in England and Wales (Office for National Statistics, 2021).

LSOA boundaries were downloaded from the Lle Geo-Portal (Lle: A Geo-Portal for Wales, 2011). Lle is a partnership between the Welsh Government and Natural Resources Wales, serving as a hub of open-source data, primarily covering the environment. LSOAs vary in size but are the smallest units of geography at which census data is estimated and are designed to be as homogenous as possible with respect to type of dwelling and urban/rural areas (Office for National Statistics, 2021). There are 1,909 LSOAs in Wales, each containing a number of households between 400 and 1,200 and a population between 1,000 and 3,000 (Office for National Statistics, 2021), with a mean population of approximately 1,500 (Public Health England, 2018). The classifications of rural or urban 2011 LSOAs were acquired from the Department for Environment, Food & Rural Affairs (Department for Environment, Food & Rural Affairs, 2021). LSOAs will be referred to as census areas.

Green space data was downloaded from Ordnance Survey (Ordnance Survey, 2021). This contains publicly accessible green spaces, including public parks or gardens, play spaces, sports areas or playing fields, churchyards or burial grounds, allotments or community growing spaces and golf courses. These are areas that the public can use for recreational activities and outside leisure, but sites are only included where a definitive boundary exists, and the entire site within it is a green space.

Biodiversity data was downloaded from the National Biodiversity Network (NBN) Atlas Wales (National Biodiversity Network, 2021). The NBN Atlas is the largest repository of biodiversity data in the UK, with over 200 million records of over 46,000 species, integrating multiple sources of information from citizen science volunteers to established groups such as the UK Butterfly Monitoring Scheme (National Biodiversity Network, 2021). All records across Wales in 2018 were downloaded for birds, butterflies and plants. There were 408,554 bird records, 17,198 butterfly records and 32,841 plant records. All records were either 'Accepted', 'Accepted – correct' or 'Accepted – considered correct'. The links used to download each set of records are in Appendix A.

2.2. Covariates

Socio-demographic variables were acquired from the survey responses. These variables were age, gender, ethnicity and economic status. We also used responses from a question on gross income to conduct a stratification analysis using income groups.

2.3. Study design

This national cross-sectional study linked individual mental well-being scores and socio-demographic information to area-level publicly accessibly green space and biodiversity metrics in Wales, UK. The species richness of birds, butterflies and plant were calculated by determining whether a recorded sighting fell within the census area boundary. A total species richness measure was created by adding the number of recorded bird, butterfly and plant species in each census area. The total area of publicly accessible green space and the species richness within each census area were determined using QGIS, version 3.16.0-Hannover (QGIS Development Team, 2021). Green space data and biodiversity indices were linked to national survey responses based on the census area IDs in R, version 4.1.0 (R Core Team, 2021). Figs. 1 and 2 outline the linkage process. An initial cohort of 10,937 NSW respondents was reduced to 10,911 as a census area ID was not available for 26 respondents (Fig. 1). After removing respondents who had missing data for any of the environmental or socio-demographic variables, the size of the cohort was 8,640. 1,761/1,909 (92 %) census areas were included in the final cohort.

To investigate the differences between groups of people with difference economic circumstances, we stratified the cohort according to
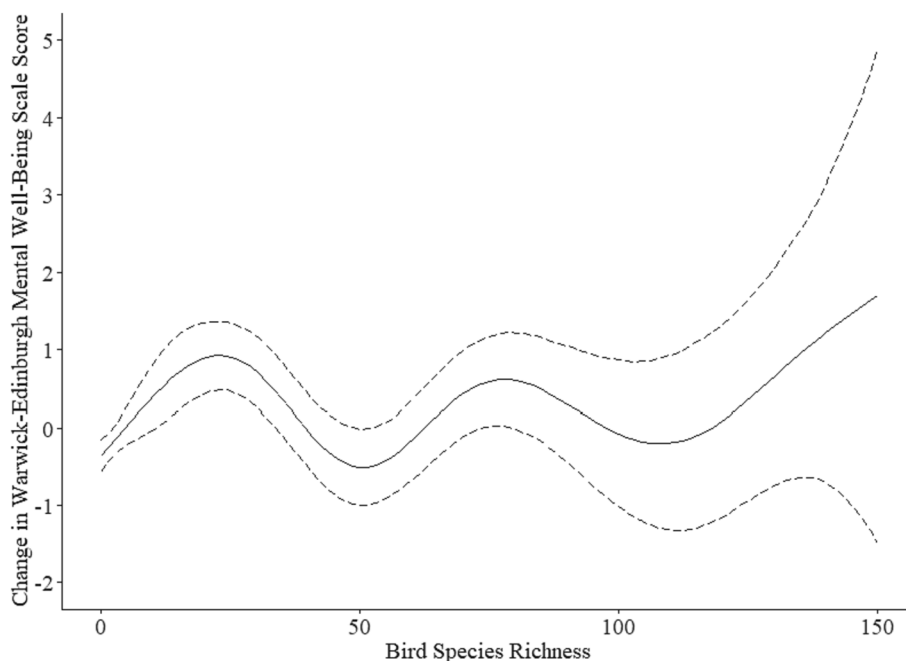
Fig. 4. The relationship between bird species richness and mental well-being, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.

Table 5
Proportion of the cohort ($n = 7{,}669$) in each income group.

Group	Income (£)	Proportion of Cohort (%)
1	< 10,400	27.6
2	10,400 – 20,799	35.9
3	20,800 – 31,099	19.6
4	31,100 – 41,499	11.7
5	> 41,500	5.2

income group, and ran an adjusted model for green space and species richness. We also stratified by rural and urban census areas. Furthermore, to account for uncertainty with the recording of the species sightings, we performed a sensitivity analysis with a series of adjustments to test the robustness of our results.

2.4. Statistical analysis

The statistical analysis was conducted in R (version 4.1.3). The plots in Appendix B, D and E were produced using the mgcViz package (Fasiolo et al., 2020). All tables were produced using the stargazer package (Hlavac, 2022). Generalised additive models (GAMs, 'mgcv' package, version 1.8-36 (Wood, 2011)) were used as they fit smooth functions to the predictors, so they can model non-linear data. Previous studies suggest that some of the relationships may be non-linear. For example, mental health and green space availability vary non-linearly with age across both sexes (Astell-Burt et al., 2014), and an inverted U-shape of stress recovery was found with increased plant species richness (Lindemann-Matthies & Matthies, 2018). A separate GAM was fit with each of the five predictors initially, then again adjusting for the socio-demographic factors. If any predictor was identified to have an effective degrees of freedom of one (a linear relationship), the GAM was rerun with the smooth term removed, allowing a coefficient to be identified.

3. Results

The mean WEMWBS score was 51.19 (s.d. 9.46), the median was 52

(IQR: 46–58) on a scale from 14 to 70, with 14 representing the lowest level of mental well-being and 70 representing the maximum level (Tennant et al., 2007).The cohort had a median age of 56 (IQR: 39–69), from a range of 16 to 97. Further socio-demographic characteristics of the cohort are outlined in Table 1.

A correlation matrix of green space and species richness is displayed in Table 2, while the mean and standard deviations are in Table 3. An overview of the distribution of publicly accessible green spaces and of the recorded bird, butterfly and plant species across Wales is presented in Fig. 3. The most common and widely recorded group was birds (Table 3, Fig. 3). Total species richness has a high correlation with bird and plant species richness (Table 2), as a result of birds and plants comprising most of the total (Table 3).

In unadjusted models, we found evidence of non-linear relationships between green space, bird, plant and total species richness (Table 4, Appendix B). However, the relationship was linear for butterfly species richness (Table 4, Fig. B4). In adjusted models, the only relationship to remain statistically significant was bird species richness, which was highly non-linear, showing increases and reductions in well-being depending on the number of recorded species (Table 4, Fig. 4). Females consistently had lower well-being than males, three ethnic groups consistently had higher well-being than White Welsh/English/Scottish/Northern Irish/British, and four economic statuses consistently had lower well-being compared to full time students (Table 4).

To mitigate uncertainty in the accuracy of the recorded locations of sighting, and the corresponding lack of coverage by certain groups (Fig. 3), we performed a sensitivity analysis in addition to our main analysis, but expanded the LSOA borders by 500 m, restricted the species records to only include sightings that had been recorded inside a 1x1 km grid reference or smaller, and recalculated which records occurred within these expanded borders. In addition to bird species richness, we now found plant species richness and total species richness to be associated with well-being (Appendix D).

Finally, we reran the main analysis but removed an LSOA if it did not have at least two recorded species for each of the different groups in Appendix E. For example, in the bird species richness models, each LSOA must have had two or more species recorded to remain included. In this analysis, only birds were associated with well-being (Table E1, Fig. E1).

Table 6
Generalized Additive Model outputs for the adjusted bird species richness models, stratified by income group.

|	Dependent variable:				
	Warwick-Edinburgh Mental Well-Being Scale Score				
	Income Group 1	Income Group 2	Income Group 3	Income Group 4	Income Group 5
Bird Species Richness	edf: 4.902	0.003 (0.005)	edf: 7.901**	edf: 4.639	edf: 7.008
Gender (Male)	–	–	–	–	–
Gender (Female)	0.153 (0.477)	−0.602 (0.341)	0.493 (0.427)	1.146* (0.573)	0.108 (0.809)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–	–	–	–	–
White (Irish)	−2.792 (3.017)	−0.165 (2.741)	−3.846 (3.644)	0.338 (3.113)	1.278 (3.723)
White (Gypsy or Irish Traveller)	−1.602 (5.761)				
White (Other)	4.197* (1.975)	0.863 (1.251)	0.827 (2.360)	0.901 (2.901)	4.655 (2.499)
Mixed (White and Black Caribbean)	−3.077 (3.922)	7.589* (3.547)	2.933 (8.124)	7.725 (8.169)	
Mixed (White and Black African)	−1.002 (5.769)	2.519 (4.995)	2.537 (5.746)	−2.771 (5.794)	
Mixed (White and Asian)	−7.660 (9.962)	4.881 (4.334)	−3.539 (5.745)	8.116 (8.177)	
White (Polish)	4.192 (2.597)	5.448** (2.058)	−0.523 (2.584)	−5.707 (8.172)	5.895 (5.245)
Mixed (Other)	9.230 (5.766)	4.736 (5.002)	2.498 (5.736)		
Asian (Indian)	6.815 (4.471)	2.014 (4.327)	6.748 (3.629)	−0.687 (2.906)	7.610* (3.804)
Asian (Pakistani)	−5.063 (4.081)	6.263 (4.327)	−11.069 (8.098)		6.503 (7.462)
Asian (Bangladeshi)	4.932 (3.337)	7.942 (4.324)	−4.206 (5.765)		
Asian (Chinese)	5.120 (7.055)	0.697 (4.995)	−0.673 (5.734)	8.373 (5.784)	9.430 (5.596)
Asian (Other)	8.666** (3.345)	2.544 (3.276)	4.092 (5.824)	−0.427 (4.731)	
Black (African)	1.443 (3.356)	5.747* (2.916)	−4.085 (4.193)	6.368 (8.160)	
Black (Caribbean)	8.625 (9.972)		1.503 (8.099)	8.933 (8.168)	
Black (Other)	12.861** (4.984)		−5.090 (5.736)		
Other (Arab)	3.167 (3.793)		−9.685 (8.110)	2.317 (8.425)	−2.753 (7.378)
Other (Any Other Ethnic Group)	−0.308 (3.332)	4.202 (2.169)	9.972** (3.316)	−10.035 (8.173)	3.609 (3.706)
Full Time Student	–		–	–	–
Paid Employment or Self-Employment	−1.768 (1.201)	−0.393 (1.220)	0.801 (2.014)	4.642 (2.741)	−2.665 (3.106)
Government Sponsored Training Scheme	3.738 (7.352)	9.380 (8.719)			
Unpaid Work for Own or Relative-Owned Business	0.302 (4.229)	3.594 (5.136)		13.245 (8.605)	
Waiting to Start Obtained Job	−4.136 (4.565)	−8.265 (5.117)	10.547 (8.378)	16.713 (8.582)	−3.425 (8.039)
Unemployed and Looking for Work	−5.879*** (1.460)	−3.514* (1.765)	−6.539 (4.182)	−5.912 (4.900)	
Not Working Due to Temporary Sickness or Injury	−8.338** (2.985)	−5.599 (4.490)		9.464 (8.591)	
Unable to Work Due to Long-Term Sickness or Injury	−11.831*** (1.337)	−8.778*** (1.504)	−6.573* (3.085)	0.376 (3.846)	−16.566** (5.044)
Retired	−1.431 (1.410)	−0.546 (1.352)	1.753 (2.135)	6.250* (2.889)	−4.334 (3.562)
Looking After Home or Family	−2.131 (1.280)	−3.905** (1.485)	3.894 (2.770)	5.844 (3.448)	−13.065** (4.525)
Doing Something Else	−4.881 (2.677)	−2.816 (3.502)	11.598* (4.534)	6.135 (5.436)	4.861 (8.054)
Age	edf: 4.130*	edf: 3.666***	edf: 2.824	0.059* (0.026)	0.068 (0.039)
Intercept	51.087*** (1.182)	52.153*** (1.255)	51.492*** (2.016)	44.422*** (2.939)	53.482*** (3.294)
Observations	2,114	2,757	1,502	900	396
Adjusted R²	0.139	0.067	0.043	0.036	0.070
Log Likelihood	−7,874.515	−9,869.887	−5,289.463	−3,179.176	−1,364.083
Note:	*p < 0.05; **p < 0.01; ***p < 0.001 edf = effective degrees of freedom				
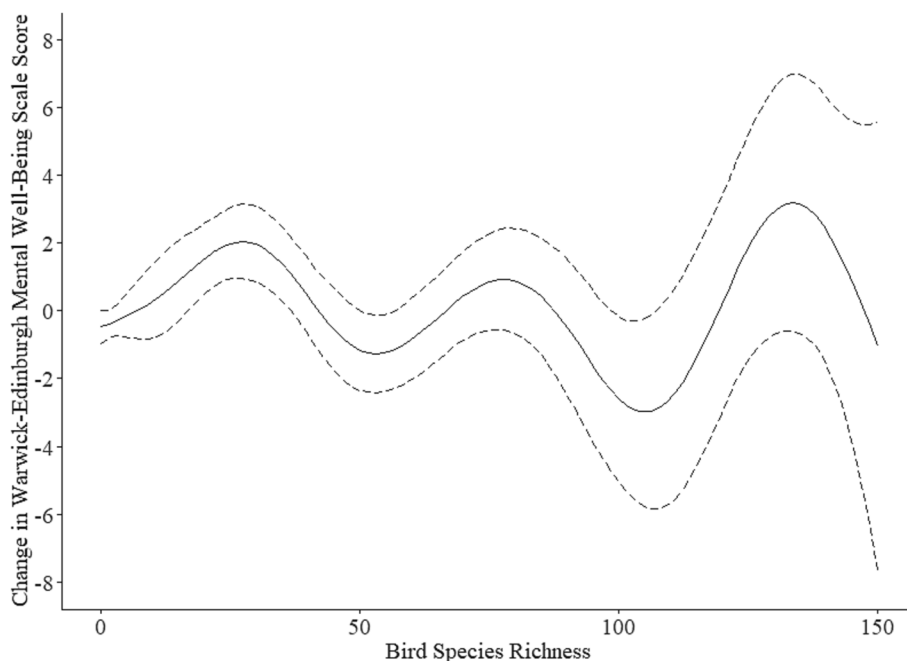
Fig. 5. The relationship between bird species richness and mental well-being in income group 3, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.

3.1. Stratified analysis

We stratified our results to investigate whether publicly accessible green space or species richness varied by socio-economic circumstances. In the National Survey for Wales, respondents are asked for their total personal income from all sources over the last 12 months before tax in one of five groups, though 971 respondents did not have these data, leading to a cohort size of 7,669 (Fig. 1). The proportion of the cohort in each group is presented in Table 5. For context, in April 2018 the median gross weekly earnings for full-time workers in Wales was £509 (Welsh Government, 2018), equivalent to £26,428 a year.

An unadjusted and an adjusted model were created for each of the five predictors (Fig. 2), for each income group (Table 5). We found no evidence of an association between the amount of publicly accessible green space, butterfly species richness, plant species richness or total species richness for any income group (Appendix C). However, we did find evidence of a non-linear relationship for bird species richness for participants in income group 3 in which respondents had an income between £20,800 and £31,099 (Table 6, Fig. 5). The relationship was similar to the full cohort (Table 4), in that increases and reductions in well-being are seen depending on the number of recorded species (Fig. 4).

We also stratified our results according to whether a census area was classified as rural or urban. In rural areas, there were no associations between green space or species richness with mental well-being (Table 7). In urban areas, there was a non-linear relationship between bird species richness and well-being (Table 7, Fig. 6), but not to the same extent as with the full cohort (Table 4, Fig. 4). After a peak at around 25 recorded bird species, the curve falls to around 60 recorded species, then increase up to the maximum recorded species (Fig. 6). For total species richness, a non-linear relationship with well-being was also found (Table 7). However, the wide confidence intervals after 100 recorded total species makes it difficult to determine whether this relationship is positively or negative associated with well-being (Fig. 7). Finally, there was evidence of a linear relationship between butterfly species richness and well-being where an increase of one butterfly species recorded in an urban area was associated with an increase in mental well-being score of 0.131 (Table 7, Fig. 8).

4. Discussion

As a single predictor, we found evidence of an almost quadratic relationship between the area of publicly accessible green space and mental well-being (Table 4, Fig. B1). However, this relationship did not remain after adjusting for socio-demographic factors (Table 4, Fig. B2). Previous research in the UK using similar methodologies have found similar results. In England, those living in LSOAs with a greater proportion of green space had better well-being scores, determined using the short version of the WEMWBS, but this relationship did not remain after adjustment (Houlden et al., 2017). A more recent study evaluated well-being using questions from the Office of National Statistics, finding that the proportion of green space within an LSOA, divided into quintiles, was not associated with well-being (White, Pahl, et al., 2017). Furthermore, in Scotland, there were no associations between well-being, determined using the World Health Organization Five Well-being Index (WHO-5), and perceived green space proximity, green space visit frequency or green space visit length in adjusted models (McDougall et al., 2022). Our study concurs with previous cross-sectional studies on green space and mental well-being (Houlden et al., 2018), finding no evidence of an association in adjusted models (Table 4, Figs. B1 and B2).

Total species richness followed a similar pattern to the total area of publicly accessible green space. In a single predictor model, we found evidence of a non-linear relationship between total species richness and mental well-being (Table 4, Fig. B8), but the statistical significance does not remain when covariates are adjusted for (Table 4, Fig. B9). This contrasts with previous research on composite measures of biodiversity. In a study in Bradford, England, the authors created an ecological richness score, described as the first principal component from plant, bird, bee/butterfly species and habitat number, which accounted for 84 % of the variance in the four aforementioned variables (Wood et al., 2018). There was no evidence that age and ethnicity explained variation in restoration and sex had a negligible effect, but ecological richness explained 43 % of the variation in the restorative benefit of green space (Wood et al., 2018). We did find that total species richness was associated with well-being when we expanded the LSOA borders and only included records with better location accuracy (Table D1, Fig. D3) and

Table 7
Generalized Additive Model outputs for the adjusted models, stratified by rural or urban Lower layer Super Output Areas.

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score									
	Green Space (Rural)	Green Space (Urban)	Bird Species (Rural)	Bird Species (Urban)	Butterfly Species (Rural)	Butterfly Species (Urban)	Plant Species (Rural)	Plant Species (Urban)	Total Species (Rural)	Total Species (Urban)
Total Area of Publicly Accessible Green Space	edf: 1.722	edf: 2.195								
Bird Species Richness			edf: 6.103	edf: 3.996***						
Butterfly Species Richness					−0.017 (0.031)	0.131* (0.063)				
Plant Species Richness							0.003 (0.003)	edf: 1.544		
Total Species Richness									0.002 (0.002)	edf: 6.776**
Gender (Male)	−	−	−	−	−	−	−	−	−	−
Gender (Female)	−0.126 (0.303)	−0.551* (0.258)	−0.144 (0.303)	−0.544* (0.258)	−0.124 (0.303)	−0.523* (0.258)	−0.118 (0.303)	−0.549* (0.258)	−0.121 (0.303)	−0.554* (0.258)
White (Welsh/ English/Scottish/ Northern Irish/ British)	−	−	−	−	−	−	−	−	−	−
White (Irish)	2.004 (2.163)	−2.377 (1.816)	2.083 (2.163)	−2.224 (1.810)	2.078 (2.164)	−2.244 (1.813)	2.008 (2.164)	−2.259 (1.814)	2.037 (2.164)	−2.247 (1.810)
White (Gypsy or Irish Traveller)	−7.091 (8.601)	−1.050 (6.541)	−7.208 (8.598)	−1.213 (6.529)	−7.213 (8.604)	−1.181 (6.540)	−7.129 (8.603)	−1.172 (6.542)	−7.168 (8.603)	−1.174 (6.529)
White (Polish)	−0.113 (3.868)	2.660 (1.374)	−0.409 (3.868)	2.494 (1.373)	−0.215 (3.870)	2.482 (1.375)	−0.190 (3.869)	2.625 (1.374)	−0.191 (3.869)	2.568 (1.372)
White (Other)	2.144 (1.425)	2.858** (1.063)	2.277 (1.423)	2.782** (1.062)	2.253 (1.425)	2.885** (1.063)	2.227 (1.424)	2.863** (1.063)	2.242 (1.424)	2.820** (1.062)
Mixed (White and Black Caribbean)	7.233 (6.084)	1.741 (2.436)	7.151 (6.083)	1.650 (2.432)	7.086 (6.086)	1.715 (2.436)	7.173 (6.085)	1.708 (2.437)	7.216 (6.087)	1.680 (2.432)
Mixed (White and Black African)	−0.234 (4.318)	1.176 (3.766)	−0.323 (4.317)	1.120 (3.763)	−0.368 (4.320)	1.023 (3.767)	−0.313 (4.319)	1.213 (3.767)	−0.312 (4.319)	0.925 (3.765)
Mixed (White and Asian)	−0.147 (6.084)	2.107 (3.767)	−0.360 (6.081)	2.017 (3.768)	−0.180 (6.087)	2.102 (3.767)	−0.174 (6.086)	2.091 (3.768)	−0.154 (6.087)	1.933 (3.766)
Mixed (Other)	5.361 (4.314)	5.001 (4.617)	5.528 (4.316)	4.783 (4.609)	5.356 (4.316)	5.024 (4.616)	5.444 (4.315)	4.998 (4.618)	5.429 (4.315)	4.818 (4.609)
Asian (Indian)	2.825 (3.559)	4.423* (1.889)	2.622 (3.515)	4.469* (1.887)	2.935 (3.516)	4.325* (1.890)	2.978 (3.516)	4.410* (1.890)	2.971 (3.516)	4.576* (1.887)
Asian (Pakistani)	1.388 (4.971)	0.200 (2.678)	1.856 (4.967)	0.126 (2.674)	1.605 (4.971)	0.243 (2.677)	1.611 (4.970)	0.235 (2.678)	1.648 (4.971)	0.125 (2.674)
Asian (Bangladeshi)	−3.507 (3.852)	5.678* (2.565)	−3.705 (3.853)	5.563* (2.561)	−3.539 (3.856)	5.697* (2.565)	−3.554 (3.853)	5.682* (2.566)	−3.579 (3.853)	5.590* (2.561)
Asian (Chinese)		4.948 (2.666)		5.039 (2.662)		5.002 (2.666)		4.980 (2.667)		5.054 (2.662)
Asian (Other)	−0.703 (2.875)	7.532*** (2.190)	−0.803 (2.877)	7.584*** (2.186)	−0.716 (2.876)	7.523*** (2.189)	−0.683 (2.876)	7.505*** (2.190)	−0.664 (2.877)	7.618*** (2.186)
Black (African)	7.336 (4.975)	1.548 (1.950)	7.225 (4.975)	1.625 (1.948)	7.233 (4.977)	1.463 (1.950)	7.317 (4.976)	1.549 (1.950)	7.360 (4.978)	1.723 (1.948)
Black (Caribbean)		5.335 (5.364)		6.334 (5.317)		6.130 (5.325)		6.110 (5.327)		6.383 (5.317)
Black (Other)	−21.270* (8.658)	1.700 (3.263)	−21.282* (8.654)	1.695 (3.257)	−21.445* (8.661)	1.781 (3.262)	−21.357* (8.660)	1.760 (3.263)	−21.323* (8.661)	1.723 (3.257)
Other (Arab)	−6.077 (8.603)	1.465 (3.087)	−5.560 (8.627)	1.491 (3.081)	−6.207 (8.607)	1.469 (3.086)	−6.115 (8.606)	1.458 (3.087)	−6.258 (8.607)	1.517 (3.082)

Table 7 (*continued*)

	Green Space (Rural)	Green Space (Urban)	Bird Species (Rural)	Bird Species (Urban)	Butterfly Species (Rural)	Butterfly Species (Urban)	Plant Species (Rural)	Plant Species (Urban)	Total Species (Rural)	Total Species (Urban)
				Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score						
Other (Any Other Ethnic Group)	5.922* (2.872)	2.529 (1.638)	5.725* (2.872)	2.455 (1.636)	5.837* (2.872)	2.564 (1.638)	5.880* (2.872)	2.531 (1.638)	5.894* (2.873)	2.531 (1.636)
Full Time Student	–	–	–	–	–	–	–	–	–	–
Paid Employment or Self-Employment	0.105 (1.168)	0.618 (0.741)	0.009 (1.166)	0.583 (0.741)	0.032 (1.168)	0.631 (0.740)	0.031 (1.168)	0.607 (0.741)	0.031 (1.168)	0.589 (0.741)
Government Sponsored Training Scheme	8.047 (8.682)	1.050 (6.657)	7.775 (8.680)	1.496 (6.647)	8.020 (8.688)	1.162 (6.656)	7.928 (8.684)	1.123 (6.658)	7.945 (8.685)	1.551 (6.647)
Unpaid Work for Own or Relative-Owned Business	5.305 (3.689)	1.354 (3.840)	4.977 (3.689)	1.463 (3.832)	5.233 (3.694)	1.410 (3.838)	5.082 (3.688)	1.379 (3.839)	5.040 (3.690)	1.501 (3.832)
Waiting to Start Obtained Job	−4.081 (3.669)	−0.128 (4.185)	−4.332 (3.665)	0.103 (4.178)	−4.258 (3.669)	−0.111 (4.184)	−4.260 (3.669)	−0.159 (4.186)	−4.237 (3.669)	−0.045 (4.178)
Unemployed and Looking for Work	−5.508*** (1.659)	−6.122*** (1.059)	−5.509*** (1.658)	−6.071*** (1.059)	−5.526*** (1.660)	−6.109*** (1.059)	−5.491*** (1.660)	−6.135*** (1.059)	−5.497*** (1.660)	−6.096*** (1.058)
Not Working Due to Temporary Sickness or Injury	−12.247** (4.460)	−5.962* (2.569)	−12.440** (4.458)	−6.047* (2.564)	−12.287** (4.462)	−5.935* (2.568)	−12.246** (4.461)	−5.991* (2.569)	−12.239** (4.462)	−6.113* (2.565)
Unable to Work Due to Long-Term Sickness or Injury	−11.575*** (1.408)	−10.800*** (1.407)	−11.749*** (1.407)	−10.790*** (0.916)	−11.717*** (1.407)	−10.756*** (0.916)	−11.669*** (1.407)	−10.799*** (0.916)	−11.651*** (1.408)	−10.776*** (0.916)
Retired	−1.334 (1.267)	1.486 (0.881)	−1.432 (1.264)	1.429 (0.880)	−1.422 (1.267)	1.467 (0.879)	−1.419 (1.266)	1.467 (0.881)	−1.415 (1.266)	1.457 (0.880)
Looking After Home or Family	−2.730 (1.401)	−1.646 (0.877)	−2.817* (1.398)	−1.628 (0.876)	−2.831* (1.400)	−1.626 (0.876)	−2.829* (1.400)	−1.648 (0.876)	−2.831* (1.400)	−1.617 (0.876)
Doing Something Else	−2.696 (2.318)	−0.412 (2.071)	−2.720 (2.316)	−0.355 (2.068)	−2.755 (2.319)	−0.378 (2.070)	−2.759 (2.318)	−0.427 (2.071)	−2.752 (2.318)	−0.338 (2.067)
Age	edf: 5.037***	edf: 3.343**	edf: 4.989***	edf: 3.382**	edf: 5.047***	edf: 3.3**	edf: 5.039***	edf: 3.328**	edf: 5.041***	edf: 3.373**
Intercept	52.774*** (1.170)	51.097*** (0.745)	52.880*** (1.167)	51.127*** (0.744)	52.882*** (1.171)	51.050*** (0.744)	52.786*** (1.171)	51.108*** (0.745)	52.736*** (1.178)	51.117*** (0.744)
Observations	3,346	5,294	3,346	5,294	3,346	5,294	3,346	5,294	3,346	5,294
Adjusted R^2	0.084	0.104	0.085	0.107	0.083	0.104	0.084	0.103	0.083	0.107
Log Likelihood	−11,963.59	−19,287.49	−11,963.18	−19,278.65	−11,964.56	−19,286.29	−11,964.2	−19,288.23	−11,964.41	−19,280.31

Note: *p < 0.05; **p < 0.01; ***p < 0.001.
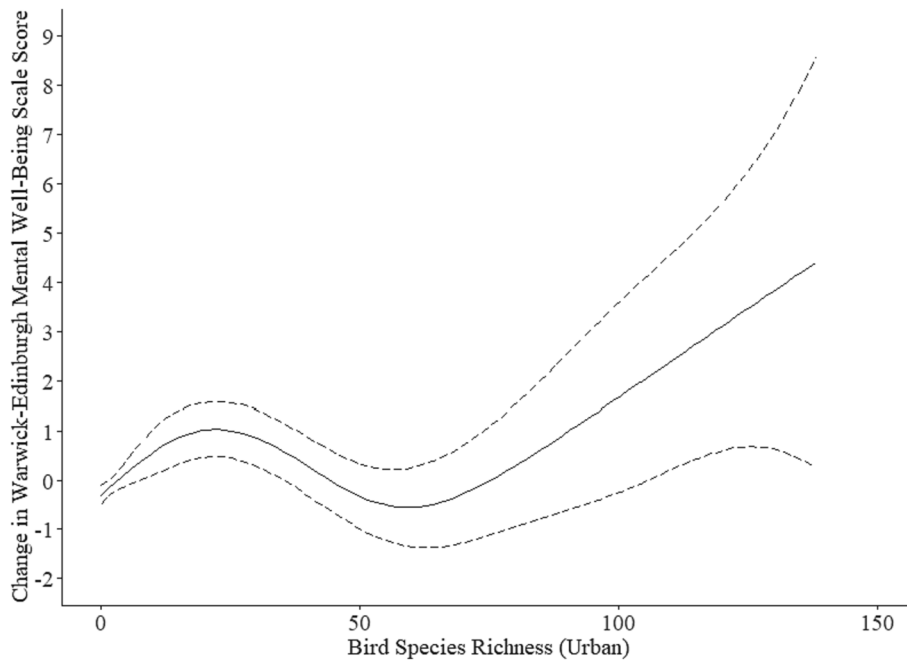edf = effective degrees of freedom.

Fig. 6. The relationship between bird species richness and mental well-being in urban Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.
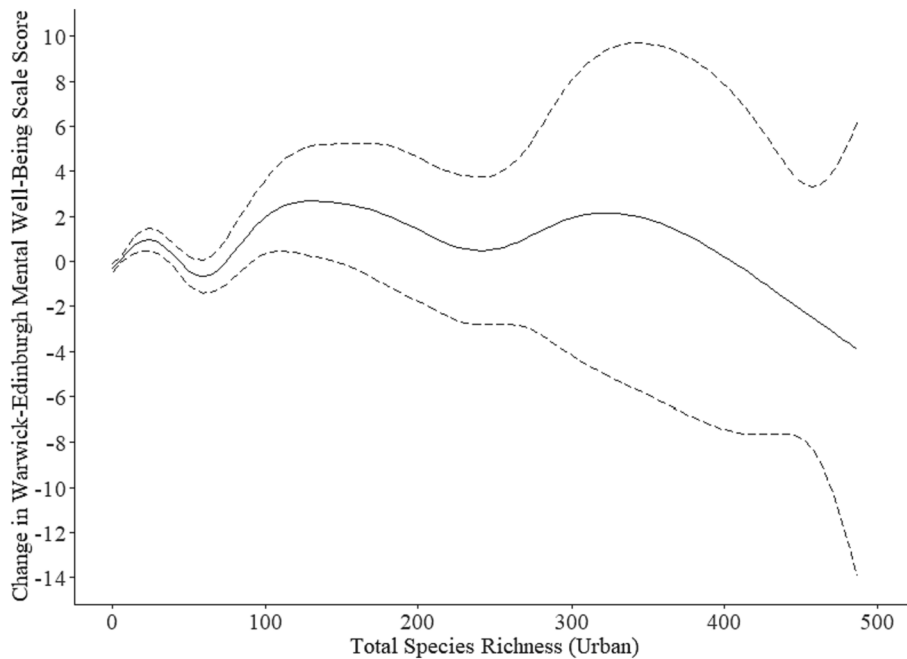

Fig. 7. The relationship between total (bird + butterfly + plant) species richness and mental well-being in urban Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95 % confidence interval.

by stratifying by rural and urban areas (Table 7, Fig. 7). This suggests that associations with biodiversity may be sensitive to changing study area size, and may be more apparent in urban areas compared to rural.

In the univariate models, all species richness metrics were associated with mental well-being (Table 4, Figs. 4, B3-4, B6, B8). These findings are broadly similar to previous research conducted in parks in Sheffield, England (Cameron et al., 2020; Dallimer et al., 2012; Fuller et al., 2007), but the inclusion of socio-demographic factors in this study provides a greater level of understanding. One study used species richness of bird, butterfly and plant species and looked at individual components of

mental well-being, namely reflection, distinct identity, continuity with past and attachment (Fuller et al., 2007). They found that bird species richness was positively associated with continuity with past and attachment, butterfly species richness had no associations and plant species richness was positively associated with reflection and distinct identity (Fuller et al., 2007). A later study looked at both actual and perceived levels of bird, butterfly and plant species richness (Dallimer et al., 2012). All perceived species richness levels were significantly positively related to mental well-being, but with the actual species richness levels mental well-being increased with bird species richness,
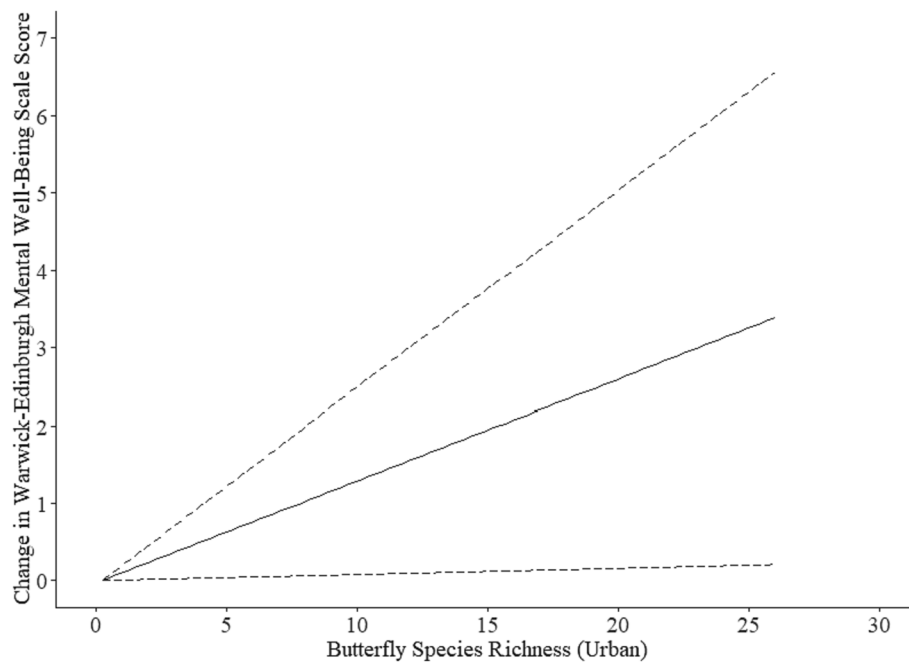
Fig. 8. The relationship between butterfly species richness and mental well-being in urban Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.
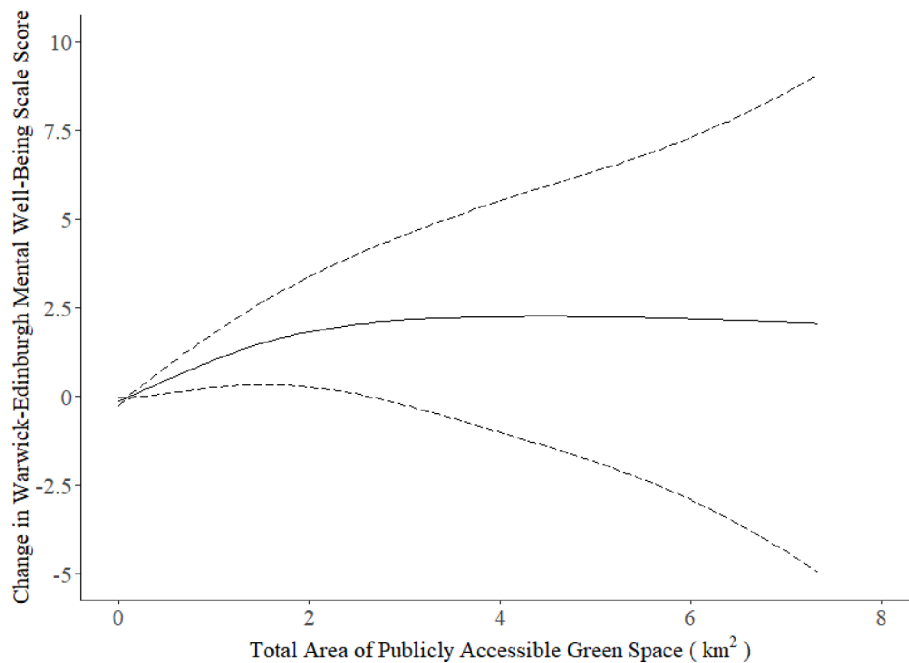

Fig. B1. The relationship between the total area of publicly accessible green and mental well-being in Lower layer Super Output Areas. The dotted lines represent the 95% confidence interval.

decreased with plant species and there was no relationship with butterfly species richness (Dallimer et al., 2012). However, the coefficient for plant species richness was small (-0.1, s.e. 0.003) across reflection, continuity with the past and attachment (Dallimer et al., 2012). Furthermore, although the authors mention that demographic information was collected, namely age, income, sex and ethnicity (Dallimer et al., 2012), there is no mention of controlling for these variables in their analysis. A further study found bird species richness to be associated with well-being, determined using the Recovering Quality of Life Scale (Cameron et al., 2020).

A study in Melbourne, Australia, looked at how green space, blue space and biodiversity affected mental well-being using three neighbourhood buffers (Mavoa et al., 2019). They found that fauna species richness was significantly associated with better mental well-being at all neighbourhood buffer levels (400 m, 800 m, and 1,600 m) with flora species richness significantly associated with better mental well-being at the 400 m and 1,600 m level (Mavoa et al., 2019). These models were adjusted for age, sex, income, education, work status, household structure and neighbourhood socio-economic disadvantage. Our study finds plant species richness was not associated with mental well-being in
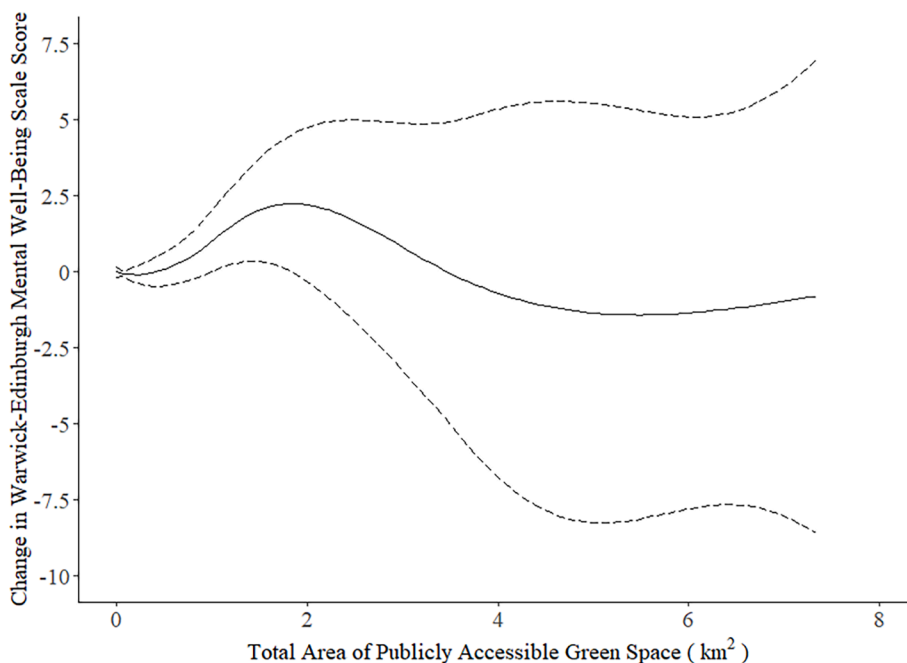
Fig. B2. The relationship between the total area of publicly accessible green and mental well-being in Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.
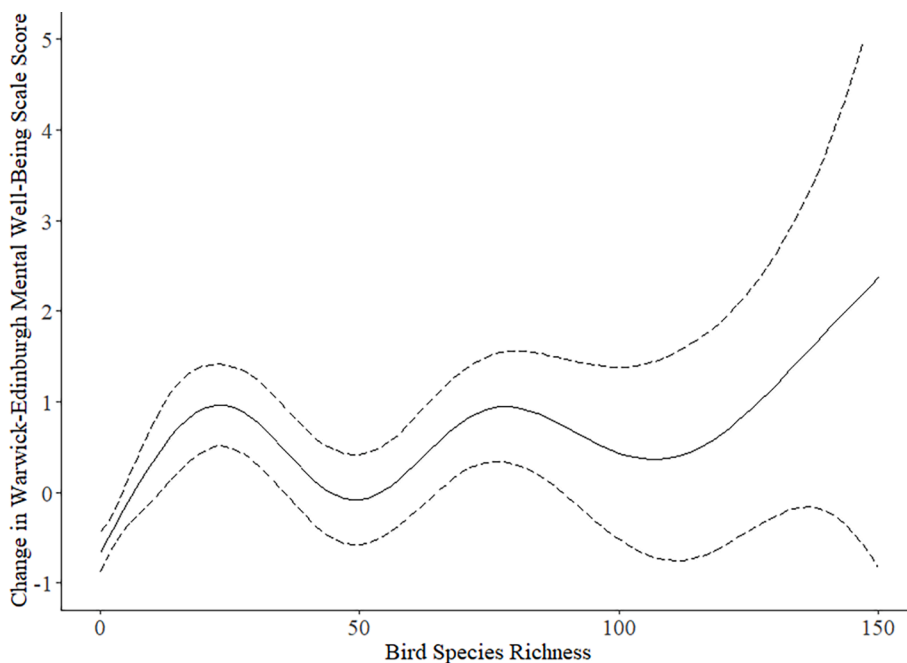

Fig. B3. The relationship between bird species richness and mental well-being in Lower layer Super Output Areas. The dotted lines represent the 95% confidence interval.

adjusted models (Table 4, Fig. B7), although associations did appear with the LSOA borders expanded by 500 m and with more accurate records included (Table D1, Fig. D2). However, our bird species richness results are in agreement, as we found a non-linear relationship after adjusting for age, gender, ethnicity and economic status (Table 4, Fig. 4). One reason for the different results might be the inclusion of neighbourhood buffers in the Australian study, whereas many LSOAs are much larger than a buffer with a radius of 1,600 m^2. People may respond more strongly to certain elements of the natural environment in the immediate vicinity around their household, for example a previous

study identified that life satisfaction was greater for respondents who had a nature view within 500 m of the home, compared with respondents who had a nature view greater than 500 m away (Chang et al., 2020).

Several other studies across different countries have found bird species richness to be associated with well-being (Aerts et al., 2018; Methorst et al., 2020), in addition to the work in England mentioned previously (Dallimer et al., 2012; Fuller et al., 2007). Using a psychological well-being index based on work from Dallimer et al., (2012), bird species richness was associated with this index for residents in
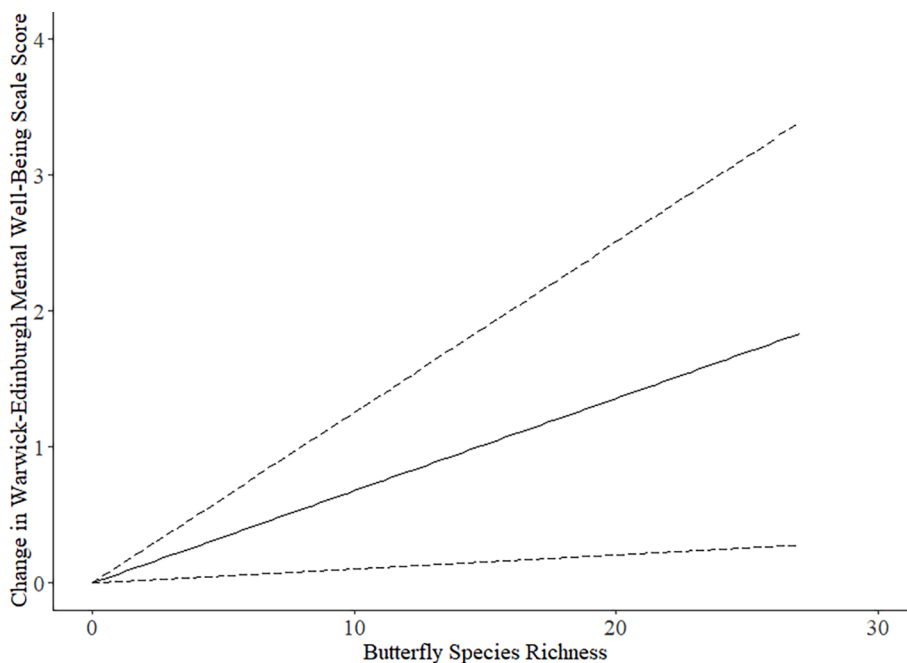
Fig. B4. The relationship between butterfly species richness and mental well-being in Lower layer Super Output Areas. The dotted lines represent the 95% confidence interval.
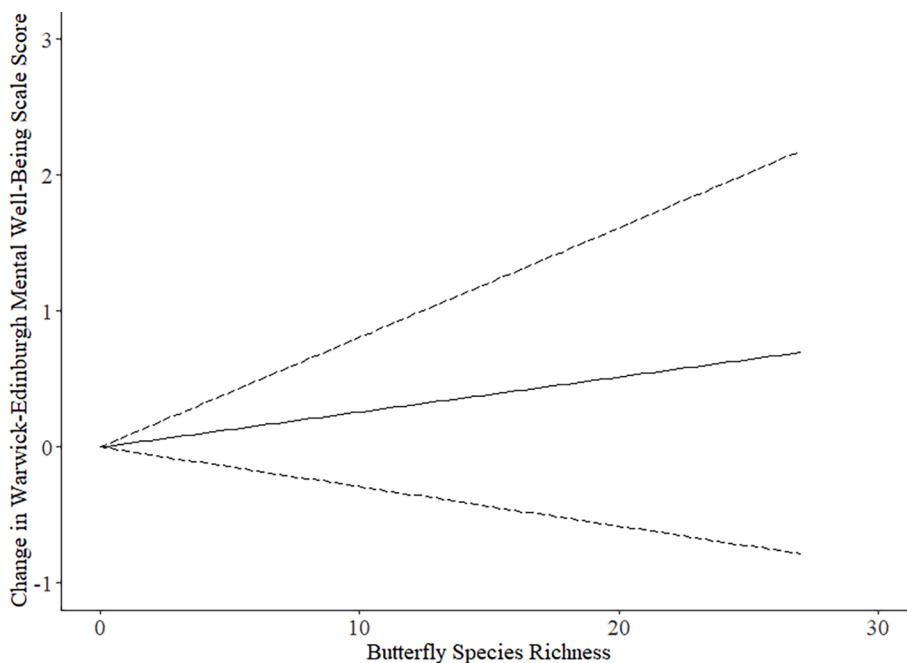

Fig. B5. The relationship between butterfly species richness and mental well-being in Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.

Melbourne, Australia (Taylor et al., 2018). However, no relationship was found between bird species richness and that index in Sydney, Australia or in Auckland or Wellington, New Zealand, and no relationship was found for well-being determined using the WHO-5 scale or personal well-being in any city (Taylor et al., 2018). This is further supported by an earlier study of nine cities and towns in Australia that found bird species richness to be associated with neighbourhood well-being, but not for personal well-being (Luck et al., 2011), and a study in Ottawa, Canada, which found neighbourhood well-being to be positively associated with neighbourhood well-being (Hepburn et al., 2021). Our results add to this growing collection of correlational data between mental well-being and bird species richness, but our results suggest that these relationships might be more complex (Fig. 4) than the previously implied linear relationships, As the WEMWBS covers both eudaimonic and hedonic and psychological functions, clearer relationships might be seen with indices that cover more specific aspects of well-being. However, we do see a clearer relationship in urban areas compared with the overall cohort, where increasing bird species
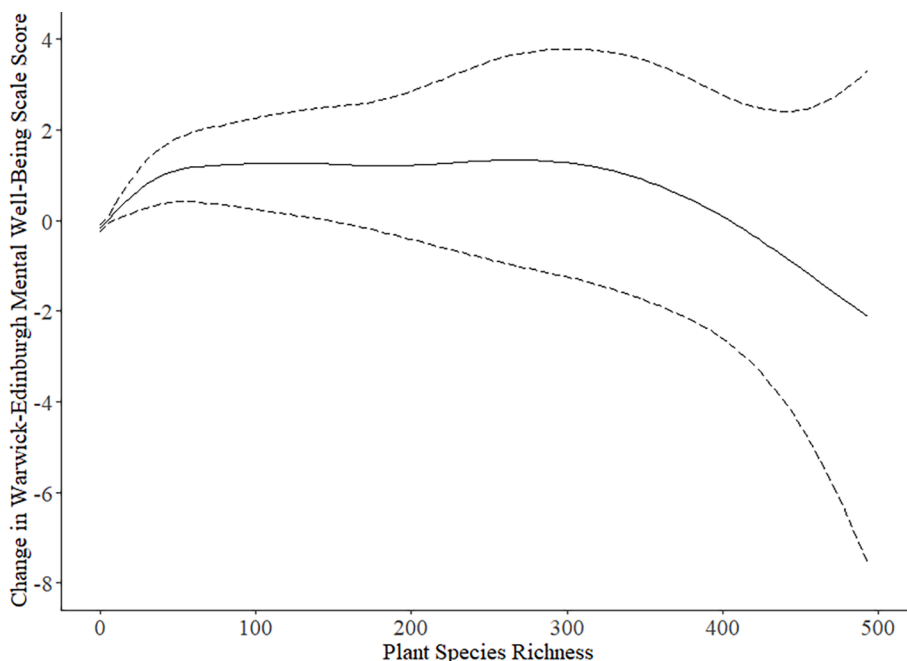
Fig. B6. The relationship between plant species richness and mental well-being in Lower layer Super Output Areas. The dotted lines represent the 95% confidence interval.
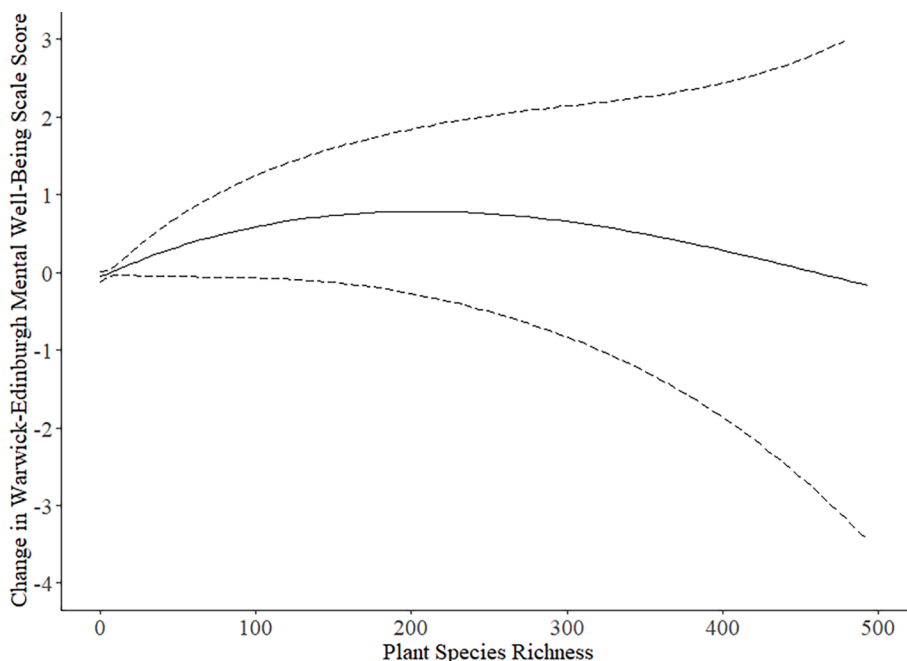

Fig. B7. The relationship between plant species richness and mental well-being in Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95% confidence interval.

richness past 60 recorded species shows an increase in well-being, notwithstanding the lower confidence interval which does cross zero into the negative in parts (Fig. 6).

We found that mental well-being was associated with bird species richness for respondents in income group 3, who earnt between £20,800 and £31,099 (Table 6, Fig. 5). However, there were no other associations for the other income groups for bird species richness (Table 6), or for any income for any other taxa (Appendix C). This suggests that most of the variation in mental well-being is driven by the participants socio-demographic circumstances, and this likely explains why many of the

relationships found in our univariate models (Table 4, Appendix B) do not remain once these covariates are adjusted for. This adds further weight to suggestions in previous reviews that such information should continue to be included in future work (Korpela et al., 2018; Markevych et al., 2017).

Internationally, natural environments are frequently highlighted as vital to health and well-being, resulting in calls for their protection and improvement in long-term objectives (World Health Organization, 2018). All United Nations Member States adopted the 17 Sustainable Development Goals as part of the 2030 Agenda for Sustainable
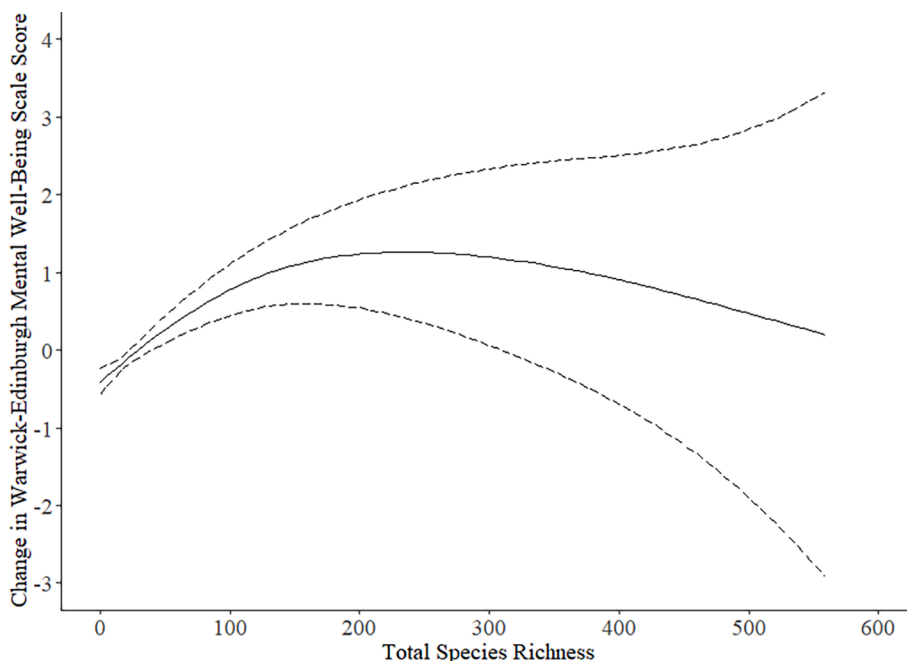
Fig. B8. The relationship between total (bird + butterfly + plant) species richness and mental well-being in Lower layer Super Output Areas. The dotted lines represent the 95 % confidence interval.
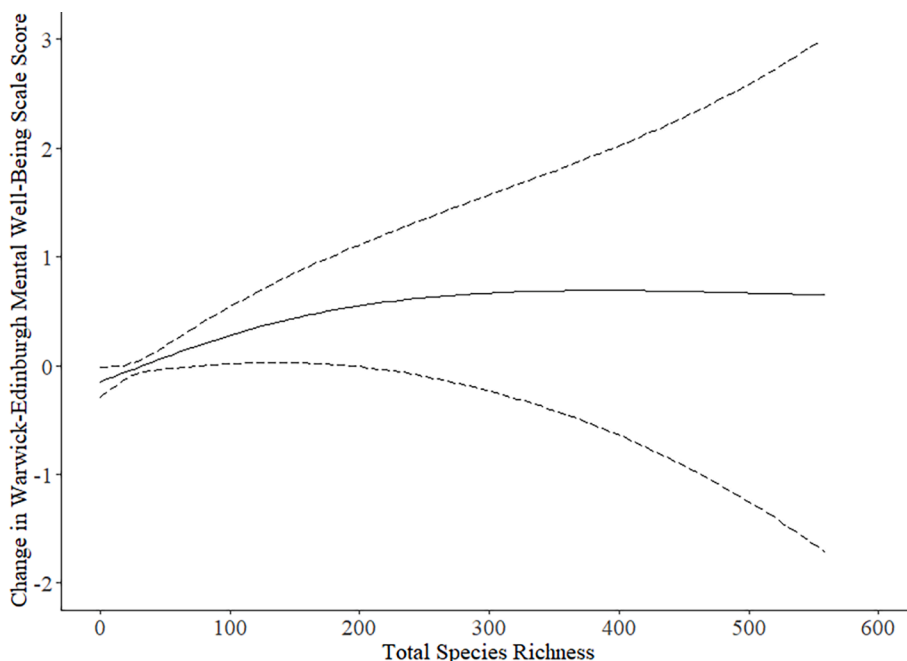

Fig. B9. The relationship between total (bird + butterfly + plant) species richness and mental well-being in Lower layer Super Output Areas, after adjusting for age, gender, ethnicity and economic status. The dotted lines represent the 95 % confidence interval.

Development, and one of the goals is to ensure the conservation, restoration and sustainable use of terrestrial ecosystems and to halt biodiversity loss (United Nations, 2015). Additionally, one of the targets in the first draft of the post-2020 global biodiversity framework is to "Increase the area of, access to, and benefits from green and blue spaces, for human health and well-being in urban areas and other densely populated areas", with the aim of completion by 2030 (Convention on Biological Diversity, 2021). This study serves as further evidence that a biodiverse environment may be beneficial for well-being for residents in urban areas, as we found that bird, butterfly and total species richness were associated with well-being in urban LSOAs (Table 7, Figs. 6-8).

This study has several strengths. This study linked three datasets together to assess how exposure to publicly accessible green space and biodiversity affects mental well-being. This study takes place across Wales, and is one of few studies to assess exposure to both biodiversity and green space at a national level. Several socio-demographic factors were accounted for in adjusted models. The use of non-linear models suggests that associations between biodiversity and mental well-being are more complex than the linear relationships that previous studies suggest. Finally, this study uses a validated scale to measure mental

Table C1
Generalized Additive Model outputs for the green space adjusted models, stratified by income group.

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score				
	Income Group 1	Income Group 2	Income Group 3	Income Group 4	Income Group 5
Area of Publicly Accessibly Green Space	0.772 (0.923)	0.121 (0.521)	−0.019 (0.685)	0.645 (0.778)	1.299 (1.322)
Gender (Male)	–	–	–	–	–
Gender (Female)	0.135 (0.478)	−0.604 (0.341)	0.544 (0.429)	1.092 (0.573)	−0.052 (0.810)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–	–	–	–	–
White (Irish)	−2.884 (3.017)	−0.177 (2.744)	−3.753 (3.656)	0.397 (3.113)	1.169 (3.764)
White (Gypsy or Irish Traveller)	−1.520 (5.765)				
White (Polish)	4.222 (2.598)	5.457** (2.058)	−0.535 (2.591)	−6.501 (8.173)	5.852 (5.292)
White (Other)	4.111* (1.975)	0.870 (1.251)	0.863 (2.374)	0.608 (2.904)	4.390 (2.523)
Mixed (White and Black Caribbean)	−3.029 (3.926)	7.574* (3.547)	2.796 (8.160)	7.353 (8.187)	
Mixed (White and Black African)	−0.528 (5.767)	2.501 (4.995)	2.370 (5.768)	−2.394 (5.777)	
Mixed (White and Asian)	−8.056 (9.971)	4.956 (4.333)	−3.928 (5.776)	7.981 (8.190)	
Mixed (Other)	9.488 (5.770)	4.763 (5.002)	1.741 (5.769)		
Asian (Indian)	6.739 (4.474)	2.014 (4.327)	6.154 (3.649)	−1.238 (2.988)	7.628* (3.777)
Asian (Pakistani)	−5.351 (4.083)	6.241 (4.330)	−11.639 (8.150)		6.197 (7.494)
Asian (Bangladeshi)	4.984 (3.340)	7.963 (4.324)	−3.320 (5.770)		
Asian (Chinese)	5.049 (7.062)	0.639 (4.993)	−0.578 (5.767)	8.473 (5.794)	8.782 (5.638)
Asian (Other)	8.642** (3.348)	2.542 (3.277)	3.705 (5.846)	−0.139 (4.722)	
Black (African)	1.415 (3.357)	5.745* (2.917)	−4.803 (4.217)	6.115 (8.177)	
Black (Caribbean)	8.301 (9.982)		0.872 (8.150)	7.360 (8.262)	
Black (Other)	13.149** (4.985)		−5.565 (5.768)		
Other (Arab)	3.070 (3.792)		−9.660 (8.152)	2.114 (8.442)	−2.698 (7.461)
Other (Any Other Ethnic Group)	−0.603 (3.333)	4.222 (2.170)	9.721** (3.334)	−10.192 (8.185)	3.624 (3.749)
Full Time Student	–	–	–	–	–
Paid Employment or Self-Employment	−1.657 (1.202)	−0.393 (1.220)	0.928 (1.992)	4.963 (2.741)	−2.188 (3.130)
Government Sponsored Training Scheme	3.615 (7.355)	9.354 (8.719)			
Unpaid Work for Own or Relative-Owned Business	0.473 (4.218)	3.575 (5.136)		12.997 (8.618)	
Waiting to Start Obtained Job	−4.315 (4.567)	−8.215 (5.116)	10.333 (8.422)	16.781 (8.602)	−2.887 (8.071)
Unemployed and Looking for Work	−5.916*** (1.462)	−3.524* (1.765)	−5.734 (4.175)	−6.546 (4.945)	
Not Working Due to Temporary Sickness or Injury	−8.223** (2.988)	−5.620 (4.490)		9.543 (8.610)	
Unable to Work Due to Long-Term Sickness or Injury	−11.787*** (1.340)	−8.802*** (1.503)	−6.570* (3.083)	0.611 (3.849)	−14.426** (5.061)
Retired	−1.384 (1.413)	−0.549 (1.353)	2.187 (2.129)	6.501* (2.888)	−3.818 (3.593)
Looking After Home or Family	−2.088 (1.284)	−3.925** (1.485)	3.877 (2.759)	6.166 (3.453)	−12.650** (4.546)
Doing Something Else	−4.912 (2.677)	−2.821 (3.502)	12.102** (4.548)	6.691 (5.443)	4.092 (8.115)
Age	edf: 4.191*	edf: 3.666***	0.033 (0.018)	0.059* (0.026)	0.071 (0.039)
Intercept	50.968*** (1.190)	52.212*** (1.249)	51.267*** (2.010)	44.099*** (2.939)	52.733*** (3.311)
Observations	2,114	2,757	1,502	900	396
Adjusted R^2	0.137	0.067	0.029	0.031	0.045
Log Likelihood	−7,874.915	−9,870.003	−5,295.847	−3,179.799	−1,366.516
Note:	*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$ edf = effective degrees of freedom				

Table C2

Generalized Additive Model outputs for the butterfly species richness adjusted models, stratified by income group.

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score				
	Income Group 1	Income Group 2	Income Group 3	Income Group 4	Income Group 5
Butterfly Species Richness	edf: 2.656	−0.015 (0.052)	edf: 3.53	0.001 (0.069)	−0.001 (0.081)
Gender (Male)	–	–	–	–	–
Gender (Female)	0.115 (0.478)	−0.603 (0.341)	0.516 (0.429)	1.093 (0.573)	−0.025 (0.812)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–	–	–	–	–
White (Irish)	−2.891 (3.015)	−0.158 (2.742)	−3.690 (3.726)	0.359 (3.115)	1.018 (3.766)
White (Gypsy or Irish Traveller)	−1.522 (5.761)				
White (Polish)	4.197 (2.597)	5.479** (2.059)	−0.685 (2.590)	−6.305 (8.173)	5.938 (5.299)
White (Other)	4.088* (1.975)	0.877 (1.251)	0.962 (2.371)	0.557 (2.905)	4.535 (2.541)
Mixed (White and Black Caribbean)	−3.060 (3.923)	7.569* (3.547)	2.816 (8.143)	7.403 (8.190)	
Mixed (White and Black African)	−0.566 (5.763)	2.482 (4.995)	2.344 (5.756)	−2.447 (5.786)	
Mixed (White and Asian)	−8.202 (9.964)	4.977 (4.334)	−3.891 (5.765)	7.897 (8.193)	
Mixed (Other)	9.479 (5.766)	4.771 (5.002)	1.706 (5.758)		
Asian (Indian)	6.680 (4.472)	2.010 (4.327)	6.156 (3.642)	−0.677 (2.912)	7.559* (3.790)
Asian (Pakistani)	−5.430 (4.080)	6.270 (4.327)	−11.636 (8.133)		6.105 (7.504)
Asian (Bangladeshi)	5.074 (3.338)	8.009 (4.327)	−3.350 (5.758)		
Asian (Chinese)	4.998 (7.057)	0.618 (4.993)	−0.604 (5.756)	8.490 (5.797)	8.651 (5.651)
Asian (Other)	8.784** (3.349)	2.528 (3.277)	3.687 (5.834)	−0.182 (4.724)	
Black (African)	1.365 (3.355)	5.768* (2.918)	−4.668 (4.210)	6.049 (8.180)	
Black (Caribbean)	8.214 (9.975)		0.844 (8.133)	8.400 (8.170)	
Black (Other)	13.059** (4.981)		−5.553 (5.756)		
Other (Arab)	3.008 (3.789)		−9.670 (8.134)	2.063 (8.445)	−2.751 (7.471)
Other (Any Other Ethnic Group)	−0.629 (3.331)	4.218 (2.169)	9.724** (3.328)	−10.305 (8.188)	3.497 (3.752)
Full Time Student	–	–	–	–	–
Paid Employment or Self-Employment	−1.615 (1.202)	−0.386 (1.221)	0.922 (1.987)	4.941 (2.744)	−2.427 (3.126)
Government Sponsored Training Scheme	3.591 (7.350)	9.498 (8.734)			
Unpaid Work for Own or Relative-Owned Business	−0.380 (4.247)	3.566 (5.136)		13.459 (8.605)	
Waiting to Start Obtained Job	−4.348 (4.563)	−8.224 (5.116)	10.280 (8.404)	16.695 (8.606)	−3.253 (8.075)
Unemployed and Looking for Work	−5.919*** (1.461)	−3.520* (1.765)	−6.190 (4.190)	−6.024 (4.908)	
Not Working Due to Temporary Sickness or Injury	−8.215** (2.988)	−5.634 (4.489)		9.456 (8.614)	
Unable to Work Due to Long-Term Sickness or Injury	−11.801*** (1.338)	−8.813*** (1.503)	−6.595* (3.077)	0.568 (3.851)	−14.791** (5.061)
Retired	−1.332 (1.412)	−0.553 (1.352)	2.132 (2.124)	6.522* (2.892)	−4.116 (3.585)
Looking After Home or Family	−2.050 (1.282)	−3.929** (1.485)	3.976 (2.752)	6.128 (3.458)	−12.768** (4.553)
Doing Something Else	−4.941 (2.679)	−2.826 (3.502)	12.058** (4.538)	6.652 (5.447)	3.765 (8.121)
Age	edf: 4.173*	edf: 3.673***	0.035 (0.018)	0.059* (0.026)	0.076 (0.039)
Intercept	51.030*** (1.183)	52.236*** (1.247)	51.297*** (1.999)	44.182*** (2.940)	52.931*** (3.315)
Observations	2,114	2,757	1,502	900	396
Adjusted R²	0.138	0.067	0.033	0.030	0.042
Log Likelihood	−7,874.297	−9,869.970	−5,294.109	−3,180.153	−1,367.013
Note:	*p < 0.05; **p < 0.01; ***p < 0.001 edf = effective degrees of freedom				

Table C3

Generalized Additive Model outputs for the plant species richness adjusted models, stratified by income group.

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score				
	Income Group 1	Income Group 2	Income Group 3	Income Group 4	Income Group 5
Plant Species Richness	edf: 2.996	edf: 1.789	0.001 (0.005)		−0.001 (0.010)
Gender (Male)	–	–	–	–	–
Gender (Female)	0.153 (0.477)	−0.604 (0.341)	0.543 (0.429)	1.105 (0.572)	−0.023 (0.811)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–	–	–	–	–
White (Irish)	−3.088 (3.016)	−0.254 (2.742)	−3.781 (3.657)	0.450 (3.110)	1.012 (3.767)
White (Gypsy or Irish Traveller)	−1.348 (5.759)				
White (Polish)	4.162 (2.595)	5.479** (2.057)	−0.531 (2.591)	−6.230 (8.162)	5.934 (5.299)
White (Other)	4.122* (1.978)	0.859 (1.251)	0.868 (2.375)	0.573 (2.900)	4.530 (2.522)
Mixed (White and Black Caribbean)	−2.921 (3.921)	7.590* (3.546)	2.803 (8.160)	7.437 (8.179)	
Mixed (White and Black African)	−0.911 (5.763)	2.527 (4.993)	2.378 (5.767)	−2.396 (5.771)	
Mixed (White and Asian)	−7.972 (9.958)	4.982 (4.331)	−3.921 (5.776)	8.018 (8.182)	
Mixed (Other)	9.602 (5.763)	4.799 (5.000)	1.746 (5.769)		
Asian (Indian)	6.466 (4.471)	2.057 (4.326)	6.162 (3.649)	−0.604 (2.909)	7.558* (3.782)
Asian (Pakistani)	−5.256 (4.078)	6.204 (4.326)	−11.630 (8.150)		6.116 (7.506)
Asian (Bangladeshi)	5.085 (3.335)	8.011 (4.323)	−3.311 (5.770)		
Asian (Chinese)	5.160 (7.053)	0.671 (4.991)	−0.570 (5.767)	8.548 (5.789)	8.649 (5.644)
Asian (Other)	8.771** (3.345)	2.489 (3.276)	3.707 (5.845)	−0.304 (4.718)	
Black (African)	1.479 (3.354)	5.735* (2.916)	−4.795 (4.216)	6.104 (8.169)	
Black (Caribbean)	8.412 (9.970)		0.880 (8.149)	8.473 (8.159)	
Black (Other)	13.280** (4.979)		−5.555 (5.768)		
Other (Arab)	3.183 (3.788)		−9.658 (8.151)	2.071 (8.433)	−2.755 (7.471)
Other (Any Other Ethnic Group)	−0.437 (3.330)	4.205 (2.169)	9.726** (3.335)	−10.155 (8.177)	3.493 (3.752)
Full Time Student	–	–	–	–	–
Paid Employment or Self-Employment	−1.688 (1.200)	−0.448 (1.221)	0.929 (1.990)	4.944 (2.739)	−2.425 (3.124)
Government Sponsored Training Scheme	3.646 (7.346)	9.301 (8.716)			
Unpaid Work for Own or Relative-Owned Business	0.203 (4.217)	3.566 (5.134)		13.547 (8.592)	
Waiting to Start Obtained Job	−4.578 (4.563)	−8.232 (5.115)	10.343 (8.420)	16.770 (8.593)	−3.163 (8.251)
Unemployed and Looking for Work	−5.873*** (1.459)	−3.590* (1.766)	−5.733 (4.174)	−6.321 (4.905)	
Not Working Due to Temporary Sickness or Injury	−8.247** (2.985)	−5.643 (4.488)		9.602 (8.601)	
Unable to Work Due to Long-Term Sickness or Injury	−11.814*** (1.337)	−8.804*** (1.502)	−6.567* (3.083)	0.632 (3.845)	−14.797** (5.054)
Retired	−1.361 (1.410)	−0.577 (1.352)	2.186 (2.127)	6.589* (2.886)	−4.118 (3.585)
Looking After Home or Family	−2.144 (1.280)	−3.955** (1.484)	3.885 (2.756)	6.151 (3.449)	−12.772** (4.551)
Doing Something Else	−4.965 (2.676)	−2.919 (3.502)	12.110** (4.547)	6.699 (5.438)	3.764 (8.119)
Age	edf: 4.146*	edf: 3.661***	0.033 (0.018)	0.056* (0.026)	0.076 (0.039)
Intercept	51.041*** (1.182)	52.268*** (1.247)	51.258*** (2.003)	44.332*** (2.937)	52.929*** (3.309)
Observations	2,114	2,757	1,502	900	396
Adjusted R²	0.139	0.068	0.029	0.033	0.042
Log Likelihood	−7,873.360	−9,869.383	−5,295.842	−3,179.321	−1,367.011
Note:	*p < 0.05; **p < 0.01; ***p < 0.001 edf = effective degrees of freedom				

Table C4

Generalized Additive Model outputs for the total (bird + butterfly + plant) species richness adjusted models, stratified by income group.

|	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score				
	Income Group 1	Income Group 2	Income Group 3	Income Group 4	Income Group 5
Total Species Richness	edf: 1.307	0.001 (0.003)	edf: 5.084	edf: 1.374	0.0001 (0.006)
Gender (Male)	–	–	–	–	–
Gender (Female)	0.149 (0.477)	−0.598 (0.341)	0.564 (0.428)	1.100 (0.573)	−0.025 (0.811)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–	–	–	–	–
White (Irish)	−2.779 (3.017)	−0.171 (2.742)	−3.683 (3.677)	0.328 (3.114)	1.020 (3.767)
White (Gypsy or Irish Traveller)	−1.464 (5.763)				
White (Polish)	4.243 (2.597)	5.463** (2.058)	−0.513 (2.589)	−6.352 (8.172)	5.941 (5.302)
White (Other)	4.106* (1.976)	0.874 (1.251)	0.845 (2.370)	0.561 (2.904)	4.532 (2.522)
Mixed (White and Black Caribbean)	−2.960 (3.925)	7.594* (3.547)	3.079 (8.145)	7.436 (8.189)	
Mixed (White and Black African)	−0.729 (5.766)	2.517 (4.995)	1.990 (5.759)	−2.540 (5.784)	
Mixed (White and Asian)	−7.888 (9.968)	4.926 (4.333)	−3.672 (5.768)	7.958 (8.194)	
Mixed (Other)	9.550 (5.768)	4.772 (5.002)	1.748 (5.759)		
Asian (Indian)	6.764 (4.473)	2.028 (4.327)	6.240 (3.644)	−0.667 (2.912)	7.555* (3.784)
Asian (Pakistani)	−5.264 (4.082)	6.263 (4.327)	−11.470 (8.135)		6.102 (7.507)
Asian (Bangladeshi)	5.032 (3.338)	7.962 (4.324)	−3.730 (5.763)		
Asian (Chinese)	5.142 (7.059)	0.675 (4.994)	−0.761 (5.756)	8.501 (5.795)	8.657 (5.653)
Asian (Other)	8.727** (3.348)	2.544 (3.276)	3.428 (5.836)	−0.216 (4.723)	
Black (African)	1.526 (3.358)	5.746* (2.916)	−4.772 (4.210)	6.088 (8.179)	
Black (Caribbean)	8.429 (9.978)		1.127 (8.135)	8.366 (8.169)	
Black (Other)	13.255** (4.984)		−5.317 (5.760)		
Other (Arab)	3.100 (3.790)		−9.665 (8.135)	2.102 (8.444)	−2.746 (7.474)
Other (Any Other Ethnic Group)	−0.436 (3.333)	4.214 (2.169)	9.876** (3.329)	−10.232 (8.190)	3.500 (3.754)
Full Time Student	–	–	–	–	–
Paid Employment or Self-Employment	−1.722 (1.202)	−0.397 (1.220)	0.893 (1.987)	4.941 (2.742)	−2.426 (3.124)
Government Sponsored Training Scheme	3.510 (7.352)	9.353 (8.719)			
Unpaid Work for Own or Relative-Owned Business	0.155 (4.220)	3.591 (5.136)		13.437 (8.602)	
Waiting to Start Obtained Job	−4.337 (4.565)	−8.229 (5.116)	10.504 (8.407)	16.739 (8.604)	−3.271 (8.186)
Unemployed and Looking for Work	−5.867*** (1.462)	−3.518* (1.765)	−5.754 (4.168)	−6.052 (4.908)	
Not Working Due to Temporary Sickness or Injury	−8.181** (2.987)	−5.605 (4.489)		9.521 (8.612)	
Unable to Work Due to Long-Term Sickness or Injury	−11.795*** (1.338)	−8.790*** (1.503)	−6.674* (3.078)	0.567 (3.849)	−14.793** (5.053)
Retired	−1.424 (1.412)	−0.550 (1.352)	2.042 (2.125)	6.535* (2.889)	−4.116 (3.584)
Looking After Home or Family	−2.145 (1.282)	−3.915** (1.485)	3.960 (2.753)	6.117 (3.453)	−12.764** (4.555)
Doing Something Else	−5.081 (2.676)	−2.824 (3.502)	11.926** (4.541)	6.667 (5.444)	3.764 (8.121)
Age	edf: 4.181*	edf: 3.666***	0.034 (0.018)	0.058* (0.026)	0.075 (0.039)
Intercept	51.073*** (1.184)	52.176*** (1.252)	49.550*** (2.053)	44.228*** (2.941)	52.928*** (3.312)
Observations	2,114	2,757	1,502	900	396
Adjusted R²	0.138	0.067	0.033	0.031	0.042
Log Likelihood	−7,874.291	−9,869.908	−5,294.736	−3,180.097	−1,367.013
Note:	*p < 0.05; **p < 0.01; ***p < 0.001 edf = effective degrees of freedom				
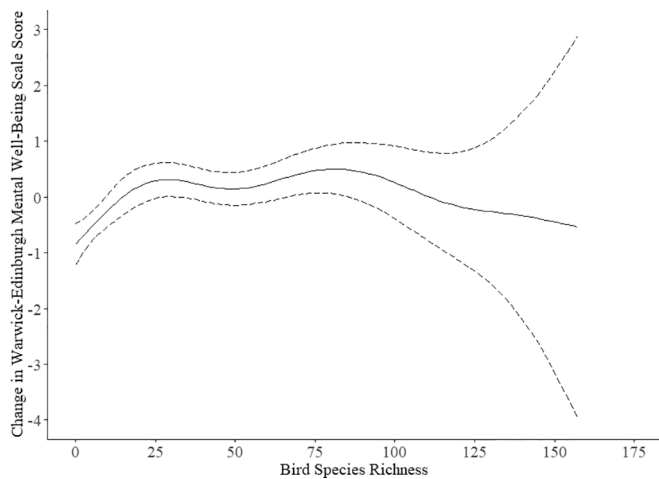
Fig. D1. The relationship between bird species richness and mental well-being in Lower layer Super Output Areas (LSOAs), after adjusting for age, gender, ethnicity and economic status. The LSOA borders have been expanded by 500 m and only species records with a 1x1 km grid reference or better have been included. The dotted lines represent the 95 % confidence interval.
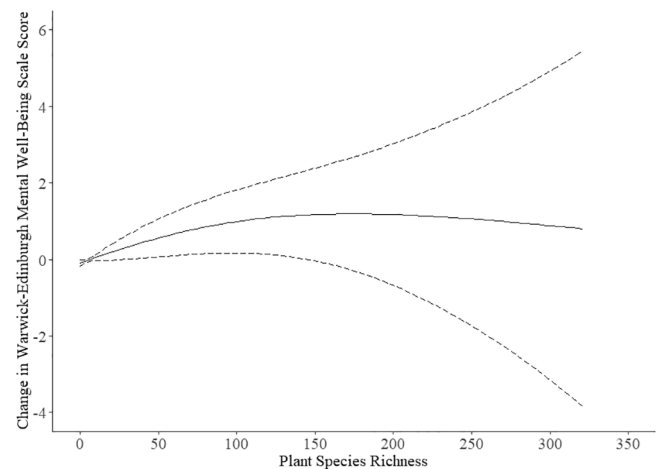

Fig. D3. The relationship between total (bird + butterfly + plant) species richness and mental well-being in Lower layer Super Output Areas (LSOAs), after adjusting for age, gender, ethnicity and economic status. The LSOA borders have been expanded by 500 m and only species records with a 1x1 km grid reference or better have been included. The dotted lines represent the 95 % confidence interval.

Fig. D2. The relationship between plant species richness and mental well-being in Lower layer Super Output Areas (LSOAs), after adjusting for age, gender, ethnicity and economic status. The LSOA borders have been expanded by 500 m and only species records with a 1x1 km grid reference or better have been included. The dotted lines represent the 95 % confidence interval.

well-being across a relatively large sample size. Using green space data and routinely collected biodiversity data and survey responses appears to be a viable way to investigates relationships between nature and well-being.

However, this study has several limitations. There is a temporal mismatch between the survey data collection and the records of bird, butterfly and plant species. The NSW for 2018–19 was conducted between April 2018 and March 2019, but the species records were collected for 2018 only.

Secondly, this study did not have information on which publicly accessible green spaces people may visit or what species they encounter. Previous research suggests that visitation to green spaces has a stronger effect on well-being than the amount of green space (Coldwell & Evans, 2018). In addition, the species included in this study may not be present or recorded in a publicly accessible green space. However, direct interaction is not the only way to experience nature. An indirect experience, such as viewing nature out of the window in your home or hearing birdsong, can benefit mental well-being (Methorst et al., 2020).
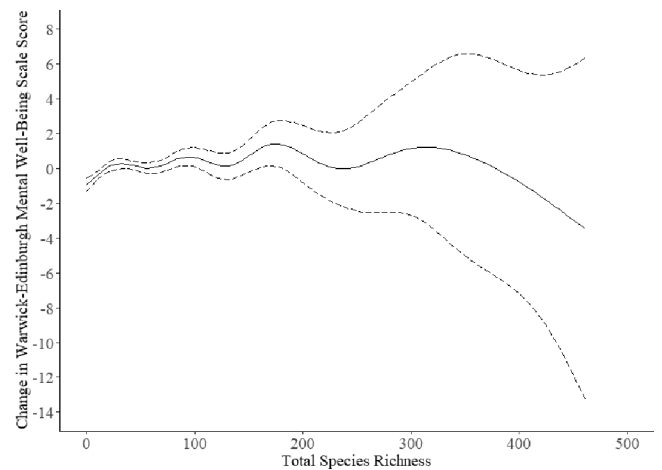
A study in Singapore found that life satisfaction was associated with a view of nature within 500 m from the home and from the workplace (Chang et al., 2020). Furthermore, perception of biodiversity does not always correlate with measured levels of biodiversity, with previous research finding both positive correlations (Fuller et al., 2007; Southon et al., 2018) and negative correlations (Dallimer et al., 2012). The benefits of perceived biodiversity on mental well-being are often stronger than objective measures (Gonçalves et al., 2021; Schebella et al., 2019), though more research is required on this topic (Marselle, Lindley, et al., 2021).

Furthermore, an assumption in the methods of this study is that it is only the amount of publicly accessible green space and/or the biodiversity within a census area that may affect their mental well-being. Private gardens can have significant amounts of biodiversity (Loram et al., 2008), and associations between mental well-being and private gardens have been reported in previous research (de Bell et al., 2020; Howarth et al., 2020; Krols et al., 2022). However, this is an area that requires more research using study designs that can identify causal mechanisms (Wendelboe-Nelson et al., 2019).

In addition, nature reserves and protected areas are not included in the OS Open Greenspace dataset. These areas are likely to be more biodiverse than the surrounding landscape. The records in the NBN Atlas are collated from citizen science volunteers and established groups, therefore recorder effort may be inconsistent with respect to geographic coverage and methodology used (Bowler et al., 2022; Thompson et al., 2023). Therefore, caution should be used when interpretating the results from this study, as the biodiversity measures are likely an underestimation. Any associations are as a result of the recorded sightings in this database and comparisons with different data collection methods should also be done with caution.

Finally, census areas vary in size. A potential solution to this, which has been used in previous studies, would be to create a buffer around the individual's home, which would more accurately depict the natural environment surrounding each home. For example, a study in Perth, Australia, found that an additional hectare of parkland within 1.6 km of the home (approximately a 10–15 min walking distance) was associated with an increase of 0.07 (p < 0.0001) WEMWBS score, and every one percent increase in park area (as a percentage of the land area within the neighbourhood) was associated with an increase of 0.12 (p = 0.0006) WEMWBS score (Wood et al., 2017). Furthermore, for every additional park (of any type) the WEMWBS score increased by 0.11 (p = 0.029) (Wood et al., 2017). Previous research in Wales has utilised individual-

Table D1

Generalized Additive Model outputs for the green space and species richness adjusted models after expanding the Lower layer Super Output Area borders by 500 m and restricting the species records to only include records with a 1x1 km grid reference or better.

|	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score				
	Green Space	Bird Species	Butterfly Species	Plant Species	Total Species
Total Area of Publicly Accessible Green Space	edf: 1.477				
Bird Species Richness		edf: 4.488***			
Butterfly Species Richness			edf: 1.080		
Plant Species Richness				edf: 1.632*	
Total Species Richness					edf: 7.596***
Gender (Male)	–	–	–	–	–
Gender (Female)	−0.352 (0.193)	−0.339 (0.193)	−0.346 (0.193)	−0.343 (0.193)	−0.339 (0.193)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–	–	–	–	–
White (Irish)	0.138 (1.318)	0.193 (1.316)	0.184 (1.317)	0.121 (1.318)	0.169 (1.316)
White (Gypsy or Irish Traveller)	−3.147 (5.204)	−3.297 (5.200)	−3.305 (5.207)	−3.003 (5.204)	−3.154 (5.199)
White (Polish)	2.200 (1.270)	2.374 (1.270)	2.215 (1.271)	2.226 (1.270)	2.399 (1.270)
White (Other)	2.542** (0.827)	2.600** (0.826)	2.603** (0.827)	2.587** (0.827)	2.606** (0.826)
Mixed (White and Black Caribbean)	1.966 (2.092)	2.011 (2.090)	1.987 (2.093)	2.021 (2.092)	2.071 (2.090)
Mixed (White and Black African)	0.797 (2.849)	0.477 (2.846)	0.775 (2.849)	0.775 (2.848)	0.552 (2.847)
Mixed (White and Asian)	1.582 (3.004)	1.568 (3.002)	1.552 (3.005)	1.627 (3.004)	1.616 (3.001)
Mixed (Other)	4.840 (3.004)	4.793 (3.003)	4.841 (3.005)	4.876 (3.004)	4.935 (3.002)
Asian (Indian)	3.978** (1.507)	3.964** (1.504)	4.082** (1.505)	4.106** (1.505)	3.995** (1.504)
Asian (Pakistani)	2.111 (2.020)	2.353 (2.020)	2.112 (2.021)	2.057 (2.020)	2.444 (2.020)
Asian (Bangladeshi)	2.692 (2.070)	2.584 (2.068)	2.575 (2.070)	2.714 (2.070)	2.626 (2.067)
Asian (Chinese)	4.237 (2.500)	4.404 (2.498)	4.295 (2.500)	4.340 (2.500)	4.530 (2.498)
Asian (Other)	4.475** (1.679)	4.423** (1.678)	4.520** (1.679)	4.486** (1.679)	4.413** (1.678)
Black (African)	2.447 (1.714)	2.609 (1.713)	2.442 (1.714)	2.509 (1.714)	2.686 (1.713)
Black (Caribbean)	4.812 (4.027)	5.150 (4.023)	4.958 (4.027)	5.014 (4.027)	5.233 (4.023)
Black (Other)	−0.625 (3.004)	−0.535 (3.001)	−0.687 (3.004)	−0.600 (3.004)	−0.471 (3.001)
Other (Arab)	0.621 (2.854)	0.661 (2.851)	0.644 (2.854)	0.696 (2.853)	0.701 (2.850)
Other (Any Other Ethnic Group)	3.367* (1.378)	3.423* (1.377)	3.401* (1.378)	3.405* (1.378)	3.495* (1.376)
Full Time Student	–	–	–	–	–
Paid Employment or Self-Employment	0.604 (0.615)	0.583 (0.615)	0.607 (0.615)	0.561 (0.615)	0.569 (0.615)
Government Sponsored Training Scheme	3.451 (5.269)	3.205 (5.265)	3.275 (5.270)	3.324 (5.269)	3.100 (5.264)
Unpaid Work for Own or Relative-Owned Business	2.322 (2.569)	2.309 (2.567)	2.185 (2.572)	2.287 (2.569)	2.240 (2.568)
Waiting to Start Obtained Job	−2.002 (2.771)	−2.019 (2.768)	−2.089 (2.771)	−2.123 (2.771)	−2.060 (2.768)
Unemployed and Looking for Work	−5.693*** (0.868)	−5.573*** (0.868)	−5.670*** (0.868)	−5.692*** (0.868)	−5.574*** (0.868)
Not Working Due to Temporary Sickness or Injury	−7.397*** (2.206)	−7.340*** (2.204)	−7.422*** (2.206)	−7.455*** (2.206)	−7.428*** (2.204)
Unable to Work Due to Long-Term Sickness or Injury	−11.005*** (0.754)	−10.909*** (0.755)	−11.014*** (0.754)	−11.031*** (0.754)	−10.890*** (0.755)
Retired	0.259 (0.707)	0.238 (0.707)	0.260 (0.707)	0.240 (0.707)	0.236 (0.707)
Looking After Home or Family	−2.015** (0.732)	−2.025** (0.732)	−2.031** (0.731)	−2.053** (0.731)	−2.009** (0.732)
Doing Something Else	−1.222 (1.502)	−1.281 (1.501)	−1.185 (1.502)	−1.267 (1.502)	−1.239 (1.501)
Age	edf: 4.855***	edf: 4.906***	edf: 4.847***	edf: 4.849***	edf: 4.916***
Intercept	51.624*** (0.618)	51.625*** (0.618)	51.618*** (0.618)	51.648*** (0.618)	51.630*** (0.618)
Observations	8,979	8,979	8,979	8,979	8,979
Adjusted R²	0.094	0.096	0.094	0.095	0.096
Log Likelihood	−32,486.28	−32,478.98	−32,487.44	−32,485.73	−32,479.5
Note:	*p < 0.05; **p < 0.01; ***p < 0.001 edf = effective degrees of freedom				
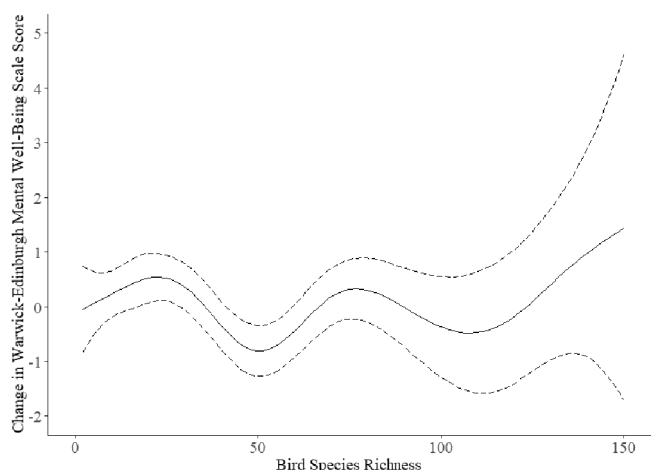
Fig. E1. The relationship between bird species richness and mental well-being in Lower layer Super Output Areas (LSOAs), after adjusting for age, gender, ethnicity and economic status. LSOAs were excluded if they did not record at least two bird species. The dotted lines represent the 95% confidence interval.

level health and mental well-being data and household-level exposure to green (and blue) space (Mizen et al., 2019; Song et al., 2018; Thompson et al., 2020), though measures of biodiversity were not included. Future research could therefore look at household-level access to both green space and biodiversity to assess the impacts on health and mental well-being.

To deal with some of these limitations, we performed a sensitivity analysis with a series of adjustments to the data (Appendix D-E). Plant species richness and total species richness are associated with well-being in models where the LSOA borders have been expanded by 500 m and less accurate species records are excluded (Table D1, Fig. D2-3), suggesting that associations between mental well-being and plant species richness and total species richness might be sensitive to changing study area size with records of observed species that are recorded more accurately. Bird species richness remained associated with well-being in this model (Table D1, Fig. D1), and in a second model where LSOAs were excluded if they did not have two or more species recorded in them (Appendix E). This suggests that relationships between bird species richness and mental well-being are consistently non-linear, robust to changing study areas and remain when we restrict the data to increase our confidence of the accuracy of the records.

Table E1
Generalized Additive Model outputs for the green space and species richness adjusted models after removing Lower layer Super Output Areas without at least two bird species recorded with them.

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score							
	Bird Species Univariate	Bird Species Multivariate	Butterfly Species Univariate	Butterfly Species Multivariate	Plant Species Univariate	Plant Species Multivariate	Total Species Univariate	Total Species Multivariate
Bird Species Richness	edf: 5.7	edf: 5.943*						
Butterfly Species Richness			edf: 1.455	edf: 1.018				
Plant Species Richness					edf: 1.571	0.0002 (0.003)		
Total Species Richness							edf: 1.404	edf: 3.048
Gender (Male)	–		–		–			–
Gender (Female)		−0.407 (0.254)		0.393 (0.772)		−0.214 (0.396)		−0.419 (0.249)
White (Welsh/ English/Scottish/ Northern Irish/ British)	–		–		–			–
White (Irish)		1.272 (1.850)		2.297 (6.137)		−0.740 (2.534)		0.940 (1.814)
White (Gypsy or Irish Traveller)		−3.300 (6.256)						−3.507 (6.264)
White (Polish)		2.364 (1.857)		1.002 (5.087)		3.156 (3.117)		2.193 (1.820)
White (Other)		2.383* (1.150)		−0.093 (3.096)		2.264 (1.721)		2.214* (1.107)
Mixed (White and Black Caribbean)		0.479 (3.481)						0.479 (3.486)
Mixed (White and Black African)		−0.602 (2.950)		−2.358 (8.625)		−2.629 (6.168)		−0.562 (2.955)
Mixed (White and Asian)		8.247 (5.113)		7.409 (8.648)				8.516 (5.118)
Mixed (Other)		4.669 (3.958)				5.910 (8.701)		4.580 (3.963)
Asian (Indian)		5.433* (2.216)		13.879 (8.649)		9.372* (4.355)		5.322* (2.218)
Asian (Pakistani)		3.950 (3.349)				6.871 (5.038)		4.191 (3.141)
Asian (Bangladeshi)		0.805 (2.800)		−3.821 (6.105)		−6.345 (8.698)		1.064 (2.803)
Asian (Chinese)		4.090 (4.426)						3.980 (4.432)
Asian (Other)		2.546 (2.095)		−14.648 (8.633)		1.054 (3.565)		2.565 (2.098)
Black (African)		−0.138 (3.367)		5.935 (8.652)		5.251 (5.031)		−0.420 (3.370)
Black (Caribbean)		9.120 (8.837)						8.466 (8.849)
Black (Other)		4.284 (5.103)						4.609 (5.111)

(continued on next page)

Table E1 (*continued*)

	Dependent variable: Warwick-Edinburgh Mental Well-Being Scale Score							
	Bird Species Univariate	Bird Species Multivariate	Butterfly Species Univariate	Butterfly Species Multivariate	Plant Species Univariate	Plant Species Multivariate	Total Species Univariate	Total Species Multivariate
Other (Arab)		−3.325 (5.117)						−2.973 (5.120)
Other (Any Other Ethnic Group)		2.383 (2.148)		−4.848 (8.616)		2.785 (3.299)		2.470 (2.152)
Full Time Student		−		−		−		−
Paid Employment or Self-Employment		0.670 (0.892)		−0.942 (2.630)		0.164 (1.457)		0.702 (0.886)
Government Sponsored Training Scheme		1.419 (6.525)		5.379 (9.003)		7.504 (8.817)		1.193 (6.534)
Unpaid Work for Own or Relative-Owned Business		6.059 (3.244)		3.739 (6.689)		7.559 (4.591)		6.082 (3.247)
Waiting to Start Obtained Job		−4.015 (4.026)				−6.439 (5.186)		−6.972 (3.696)
Unemployed and Looking for Work		−4.181[**] (1.329)		−3.734 (4.292)		−4.705* (2.172)		−4.685[***] (1.279)
Not Working Due to Temporary Sickness or Injury		−5.320 (3.238)		−7.658 (9.018)		−4.362 (5.230)		−4.703 (2.926)
Unable to Work Due to Long-Term Sickness or Injury		−9.971[***] (1.110)		−13.446[**] (4.162)		−11.884[***] (1.795)		−9.744[***] (1.089)
Retired		0.270 (0.994)		−0.870 (2.864)		−0.327 (1.595)		0.317 (0.987)
Looking After Home or Family		−1.202 (1.075)		−6.763* (3.144)		−2.137 (1.759)		−1.273 (1.067)
Doing Something Else		−0.063 (2.072)		−0.828 (5.503)		0.226 (2.794)		0.386 (1.999)
Age		edf: 4.642[***]		edf: 4.062		edf: 4.694*		edf: 4.782[***]
Intercept	51.736[***] (0.129)	51.898[***] (0.897)	52.201[***] (0.385)	53.286[***] (2.637)	51.931[***] (0.202)	52.532[***] (1.471)	51.699[***] (0.127)	51.865[***] (0.890)
Observations	5,014	5,014	517	517	2,005	2,005	5,225	5,225
Adjusted R^2	0.002	0.067	−0.0004	0.041	0.0001	0.074	0.0001	0.067
Log Likelihood	−18,208.6	−18,055.77	−1,858.02	−1,858.54	−7,259	−7,194.481	−18,984.9	−18,822.35
Note:	$p < 0.05$; $p < 0.01$; $p < 0.001$ edf = effective degrees of freedom							

5. Conclusion

This study looked into relationships between publicly accessible green space availability and biodiversity with mental well-being across Wales. The results of this study support findings from previous research. We report that the area of publicly accessible green space was not associated with better mental well-being after adjustment for socio-demographic factors for the overall cohort (Table 4, Fig. B2), or by stratifying for income group (Table C1) or rural/urban LSOAs (Table 7). Similar findings have been reported in previous studies in the UK (Houlden et al., 2017, 2018; McDougall et al., 2022; White, Pahl, et al., 2017).

For biodiversity, the results from our unadjusted models (Table 4, Figs. B3-4, B6, B8) support studies in Sheffield, England (Dallimer et al., 2012; Fuller et al., 2007). However, after adjusting for socio-demographic factors, only bird species richness is associated with mental well-being (Table 4, Fig. 4). These results were robust to modifying the LSOA boundaries and omitting less accurate species records (Table D1, Fig. D1) and to restricting the cohort to only include LSOAs with two or more species recorded (Appendix E). Furthermore, there was little to no evidence of relationships between biodiversity or green space with well-being across different income groups (Table C2-4), with the exception of group 3 for bird species richness (Table 6, Fig. 4). Finally, relationships were apparent between bird, butterfly and total species richness with well-being in urban LSOAs (Table 7, Figs. 6-8), but there was no evidence of relationships between any environmental metric in rural LSOAs (Table 7). Overall, using green space data and

routinely collected survey and biodiversity is a viable way to investigate associations between nature and well-being, as our results are in line with previous literature. Future research should be conducted to see whether relationships between biodiversity and mental well-being are present longitudinally, to ascertain any causal mechanisms underlying this association before recommendations on improving accessible greenspace quality to benefit mental well-being are made.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A

The links to the National Biodiversity Network Atlas (Wales) used to download the records of birds, butterflies and plants.

The links to the National Biodiversity Network Atlas (Wales) used to download the records of birds, butterflies and plants.

Link to bird records: https://wales-records.nbnatlas.org/occurrences/search?q=species_group%3ABirds%20AND%20identification_verification_status%3A(%22Accepted%22%20OR%

20%22Accepted%20-%20correct%22%20OR%20%22Accepted%20-%
20considered%20correct%22%20OR%20%22verified%22)%20AND%
20occurrence_date%3A%5B2018-01-01T00%3A00%3A00Z%20TO%
202018-12-31T00%3A00%3A00Z%5D&qc=cl28%3AWales#tab_ma
pView.

Link to butterfly records: https://wales-records.nbnatlas.
org/occurrences/search?q=identification_verification_status%3A(%
22Accepted%22%20OR%20%22Accepted%20-%20correct%22%20OR
%20%22Accepted%20-%20considered%20correct%22%20OR%20%
22verified%22)%20AND%20occurrence_date%3A%
5B2018-01-01T00%3A00%3A00Z%20TO%202018-12-31T00%3A00%
3A00Z%5D&fq=kingdom%3A%22Animalia%22&fq=phylum%3A%
22Arthropoda%22&fq=class%3A%22Insecta%22&fq=order%3A%
22Lepidoptera%22&fq=(family%3A%22Hesperiidae%22%20OR%
20family%3A%22Lycaenidae%22%20OR%20family%3A%22Nymph
alidae%22%20OR%20family%3A%22Pieridae%22)&qc=cl28%
3AWales.

Link to plant records: https://wales-records.nbnatlas.org/occ
urrences/search?q=species_group%3APlants%20AND%20identific
ation_verification_status%3A(%22Accepted%22%20OR%20%22Acce
pted%20-%20correct%22%20OR%20%22Accepted%20-%20considere
d%20correct%22%20OR%20%22verified%22)%20AND%20occ
urrence_date%3A%5B2018-01-01T00%3A00%3A00Z%20TO%20201
8-12-31T00%3A00%3A00Z%5D&qc=cl28%3AWales.

Appendix B

Plots of the relationships between green space and butterfly, plant and total species richness for the main unadjusted and adjusted analysis, and for bird species richness in the unadjusted analysis (Fig. B3, Fig. B5).

Appendix C

Generalized Additive Model outputs for the adjusted green space, butterfly species richness, plant species richness and total species richness models, stratified by income group (Table C2, Table C3, Table C4).

Appendix D

We conducted further analysis by restricting the species records to only include records with a 1×1 km grid reference or better and expanding the Lower layer Super Output Area borders by 500 m. We report the model outputs and the plots of the non-linear relationships for bird, plant and total species richness.

Appendix E

We conducted further analysis by restricting the Lower layer Super Output Areas to only include those which had a minimum of two species recorded. We report the model outputs and the plot of the non-linear relationship for bird species richness .

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