Doses of Neighborhood Nature: Benefits for Mental Health of Living with Nature

Running title: Variation in Nature and Mental Health

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Summary

Experiences of nature provide many mental health benefits, particularly for people living in urban areas. The natural characteristics of city residents' neighborhoods are likely to be critical determinants of the daily nature dose that they receive, however which characteristics are important remains unclear. One possibility is that the greatest benefits are provided by characteristics that are most visible during the day and so most likely to be experienced by people. We demonstrate that of five neighborhood nature characteristics tested, vegetation cover and afternoon bird abundances were positively associated with a lower prevalence of depression, anxiety and stress. Further, dose-response modelling shows a threshold response where the population prevalence of mental health issues is significantly lower beyond minimum limits of neighborhood vegetation cover (depression >20% cover, anxiety >30% cover, stress >20% cover). Our findings demonstrate quantifiable associations of mental health with the characteristics of nearby nature that people actually experience.

Background

The economic costs of anxiety and mood disorders, such as depression, have been estimated at €187.4 billion.yr^{-1} for Europe alone (Gustavsson et al. 2012, Olesen et al. 2012). Alongside stress, they are some of the most prevalent work-related health issues (13.7% of all reported work-related cases; Eurostat 2012). This growing problem has, at least in part, been attributed to the increasing disconnect between people and the natural world that is resulting from more urbanized, sedentary lifestyles (the 'extinction of experience'; Miller 2005, Soga and Gaston 2015). This is supported by research that shows interactions with nature promote psychological restoration (Kaplan 1995), improved mood (Hartig et al. 2003, Barton and Pretty 2010, Roe and Aspinall 2011), improved attention (Hartig et al. 2003, Ottosson and Grahn 2005) and reduced stress and anxiety (Ulrich et al. 1991, Grahn and Stigsdotter 2003, Hartig et al. 2003, Maas et al. 2009).

The causal factors behind poor mental health are complex and diverse (Kinderman et al. 2015), and cultural and socio-economic differences between regions may influence responses to interactions with nature (reviewed by Keniger et al. 2013). Understanding and capitalizing on the mechanisms by which natural environments provide psychological benefits nonetheless has the potential to be a novel and cost-effective approach to reducing the prevalence of some forms of mental ill health (Hartig et al. 2014, Shanahan et al. 2015b). Indeed, nature is likely to influence mental health through a range of mechanistic pathways (Shanahan et al. 2015b). Attention restoration theory proposes that the natural world promotes recovery from mental fatigue that occurs during the performance of cognitive tasks that require prolonged maintenance of directed attention (Kaplan 1995), while stress reduction theory argues that natural environments facilitate reductions in physiological arousal following stress (Ulrich et al. 1991). Both of these complementary theoretical frameworks lead to improved mental health from experiencing nature, through decreased rumination, increased cognition and reduced stress (Berman et al. 2012; Jiang et al. 2014; Tyrväinen et al. 2014; Bratman et al. 2015).

Increasingly, evidence suggests that the availability and quality of neighborhood green spaces are associated with greater well-being (White et al. 2013) and lower levels of depression, anxiety and stress (Beyer et al. 2014). These benefits may be gained from intentionally interacting with nature (such as through visiting neighborhood green spaces or spending time in a garden), from incidental interactions whereby people are exposed to nature as they engage in other activities (such as walking to the shops), or indirectly while not actually being present in nature (such as viewing it through a window; Keniger et al. 2013). The natural environment around the home is the nature that most people will experience every day, and therefore through all three kinds of nature interactions will significantly contribute towards people's daily nature experience.

To date, most research into the health benefits of nature has considered the role of green spaces per se. The role of specific biological components of those spaces remains unclear, although these need to be identified effectively to guide planning to operationalize the use of nature as a health promoting tool. In urban areas, two of the most visible elements of nature are vegetation cover and bird communities. The presence of vegetation has been found to have positive mental health benefits, including, but not limited to, helping to reduce stress and promoting restoration from mental fatigue (e.g., Fuller et al. 2007, Alvarsson et al. 2010, Dallimer et al. 2012). Having more bird species in the environment and watching birds has been shown to be good for people's psychological well-being (Fuller et al. 2007, Curtin 2009, Brock et al. 2015; Cox and Gaston 2016), while listening to bird song has been shown to contribute towards perceived attention restoration and stress recovery (Ratcliffe et al. 2013).

Previous studies investigating the relationship between components of biodiversity and psychological well-being have focused on measuring absolute diversity (how much diversity is estimated actually to be present; Fuller et al. 2007, Luck et al. 2011), and/or the diversity that people perceive to be present (Dallimer et al. 2012, Shwartz et al. 2014, Belaire et al. 2015). However, these may not reflect the biodiversity that people actually experience. In particular, daily activity levels of people and other organisms often differ, so understanding the well-being effects of the diversity that people actually experience requires consideration of lower than actual values.

Here we address two key questions. First, what components of nature are linked to positive mental health outcomes? To answer this, we explore the relationships between three established self-reported measures of mental health for depression, anxiety and stress, and five metrics of neighborhood nature (vegetation cover, estimated actual abundance and richness of birds, and the abundance and richness of birds that people are likely to experience). Our second question is whether there is a threshold in the mental health response. To answer this, we use dose-response modelling to estimate the point at which neighborhood vegetation cover (a tangible component of nature that relevant stakeholders can manage) influences the prevalence of depression, anxiety and stress, and the reduction in prevalence that could be achieved through enhanced exposure across the urban population.

Assessment of mental health and participants

We delivered an urban lifestyle questionnaire online (see Shanahan et al. 2016 for details) through a market research company (Shape the Future Ltd) to 1,023 adults enrolled in their survey database. All participants lived within the urban limits of the 'Cranfield triangle', a region in southern England, U.K., comprising the three adjacent towns of Milton Keynes, Luton, and Bedford. Together they comprise an urbanized area of c.157 km^2 and an urban population of c.524,000 (2011 Census, UK). The triangle represents great variation in human population density (including examples of low and high density living), urban history and urban form. The survey was delivered in May 2014, a period of reasonably mild weather when respondents were most likely to engage with nature around their home, and so the benefits of nature may be more pronounced. Participants were self-selecting and were compensated with either a nominal fee or a prize draw entry (see supplemental appendix S1 for ethical clearance). A subset of 263 respondents for whom there was both vegetation and bird survey data, was then used in the analysis (see the metrics of neighborhood nature section below).

Survey respondents were asked to complete the short version of the Depression, Anxiety and Stress Scale (DASS 21; Lovibond and Lovibond 1995). On a four-point scale respondents rated the extent to which each of 21 statements applied to them over the previous week (seven statements for each of depression, anxiety and stress; table S2a). To characterize the degree of severity for each mental disorder relative to the wider population, these scores were summed for each disorder before banding as normal, mild, moderate, severe or extremely severe (table S2b; Lovibond and Lovibond 1995). If a respondent did not score a statement, then the relevant disorder for that respondent was discarded from the analysis (remaining respondents; depression = 248, anxiety = 259, stress = 240).

The survey collected socio-demographic and personal circumstance data that could potentially influence mental health, including age, gender, the primary language spoken at home, personal annual income, the number of days exercised for 30 minutes or more during the survey week (an indicator of physical activity), self-assessment of health and highest formal qualification. As a potential confound of recent nature exposure, we asked respondents relatively how much time they spent out of doors in the previous week (supplemental table S1 shows how these variables were used for analysis). Respondents were requested to provide a full UK postcode so that their neighborhood could be characterized (one UK postcode covers approximately 20 households). Based on the postcode the English Index of Multiple Deprivation (IMD) was used to assess the level of socio-economic disadvantage (*Sharegeo.ac.uk*, data sourced from *Data.gov.uk*). Finally, using the UK gridded population based on the Census 2011 and Land cover map 2007 (Reis et al. 2016) we calculated neighborhood population density (see supplemental appendix S2 for full description of these two variables).

Metrics of neighborhood nature

We measured five key components of nature that people were exposed to around the home. We first measured neighborhood vegetation cover as vegetation ≥0.7 m in height, within a 250 m buffer around the centroid of each respondent's postcode, approximately reflecting the viewscape from, and the area immediately adjacent to, people's homes. Vegetation cover maps were derived from airborne hyperspectral and LiDAR (Light Detection and Ranging) data; full details of spatial product development are provided in the supplemental appendix S3.

We conducted extensive bird surveys within the towns to generate a further four metrics of neighborhood nature. We estimated actual bird abundance and species richness as that recorded during early morning surveys when birds are most active and so most likely to be recorded (supplemental appendix S4). We also estimated the bird abundance and species richness that people were likely to experience, as those birds that were recorded during afternoon surveys when most people are also active (supplemental appendix S4). These were derived from point count surveys, using distance sampling, at up to four locations within 116 tiles, each of 500×500 m squares that were selected randomly across the three towns (full details are provided in supplemental appendix S4). We estimated neighborhood bird abundances and richness for those respondents whose 250 m neighborhood buffer overlapped with at least one bird survey location within a survey tile (respondents = 263; tiles = 84; see supplemental table S3 for socio-demographics of subset; supplemental figure S1 illustrates an example of overlap). This subset of respondents was used in subsequent analyses.

The neighborhood vegetation cover varied nine-fold across the 263 respondents (table S4). Pearson's rank sum tests of the five metrics of neighborhood nature showed that actual and afternoon species richness were highly correlated (Pearson's $r = 0.72$, p

<0.0001), while the remaining nature variables were either weakly or not correlated (*r* <0.28; see supplemental table S5 for correlation matrix between nature variables).

Relationships between mental health and neighborhood nature

We used ordinal regression to explore relationships between the five metrics of neighborhood nature and each mental health disorder in turn. We incorporated age, gender, language, income, physical activity, self-assessment of health, level of education, relative time out of doors in the previous week, neighborhood population density and the IMD as covariates. We standardized the five nature metrics and neighborhood population density such that each had mean zero and standard deviation one. Because multicollinearity of >0.7 can severely distort model estimation (e.g. Dormann et al. 2013, Cade 2015), we built two models for each mental state, including either actual or afternoon species richness in each along with the other three nature metrics and covariates. We used the 'MuMIn' package (Bartoń 2015) to produce all subsets of models based on the global model and rank them based on the Akaike Information Criterion (AICc). Over-dispersion in models is problematic in AICc analysis and may be due to not accounting for important covariates or multicollinearity, which can result in selection of overly complex models that can lead to poor inference. Following Burnham and Anderson (2002, p.131) and Richards (2008) we reduced the retention of overly complex models by excluding from the set of candidate models all models that are more complicated versions of any model with a lower AICc value (i.e., nesting of models). To be 95% sure that the most parsimonious models were maintained within the best supported model set, we then retained all models where ΔAICc < 6 (Richards 2005, 2008). We then calculated averaged parameter estimates and standard errors using model-averaging among the retained models (Burnham and Anderson 2002).

People living in neighborhoods with higher levels of vegetation cover and afternoon bird abundances had reduced severity of depression, anxiety and stress (table 1; figure 1). In contrast, there was no relationship with the estimated actual neighborhood bird abundance and species richness, or afternoon species richness (table 1). Respondents who spent less time out of doors than usual in the last week had worse depression and anxiety (table 1). Respondents over the age of 45 years were less likely to suffer from depression than younger respondents, while those between 46 and 60 years were less likely to suffer from anxiety (table 1). Mental health was positively correlated with self-reported physical health (table 1; inherent bias within self-reported surveys is here, at least in part, mitigated through large sample sizes and a robust ordinal regression analytical approach).

Here we have shown that metrics of nature that were most visible during the day and so most likely to be experienced by people, namely vegetation cover and afternoon bird abundances, were positively associated with a lower population prevalence of depression, anxiety and stress. This may have arisen for a range of non-mutually exclusive reasons. First, experiences of visible nature may act to improve people's mental health, as predicted from previous empirical studies of interactions between nature and well-being (see Introduction for references). Second, people with no or low mental health dis-orders may be self-selected by electing to move into neighborhoods that are greener. Third, they may provide resources for birds, thereby increasing opportunities for closer interactions throughout the day. Thus it is unclear whether a lower population prevalence of poor mental health is shaped by the natural environment people live in, or whether people move to a neighborhood that reflects that trait, or whether it is some combination of these factors. However, we found no relationship with the metrics estimating actual bird community composition or actual or afternoon species richness; nor were there relationships between mental health and covariates such as the IMD, education or population density, although this is not entirely unsurprising given the complex nature of mental health disorders and that previous studies have recorded wide variation in these relationships across different human populations (e.g. Das et al. 2007). The difference in the associations of actual and visable bird abundance with mental health is indicative of an effect of visible nature on mental health. Notwithstanding, future research needs to focus on further unpicking causal pathways, such as through studies of brain activity and function during exposure to nature (e.g. Bratman et al. 2012, 2015).

The shape of the relationships between vegetation cover and the increasing severity of each mental health disorder suggests that the greatest benefits were gained by those respondents with mild or moderate mental health disorders (figure 1). This may be because the severity of depression often determines behaviors, and thus the degree to which people engage with nature. So people suffering from severe mental health disorders may be less likely to venture out of doors, and the mechanisms behind their disorders may be different, thereby reducing the positive influence of nature. Respondents who spent relatively less time out of doors in the survey week were more likely to report worse depression and anxiety. Intriguingly this suggests that the relative nature experienced is a significant contribuing factor.

We found no relationship between mental health and either measure of bird richness or that of actual abundance. Given that most people cannot distinguish between species (Dallimer et al. 2012, Shwartz et al. 2014) benefits may be provided through directly experiencing abundance, with richness contributing when people can see multiple species within a relatively small timeframe, such as around a feeder (Cox & Gaston 2015). Although the positive benefits for mental health of interacting with birds is compeling, in this study it was not possible to determine the actual abundances of birds that respondents interacted with and thus there may be more than one explanation for the positive associations between afternoon bird abundances and improved mental health. First, as seems likely, the abundances recorded by ecologists in the afternoon may be a good representation of the birds that most people experience and gain benefits from. Second, these abundances may be a proxy for another biological component.

Dose-response relationships between neighborhood vegetation cover and mental health

We next calculated the dose-response of each mental health disorder within the survey population that could be attributed to levels of neighborhood vegetation cover. We created a further three binary response variables, those with normal mental health for each of depression, anxiety and stress, and those suffering with mild or worse cases (Lovibond and Lovibond 1995). We used logistic regression for each binary response variable in turn to estimate the relative odds of occurrence in an individual given specific risk factors that were statistically significant in the previous analysis. Each covariate (i.e., risk factor) was transformed into a binary factor conveying 'high' versus 'low' risk (see supplemental table S6). For each mental health disorder we ran multiple logistic regression models. The first model contained the risk factors described above with the binary factor vegetation cover set at 10%, below which the risk of poor mental health was 'high'. The model was then repeated applying an incrementally increased break point in vegetation cover (i.e., <15%; <20%; <25%; 30%; <35%). We identified the point at which the health gains were first recorded as better than the null model on a plot of dose versus the odds ratio for use in the analysis described below (i.e., the confidence interval did not overlap with an odds ratio of one).

For each mental health disorder we calculated the population average attributable fraction to estimate the proportion of cases in the population attributable to each of the predictor variables (or risk factors; e.g., Rueckinger et al. 2009). Each risk factor was removed sequentially from the population by classifying every individual as low risk. The probability of each person experiencing mild or worse depression, anxiety or stress was then calculated, where the sum of all probabilities across the population was the adjusted number of disease cases expected if the risk factor were not present. The attributable fraction was calculated by subtracting this adjusted number of cases from the observed number of cases. The risk factors were removed in every possible order, and an average attributable fraction from all analyses was obtained (table 2).

After accounting for covariates, the odds of having mild or worse depression were significantly lower when neighborhood vegetation cover reached a threshold of 20%, with gains in the odds ratio of 0.35 by 35% vegetation cover (figure 2a). There was a significantly lower chance of having anxiety and stress after 30% and 20% vegetation cover respectively, although there was greater variability in the dose-response curve (figure 2b and 2c). The power of the tests for all three mental health disorders was reduced at higher levels of vegetation cover (indicated by wider 95% confidence intervals) because the proportion of respondents reporting poor mental health declined at these levels; increasing the number of respondents may reduce the variability in the dose-response curves.

This threshold analysis has important implications for setting future research directions towards operationalizing nature as a tool for improving health and well-being for populations. While there is unlikely to be a 'one size fits all' policy for optimizing nature in cities, establishing minimum levels of vegetation cover in neighborhoods is a practical approach that could be incorporated into city design.

The results suggest that if all respondents lived in neighborhoods with vegetation cover of >20% then the total number showing symptoms of depression would be reduced by up to 11%. The number of cases of anxiety and stress could be reduced by up to 25% and 17% if vegetation cover were >30% and >20%, respectively. Within the survey population 38%, 76% and 38% of respondents were considered at risk of showing symptoms of depression, anxiety and stress respectively, because neighborhood vegetation cover levels were not met. In 2007 it was estimated that depression cost the English economy £7.5 billion and anxiety cost £8.9 billion in health costs and lost workdays (McCrone et al. 2008). Although the causes of poor mental health are diverse, a simplistic calculation would be that if minimal levels of neighborhood vegetation cover were met, it has the potential to contribute towards an annual saving of up to £0.5 and £2.6 billion per year for depression and anxiety alone. Doubtless the financial implications are marked. Consequently, manipulation of neighborhood vegetation and bird populations to 'optimal' levels can and should be encouraged to be undertaken by both private and public stakeholders. There are multiple approaches available such as through the innovative addition of green infrastructure like tree planting, the addition of green walls and roofs (Tzoulas et al. 2007), or the provision of supplementary food and nesting locations to increase local bird abundances (Fuller et al. 2008) and bring birds into closer contact with people.

Research is starting to tease apart the mechanistic pathways behind how different components of nature benefit mental health (e.g., Bratman et al. 2015, Shanahan et al. 2015a). Although this study does not demonstrate causation per se, the positive relationships between two metrics of neighborhood nature and better mental health are consistent with a mechanistic effect. Indeed, the dose-response relationship for depression, and to a lesser extent anxiety and stress, is considered to provide some evidence of causality according to Hill's criteria (Hill 1965). These benefits are likely to be provided via two pathways, first by increasing the attractiveness and appeal of green space such that people are more likely to spend time out of doors and thus increase the likelihood that they will engage in physical or social activities, and second increasing the visual complexity of the landscape enhancing its effect on mental restoration and well-being (Shanahan et al. 2015b). However, at the same time it is important to acknowledge that living close to too much, or inappropriate, nature can also provide a range of dis-services such as destruction of property from vegetation and breeding birds (e.g. Rock 2005), or increased levels of vegetation leading to feelings of decreased safety in some neighborhoods (e.g. Kuo et al. 1998). Future research into 'best' doses of nature would benefit from exploring the trade-offs between the benefits and dis-services.

Conclusion

Although the causes and drivers of poor mental health are diverse (Kinderman et al. 2015) this study suggests that even low levels of key components of neighborhood nature can be associated with better mental health, providing promise for preventative health approaches. This study shows that quantifiable reductions in the population prevalence of poor mental health can be achieved if minimal thresholds of vegetation cover are met. This has important implications for policy to set minimum levels of neighborhood nature and paves the way to test for health gains that arise from specific interventions. Obviously, optimized levels of nature are not a silver bullet for the prevention or treatment of mental health problems, but it is an approach that can and should be applied in conjunction with existing frameworks such as medical and social services, reducing crime and increasing community driven action. Indeed, optimizing the key components of nearby nature have been shown to change behavior towards increased social cohesion (e.g. Weinstein et al. 2015) and green exercise (e.g. Mitchell and Popham 2008).

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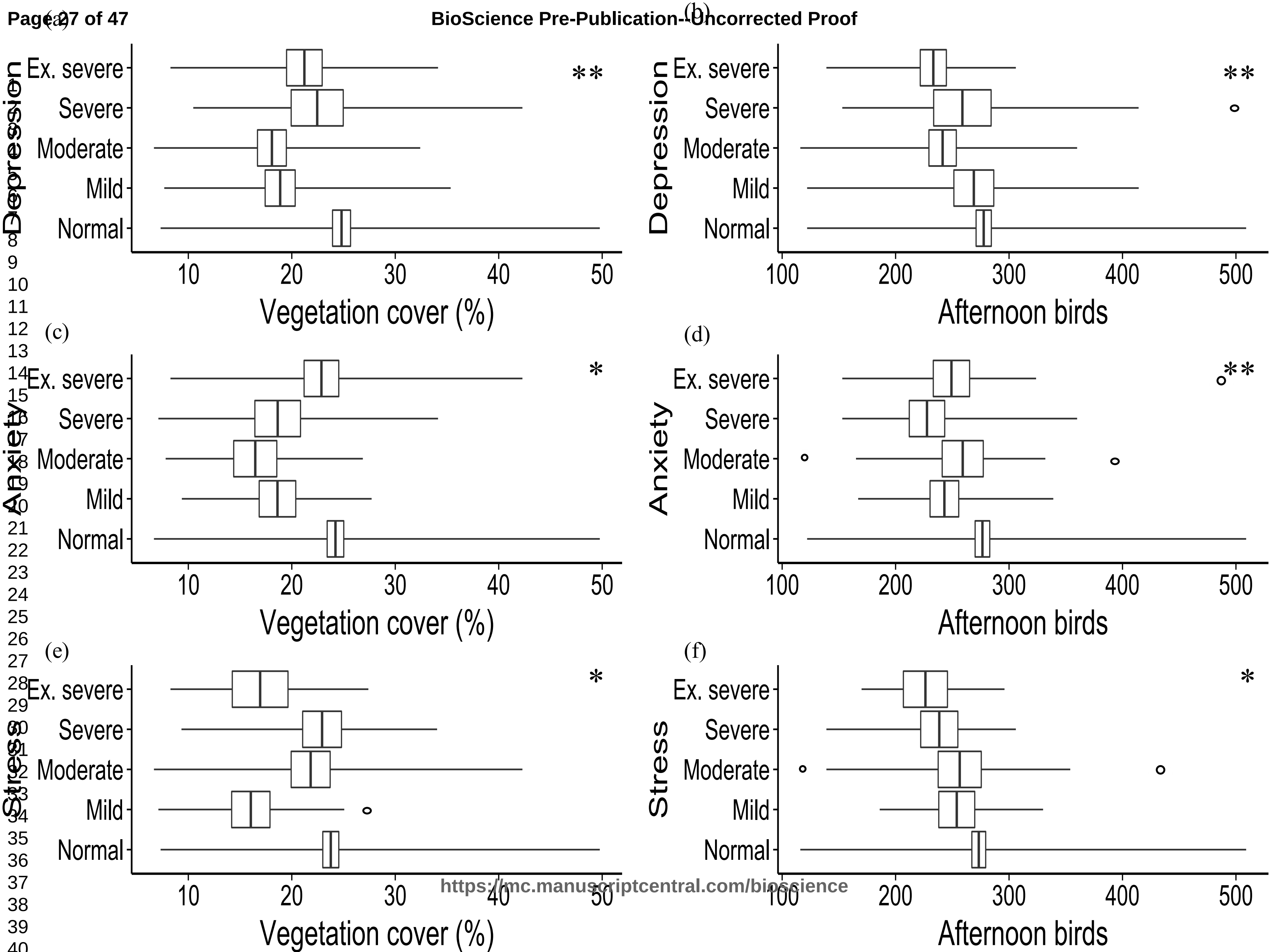
Table 1: Nested model averaging of ordinal regression showing negative relationships between two visible components of nature around the home and three mental health disorders, whilst adjusting for socio-demographic factors. For the categorical variables (listed in italics), we show the model-averaged coefficients (with standard errors in brackets) of variables relative to a comparative base factor level (e.g., age ≤30 years, so a positive coefficient suggests that those >30 years have worse mental health; other base factors are: Gender, females; Language, English is the primary language spoken at home; Relative time outdoors, Less time; Self-assessment of health, very poor; Education, 16+ education).

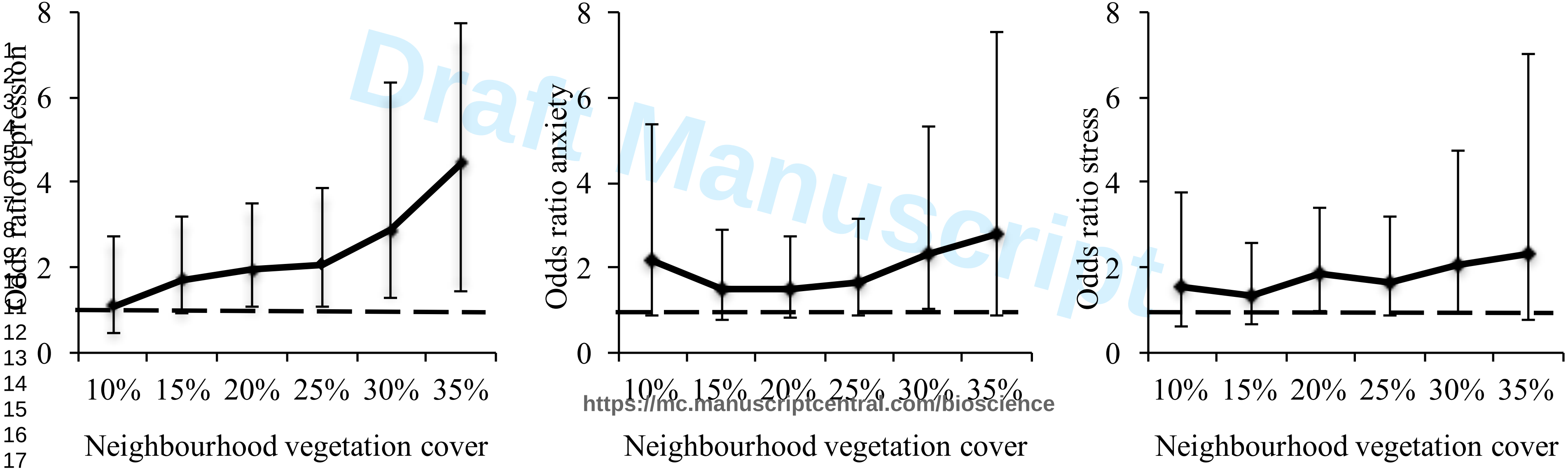
Variables	**Depression**	**Anxiety**	**Stress**
Vegetation cover	-0.41 (0.15)**	-0.34 (0.16)*	-0.30 (0.15)*
Actual abundance	-	0.26 (0.16)	0.25 (0.16)
Actual richness[+]	-	-	-
Afternoon abundance	-0.43 (0.15)**	-0.54 (0.18)**	-0.35 (0.18)*
Afternoon richness[+]	-	-	-
Gender (male)	-	0.49 (0.32)	-
Language	0.57 (0.36)	-	-
Income	0.13 (0.08)	-	-
Physical activity	-	-	-
IMD	-	-	-
Population density	-	-	-
Relative time outdoors			
About the same	-0.74 (0.33)*	-0.95 (0.36)*	0.55 (0.36)
More time	-0.84 (0.38)*	-1.29 (0.42)**	-0.88 (0.48)
Age			
Age (31 to 45 yrs)	-0.11 (0.33)	-0.02 (0.35)	0.59 (0.35)
Age (46 to 60 yrs)	-1.13 (0.39)**	-1.23 (0.44)**	-0.78 (0.46)
Age (>60 yrs)	-1.90 (0.82)*	-0.93 (0.65)	-1.70 (1.07)
Self-assessment of Health			
Poor	-1.81 (1.02)	-3.75 (1.39)**	-
Average	-2.28 (0.94)**	-3.92 (1.32)***	-
Good	-3.49 (0.95)***	-4.57 (1.32)***	-
Very good	-3.30 (0.96)***	-4.73 (1.35)***	-
Level of education			
Education (18+)	-	-	-
Education (Undergraduate)	-	-	-
Education (Postgraduate)	-	-	-

Significant variables and factor levels relative to base level are shown as: *P < 0.05; **P < 0.01; ***P < 0.001. [+] For each mental health disorder we built two identical models, testing each measure of richness separately (see methods) – variable was not retained in the top nested models where delta <6.

Table 2: Dose-response modelling shows the proportion of mental health cases in the study population attributable to various risk factors (average population attributable fraction; AAF), we show a positive association between a reduced population prevalence of depression, anxiety and stress and minimal thresholds of neighborhood vegetation cover* (depression >20% cover, anxiety >30% cover, stress >20% cover). An odds ratio above 1 indicates the mental health disorder is more likely to be present where the risk factor is present.

		Depression		**Anxiety**		**Stress**	
	Risk factor	Odds ratio (95% CI)	AFF	Odds ratio (95% CI)	AFF	Odds ratio (95% CI)	AFF
Age	Higher risk <46 years	3.28 (1.48:7.78)	0.37	2.11 (0.96:4.66)	0.22	NA	NA
Self-assessment of health	Higher risk <average health	6.0 (2.02:17.8)	0.07	3.65 (1.31:9.98)	0.49	NA	NA
Relative time outdoors	Higher risk <less time outdoors	3.30 (1.64:6.62)	0.12	2.50 (1.25:4.98)	0.09	NA	NA
Vegetation cover	Higher risk <% veg. cover*	2.00 (1.11:3.61)	0.11	2.29 (1.01:5.20)	0.25	1.76 (1.01:3.83)	0.17
Afternoon bird abundance	Higher risk <266 birds	2.03 (1.16:3.52)	0.15	3.05 (1.70:5.50)	0.24	1.70 (0.93:3.44)	0.17


(a)
(b)
(c)
(d)
(e)
(f)
Depression
Anxiety
Stress
Ex. severe
Severe
Moderate
Mild
Normal
**
*
10 20 30 40 50
Vegetation cover (%)
100 200 300 400 500
Afternoon birds


8
6
4
2
0
Odds ratio depression
10%
15%
20%
25%
30%
35%
Neighbourhood vegetation cover
Odds ratio anxiety
Neighbourhood vegetation cover
Odds ratio stress
Neighbourhood vegetation cover

Supplemental Material

Doses of Neighborhood Nature: Benefits for Mental Health of Living with Nature.

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Contents

Appendix S1. Ethical clearance

This research was conducted with approval from the Bioscience ethics committee of the University of Exeter (project number 2013/319). Participants provided written consent at the beginning of the online survey by checking a box stating their agreement to participate.

Appendix S2. Calculation of Index of Multiple Deprivation and neighborhood population density.

Index of multiple deprivation: We used the Indices of Multiple Deprivation (IMD, *Sharegeo.ac.uk*, data sourced from *Data.gov.uk*) produced by communities and local government to derive a socio-economic deprivation score for each tile. The IMD contained separate indices for separate domains of deprivation (e.g. ward level income, employment, health deprivation and disability), which were simply averaged. This IMD is provided at the postcode scale.

Neighborhood population density: We used the UK gridded population based on the Census 2011 and Land cover map 2007 (Reis et al. 2016). This dataset contains a gridded population density with a spatial resolution of 1 km x 1 km. For each 250 m buffer around the centroid of a respondent's postcode we scaled the estimated population relative to the area of the gridded population square that the buffer covered. Where the buffer covered more than one tile we weighted our estimate by the proportion of each tile that was covered.

Appendix S3. Characterization of the urban form for each tile. The urban form for each tile was characterised using airborne hyperspectral (Eagle imaging spectrometer; 12 bit, pushbroom, hyperspectral sensor with a 1000 pixel swath width, covering the visible and near infra-red spectrum 400 - 970nm) and LiDAR (Light Detection and Radar) (Leica ALS50-II) data collected by the Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) aircraft in July and September 2012. The normalized difference vegetation index (NDVI; Tucker 1979) was calculated from the hyperspectral data using a red band centered on 570nm and a near infra-red band centered on 860 nm with a spatial resolution of 2m. Histograms of NDVI were examined and a threshold of 0.2 identified as being suitable to separate vegetated (NDVI>=0.2) from non-vegetated (NDVI<0.2) pixels (Liang 2004). The LiDAR data were used in discrete return mode, with up to four returns per laser pulse. The laser point density was between one point per 25cm^2 and one point per 2m^2, depending on flight line overlap. The lastools 'lasground' function (Isenburg 2011) was used to find ground returns within the LiDAR point cloud. Pixels (2m resolution) with an NDVI greater than 0.2 and a mean height of first return more than 0.7 m above the ground were marked as trees (figure S1). Heights from discrete return LiDAR are well-known to produce biased results over vegetation (Hancock et al. 2011) and so this 0.7 m threshold may have represented a more variable vegetation threshold height, and since that bias is most usually an underestimation, it could correspond to taller vegetation (up to 1.7 m tall). We then measured neighborhood tree cover as vegetation ≥0.7 m in height, within a 250 m buffer around the centroid of each respondent's postcode. We estimated that the average area of the respondents' postcodes was 12,436 m^2, (14,257 SD), and so fell within the neighborhood buffer.

Appendix S4. **Estimation of neighborhood actual bird abundance and species richness, and the abundance and richness of birds that people are likely to experience.** We divided the landscape within the urban limits of the three towns into 500×500 m square 'tiles' (250,000 m^2), where tiles within the urban limit were defined as those within the administrative boundary that had greater than 25% urban built form, as assessed by eye (Gaston et al. 2005). As a measure of urban form within each tile we calculated the tree cover (Appendix S3), as well as the number of building polygons shown in the Ordnance Survey MasterMap (2013). We then selected a subset of 116 tiles using random sampling stratified to provide consistent variation in urban form between 0% and 50% tree cover and between 0 and 20% built cover, reflecting the range of values found in the study towns. Within each tile, up to four point locations were identified (mean per tile, 3.89 ± 0.37 SD), in order to represent the diversity of urban forms present as fully as possible, subject to access restrictions. Survey points were selected to be ≥200 m apart and ≥100 m from tile edges, such that surveys from each point sampled different birds, with fewer than four points being chosen if sufficiently separated points could not be accessed.

To measure bird abundance, we used point counts and a distance sampling procedure to account for differences in detectability among species (Buckland et al. 2001). All point counts were conducted by one of two trained researchers. To estimate actual bird abundance, two early-morning surveys (06:00 – 10:00 hours) were conducted at each point in all tiles during the breeding season, one in May and one in June; these were timed to maximize the detectability of the component species of the local breeding bird community. The abundance that people are likely to experience was estimated using two later-day surveys (10:00 – 18:00 hours) that were conducted in each tile from May – July using the same protocols as the early-morning surveys. Point counts were conducted for ten-minute periods, divided into two-minute intervals. Within each two-minute interval, the number of birds and the radial distance from the observer at which they were seen was recorded in bands of 0-20 m, 20-40 m, 40-60 m and 60-100 m. Birds were recorded independently in each two-minute period. Individuals that moved during a two-minute period were recorded in the distance band in which they were first detected.

For each individual ten-minute point count, we selected the maximum count of each species per distance band from the multiple two-minute intervals. For each band we then selected the maximum total count across visits. We used these data and the 'unmarked' package (Fiske and Chandler 2011) to calculate bird abundance corrected for detection probability, whilst adjusting for percentage tree cover >0.7 m and percentage built cover within the survey radius. We calculated a pooled detection function for species with similar morphology and behavior, assuming that these species had similar detection characteristics (table S7). This is because a number of species had small sample sizes (<40 records), which precluded appropriate distance analysis on these individual species. Species with small sample sizes that were morphologically and/or behaviorally distinct were excluded from analysis (Northern lapwing *Vanellus vanellus*; pheasant *Phasianus colchicus*; European cuckoo *Cuculus canorus*; European kingfisher *Alcedo atthis;* Grey wagtail *Motacilla cinerea*). Models failed to converge for a further five groups of species and the original abundances were used (table S7). Because detection of species might vary with time of day (Alldredge et al. 2007) we calculated detection probabilities for each species, or group of species, for both early morning and afternoon surveys. We calculated an adjusted measure of abundance in each survey tile by dividing raw abundance counts for each species by its detection probability, before summing adjusted counts across species (or unadjusted counts for those species or groups of species where models failed to converge) within each survey point to get the total abundance by survey tile.

To estimate actual species richness within each survey tile we calculated the total number of species seen across all early morning surveys. We repeated this for afternoon surveys to obtain an estimate of the species richness that people are likely to experience.

Table S1. Socio-demographic variables used in the analysis. Variables used to examine the relationship between three negative mental states (depression, anxiety and stress) and a participant's exposure to five metrics of nature intensity.

Name	Variable	Description	Supporting reference for inclusion
Age (ordinal)	Age	Respondents selected from 11 brackets: 18-20 years, then increasing increments of five years until >60 years. Responses were then banded as: 18-30 years; 31-45 years; 46-60 years; >60 years	(Astell-Burt et al. 2014a, Mroczek and Kolarz 1998, Wu et al. 2015)
Gender (categorical)	Gender	Female or Male	(Rosenfield and Mouzon 2013, Ross and Mirowsky 2006)
Language (categorical)	Primary language spoken at home	Respondents speak a language other than English at home (No or Yes)	(Bratter and Eschbach 2005, Wu et al. 2003)
Income (categorical)	Personal annual income	Respondents selected from eight brackets: No income; £1-£199 a week (£1-£10,399 per year); £200-£299 a week (£10,400-£10,599 per year); £300-£399 (£15,600-£20,799 per year); £400-£599 a week (£20,800-£31,199 per year); £600-£799 a week (£32,200-£41,599 per year); £800-£9,999 a week (£41,600-£51,999 per year); >$1,000 a week (>£52,000)	(Astell-Burt et al. 2014b, de Vries et al. 2003, Weich et al. 2001)
Physical activity (numeric)	Physical activity	Self-reported number of days in previous week that the respondent exercised for more than 30 minutes	(Barton and Pretty 2010, Cohen-Cline et al. 2015, Deslandes et al. 2009, Mitchell 2013, Richardson et al. 2013)
Physical health (ordinal)	Self-assessment of health	Respondents selected from: Very poor; poor; average; good; very good	(Maas et al. 2006, van Dillen et al. 2012)
Education (categorical)	Highest formal education	Highest qualification (selected from four categories equivalent to: General Certificate of Secondary Education (GCSE); A-levels; Bachelor's degree; Postgraduate degree)	(Fryers et al. 2003, Miech and Shanahan 2000)
Recent nature experience (factor)	Relative time spent in nature in previous week	Respondents selected from: less time; about the same time; more time.	
IMD (numeric)	Index of Multiple Deprivation	Indices of Multiple Deprivation weighted for the 250m buffer of the centroid of the respondents postcode (see appendix S2).	IMD, *Sharegeo.ac.uk*, data sourced from *Data.gov.uk*
Population density (numeric)	Population density	UK gridded population based on the census 2011 and Land cover map 2007, weighted for the 250m buffer of the centroid of the respondents postcode (see appendix S2).	(Reis et al. 2016)

Table S2. Depression, Anxiety and Stress Scale 21 (DASS 21) included in the urban lifestyle questionnaire (taken from (Lovibond and Lovibond 1995) and reproduced here for ease of reference). Seven statements rated each mental health state. a) Answers to each statement were given on a four-point scale from: did not apply to me at all; applied to me to some degree, or some of the time; applied to me to a considerable degree, or a good part of the time; applied to me very much, or most of the time. b) The severity of each mental health state was then rated by summing the relevant scores.

a) Statement	**Mental state**
I found it hard to wind down	Stress
I was aware of dryness of my mouth	Anxiety
I couldn't seem to experience any positive feeling at all	Depression
I experienced breathing difficulty (e.g. excessively rapid breathing, breathlessness in the absence of physical exertion)	Anxiety
I found it difficult to work up the initiative to do things	Depression
I tended to over-react to situations	Stress
I experienced trembling (e.g. in the hands)	Anxiety
I felt that I was using a lot of nervous energy	Stress
I was worried about situations in which I might panic and make a fool of myself	Anxiety
I felt that I had nothing to look forward to	Depression
I found myself getting agitated	Stress
I found it difficult to relax	Stress
I felt down-hearted and blue	Depression
I was intolerant of anything that kept me from getting on with what I was doing	Stress
I felt I was close to panic	Anxiety
I was unable to become enthusiastic about anything	Depression
I felt I wasn't worth much as a person	Depression
I felt that I was rather touchy	Stress
I was aware of the action of my heart in the absence of physical exertion (e.g. sense of heart rate increase, heart missing a beat)	Anxiety
I felt scared for no good reason	Anxiety
I felt life was meaningless	Depression

b)	**Depression**	**Anxiety**	**Stress**
Normal	0 – 4	0 – 3	0 - 7
Mild	5- 6	4- 5	8 – 9
Moderate	7 – 10	6 – 7	10 – 12
Severe	11 – 13	8 – 9	13 – 16
Extremely severe	14 +	10 +	17 +

Table S3. Distribution of the subset of respondents for which we calculated metrics of neighborhood nature, across socio-demographic variables within the study towns (263 respondents). For comparison we also show the distribution of the Buckinghamshire and Bedfordshire counties, 2011 Census population average.

Variable	Level	Subset of survey respondents	Local population
Gender	Female	56%	51%
	Male	44%	49%
Income	No income	5%	5%
	£1-£10,399 per year	12%	12%
	£10,400-£10,599 per year	11%	19%
	£15,600-£20,799 per year	14%	11%
	£20,800-£31,199 per year	26%	25%
	£32,200-£41,599 per year	16%	18%
	>£41,600	15%	10%
Age	18-30 years	29%	21%
	31-45 years	35%	25%
	46-60 years	27%	32%
	>60 years	9%	21%
English is not the primary language spoken at home	No	85%	72%
	Yes	15%	28%
Self-assessment of health	Very poor	1.5%	0.8%
	Poor	5.7%	2.7%
	Average	27.0%	10.7%
	Good	40.3%	33.8%
	Very good	24.7%	52%
Highest level of education (or equivalent)	16+ (Secondary)	18%	28%
	18+ (A-level)	40%	12%
	Undergraduate	33%	27%
	Postgraduate	9%	8%
Physical activity (> 30 minutes exercise a week)*	0 days	29%	-
	1 day	19.4%	-
	2 days	16%	-
	3 days	14%	-
	4 days	8%	-
	5 days	9%	-
	6 days	1%	-
	7 days	4%	-
Relative time spent out of doors in previous week*	Less time		-
	About the same		-
	More time		-

* data is unavailable for county averages

Table S4. We show a) variation in five metrics of neighborhood nature, and b) a count of respondents for the severity for each mental health disorder.

a) Variable	Mean	Range
Metrics of neighborhood nature		
Vegetation cover (%)	23 (±10)	6-50
Bird actual abundance	541 (±100)	254-886
Bird actual species richness	22 (±4)	14-33
Bird afternoon abundance	267 (±79)	116-509
Bird afternoon species richness	15 (±3)	10-23

b) Mental health	Normal	Mild	Moderate	Severe	Ex. severe
Depression	148	22	29	20	23
Anxiety	178	18	15	17	30
Stress	182	14	24	14	8

Table S5. Pearson's correlations between five metrics of neighborhood nature. For comparison we also show correlations with vegetation cover within the bird survey tiles.

Nature metric	Vegetation cover	Actual abundance	Actual richness	Afternoon abundance	Afternoon Richness
Vegetation cover	-				
Actual abundance	0.08	-			
Actual richness#	0.08	0.19	-		
Afternoon abundance	0.11	0.29	0.05	-	
Afternoon richness	0.14	0.23	0.72	0.27	-
Vegetation cover in bird survey tiles	0.57	-0.07	-0.08	0.11	-0.00

Table S6. Binary risk factors for each covariate that was significant in the first analysis.

Variable	Conversion to binary risk factor
Age	The prevalence of mood disorders begin to decline in Australia at around 45 years (Statistics 2009). We therefore created a binary risk factor, at which above 45 years the risk of having poor mental health was zero and below was one.
Self-assessment of health	There is a higher prevalence of poor mental health in people with poor physical health (e.g. Osborn 2001). We created a binary risk factor at which the risk of having poor mental health was zero in people with average to very good health, and one in people with poor to very poor health.
Relative time spent out of doors in previous week	No information was available on time spent out of doors in the previous week and mental health. We thus considered that people had an increased risk if they spent less time out of doors in the previous week than usual.
Afternoon bird abundances	No information was available on bird abundances and mental health. We thus considered that people had an increased risk if they resided in a neighborhood with afternoon bird abundances below the median neighborhood bird abundance of this study (266 individual birds).
Neighborhood vegetation cover	We created multiple binary risk factors in increasing increments of 5%, for break points of neighborhood tree cover (10%, 15%, 20%, 25%, 30%, 35%). Where the levels of neighborhood vegetation cover were below this break point the risk of poor mental health was one, and above the risk was zero.

Table S7. Pooled detection functions for species with similar morphology and behavior.

We show whether models converged (there was no difference in convergence between morning and afternoon surveys).

Species group	Species	Model converged?
Duck	Great crested grebe (*Podiceps cristatus*); Cormorant (*Phalacrocorax carbo*); Mute swan (*Cygnus olor*); Greylag goose (*Anser anser*); Canada goose (*Branta canadensis*); Mallard (*Anas platyrhynchos*); Moorhen (*Gallinula chloropus*); Coot (*Fulica atra*)	No
Raptor	Red kite (*Milvus milvus*); Buzzard (*Buteo buteo*); Sparrowhawk (*Accipiter nisus*); Kestrel (*Falco tinnunculus*); Hobby (*Falco subbuteo*); Peregrine (*Falco peregrinus*)	No
Wader	Little egret (*Egretta garzetta*); Grey heron (*Ardea cinerea*); Oyster catcher (*Haematopus ostralegus*); Common sandpiper (*Actitis hypoleucos*); Green sandpiper (*Tringa ochropus*)	No
Gull	Black-headed gull (*Chroicocephalus ridibundus*); Herring gull (*Larus argentatus*); Lesser black-backed gull (*Larus fuscus*); Common gull (*Larus canus*)	No
Woodpecker	Green woodpecker (*Picus viridis*); Great spotted woodpecker (*Dendrocopos major*)	Yes
Flier	Swift (*Apus apus*); Barn swallow (*Hirundo rustica*); House martin (*Delichon urbicum*)	No
Thrush	Song thrush (*Turdus philomelos*); Mistle thrush (*Turdus viscivorus*)	Yes
Warbler	Garden warbler (*Sylvia borin*); Blackcap (*Sylvia atricapilla*); Whitethroat (*Sylvia communis*); Lesser whitethroat (*Sylvia curruca*); Sedge warbler (*Acrocephalus schoenobaenus*); Reed warbler (*Acrocephalus scirpaceus*); Willow warbler (*Phylloscopus trochilus*); Meadow pipit (*Anthus pratensis*); Reed bunting (*Emberiza schoeniclus*)	Yes
Tit	Goldcrest (*Regulus regulus*); Coal tit (*Periparus ater*); Marsh tit (*Poecile palustris*); Long-tailed tit (*Aegithalos caudatus*); Nuthatch (*Sitta europaea*); Tree creeper (*Certhia familiaris*); Bullfinch (*Pyrrhula pyrrhula*)	Yes
Finch	Goldfinch (*Carduelis carduelis*); Greenfinch (*Chloris chloris*); Yellowhammer (*Emberiza citrinella*); Linnet (*Linaria cannabina*)	Yes
Corvid	Magpie (*Pica pica*); Jay (*Garrulus glandarius*); Jackdaw (*Corvus monedula*); Rook (*Corvus frugilegus*); Carrion crow (*Corvus corone*)	Yes

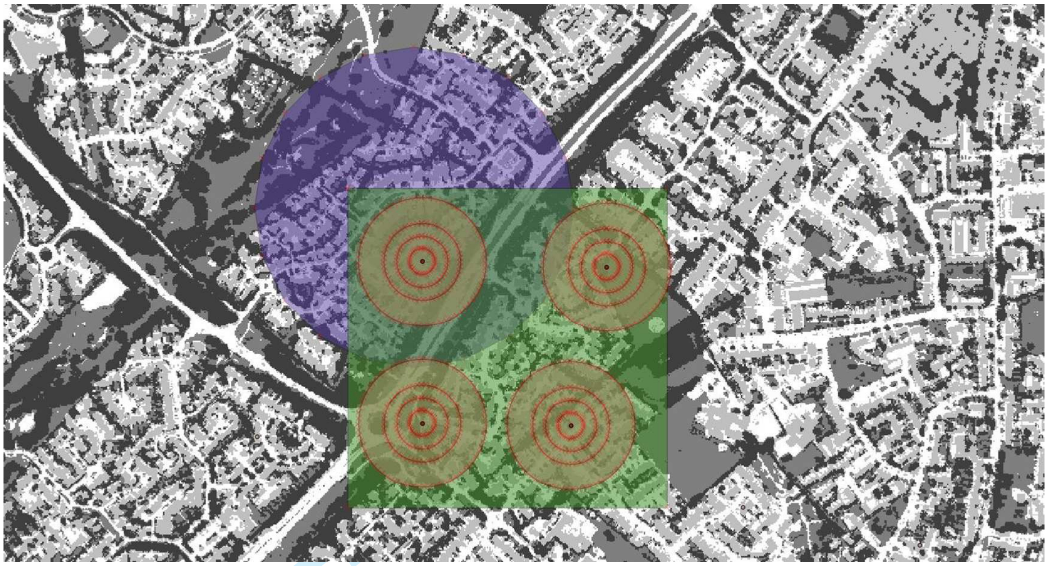

Figure S1. Remote sensing image showing how neighborhood bird abundances and richness were estimated for those respondents whose 250m-neighborhood buffer (purple) overlapped with at least one bird survey location (brown) within a survey tile (green). We show remote sensing land classifications within each urban area (dark grey, trees >0.7 m; medium grey, grass and shrubs <0.7 m; light grey, no vegetation >0.7 m; no vegetation ,0.7 m).

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Statement of Author Contributions

D.T.C.C and K.J.G conceived and designed the study. DFS, RAF and KJG designed and wrote the urban lifestyle survey. KEP and GMS managed and collated the bird survey data. KA and SH produced the remote sensing layers. DTCC carried out the analysis and wrote the paper. HLH helped write the paper. All authors edited the paper.