Title:

Health Benefits from Nature Experiences Depend on Dose

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1　**ABSTRACT**

2　Nature within cities will have a central role in helping address key global public health

3　challenges associated with urbanization. However, there is almost no guidance on how much

4　or how frequently people need to engage with nature, and what types or characteristics of

5　nature need to be incorporated in cities for the best health outcomes. Here we use a nature

6　dose framework to examine the associations between the duration, frequency and intensity of

7　exposure to nature and health in an urban population. We show that people who made long

8　visits to green spaces had lower rates of depression and high blood pressure, and those who

9　visited more frequently had greater social cohesion. Higher levels of physical activity were

10　linked to both duration and frequency of green space visits. A dose-response analysis for

11　depression and high blood pressure suggest that visits to outdoor green spaces of 30 minutes

12　or more during the course of a week could reduce the population prevalence of these illnesses

13　by up to 7% and 9% respectively. Given that the societal costs of depression alone in

14　Australia are estimated at AUD\$12.6 billion per annum, savings to public health budgets

15　across all health outcomes could be immense.

16

17　**KEY WORDS**

18　Nature dose; exposure to nature; population health

INTRODUCTION

Urbanization is emerging as one of the most important global health issues of the 21st century [1,2], with cities becoming epicenters for chronic, non-communicable physical and mental health conditions [3,4]. There is growing recognition of the crucial role of urban green spaces in addressing this public health challenge [5,6], with over 40 years of research showing that experiences of nature are linked to a remarkable breadth of positive health outcomes. This includes improved physical health (e.g. reduced blood pressure [7] and allergies [8], lower mortality from cardio-vascular disease [9], self-perceived general health [10,11]), improved mental wellbeing (e.g. reduced stress [12] and risk of poor mental health [13,14]), greater social wellbeing [15], and promotion of positive health behaviors (e.g. physical activity [16,17]). Consequently, cities across the world are investing in the provision, management and enhancement of public green spaces, with the 100 largest cities in the US alone spending over US$6 billion in 2015 [18]. Advice about how to achieve health outcomes from green spaces currently remains very general [19,20]. Evidence on how frequent or how long nature experiences need to be, or what types of nature are needed, is vital to ensure that investment in green space provision can cost-effectively help to meet the public health challenges of urbanization [21-23].

Here, for the first time we use the nature-dose framework posed by Shanahan et al. [21] to quantify the link between health outcomes and experiences of nature, as measured by *intensity* (i.e. the quality or quantity of nature itself), and the *frequency* and *duration* of a city resident's experiences. We focus on examples of health issues across four domains for which there is some prior evidence that nature exposure can provide benefits. These health issues are also particularly relevant for cities, and include mental health (the prevalence of depression), physical health (high blood pressure), social wellbeing (social cohesion), and a positive health behaviour (physical activity). These health outcomes could be tied to

44   experiences of nature through a range of mechanistic pathways (some of which are outlined

45   in Figure 1) [22]. For example, a higher level of vegetation within a landscape (a measure of

46   nature intensity) may be linked to enhanced physical, mental and social wellbeing through

47   providing a visually complex environment that can lead to reduction in stress [24], reduction of

48   mental fatigue [25], or by adding to the look and feel of a place and so providing a pleasant

49   location for social or physical activities [22] (Figure 1). Similarly, variation in duration and

50   frequency of nature exposure could also influence the long-term health outcomes people

51   experience, with even short-duration exposure to natural environments shown to deliver an

52   immediate reduction in blood pressure [7] and greater feelings of restoration [26]. Yet despite this,

53   whether and how the intensity, frequency or duration of nature exposure leads to long-term

54   and lasting effects on health remains unexplored.

55

56   Unpacking the relationship between health outcomes and the three components of nature dose

57   also allows for the exploration of dose-response relationships, including whether there is a

58   minimum dose where some effect of natire on health might be seen [21,27]. Here we therefore

59   use dose-response modelling to determine how rates of high blood pressure and depression

60   vary in response to nature experiences, including whether the outcomes continue to improve

61   or plateau [21]. We examine the scale of the population health benefits that could arise if these

62   nature dose recommendations are met, and the impact of this on the public health purse.

63   **RESULTS**

64   The first stage of our analysis was to examine the relationship between individual-level

65   experiences of nature and four health outcomes in a population sample of 1538 residents of

66   Brisbane City, Australia. These health outcomes included whether the respondent scored as

67   having mild or worse depression determined from an established 7 item questionnaire [28],

68 whether the respondent reported being under treatment for high blood pressure, perceptions

69 of social cohesion derived from three survey questions[29-31], and the self-reported number of

70 days on which physical exercise occurred for more than 30 minutes during the survey week.

71

72 We measured experiences of nature across three components, including the usual frequency

73 of outdoor green space visits across a year, the average duration of visits to green space

74 across a week, and the intensity of nature (measured as the highest level of vegetation

75 complexity within any of the green spaces that a respondent visited, following a hypothesis

76 that higher levels of vegetation lead to greater health outcomes; Table 1, Figure 2).

77 Multivariate analyses revealed that a longer duration of individual nature experiences was

78 significantly linked to a lower prevalence of depression and of high blood pressure, and

79 increased physical activity. A higher frequency of green space visitation was an important

80 predictor for increased social cohesion, and both duration and frequency showed a significant

81 positive relationship with higher levels of physical activity (Table 1). These multivariate

82 analyses accounted for key covariates including age, gender, Body Mass Index (BMI; weight

83 in kilograms/square of height in meters), and socio-economic indicators including the

84 income, education, and neighborhood socio-economic disadvantage (Index of Socio-

85 economic Disadvantage, IRSD; Table 1) [32]. We also found that people with a stronger self-

86 reported connection to nature (measured using the Nature Relatedness scale [33]) had greater

87 levels of social cohesion and physical activity, but did not show a reduced prevalence of

88 depression or high blood pressure (Table 1).

89

90 We examined the dose-response relationship between the odds of a respondent being

91 recorded as having high blood pressure or depression and incremental increases in the

92   duration of nature experiences, while accounting for covariates (Figure 3, Table 2). We found

93   that the odds were significantly lower than the null model for depression when reported green

94   space visits were an average of 30 minutes or more (i.e. the confidence interval did not

95   overlap with an odds ratio of one; Figure 3a), with a slight increase in mean gains until a

96   duration of 1 hour 15 minutes. For high blood pressure, there was also a significant health

97   improvement after 30 minutes of exposure, though the dose-response curve showed high

98   variability at higher exposure levels (Figure 3b). The power of the test for high blood

99   pressure and depression was reduced at higher durations (indicated by wider 95% confidence

100   intervals).

101

102   We found that the proportion of cases of depression and high blood pressure in the population

103   that can be attributed to city residents failing to spend an average of 30 minutes or more

104   during a green space visit across the course of their week (the 'population attributable

105   fraction') was 0.07 for depression, and 0.09 for high blood pressure (Table 2); that is, up to

106   7% of depression cases and 9% of high blood pressure cases recorded in the study could

107   potentially be reduced if the green space visitation duration was 30 minutes or more.

108

109   **DISCUSSION**

110   The results here suggest that nature experiences in urban green spaces may be having a

111   considerable impact on population health, and that these benefits could be higher if more

112   people were engaged in nature experiences. Specifically, our results suggest that up to a

113   further 7% of depression cases and 9% of high blood pressure cases could be prevented if all

114   city residents were to visit green spaces at least once a week for an average duration of 30

115   minutes or more. The societal costs of depression are estimated at AUD$12.6 billion per

116   annum for employed Australians alone [34], and the direct costs of hypertension in the United

117   States have been estimated at US$48 billion [35]. Given that our results show nature

118   experiences, if causal in nature, could simultaneously lead to a suite of health benefits for

119   mental health (depression), physical health (high blood pressure), social health (social

120   cohesion), and a positive health behavior (physical activity), the cumulative cost savings

121   across all health outcomes could be immense if this behavioral change was targeted.

122

123   Our finding that the duration, and frequency of nature interactions are varyingly associated

124   with the four health outcomes has potentially important implications for the design of health

125   interventions, and also reveals new hypotheses that warrant further attention. For example,

126   while provision and quality of green spaces is undoubtedly important, health programs

127   aiming to reduce the prevalence of depression or high blood pressure might also focus on

128   behavioral interventions, for example, promoting longer duration green space visits. In

129   contrast, improved social cohesion in communities is a well-known benefit of public green

130   spaces [36,37], and interventions that aim to enhance social cohesion might fruitfully focus on

131   increasing residents' frequency of visits. [38]Social cohesion is itself important for public

132   health, as it is positively associated with physical and mental wellbeing [39]. These flow-on

133   benefits are likely to add considerably to the economic and social value of urban green space.

134

135   Here physical activity was associated with both higher duration and frequency of green space

136   visits, which is important given it can reduce the risk of a wide range of non-communicable

137   diseases such as diabetes, cardiovascular disease and obesity [58]. Green spaces are often

138   considered settings that directly facilitate exercise [40], and visiting green spaces can

139   incidentally entails walking, running or cycling. Vegetated areas also offer shade and

140 improved temperature regulation [41], providing a pleasant location for physical activity. This is

141 particularly relevant in cities such as Brisbane, a sub-tropical location with hot summers and

142 a mean of 113 cloudless days per year [42]. However, while many studies have found that more

143 people undertake physical activity (e.g. cycling and walking) in greener neighbourhoods [17],

144 the results are sometimes mixed; for example, these patterns could be due to other activities

145 such as gardening [43], or because active people self-select into greener neighbourhoods [44].

146 While our results add to the body of knowledge on this subject, these varying explanations

147 require further attention.

148

149 Our measure of nature intensity (vegetation complexity) showed no association with any of

150 the health outcomes measuredOther studies have found that higher levels of plant, butterfly

151 and bird species richness (or perceived species richness) can enhance a person's feelings of

152 restoration [13,14], and future work might fruitfully explore the effect of such measures within

153 the nature dose framework. There are also other hypotheses describing relationships between

154 health and vegetation complexity; for example, studies have found that more people tend to

155 visit public green spaces with moderate levels of vegetation cover (rather than high or low) [45],

156 and vegetation is also likely to influence the perception of safety of an area [25]. Systematic

157 consideration of nature dose-response relationships will therefore be critical to understanding

158 how to enhance health outcomes from exposure to nature.

159

160 We observed significantly fewer cases of depression and high blood pressure in people who

161 spent an average of 30 minutes or more visiting green space in the survey week, and there

162 was some indication that longer duration visits may be associated with an even lower

163 prevalence of depression. However, here we traded-off accuracy in detecting differences

164   across the incremental increases in dose for achieving a high level of representation across

165   the population (i.e. sampling did not target respondents with varying durations of nature

166   exposure). Given that this type of dose-response relationship could contribute further

167   evidence for causality according to Hill's criterion [46], future studies would benefit from

168   achieving relatively even sampling representation across the relevant nature dose levels. An

169   added consideration when interpreting the results outlined here is that the effects of

170   depression itself can influence a person's activity levels [47], and so could reduce the likelihood

171   that a person visits green-space. The same effect could also occur for high blood pressure,

172   where people who have other risk factors such as obesity might also be less likely to visit

173   green spaces (note, BMI and physical activity were considered as covariates here, so these

174   effects are somewhat accounted for). Thus, studies that explore changes over time within

175   individuals and across populations could be a particularly powerful way to further elucidate

176   dose-response relationships between nature and health.

177

178   This study used a self-report online survey, an approach which brings a number of benefits

179   (such as the large sample size and a high level of stratification across the population), as well

180   as limitations. For example, recalling events can pose challenges, question order can affect

181   responses, and many other factors can affect how well a person responds to questions [48].

182   While we used measures to minimize these limitations, other methods such as longitudinal

183   studies using tracking technologies might provide complementary understanding of nature-

184   dose relationships. Future research exploring the role of a broader range of socio-

185   demographic and community factors related to health outcomes, but which also have the

186   potential to influence interaction with nature (e.g. marital status and crime) will also shed

187   light on the mechanistic pathways linking nature exposure to health.

188

189   Nature relatedness, or the differences in the way people view their connection with the

190   natural world, could both drive interactions with nature and enhance wellbeing in its own

191   right [49]. We found that higher levels of nature relatedness predicted greater feelings of social

192   cohesion and higher levels of physical activity. This supports other research which has found

193   that people with higher nature relatedness scores also often report better wellbeing, happiness

194   and life satisfaction [33,50], and lower levels of anxiety [51]. A limitation of studies so far within

195   this area is that they are often single time-point studies, and research is needed to whether

196   actively altering this trait might influence health and wellbeing.

197

198   Interactions with nature simultaneously deliver mental, physical and social health outcomes

199   for a population through multiple pathways [22]. By harnessing the synergistic potential of

200   these pathways, contact with nature has the potential to lower not just the prevalence of single

201   chronic conditions, but also multiple chronic or acute medical conditions that co-occur within

202   one person. However, here we have also shown that the different components of experiences

203   of nature (the frequency, duration or intensity) variously influence the health outcomes. This

204   has important implications for the design of health interventions targeting improvements in

205   the four health domains examined here. Ongoing efforts to unpack the nature-health

206   relationship will be vital to combat the emerging public health challenges associated with

207   urbanization, and to ensure that investment in green space provides value for money [21-23].

208

209

210   **MATERIALS AND METHODS**

211   **Survey**

212   This research was conducted in accordance with approved guidelines, and all protocols were

213   received Institutional Human Research Ethics Approval (Behavioural & Social Sciences

214   Ethical Review Committee, University of Queensland), project number 2012000869.

215   Informed consent was obtained from all respondents. The full survey is available in the

216   supplementary material.

217

218   We surveyed 1538 Brisbane residents aged 18-70 years to obtain information on health and

219   experiences of nature. The survey was delivered online by Q&A Market Research Ltd to their

220   existing market research database of potential respondents, and carried out in November

221   2012. This time period was chosen as it is prior to the onset of higher summer temperatures,

222   ensuring that the outcomes were minimally affected by seasonal conditions and because it is

223   prior to the summer holiday period which could also affect participation and the measured

224   behaviors [52]. Brisbane City has high overall levels of public green space ($>200m^2$ per person)

225   and tree cover (36%), both of which are spread rather evenly across the socio-economic

226   gradient [53]. Thus baseline exposure to nature outside of the experiences measured in this

227   study (i.e. through day-to-day activities at home or work) is likely to be high across city

228   residents.

229

230   The respondent group was recruited based on whether they fulfilled a number of stratification

231   criteria across a range of factors, which ultimately ensured that the socio-demographic

232   distribution closely reflected that of the actual population (Table S1), according to age

233   (similar numbers above and below 45), sex (similar numbers of males and females), income

234 quartiles within the city, and respondents' addresses were spread evenly among four spatial

235 zones reflecting the four quartiles of tree cover across the city (Figure S1). A Pearson's rank

236 sum test was conducted to compare the proportion of representation within the different

237 stratification criteria against that of the real population, and showed that the characteristics of

238 the surveyed population were well correlated with that of the actual population (correlation

239 coefficient = 0.67, t = 7.14, p<0.0001).

240

241 Socio-demographic variables that are tied to health outcomes were collected, including age,

242 sex, personal annual income, highest formal qualification, presence of children under 16 in

243 the home, the primary language spoken at home, and number of days the respondent normally

244 spends at work per week. Respondents also provided information on their height and weight,

245 from which we calculated BMI. The Australian census-derived Index of Relative Socio-

246 economic Disadvantage (IRSD) was used as a measure of the level of socio-economic

247 disadvantage in the respondent's neighborhood, calculated for the finest possible spatial scale

248 (Statistical Area 1, mean area = $0.44km^2$, [54]). We also measured a person's connection to

249 nature using the Nature Relatedness scale [33], as this could moderate any benefits gained from

250 experiences of nature. All variables are described in detail in Table 3.

251

252 **Experiences of nature**

253 Respondents were invited to report on any visit within the previous week to a place they

254 considered 'outdoor green space', and were asked to name or describe the location. We

255 manually geo-located these locations based on the descriptions where possible. Three aspects

256 of nature dose were measured, encompassing the duration and frequency of experiences, and

257 nature intensity, through a mixture of self-report and remote sensing analysis. Nature dose

258 questions were asked in the survey before the health questions to avoid any potential priming

259 effects of a person's health status on self-reported nature dose (e.g. see [48]).

260

261 *Duration of experiences of nature:* Average duration of green space visits was estimated

262 based on self-reported time spent during each visit across the survey week. We chose this

263 timeframe as it provided a short and recent reference period to improve accuracy [48]. Note that

264 this measure of duration is indelibly linked to frequency, as to achieve a duration measure the

265 respondent must have visited a green space at least once during the survey week. Duration

266 was selected from a time category (1-29 minutes; 30 minutes to one hour; one to two hours;

267 two to three hours; three to four hours; four or more hours), and the mid-point of each

268 selected category was summed (with four or more hours being treated as 'four'), and this

269 value was averaged across all visits.

270

271 *Frequency of experiences of nature.* Given that frequency of visitation would be highly

272 correlated with duration if measured on the same time scale, here it was estimated based on

273 the respondent's self-reported frequency of visits to green spaces where their usual frequency

274 of visits across a year was selected from the following categories: never; once a year; once

275 every three months; two to three times a month; once a month; once or more per week. This

276 approach also allowed us to account for people who use green spaces infrequently (i.e. less

277 than once a week who were missed by the duration measure).

278

279   *Nature intensity.* Here we generated one possible measure of nature intensity, the vegetation

280   complexity within the most complex map-able green space each respondent visited

281   (hypothesizing that more complex vegetation leads to better health outcomes by promoting

282   attention restoration, and increasing the appeal of green spaces; Figure 1; this measure also

283   tends to correlate with plant and animal diversity [55,56]). Most (77%) of respondents only

284   visited one or two green space locations so other measures such as the most common, or

285   average complexity were not useful here. Analyses involving nature intensity were limited to

286   respondents for whom the visited green space a) could be geo-located, and b) had established

287   boundaries within the Brisbane City limits to ensure we vegetation was measured within the

288   visited area. Complexity was measured using LiDAR-derived maps of vegetation cover at a

289   5x5m resolution (details provided in the supplementary material). Five separate vegetation

290   strata were used that have relevance to the human experience of nature, including 0.15-1m

291   (likely to influence access and egress); 1-2m (the line of sight may be affected); and three

292   layers likely to provide varying levels of shade and visual vegetation complexity, 2-5m; 5-

293   10m; 10m+. For each of the vegetation strata we created a binary grid layer (where 1

294   indicated vegetation was present), and we summed all five of these layers for each 5x5m

295   pixel. We calculated the average summed measure across the entire green space. Higher

296   values of vegetation complexity were achieved in green spaces with higher vegetation cover

297   and more complex vegetation structure. This measure was calculated for 664 survey

298   respondents who visited green spaces within the study area, and only these respondents were

299   used in relevant analyses.

300

301   **Health response measures**

302   Respondents provided information on four health outcomes:

303   *Mental health*. A measure of depression was generated based on the depression component of

304   the Depression, Anxiety and Stress scale [28]. Scores were converted to a binary measure where

305   0 indicates no depression and 1 indicates mild or worse depression.

306   *Physical health*. Respondents reported whether they were currently receiving treatment for

307   high blood pressure, coded as a binary measure where 0 indicates no treatment and 1

308   indicates treatment.

309   *Social health*. Respondent's perceptions of social cohesion were estimated based on three

310   previously developed questions that measure trust, reciprocal exchange within communities,

311   and general community cohesion [29-31] (see supplementary material for details). The scores

312   across all three questions were averaged.

313   *Health behavior*. Respondents provided a self-report indication of physical activity,

314   specifically the number of days they exercised for 30 minutes or more during the survey

315   week (regardless of location; 'green exercise' and exercise in other locations were not

316   differentiated). The resulting count variable was between 0 and 7.

317

318   **Statistical Analyses**

319   All analyses outlined here were conducted in the software package R [57]. We used an

320   exploratory approach to examine the correlation between each health response and potential

321   predictors (outlined in detail in Table S1), including socio-demographic variables, BMI,

322   physical activity (where it was not also the response variable), and the three nature

323   experience measures. We used generalized linear models (binomial) for depression and high

324   blood pressure, linear regression models for social cohesion, and negative binomial

325   generalized linear models for physical activity. The three measures of nature dose were

326   correlated (significant Spearman's rank test correlations of 0.50-0.57), so to avoid issues

327   associated with multicollinearity we generated four predictor model sets for each health

328   response: i) all socio-demographic variables (but excluding the frequency, duration and

329   intensity of nature experiences); ii) socio-demographic variables plus duration of nature

330   experiences; iii) socio-demographic variables plus frequency of nature experiences; iv) socio-

331   demographic variables plus nature intensity. Neighborhood socioeconomic disadvantage

332   (IRSD) was reverse square-root transformed and BMI was log transformed to ensure models

333   met assumptions of normality. We calculated the model averaged coefficient estimates for

334   each predictor variable by generating models with all possible variable combinations, and

335   averaged the coefficient for each across all models in which it was present (using the R

336   package MuMln).

337

338   To further explore any relationships which became evident from the analyses above, we

339   conducted dose-response modelling for the two binary health measures (depression and high

340   blood pressure) where there was evidence for an effect of any one of the three nature dose

341   variables. Dose response modelling is readily achieved for binary response variables [58]; social

342   cohesion and physical activity did not lend themselves readily to this analytical approach

343   because there is no threshold where a score is 'good' or 'bad'. To carry out this approach we

344   first built a logistic regression model where the predictor variables were treated as 'risk

345   factors', an established practice in population epidemiology [59,60]. The relative odds of

346   occurrence of either depression or high blood pressure in an individual were calculated given

347   a person's specific risk factors (e.g. age) or duration, frequency or intensity of nature

348   experiences. We used only the predictor variables that were statistically significant in the

349   analysis in Table 1, and transformed each into a binary risk factor using existing evidence

350   where possible. For example, for age the risk of being diagnosed with hypertension begins to

351 increase steeply at age 45 years [61], and the prevalence of affective mood disorders such as

352 depression begins to decline in Australia at about 45 [62]. We therefore used 45 years to create

353 a binary risk factor above which the risk of having depression was zero, and below one (and

354 vice versa for high blood pressure). Similarly, Australian guidelines recommend physical

355 activity on most, if not all days per week [63], and we therefore created a binary risk factor as

356 people who exercised for 30 minutes on 5 days or more (0) and those who did not (1).

357 Respondents who were 'overweight' (≥25 BMI [64]) were categorized as a risk factor of 1, and

358 those under as 0. Where no definitive information was available we used the results from

359 Table 1 to guide the direction of the risk categorization; this includes whether children were

360 present in the home, whether a person works (treated as a binary work or no-work), and

361 income and neighborhood disadvantage (IRSD; with the binary categorization reflecting

362 whether the respondent fell into the top half or bottom half of the population values).

363 Variables for which no threshold could be estimated were omitted from these analyses (as

364 was the case for social cohesion and nature relatedness).

365

366 To create a dose-response curve, we ran the logistic regression models described above with

367 incrementally increased thresholds of nature experiences (e.g. for duration a person's risk

368 factor was varied based on whether they met incremental thresholds including >0 minutes;

369 ≥15 minutes; ≥30 minutes; ≥45 minutes; ≥1 hour and so forth until the maximum time of 4

370 hours), and determined the odds ratio that a person who fell within that category would have

371 the condition. We identified the point at which health gains were first recorded as better than

372 the null model on plots of nature dose versus the odds ratio for use in the analysis described

373 below.

374

375   A population average attributable fraction analysis was used to estimate the proportion of

376   depression and high blood pressure cases in the population attributable to each of the

377   predictor variables or 'risk factors' [60]. Within a multivariate logistic regression environment,

378   each risk factor was removed sequentially from the population by classifying every individual

379   as unexposed (i.e. risk factor of 0). The probability of each person having the disease was

380   then calculated, where the sum of all probabilities across the population was the adjusted

381   number of disease cases expected if the risk factor was not present. The attributable fraction

382   was calculated by subtracting this adjusted number of cases from the observed number of

383   cases. The risk factors were removed in every possible order, and an average attributable

384   fraction from all analyses was obtained.

385

395

396   **ADDITIONAL INFORMATION**

397   **Competing financial interests**

398 The authors declare there are no competing financial interests associated with this

399 study.

400

401 **Author Contributions**

402 DFS, RB, KJG, BBL, RAF conceived the idea and developed and delivered the survey. DFS

403 carried out the analyses. DFS and RAF wrote the manuscript. RB, KJG, BBL, JD, EB, RAF

404 provided advice and interpretation of the analysis, edited multiple versions of the manuscript,

405 and contributed to revisions.

406

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588

589 Figure 1. Hypothesized pathways to the mental, physical, social and behavioral health

590 outcomes from experiences of nature explored in this study, based on the framework outlined

591 by Shanahan et al. [22].

592

593 Figure 2. The bivariate relationships between health responses (A-D) and nature experiences,

594 comprising (i) the average duration of visits to green space; (ii) the normal reported

595 frequency of visits to green space; and (iii) the nature intensity, measured as vegetation

596 complexity within the best visited public green space. Error bars are standard errors.

597

598 Figure 3. Dose-response graphs showing the adjusted odds ratio from logistic regression for

599 incrementally increasing average duration of green space visits. 95% confidence intervals are

600 shown. An odds ratio above one indicates an individual is more likely to have the disease

601 where the threshold of green space visitation is not met.

602 Table 1. The relationship between four health outcomes (the response variables), socio-

603 demographic covariates, and nature experience predictor variables. Four models for each

604 response variable are shown: i) socio-demographic variables only; ii) socio-demographic

605 variables plus duration of nature experiences; iii) socio-demographic variables plus frequency

606 of nature experiences; iv) socio-demographic variables plus nature intensity. Model averaged

607 coefficients are shown with standard error in brackets, and the Nagelkerke / Crag and Uhler's

608 pseudo R^2. Positive coefficients indicate rates of depression and high blood pressure were

609 higher with higher values of the predictor variables, and that social cohesion and physical

610 activity increased.

611

Predictor variables	Depression	High blood pressure	Social cohesion	Physical activity
Model i)	**Pseudo R^2= 0.10**	**Pseudo R^2= 0.41**	**R^2= 0.10**	**Pseudo R^2= 0.05**
Age	-0.02 (0.01)***	0.12(0.01)***	0.01(0.00)***	-0.01(2e-3)***
Gender	-0.31(0.12)*	-0.03(0.19)	-0.08(0.03)*	-0.08(0.06)
Income	-0.00 (0.00)*	0.00 (0.00)	0.00(0.00)	0.00(0.00)
Children in home	-0.10 (0.07)	0.32 (0.12)**	0.11(0.02)***	-0.10(0.03)**
Neighborhood disadvantage	-0.03(0.02)	-0.06 (0.03)*	0.03(0.005)***	0.03(9e-3)**
Work days/week	-0.07(0.03)*	-0.04 (0.04)	0.02(0.01)*	0.00(0.01)
Highest qualification	-0.00 (0.05)	0.038 (0.08)	-0.00(0.01)	0.04(0.03)*
Ethnicity	-0.16(0.18)	0.47(0.33)	0.013(0.04)	0.03(0.08)
Physical activity frequency	-0.13(0.03)***	0.057 (0.04)	0.03(0.01)***	NA
BMI	1.28(0.29)***	3.67 (0.46)***	-0.04(0.07)	-0.07(0.10)
Social cohesion	-0.42(0.10)***	-0.28(0.16)	0.17(0.03)***	0.15(0.05)**
Nature relatedness	-0.06 (0.10)	-0.07 (0.16)	0.01(0.00)***	0.20(0.05)***
Model ii)	**Pseudo R^2= 0.10**	**Pseudo R^2= 0.42**	**R^2= 0.11**	**Pseudo R^2= 0.08**
	n = 1538	**n = 1538**	**n = 1538**	**n = 1538**
+ Nature experience duration	-0.16 (0.06)*	-0.23(0.1)*	0.11(0.03)***	0.19(0.03)***
Model iii)	**Pseudo R^2= 0.10**	**Pseudo R^2= 0.41**	**R^2=0.12**	**Pseudo R^2= 0.0.06**
	n = 1538	**n = 1538**	**n = 1538**	**n = 1538**
+ Nature experience frequency	-0.06(0.04)	0.09 (0.09)	0.16(0.02)***	0.16(0.01)***
Model iv)	**Pseudo R^2= 0.10**	**Pseudo R^2= 0.41**	**R^2=0.10**	**Pseudo R^2= 0.0.08**
	n = 664	**n = 664**	**n = 664**	**n = 664**
+ Nature experience intensity	-0.16(0.10)	0.29 (0.02)	0.00(0.02)	0.00(0.08)

612 Significance: * $p<0.05$; ** $p<0.01$; *** $p <0.001$.

613

614   Table 2. The odds ratios for a person having depression or high blood pressure where specific

615   risk factors are present (the result for each variable was calculated while accounting for all

616   their other risk factors; i.e. multivariate analyses), and the proportion of disease cases in the

617   study population attributable to various risk factors (average population attributable fraction).

618   An odds ratio above 1 indicates the disease is more likely to be present where the risk factor

619   is present. n = 1538.

620

	Depression:			**High blood pressure:**		
	Risk factor	Odds ratio (95% confidence intervals)	Average attributable fraction	Risk factor	Odds ratio (95% confidence intervals)	Average attributable fraction
Age	Higher risk ≤45 years	1.62(1.25,2.09)	0.13	Higher risk ≥45 years	16.56(9.71,28)	0.44
Gender	Higher risk for males	1.31(1.05,1.65)	0.07	*NA*		
Children	*NA*			Higher risk with children	2.02(1.27,3.21)	0.04
Income	Higher risk for bottom half of population	1.33(1.05,1.7)	0.06	*NA*		
Neighborhood disadvantage	*NA*			Higher risk for bottom half of population	1.5(1.05,2.15)	0.06
Work	Higher risk for non-workers	1.47(1.12,1.95)	0.05	*NA*		
Physical activity	Higher risk for those that exercise for <5 days/week	2.05(1.46,2.89)	0.27	Higher risk for those that exercise <5 days/week	0.81(0.50,1.29)	
BMI	Higher risk BMI > 25	1.28(1,1.62)	0.06	Higher risk BMI > 25	4.34(2.76,6.81)	0.28
Nature experience duration	Higher risk where duration of visits <30 minutes	1.37(1.09,1.74)	0.07	Higher risk where duration of visits <30 minutes	1.76(1.21,2.53)	0.09

621

622   Table 3. Descriptions of the variables tested for correlation with each of the four health

623   responses.

Variable name	Description
Age	Respondent's age in years, selected from 11 categories.
Gender	Gender, for analysis purposes male = 0, female = 1.
Income	Personal income selected from categories defined based on the income question provided in the Australian census (categories included weekly income of: nil or negative; $1-$199; $200-$299; $300-$399; $400-$599; $600-$799; $800-$999; $1000-$1249; $1250-$1499; $1500-$1999; $2000+). For analysis purposes the lowest value of the income bracket indicated by respondent was used, and variable was treated as numeric ordinal.
Neighborhood disadvantage	The Index of Socioeconomic Disadvantage (IRSD), a census derived indicator provided by the Australian Bureau of Statistics was used. Variable is continuous (between 650-1150 in this sample), with low scores indicating greater deprivation. The neighborhood value for each respondent's address was used at the finest available spatial scale (Australian Census Statistical Area 1).
Children living at home	The presence or absence of people living in a respondent's home who were under 16 years at the time of the survey.
Work days per week	Number of days the respondent works in an average week.
Highest qualification	The highest formal educational qualification achieved by the respondent, grouped into five categories (5 = highest qualification possible, e.g. post-graduate qualification; 1 = lowest qualification possible, e.g. year 10 of school).
Language (non-English = 1)	An indication of the language primarily spoken at home. For analysis purposes 0 = English, 1 = not English.
Frequency of physical activity	Number of days the respondent carried out physical activity for 30 minutes or more.
BMI	Respondent's Body Mass Index (BMI), weight in kilograms divided by height in meters squared.
Social cohesion	Score to indicate perceptions of social cohesion derived from three questions, described in detail in the Supplementary Material.
Green space visitation frequency	Ordinal variable indicating the self-reported frequency of visits to public green spaces selected from categories, including: never; once a year; once every three months; once a month; 2-3 times a month; once or more per week. Ordered numeric variable.
Green space visitation duration	Average time spent during each visit to public green spaces reported for the survey week. Ordered numeric variable.
Green space visitation intensity	The 'volume' of vegetation within the most heavily vegetated green space visited by each respondent. The variable was calculated by estimating average vegetation volume from five structural layers across the entire green space. Green spaces with the most structurally complex vegetation across large areas score highest. Continuous variable.

624

Ecosystem property

Characteristics of nature within green space
e.g. structural complexity of vegetation.

Ecosystem function

Visual characteristics of green space
Provides a view that requires limited concentration
or focus, and does not stimulate a stress response.

Biophysical changes to the environment
Temperature regulation through shade provision,
evapotranspiration, high albedo of vegetation.
Soft ground surface, open clear space.

Effect on people

Reduced stress
Autonomic generation of psychophysiological
stress reduction response. Recovery from fatigue
of directed attention. Increase in positive affect.

Appealing location
Appeal of location (both climatically and visually)
that encourages physical activity and time spent
in community spaces.

Health benefit

Mental health:
Improved mental health,
including reduced levels
of depression [12,13,14,25].

Physical health:
Reduced stress,
improved blood
pressure [7,9,24].

Social health:
Increased contact with
community, increased
social cohesion [15].

Health behavior:
Increased physical
activity [16,17,26].

Feed back processes

	i) Duration	ii) Frequency	iii) Intensity

A. Depression

B. High blood pressure

C. Social cohesion

D. Physical activity

Average duration of green space visits (minutes)

Usual frequency of green space visits

Vegetation complexity of visited green space

A

Odds ratio depression

Average green space visit
duration (minutes)

B

Odds ratio
high blood pressure

Average green space visit
duration (minutes)