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Use of natural environments is associated with reduced inequalities in child mental wellbeing: A cross-sectional analysis using global positioning system (GPS) data

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ABSTRACT

Exposure to natural environments may benefit child mental wellbeing whilst offering a lever to reduce health inequalities. However, understanding of these relationships is limited by evidence from indirect measures of exposure. We objectively measured children's direct use of natural environments—and use in low or high physical activity (PA) states—and associated this with their mental wellbeing. We then examined moderation by sex and household income.

Using global positioning system and accelerometry data from children (n = 640), we measured mean daily time in natural environments ('total use'), which we stratified by PA level as 'passive use' (sedentary and light PA) and 'active use' (moderate and vigorous PA). Logistic regression associated exposures with dichotomised Strengths and Difficulties Questionnaire outcomes (internalising difficulties; externalising difficulties; prosocial behaviour), with interactions to examine moderation.

A 10-minute increase in total use was associated with 10.5 % lower risk of abnormal internalising outcomes (OR: 0.895; 95 % CI 0.809, 0.990), and 13.2 % lower risk of abnormal externalising outcomes (OR: 0.868; 95 % CI 0.776, 0.990). This suggests that ∼ 60 min of daily total use was associated with 50 % lower risk of abnormal internalising and externalising outcomes. The relative effects of passive and active use were equal, but their associations were moderated by income independently for specific outcomes. For externalising outcomes, the risk of abnormal scores in lower-income children reduced as passive use increased (P = 0.027) but remained constant for higher-income children. For prosocial outcomes, the likelihood of normal scores increased with active use in lower-income children, but not higher-income children (P = 0.005). Sex did not moderate these associations.

The findings suggest that targeted interventions supporting disadvantaged children to use natural environments could help address inequalities in mental wellbeing. Further, the moderated associations with types of use suggest the equigenic effects of natural environments may operate through multiple pathways.

1. Introduction

Mental health conditions are a leading cause of health burden in the 10-to-24-year age group (Gore et al., 2011). Globally, 11–16 % of children and adolescents are estimated to experience mental disorders (Polanczyk et al., 2015), with half of all mental disorders emerging before age 14 (Kessler et al., 2005). Early onset predicts lower educational attainment and increased risk of substance abuse, self-harm, psychiatric disorders, and criminal behaviour in adulthood (Belfer, 2008; Eaton et al., 2008), leading to substantial economic and societal costs (WHO, 2007). Moreover, socioeconomic inequalities in child and adolescent mental health are stark, with disadvantaged youth facing 2–3 times higher risk than their advantaged peers, along with lower access to support and services (Reiss, 2013). Given that mental health problems are both a result—and cause—of socioeconomic deprivation, interventions that can disrupt this cycle are urgently needed.

Exposure to natural environments, which encompass both greenspace (e.g., parks, forests, public gardens) and bluespace (e.g., rivers, lakes, coastal areas), is a promising determinant of mental health (Hartig et al., 2014). Notably, exposure to natural environments is associated with improved mental health in children, including lower rates of depression, anxiety, stress, and behavioural problems (reviewed by

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Tillmann et al., 2018; Moll et al., 2022; Sakhvidi et al., 2022). Several interrelated mechanisms have been proposed to explain these benefits (Markevych et al., 2017; Elliott et al. 2023). Firstly, natural environments may provide opportunities for stress reduction and restoration of cognitive capacities (van den Berg et al., 2010; Ward Thompson et al., 2012). Secondly, natural environments may promote physical activity and social interaction, which positively affect mental health (Kemperman & Timmermans, 2014; Mitchell, 2013). Thirdly, exposure to natural environments may reduce exposure to harmful environmental factors, such as air pollution and noise (Dadvand et al., 2015b).

These mechanisms can disrupt the usual pathways by which socioeconomic disadvantage is converted to health disadvantage, potentially reducing health inequalities by disproportionately benefiting disadvantaged groups. This concept, known as "equigenesis" (Mitchell et al., 2015), suggests that natural environments may help narrow the gap in mental health outcomes between advantaged and disadvantaged populations. However, the evidence for equigenesis in the context of natural environments and mental health is by no means conclusive. Whilst some studies find greater benefits for disadvantaged groups (McCrorie et al., 2021; Triguero-Mas et al., 2015), others do not (Feng and Astell-Burt, 2017; Sugiyama et al., 2016). This inconsistency limits our understanding of which groups may benefit most from natural environments by factors such as socioeconomic position (SEP), ethnicity, and gender/sex. Without this, we cannot develop targeted interventions to maximise health equity and risk the unintended consequence of exacerbating inequalities.

A major limitation of existing research on the nature-health relationship is the reliance on indirect measures of exposure to natural environments. To date, most studies have measured exposure indirectly using availability within the residential neighborhood, defined by coverage within distance buffers or administrative units (Nordbø et al., 2018). These measures are subject to several methodological issues, including ecological bias (assuming all individuals within an area have the same level of exposure) and the modifiable areal unit problem (where different geographic boundaries can lead to different results) (Chaix et al. 2009). Moreover, indirect measures fail to capture the dynamic nature of human mobility and the temporal and spatial heterogeneity in individual-level exposures (Chaix et al. 2009). These limitations have been cited as potential explanations for the inconsistent findings in the literature and prompted calls for more rigorous exposure assessments (Markevych et al., 2017; Tillmann et al., 2018).

Furthermore, the use of indirect measures of exposure limits our mechanistic understanding through which natural environments may influence mental health (Markevych et al., 2017). Residential proximity to natural environments can provide insights into some beneficial pathways, such as reduced air pollution improving cognitive function in children (Dadvand et al., 2015a). However, indirect measures are less informative for mechanisms dependent on individual behavioural components (e.g., physical activity, social interactions) (Kruize et al. 2020). This is because living near natural environments does not guarantee their use. Perceptions of the quality or safety of natural environments can influence their use, potentially explaining observed gender or contextual differences in findings from studies measuring exposure indirectly (Astell-Burt et al., 2014; Mitchell and Popham, 2007). To date, only a handful of studies have attempted to quantify use of natural environments in relation to mental health (McEachan et al., 2018; Amoly et al., 2014; Garrett et al., 2023). These have typically relied on self-reported measures, which are subjective and prone to recall bias (Coughlin, 1990). Indeed, surveys of children's use of natural environments are often completed by parents (McEachan et al., 2018; Amoly et al., 2014) and may underestimate certain types of use, particularly that which is informal or incidental.

The advent of smartphones and wearable devices that track Geographic Positioning System (GPS) location data from individuals offers a promising alternative to questionnaires. They enable objective measurement of an individual's dynamic exposure to natural environments during daily movement beyond the residential neighbourhood. By combining time-weighted GPS data with accelerometry, it is possible to examine not only the amount of time spent in natural environments but also the specific activities undertaken during that time (e.g., sedentary behavior, light physical activity, moderate-to-vigorous physical activity) (e.g., Wheeler et al., 2010). This detailed information can provide valuable insights into the mechanisms linking natural environments to mental health and inform the development of targeted interventions that optimise the use of existing natural environments, particularly in areas where access is limited.

GPS are increasingly being used to determine children's use of natural environments (Wheeler et al., 2010; Almanza et al., 2012; Olsen et al., 2022). However, to our knowledge, only one study to date has used GPS-based measures of natural environment use to investigate associations with children's mental wellbeing (Ward et al., 2016). While this study found a positive relationship between time spent in natural environments and emotional wellbeing, the sample size was small (n = 72), and potential moderators, such as sex and socioeconomic position (SEP), were not explored. This is a limitation given that previous studies have reported variation in use of natural environments by gender/sex and SEP (Wheeler et al., 2010; Olsen et al., 2022). Therefore, it remains unclear whether these differences in use translate to differential mental health benefits, which would inform whether interventions need to be tailored to meet the needs of different groups.

To address these gaps, we used GPS and accelerometry data from a nationally representative sample of Scottish children (n = 640) to objectively measure their use of natural environments and examine associations with mental wellbeing indicators. Furthermore, we explored moderation by sex and socioeconomic position (SEP). We operationalized 'use' as the mean daily minutes spent in natural environments, further categorised into 'passive use' (representing low physical activity (PA) behaviors, such as walking and sitting) and 'active use' (representing high PA behaviors, such as running). Our specific research questions were:

Is the use of natural environments associated with better mental wellbeing in children?
Do the associations between natural environment use and mental wellbeing vary by the type of use (passive vs. active)?
Are the associations between natural environment use and mental wellbeing moderated by sex and socioeconomic position?

2. Methodology

2.1. Study sample

We used data from Studying Physical Activity in Children's Environments across Scotland (SPACES), which provided a unique combination of device-measured physical activity data, high-frequency and resolution GPS location data, and geocoded home address locations (McCrorie et al., 2018). SPACES participants were subsampled from Birth Cohort 1 of Growing Up in Scotland (GUS); a nationally representative longitudinal cohort study (n = 5,217) established in 2005. A full description of how the GUS survey design ensured national representativeness across socioeconomic and geographic conditions is available elsewhere (Bradshaw et al. 2007). Briefly, eligible children (who met date of birth criteria) were identified using Child Benefit records and sampled within a hierarchical area-level framework comprising Primary Sampling Units (PSU), stratified by area-level deprivation and urbanicity, nested within Local Authorities (Bradshaw et al. 2007). Each participant was allocated a PSU and strata, to reflect sampling design, and a sample weighting to correct for differential selection probabilities and non-response (Bradshaw et al. 2007).

During sweep 8 of GUS interviews (September 2014 to November 2015 when participants were 9–11 years old: ScotCen Social Research, 2015), 90 % (n = 2,162) of parents consented to be contacted by researchers about SPACES. Parents were then sent study information, consent forms, and wearable devices by post. Between May 2015 and May 2016 (when participants were 10–11 years old), SPACES participants were asked to wear an accelerometer (ActiGraph GT3X +) and GPS device (Qstarz BTQ1000XT; Qstarz International Co., Ltd, Taiwan) during waking hours (5am to 11 pm) for eight consecutive days. Accelerometers recorded physical activity (PA) data as 'counts'—a unitless representation of movement intensity—from the vertical axis. GPS devices recorded longitude/latitude, speed, measures of signal strength (signal-to-noise ratio: SNR) and positional accuracy (dilution of precision: DOP). Both devices recorded data in 10-second epochs allowing their outputs to be matched by epoch timestamp. Times when the accelerometer was not worn (60 consecutive minutes with no PA recorded), where positional accuracy was low (DOP > 10), or potentially anomalous (speed ≥ 100 kph) were removed (0.22 % of matched epochs).

2.2. Outcomes

Child mental wellbeing was assessed in GUS with the well-validated parent-reported Strengths and Difficulties Questionnaire (SDQ). The SDQ contains four difficulties subscales, but amalgamating these into two broader scales is preferable in low-risk or general population samples (Goodman et al., 2010). Two subscales (Emotional Problems, Peer Problems) can be summed to represent 'internalising' emotional difficulties, such as anxiety and depression. Two (Conduct Problems, Hyperactivity) can be summed to represent 'externalising' behavioural difficulties, such as aggression and disruption (Goodman et al., 2010). Scores for amalgamated scales range 0–20 with higher scores indicating greater difficulties. Outcomes were counted as missing if either of their components were missing. The fifth domain of the SDQ is a strength (prosocial behaviour), which represents positive social actions and altruistic behaviours. Scores for this scale range 0–10 with higher scores indicating positive behaviour.

While it is possible to treat SDQ scores as continuous (Richardson et al. 2017; McCrorie et al., 2021), we dichotomised SDQ outcomes (normal/abnormal) using thresholds identifying the most extreme 10 % of scores from 18,222 British 5–16-year-olds (≥8 for Internalising; ≥ 11 for Externalising; ≤ 6 for Prosocial (Goodman et al., 2010)). The primary reason for this was that, while not diagnostic, dichotomised SDQ scores can identify individuals at higher-risk of clinical disorders (Goodman et al., 2000), which can provide a stronger signal for detecting associations in low-risk samples. This was an important consideration given the sample characteristics. Descriptive statistics (Supplementary, A1) indicated the sample was biased towards lower-risk individuals, with relatively low (Internalising median 2, IQR 0–4; Externalising median 3, IQR 2–6) or high (Prosocial median 9, IQR 8–10) scores compared to possible ranges. In such cases, the sample size needed to detect a given effect size may be larger compared to a situation where the data are more balanced with higher variability. This was a factor given the smaller sample size of SPACES participants who provided GPS and PA data (n = 640) compared to those who provided PA data only (n = 774; McCrorie et al., 2021) and GUS (sweep 5; n = 2909; Richardson et al. 2017). Additionally, dichotomising the scores avoided violating parametric assumptions associated with treating bounded, Likert-derived scales as continuous, and enabled easy interpretation of odds ratios.

2.3. Exposure measures

GPS locations identified as being recorded indoors (SNR ⟨200) were removed and remaining locations were buffered by 2.6 m, i.e., the positional accuracy of devices in semi-open environments (Schipperijn et al., 2014), using the 'sf' package in R (Pebesma, 2018). Thresholds were confirmed by comparing performance characteristics of alternative values (Supplementary, A2). Buffered locations were spatially joined to digital landcover data from 2015 Ordnance Survey MasterMap Topography. MasterMap is the most detailed, accurate, and comprehensive geographical data of the UK's landscape. Landcover is classified within the 'make' feature attribute into three broad classes: manmade, natural, and private gardens. Natural landcover comprises vegetation, water, rock, and bare soil whereas man-made landcover comprises paved surfaces and buildings. Private gardens can have either (or both) landcovers, hence are coded as 'multiple'. The 'make' landcover classification refers to the origin of landcover rather than the landuse in which the landcover is situated. Hence, a grassy area is classed as 'natural' regardless of whether it is in a park, an agricultural pasture, or a road verge (which are manmade landuses). GPS locations whose buffers intersected natural landcover were considered to indicate 'use' of NE. Used locations were then stratified by the physical activity data recorded at that location. We used published thresholds of accelerometer counts per minute (cpm) for sedentary and light activity (0–2296 cpm) to classify 'passive use', and thresholds for moderate and vigorous activity (≥2296 cpm) to classify 'active use' (Trost et al., 2011). We use these terms for brevity when discussing results and acknowledge that low PA activities, such as walking, are not necessarily 'passive'. Daily duration (minutes) of total use, passive use, and active use were estimated by multiplying counts of GPS-accelerometer epochs by 10 s. Daily durations were then averaged across days that passed inclusion criteria (at least one day with ≥ 5-hours data per day). Final metrics indicated mean daily time (minutes) in natural environments ("total use") and mean daily time in natural environments at low PA states ("passive use") or high PA states ("active use") across valid days for each participant.

2.4. Moderators

We explored moderation by SEP and sex. Participant sex data were obtained from GUS. Gender data were unavailable. Equivalised household income data obtained from GUS provided a measure of socioeconomic position (SEP). These pre-tax estimates of income (collected as bands with 1–17 levels) were equivalised to reflect variation in household size and composition resulting in 131 levels that were subsequently handled as continuous.

2.5. Covariates

Potential covariates that may be associated with mental wellbeing outcomes and/or exposure were considered as candidate control variables in the analysis. Higher PA can positively impact mental wellbeing (Rose & Soundy, 2020), so total PA (mean total daily cpm) was included to separate the effect of total PA from activity within NE. Maternal age can influence child behavioural and cognitive outcomes (Tearne et al., 2015), so was included from GUS. Residential urbanicity can influence mobility (McCrorie et al., 2020), so a dichotomous (urban/rural) measure was included (Scottish Government, 2016). Exposure to private gardens can influence mental wellbeing (McCrorie et al., 2021), so we measured children's mean daily time in gardens. This was quantified in a similar manner to exposure measures: counts of GPS buffers intersecting the private gardens landcover class were converted to mean daily duration (minutes). Season of device wear can influence mobility (McCrorie et al., 2020), so a binary measure (corresponding with daylight savings, winter: 25 October 2015–27 March 2016) was included. Finally, residential availability of natural environments has previously been associated with SDQ outcomes within both GUS (Richardson et al. 2017) and SPACES (McCrorie et al., 2021), yet it is unclear if this is related to use, to beneficial indirect effects (e.g. visual environment; reduced noise and air pollution), or associations with other neighbourhood-level factors (e.g., socioeconomic disadvantage, urbanicity). Furthermore, whilst the availability of nearby natural environments may be associated with use (Olsen et al., 2022), it does not necessarily guarantee use. To directly address this, we included the proportion of natural landcover within 100–500 m of home (residential NE) to determine the effect of direct exposure (NE use) after controlling for potential indirect effects of residential availability.

2.6. Statistical analysis

Bivariate logistic and linear regression models were used to determine how binary outcomes and exposure measures varied by moderators, respectively. Multivariable logistic regressions were used to examine the association between exposure measures and binary outcomes. All analyses were conducted in R using the 'survey' package (Lumley, 2016) to account for sample weighting, clustering, and stratification within the GUS sample design (as described in '2.1 Study Sample'). To minimise parameter to case ratios, we performed backward stepwise selection on all covariates using Akaike Information Criterion (AIC (Burnham & Anderson, 2004)). Starting with the full model—containing all covariates, sex and SEP—covariates were sequentially removed if AIC improved by ≥ 2 and elimination stopped when further removal increased AIC (Burnham & Anderson, 2004) (Supplementary, A3). Sex and SEP were not subject to model selection.

Each outcome was fitted with two main effects models, one examining the effect of total use (Model 1) and another examining the relative effects of passive and active use (Model 2):

1. Outcome ~ covariates + SEP + sex + total use
2. Outcome ~ covariates + SEP + sex + passive use + active use

We fitted six additional models for each outcome examining effect moderation by sex (Models 3–5) and SEP (Models 6–8). Each of these included an interaction term between one moderator and one exposure measure while controlling for the other moderator and second exposure measure if applicable. For example:

3. Outcome ~ covariates + SEP + sex * total use
4. Outcome ~ covariates + SEP + sex * passive use + active use
5. Outcome ~ covariates + SEP + sex * active use + passive use

We used 'sjPlot' package (Lüdecke, 2023) to examine marginal effects for interaction terms whose 95 % confidence intervals (CI) did not intercept 1.

3. Results

3.1. Descriptive results

Sample size varied by outcome (Prosocial n = 640; Internalising n = 636; Externalising n = 636) and was representative across geographic and social gradients (Supplementary, A4). Participants (54 % female) returned a median 6 days (interquartile range IQR: 5, 7) with ≥ 5 h GPS data with a median 4026 (IQR: 3349, 4476) GPS per day, totalling 15.3 million GPS.

Boys were more likely to have abnormal externalising outcomes than girls, and less likely to have normal prosocial outcomes, but there was no variation in internalising outcomes by sex (Fig. 1). Abnormal internalising outcomes were more likely in lower SEP children, but externalising outcomes and prosocial outcomes did not vary by SEP (Fig. 1). Total use of natural environments averaged 78.74 (95 % CI: 73.76, 83.72) minutes per day, 77 % of which was passive (Table 1). Across the sample, passive minutes comprised an average 40.4 % (95 % CI: 38.7–42.0 %) sedentary PA, while active minutes comprised 54.2 % (95 % CI: 53.5–59.0 %)

Table 1
Mean (95% CI) estimates of exposure measures representing time in natural environments (total use) and time in natural environments while in low and high PA states (passive use and active use, respectively) with comparison by sex and socioeconomic position (SEP). Equivalised household income (SEP) was treated as continuous but summarised here at 25th and 75th percentiles.

Exposure	Sex	SEP	Time exposed (minutes)		P-value
			Mean	95 % CI	
Total use	–	–	78.74	73.76–83.72	–
Passive use	–	–	60.81	56.92–64.69	–
Active use	–	–	17.94	16.41–19.47	–
Total use	Male	–	86.48	78.40–94.57	0.011
	Female	–	72.27	66.35–78.19	–
Passive use	Male	–	64.96	58.81–71.11	0.081
	Female	–	57.33	52.30–62.36	–
Active use	Male	–	21.52	18.87–24.17	<0.001
	Female	–	14.94	13.52–16.36	–
Total use	–	£12,694	79.53	71.71–144.54	0.736
	–	£34,166	78.12	73.27–146.08	–
Passive use	–	£12,694	60.65	54.80–110.39	0.929
	–	£34,166	60.93	57.01–113.74	–
Active use	–	£12,694	18.87	16.18-–33.08	0.252
	–	£34,166	17.19	15.84–31.74	–

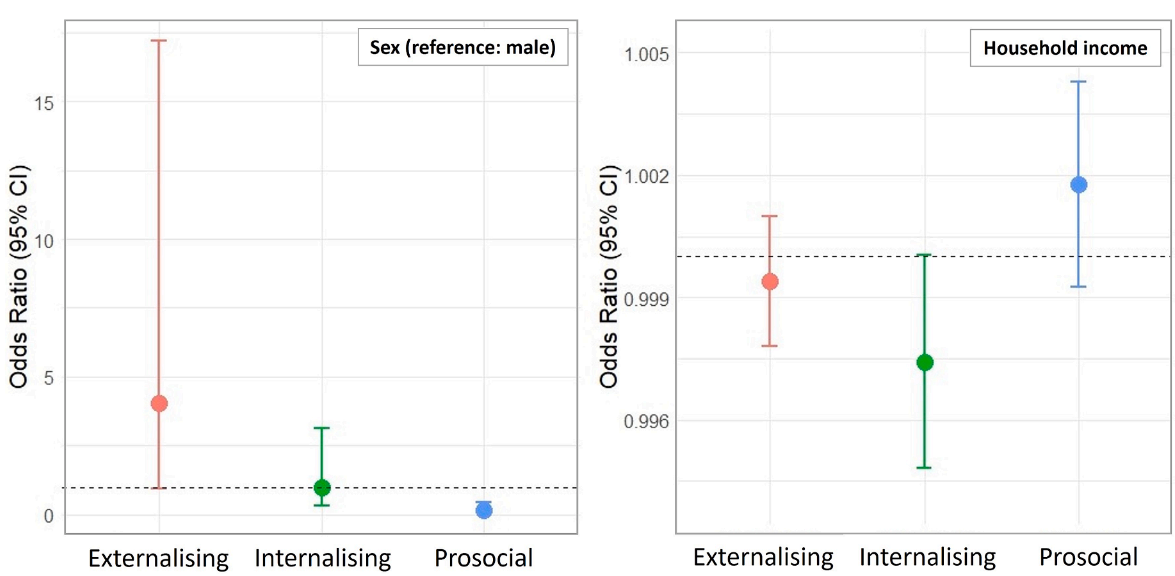

Fig. 1. Odds ratios (95% CI) comparing SDQ outcomes by sex (binary) and household income (continuous). OR for household income relate to a unit increase on a 131-level scale (median: £21,874; IQR: £12,694–£34,166).

moderate PA. Total use and active use of natural environments were higher for boys than girls, but no exposure measures varied by SEP.

3.2. Model selection

Model selection retained different covariates for each outcome. P-values reported here relate to coefficients from Model 1 (total use) for each outcome but are substantially the same in Model 2 (relative use: full results can be found in Supplementary, A5). Models fitted to internalising outcomes contained sex ($p = 0.935$), SEP ($p = 0.053$), total PA ($p = 0.254$), residential urbanicity ($p = 0.063$), and season ($p = 0.002$). Models fitted to externalising outcomes contained sex ($p = 0.052$), SEP ($p = 0.320$), maternal age ($p = 0.073$), residential urbanicity ($p = 0.410$), time in gardens ($p = 0.090$), season ($p = 0.003$), and residential NE within 100 m ($p = 0.412$). Models fitted to prosocial outcomes contained sex ($p < 0.001$), SEP ($p = 0.085$), total PA ($p = 0.241$), residential urbanicity ($p = 0.208$), and residential NE within 100 m ($p = 0.283$).

3.3. Main effects

Odds ratios (OR) from models of outcomes fitted with each measure of use are shown in Table 2. These indicated total use of natural environments was associated with reduced likelihood of abnormal internalising and externalising outcomes. Specifically, a 10-minute increase in total use was associated with 10.5 % lower risk of abnormal internalising outcomes (OR: 0.895; 95 % CI 0.809, 0.990), and 13.2 % lower risk of abnormal externalising outcomes (OR: 0.868; 95 % CI 0.776, 0.990). This meant that a 50 % reduction in the probability of abnormal internalising outcomes, from 0.0913 (0.0420, 0.187) to 0.0466 (0.0261, 0.0818), was associated with 63 min of total use (Fig. 2). Similarly, a 50 % reduction in the probability of abnormal externalising outcomes, from 0.0375 (0.0157, 0.0867) to 0.0193 (0.008, 0.0469), was associated with 49 min total use (Fig. 2). No main effects associations were found for prosocial behaviours. Outputs of Model 2 indicated the relative effects of passive use were equal to those of active use for both internalising and externalising outcomes, however coefficients for active use had greater uncertainty (Table 2).

3.4. Moderating effects

There was no evidence of effect moderation by sex on any outcome. There was no effect moderation by SEP on internalising outcomes, however, there was effect moderation by SEP on externalising and prosocial outcomes. SEP moderated the effects of both total use ($p = 0.039$) and passive use ($p = 0.027$) of natural environments on externalising outcomes, while SEP moderated the effect of active use ($p = 0.005$) of natural environments on prosocial outcomes. Examination of marginal effects indicated that passive use of natural environments was associated with reduced risk of abnormal externalising outcomes in low SEP children but had no effect on high SEP children (Fig. 3). Similarly, active use of natural environments was associated with increased likelihood of normal prosocial outcomes in low SEP children, but uncertainty surrounding predictions for high SEP children means this association should be treated with caution and may reflect lower incidence in higher SEP children (Fig. 3). Comparison of AIC of these models against Model 1 (total use) indicated that including the interaction of SEP significantly improved model fit to both outcomes (i.e., delta AIC reduced by ≥ 2).

Models predicted that after 50 min of passive use of natural environments the probability of abnormal externalising outcomes in low SEP children reduced from 0.065 (95 % CI 0.020,0.188) to 0.013 (95 % CI 0.005, 0.034), equivalent to the baseline probability of high SEP children with no exposure (0.015 95 % CI 0.004, 0.060). Similarly, 40 min of active use of natural environments increased the likelihood of normal prosocial outcomes in low SEP children from 0.827 (95 % CI 00.552, 0.949) to 0.980 (95 % CI 0.866, 0.997), equivalent to the baseline probability of high SEP children with no exposure (0.975 95 % CI 0.924, 0.992).

4. Discussion

In this nationally representative cohort study, we provide novel evidence on the relationship between children's use of natural environments and their mental wellbeing, and how this is moderated by socioeconomic factors. By objectively measuring children's direct use of natural environments, we move beyond indirect or self-reported measures of exposure to capture actual engagement. Our findings suggest that increased use of natural environments is associated with reduced risk of abnormal internalising (emotional) and externalising (behavioural) outcomes in all children. Specifically, using natural environments for around 60 min per day was associated with a ~ 50 % lower risk of abnormal internalising and externalising outcomes. The association between use and reduced risk of abnormal externalising outcomes remained even after controlling for residential availability of NE, where availability was not a significant predictor. Indeed, residential availability of NE was not retained in models fitted to internalising outcomes. This suggests that the mere presence of natural environments may not be sufficient to promote mental wellbeing; rather, active engagement and direct use of these spaces could be key. Importantly, associations between types of use and mental wellbeing were stronger for children from lower income households. This finding supports the notion that natural environments might be "equigenic", reducing health inequalities by disproportionately benefiting those from lower socioeconomic groups (Mitchell et al., 2015). By separating children's physical activity states during natural environments use, we were able to provide novel insight into how equigenic effects may arise along active and passive pathways, which has implications for targeted interventions and future research.

Table 2
Coefficients of exposures (total use; passive use; active use of NE) from logistic regressions fitted to SDQ outcomes (internalising and externalising 1 = abnormal; prosocial 0 = abnormal). Odds ratios, which were based on one-minute increments of exposure (use of NE), have been scaled to represent 10-minute increments of exposure (i.e., OR^10). Main effect of total use (Model 1) was modelled separately from the relative effects of passive and active use components (Model 2), which were modelled together. Only p-values of interaction terms on sex and socioeconomic position (SEP) on each exposure measure (Models 3–8) are shown.

SDQ Outcome	Model	NE Use by PA state	*Odds Ratios*	*95 % CI*	*P*	R^2	Exposure * Sex	Exposure * SEP
Internalising	1	Total	0.895	0.809—0.980	**0.025**	0.130	0.358	0.501
	2	Passive	0.895	0.792—1.010	0.068	0.130	0.454	0.453
	2	Active	0.895	0.556—1.424	0.623	–	0.227	0.656
Externalising	1	Total	0.868	0.776—0.980	**0.020**	0.202	0.564	**0.039**
	2	Passive	0.877	0.768—1.010	0.059	0.202	0.628	**0.027**
	2	Active	0.877	0.679—1.127	0.304	–	0.441	0.329
Prosocial	1	Total	1.010	0.923—1.105	0.818	0.120	0.288	0.355
	2	Passive	1.000	0.886—1.127	0.984	0.121	0.184	0.990
	2	Active	1.083	0.611—1.895	0.787	–	0.832	**0.005**

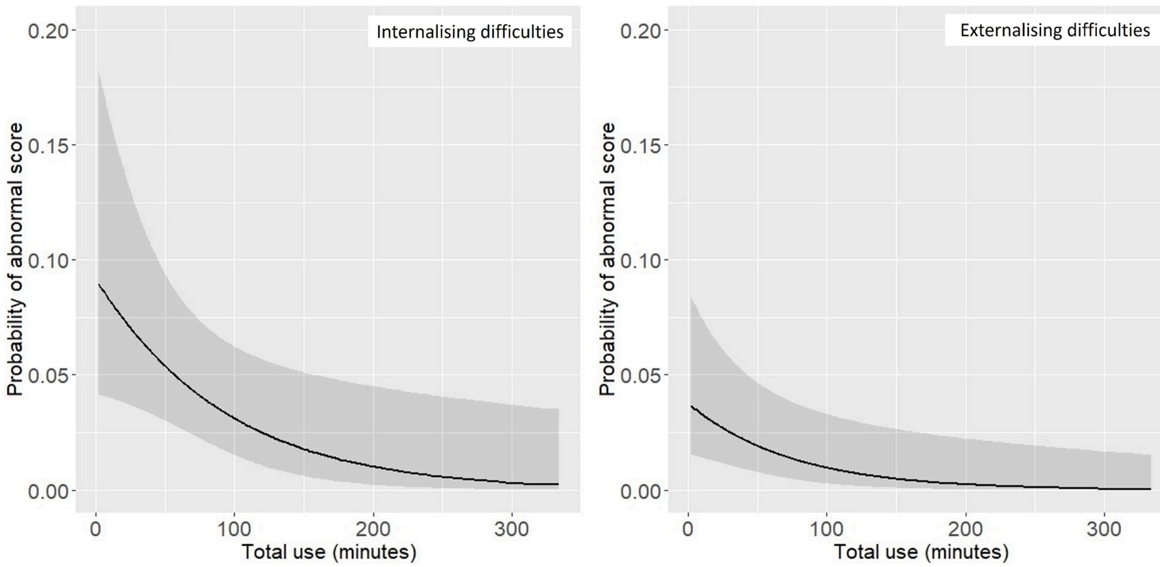

Fig. 2. Response curve showing the effects of total use of natural environments (mean daily minutes) on likelihood of abnormal internalising and externalising outcomes.

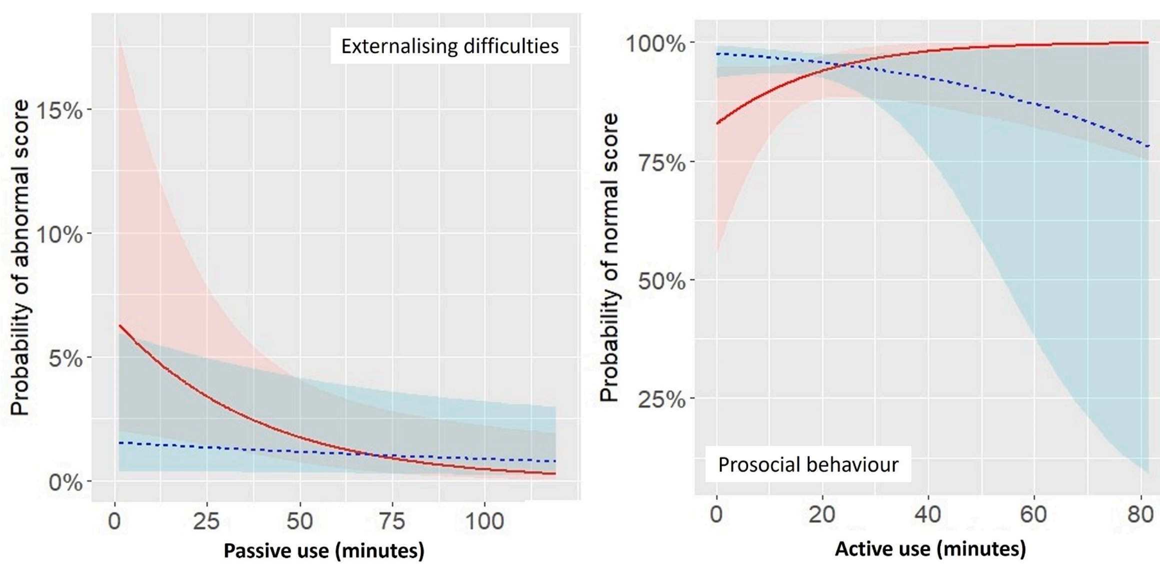

Fig. 3. Predicted marginal effects of use of natural environments (mean daily minutes) on mental wellbeing outcomes by SEP. Low SEP (red solid line) predicted for 25th percentile household income (£12,694); high SEP (blue dotted line) predicted for the 75th household income (£34,166).

4.1. Comparison with literature

Recent systematic reviews have examined the association between exposure to natural environments and child mental wellbeing, supporting the contention that exposure to nature positively influences mental health (Tillmann et al., 2018), improves children's behavioural outcomes (Sakhvidi et al., 2022), and has significant restorative effects (Moll et al., 2022). However, these reviews also found inconsistent findings. Tillman et al. (2018) reported that almost half (47 %) of 100 individual findings in 34 reviewed papers were null or negative. They found that studies using direct measures of encounters with natural environments, such as 'use of' or 'time spent in', had higher ratios of positive to null findings compared to studies using measures of residential availability, suggesting the former is the most effective approach for intervention strategies. However, only one study included in the review (Ward et al., 2016) measured direct use objectively rather than through surveys. These reviews also highlighted a gap in the underlying mechanisms of nature-health associations (Tillmann et al., 2018; Moll et al., 2022; Sakhvidi et al., 2022), which previous reviews have blamed on exposure assessment (Hartig et al., 2014; Markevych et al., 2017). Our study helps to fill this gap by objectively measuring how much time children spent using natural environments for different activities and examining moderation by sex and socioeconomic position. Our findings on the moderating role of socioeconomic status are particularly noteworthy. Whilst we found no difference in use of natural environments by SEP, we did find evidence of effect moderation by SEP, which varied by type of use and outcome.

Firstly, we found the association between passive use of natural environments and reduced externalising difficulties was stronger for children from lower income households. This suggests that mental health benefits from using natural environments may not be solely attributable to increased physical activity but driven by other mechanisms, such as stress reduction or mitigation from harmful environments (Markevych et al., 2017). Restorative pathways can only be studied in experimental settings in which antecedent conditions are measured, whilst mitigation pathways can only be explored when environmental stressors are measured. However, our results linking passive use to reduced likelihood of abnormal externalising outcomes suggests that natural environments may buffer disadvantaged children against psychosocial and environmental stressors. This finding has important implications for the design and promotion of interventions, as it suggests that providing opportunities for quiet reflection and relaxation in nature may be as important as encouraging more vigorous activities. It also has implications for research, given that physical activity is one of the most studied pathways in nature-health relationships (Tillmann et al., 2018; Markevych et al., 2017).

Secondly, we found that active use of natural environments was only associated with increased prosocial behaviour in lower income children, but not higher income children. We found similar moderation in an earlier study using the same sample, but which only measured exposure indirectly (McCrorie et al., 2021). In that study, prosocial outcomes in low-income children were positively related to increased natural environments near home whilst null associations were found for high-income children (McCrorie et al., 2021). The current study's integration of mobility data improves understanding of mechanisms underlying this relationship. It suggests that affordances for physical activity provided by natural environments interact with those for social connection (e.g., playing sports, games) to improve prosocial behaviours. This aligns with recent evidence suggesting that improved social outcomes lie on the mechanistic pathway between moderate-to-vigorous PA and mental health in disadvantaged children (Rose & Soundy, 2020).

Finally, we found similar sex differences in the use of natural environments as Wheeler et al. (2010), who measured use with GPS. Boys spent more time in natural environments than girls, particularly at high physical activity levels. However, we found no evidence of moderation in the associations between natural environment use and mental health outcomes by sex. This suggests that the mechanisms through which natural environments influence mental health may be independent of gender/sex. However, we did not account for the quality or type of natural environments used and this may be affecting use by girls. More detailed exploration of this is warranted in future research.

4.2. Strengths & Limitations

Our study has several strengths. We focused on children—an understudied group at a key development period. Our sample was nationally representative across geographic and social gradients. We used 5–7 days of data collected at high temporal and spatial resolutions for each individual in a sample size (n = 640) considered large for GPS-based health studies. However, we acknowledge some limitations. First, the cross-sectional design precludes causal inferences, and it is possible that children with better mental wellbeing are more likely to spend time in natural environments. Second, while we controlled for several potential controls, there may be residual confounding. Third, while nationally representative, our sample could be considered low-risk and further research is needed to examine the generalisability of our findings to high-risk groups and other contexts. Fourth, we did not measure perceived quality or safety of natural environments, which might provide insight into observed sex differences in use. Finally, the GPS-based measures of use defined here did not distinguish between intentional visits and incidental exposure (e.g., while in vehicles). Separating intentionality may provide more understanding of mechanisms (e.g., a conscious decision to engage with nature as opposed to incidentally passing through it).

4.3. Future research

We suggest that future research should explore whether the quality or type of natural environment influences use by boys and girls, and whether these factors influence the relationship between natural environment use and mental health. Furthermore, future research should seek to refine GPS-based measures of use to capture the intentionality for a more nuanced understanding of mechanisms and dose–response relationships. Quantifying the frequency and duration of use needed to support optimal mental wellbeing could then inform guidelines akin to physical activity recommendations.

4.4. Policy implications

Our findings support the development of interventions to increase children's engagement with natural environments, particularly in deprived communities. Such interventions should promote the use of natural environments for restoration through less vigorous activities (such as mindful nature exploration, fishing, or walking) as much as more vigorous activities (such as team sports). However, implementing these interventions may face challenges, such as ensuring equitable access to safe and high-quality natural environments in disadvantaged areas and addressing potential barriers to use, such as time constraints or lack of awareness. Collaborative efforts between policymakers, urban planners, community organisations, and public health professionals could help overcome these challenges and maximise the mental health benefits of natural environments for all children.

4.5. Conclusions

We provide robust evidence from objective measures that use of natural environments is associated with better mental wellbeing in children. Furthermore, both active and passive use of natural environments are associated with greater benefits to those from lower income households. This suggests that socioeconomic inequalities in child mental health may be reduced by encouraging the use of natural environments by disadvantaged groups.

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CRediT authorship contribution statement

Fiona Caryl: Conceptualization, Data curation, Investigation, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Paul McCrorie:** Data curation, Writing – review & editing, Funding acquisition. **Jonathan R. Olsen:** Writing – review & editing, Funding acquisition. **Richard Mitchell:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

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Data sharing statement

Studying Physical Activity in Scotland (SPACES) data used in this study are confidential and cannot be made openly available. Summary data may be available upon reasonable request subject to approval by the data custodian. Growing Up in Scotland (GUS) Cohort 1 Data can be accessed via the UK Data Service through Secure or Special Licence DOI: http://doi.org/10.5255/UKDA-Series-200020.

Patient consent for publication

Not applicable.

Ethical approval

This study used secondary analysis of data from Growing Up In Scotland (GUS) and Studying Physical Activity in Children's Environments across Scotland (SPACES). Ethical approval for GUS was granted from Scotland's Scottish "A" Multicentre Research Ethics Committee (MREC: 04/M RE 1 0/59). Ethical approval for SPACES was granted by the College of Social Sciences, University of Glasgow (CSS:400140067). Informed parental consent for data to be analysed for research purposes was obtained prior to data collection in GUS and SPACES.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108847.

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