Life in green: Associations between greenspace availability and mental health over the lifecourse - A 40-year prospective birth cohort study.

DENG, B, BODEN, J, YE, N, MORGENROTH, J, CAMPBELL, M, EGGLETON, P, MCLEOD, G and HOBBS, Matthew

Environment International 195 (2025) 109223

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

Life in green: Associations between greenspace availability and mental health over the lifecourse – A 40-year prospective birth cohort study

B. Deng [a,b,*], J. Boden [c], N. Ye [d], J. Morgenroth [d], M. Campbell [b,e], P. Eggleton [a,b], G. McLeod [c], M. Hobbs [a,b,f]

[a] Faculty of Health, University of Canterbury, Christchurch, New Zealand
[b] GeoHealth Laboratory, University of Canterbury, Christchurch, New Zealand
[c] Christchurch Health and Development Study, University of Otago, Christchurch, New Zealand
[d] School of Forestry, University of Canterbury, Christchurch, New Zealand
[e] School of Earth and Environment, University of Canterbury, Christchurch, New Zealand
[f] College of Health, Wellbeing and Life Science, Sheffield Hallam University, Sheffield, United Kingdom

ARTICLE INFO

Handling Editor: Hanna Boogaard

Keywords:
Greenspace
Mental health
Lifecourse
GIS
Epidemiology
Nature

ABSTRACT

Background: The beneficial impacts of greenspace availability on mental health are well-documented. However, longitudinal evidence using a spatial lifecourse perspective is rare, leaving the dynamics of how greenspace influences mental health across the lifecourse unclear. This study first uses prospective birth cohort data to examine the associations between greenspace availability in childhood (0–16 years) and mental health in adolescence (16 years) and between greenspace availability and mental health across adulthood (18–40 years).
Method: Data were obtained from the Christchurch Health and Development Study, comprised 1,265 cohort members born in Christchurch, New Zealand, in 1977. Mental health outcomes including depressive symptoms, anxiety disorders and suicidal ideation were assessed in adolescence (16 years), and in adulthood (18–40 years). Greenspace availability from birth to age 40 years was measured as the proportion of vegetated areas within circular buffers (radius from 100m to 3000m) around members' geocoded residential addresses using a time-series impervious surfaces data from 1985 to 2015. Bayesian Relevant Lifecourse exposure models examined the associations between childhood greenspace availability and adolescent mental health and tested for critical/sensitive age periods. Generalised Estimating Equation logistic regression models assessed the associations between greenspace availability and mental health across adulthood. These analyses were adjusted for various important individual, family, and area-level covariates.
Results: No associations were found between childhood greenspace availability and any adolescent mental health conditions. However, in adulthood, a one standard deviation increase in greenspace availability within 1500m and 2000m buffers was associated with a 12% and 13% reduced risk of depressive symptoms, respectively, after adjusting for various covariates.
Discussion: This study supports the protective effects of greenspace on adult depressive symptoms, highlighting the significance of employing a spatial lifecourse epidemiology framework to examine the long-term effects of environmental factors on health over the lifecourse.

1. Introduction

Mental health is a contemporary global public health concern, with an estimated 13% of the world's population living with mental disorders in 2019, and an even higher prevalence of 15% in high-income countries (World Health Organization [WHO], 2022). Aotearoa[1] New Zealand (NZ), as a high-income country, saw 23% of adolescents reporting clinically significant depressive symptoms, 42% possible anxiety disorders, and 21% having suicidal ideation in 2019 (Sutcliffe et al., 2023). In addition, 11.9% of New Zealanders over 15 years old reported high or very high levels of psychological distress during the last four weeks prior to the 2022/23 NZ health survey, the highest figure in the last decade

* Corresponding author at: Faculty of Health and GeoHealth Laboratory, University of Canterbury, Christchurch, New Zealand.
E-mail address: bingyu.deng@pg.canterbury.ac.nz (B. Deng).

[1] Aotearoa is the Māori name for New Zealand.

https://doi.org/10.1016/j.envint.2024.109223
Received 30 July 2024; Received in revised form 17 December 2024; Accepted 17 December 2024
Available online 20 December 2024

(Ministry of Health [MOH], 2023). Whilst the aetiology of mental health conditions is complex, individuals' mental health is shaped by different social, economic, and physical environments operating at different stages of life (Allen et al., 2014). Greenspace, as an important component of the physical environments, has been found to have beneficial impact on mental health in numerous studies of experimental (Watkins-Martin et al., 2022; Xie et al., 2022), cross-observational (Jiang et al., 2021; Osa et al., 2024; Wang et al., 2020), and short- to medium-term follow-up longitudinal design (Astell-Burt & Feng, 2019; Bao et al., 2024; Engemann et al., 2019; Mouly et al., 2023). While numerous studies have explored the associations between greenspace and mental health at various stages of life separately (Abraham Cottagiri et al., 2022; Engemann et al., 2019; Mouly et al., 2023; Osa et al., 2024), the dynamics of how greenspace influences mental health across the lifecourse remain inadequately explored. This requires a long-term longitudinal study design or if possible the adoption of a lifecourse perspective with appropriate adjustment for confounders (Li et al., 2021).

Recent research on the relationship between greenspace and mental health is advancing towards a lifecourse perspective (Li et al., 2021). This acknowledges that the origins of some health conditions may be associated with social and physical exposures over the course of an individual's life (Wagner et al., 2024). A lifecourse perspective proposes four hypotheses to explain how greenspace exposure across a person's lifecourse affects their mental health in later years, including the i) critical period hypothesis (i.e. exposure at a specific period has exclusive impact); ii) sensitive period hypothesis (i.e. exposure at some periods may have greater impact than any other periods); iii) accumulation hypothesis (i.e. effects of exposure accumulate over time with each period having an equal effect); iv) pathway theory (i.e. exposure to one risk factor increases the likelihood of exposure to another) (Madathil et al., 2018; Wagner et al., 2024). A systematic review study regarding the lifecourse associations between greenspace and mental health suggested that existing evidence is largely supportive of the accumulation hypothesis, indicating that greenspace has a cumulative beneficial effect on mental health outcomes over time (Li et al., 2021). However, such evidence is limited due to the lack of high-quality birth cohort data to provide accurate individual mental health-related data spanning decades of life and validated methods to provide time-consistent measure of greenspace across lifecourse (Jia, 2019; Li et al., 2021). Understanding and verifying how greenspace could be related to mental health is timely and especially helpful for age-specific policy that aims to improve individual's mental health in an era with a high prevalence of mental health conditions (Wagner et al., 2024; WHO, 2022).

A range of metrics have been devised to conceptualise or measure greenspace, with greenspace availability being the most commonly used (Bowie et al., 2013; Houlden et al., 2018; Vanaken & Danckaerts, 2018). Despite heterogeneous definitions, greenspace availability generally refers to the level of greenness or the amount of greenspace within a defined buffer area centred around individuals' living, schooling, or working environments (Wendelboe-Nelson et al., 2019). Three pathways have been proposed that mediate the associations between higher greenspace availability and lower risks of mental health conditions. These include reducing harms (e.g., air pollution), restoring capacities (e.g., psychological stress), and encouraging health-promoting behaviours (e.g., physical activities) (Dzhambov, Hartig, et al., 2018; Jarvis et al., 2020; Markevych et al., 2017; Zhang et al., 2021). However, these associations are heterogeneous in effect size when considering the spatial scale of greenspace availability measures. A systematic review revealed that 45.5% of studies reported no sensitivity to buffer sizes, 36.4% of studies found greater effects at larger buffers (1000m to 3000m), and 9.1% of studies found greater effects at smaller buffers (100m to 500m) (Li et al., 2021). The buffer sizes with the largest effect of greenspace on mental health remain uncertain due to many studies using only a single or limited number of buffer sizes in their design (Bezold et al., 2018; Younan et al., 2016). Additionally, the same buffer size may not work for all ages over lifecourse (Astell-Burt et al., 2014). Children may be dependent on their immediate environment due to limited mobility, whereas adults may be able to actively travel further for activities and therefore benefit more from larger buffers. To address these heterogeneities concerning spatial scales conditioned on age, different buffer sizes should be included in greenspace availability measures over lifecourse.

There are several important gaps in the literature which limit confidence in the associations between greenspace availability and mental health conditions. Firstly, although longitudinal work around this topic has seen a great increase in recent years, the follow-up period of existing studies are often short, usually less than 10 years (Osa et al., 2024). Secondly, seldom is a lifecourse or long-term greenspace measure used to define exposure (Li et al., 2021). This is because time-series greenspace data are hard to obtain, especially for studies that span multiple decades, which require consistent measurements and definitions of greenspace over time to ensure comparability and accuracy (Hobbs & Atlas, 2019; Jia, 2019). Thirdly, few studies have identified what are the most appropriate geographic scales for measuring greenspace, and it is highly likely that no single scale is applicable to every stage of the lifecourse (Astell-Burt et al., 2014). Without using lifecourse study design, this question cannot be explored. Fourthly, available evidence for the lifecourse associations between greenspace availability and multiple mental health conditions are still scarce (Osa et al., 2024), with particularly limited evidence on some mental health conditions such as anxiety disorders and suicidal ideation (Jiang et al., 2021; Mouly et al., 2023). Fifthly, individual-level data including street-level addresses and personal variables are hard to obtain, especially lifecourse data. Studies at population-level are prone to ecological fallacy (Piantadosi et al., 1988) and lack the ability to control for important individual-level covariates, such as lifestyle and parental history of mental health problems, which may greatly attenuate the associations between greenspace and mental health outcomes (Nutsford et al., 2013). In addition, many studies used postal code or larger administrative units to link greenspace data with individuals (Jarvis et al., 2021), which might lead to exposure misclassification problem (Harari-Kremer et al., 2022). Sixthly, some important time-varying area-level covariates, like area-level socioeconomic status (SES) and air pollution, which can correlate with greenspace availability and moderate its association with mental health (Jarvis et al., 2021; Mouly et al., 2023; Pearce et al., 2018), are missing in some studies. Lastly, many studies mainly focus on urban settings (Astell-Burt et al., 2014; Mouly et al., 2023), and most studies were Europe-, United Kingdom- and United States-centred (Li et al., 2021), limiting the generalisability of findings to other geographical locations such as in the global south.

Using data from a prospective birth cohort study spanning 40 years, this study aims to investigate the associations between greenspace availability and mental health conditions across the lifecourse. This study proposed four research questions: 1) Does childhood (age 0–16 years) greenspace availability relate to adolescent (age of 16 years) mental health conditions (depressive symptoms, anxiety disorders, and suicidal ideation)? 2) Is there an age period in childhood when greenspace availability is more important for adolescent mental health than any other age periods? 3) Does adulthood (18–40 years) greenspace availability relate to adult (18–40 years) mental health conditions? 4) At which buffer size for greenspace availability are the tested associations the strongest? In a spatial lifecourse epidemiology framework, we hypothesised that higher greenspace availability is related to lower risks of mental health conditions in both adolescent and adulthood, with stronger effects in adulthood. We also hypothesised that greenspace in early age periods in childhood are more important to adolescent mental health conditions.

2. Methods

2.1. Participants and settings

The Christchurch Health and Development Study (CHDS) is a prospective birth cohort study that has collected data on 1,265 individuals (including 630 females) born in 1977 in Christchurch, the largest city in the South Island of New Zealand (NZ) (Hobbs et al., 2022). The CHDS includes 97 % of all births occurring over the four-month period from April to August in 1977. The CHDS has collected 24 waves of data including birth, four months, yearly until age 16 years, and then at age 18, 21, 25, 30, 35 and 40 years. The CHDS gathered data through various methods, such as parental interviews (birth to age 16); direct interviews with cohort members (from age 8 onwards); teacher reports, standardised tests, and official medical and other records. Detailed information about the CHDS can be found in other publications (Fergusson and Horwood, 2001; Fergusson et al., 2013). The Southern Health and Disabilities Ethics Committee has approved all aspects of the CHDS data collection with an approval number as 16_STH_144, and all data were collected with the explicit written consent of study participants.

2.2. Mental health outcomes

The CHDS assessed cohort members for mental health conditions since the previous interview at ages 16, 18, 21, 25, 30, 35 and 40 years, generating mental health measures during the seven intervals: 14–16, 16–18, 18–21, 21–25, 25–30, 30–35, and 35–40 years. We defined mental health conditions in adolescence by the measures taken at the 14–16 interval, and mental health conditions in adulthood by the measures taken during the subsequent six intervals. The stratification of developmental stages into childhood, adolescence, and adulthood was informed by lifecourse theory (Elder et al., 2003; Giele & Elder, 1998) and supported by previous CHDS work (Buchanan et al., 2024; Deng, McLeod, et al., 2024; Telfar et al., 2023).

2.2.1. Depressive symptoms

At age 16, items from the Composite International Diagnostic Interview (CIDI) (WHO, 1993) were used to assess Diagnostic and Statistical Manual of mental disorders (DSM-III-R) (American Psychiatric Association [APA], 1987) symptom criteria for major depression. From age 18 onwards, symptoms of major depression were assessed using CIDI items and DSM-IV (APA, 1994) diagnostic criteria. For the purposes of the present analysis sample, members who met DSM diagnostic criteria for experiencing a major depressive episode at any point within an assessment interval were classified as having depressive symptoms during that interval (12.3% of the sample at ages 14–16, 21.5% at ages 16–18, 23.8% at ages 18–21, 21.9% at ages 21–25, 20.8% at ages 25–30, 18.9% at ages 30–35, 21.4% at ages 35–40).

2.2.2. Anxiety disorders

At age 16, the CHDS assessed cohort members using CIDI and DSM-III-R for a range of anxiety disorders (including generalised anxiety disorder, panic disorder, agoraphobia, social phobia, and specific phobia). From age 18 onward these anxiety disorders were assessed using CIDI items and DSM-IV diagnostic criteria. Sample members who met DSM diagnostic criteria for one or more anxiety disorders during the assessment interval were classified as having an anxiety disorder during that interval (16.9% of the sample at ages 14–16, 17.0% at ages 16–18, 12.9% at the ages 18–21, 17.9% at ages 21–25, 18.7% at ages 25–30, 18.6% at ages 30–35, 15.8% at ages 35–40).

2.2.3. Suicidal ideation

The CHDS asked cohort members' suicidal ideation through custom-written survey items about whether they had ever considered killing themselves or had attempted suicide during the assessment intervals (Fergusson et al., 2008). Based on their responses, we categorised cohort members as having experienced suicidal ideation during that time interval (14.6% of the sample at ages 14–16, 11.5% at ages 16–18, 14.2% at ages 18–21, 12.2% at ages 21–25, 7.3% at ages 25–30, 4.0% at ages 30–35, 8.6% at ages 35–40).

2.3. Greenspace availability

We defined greenspace availability as the proportion of vegetated areas within a given circular buffer area centred on cohort members' geocoded residential addresses. We measured greenspace availability within circular buffer areas of radius of 100m, 300m, 500m, 1000m, 1500m, 2000m, and 3000m at all data waves over the lifecourse. Due to the need for measuring greenspace over the lifecourse from birth (1977) to age 40 years (2017), it was impossible to use common means of greenspace estimation such as the Normalized Difference Vegetation Index (NDVI) (Pettorelli et al., 2005). While the Landsat series of satellites has provided continuous Earth observation since 1972, the data prior to the 1980's lacked adequate coverage of cloud-free images, had low resolution, and offered limited spectral bands necessary for estimating NDVI in NZ (Goward et al., 2006). Instead, we estimated greenspace availability using a combination of the Global 30 m impervious-surface dynamic dataset (GISD30) (Zhang, Liu, et al., 2022) and the NZ Land Cover Database (LCDB) (Landcare Research, 2018). GISD30 is a dataset that provides the global impervious surface information from 1985 to 2020 at 5-year intervals at a 30m spatial resolution. GISD30 data is available for the coverage of NZ for all timestamps other than 1990. Impervious surfaces encompass human-made features that prevent water from infiltrating the soil, such as paved land covers (e.g., roads, parking lots) and rooftops (Lu & Weng, 2006). Conversely, the opposite of impervious surfaces, thus represent land cover features that allow water to infiltrate the soil, such as vegetated land covers (e.g., lawns, shrubs, trees) or bare soil. To derive a valid measure of greenspace, we firstly masked the study area by the impervious surfaces to create an intermediate pervious surface dataset. We then masked other land cover features not indicative of greenspace, including mines or dumps, sand or gravel, landslides, permanent snow and ice, gravel or rock, lakes or ponds, and rivers and estuarine open water, using LCDB values closest in time to the GISD30 surfaces. This resulted in estimated greenspace surfaces at six timestamps from 1985 to 2015 excluding 1990. The greenspace surfaces were binary, with one denoting greenspace and zero denoting non-greenspace. We conducted a case study to validate the GISD30-derived greenspace classification by comparing it to a range of binary greenspace classifications derived from NDVI data. For this comparison, we undertook a binary classification of NDVI data. All pixels were classified as either greenspace or non-greenspace based on their NDVI value. We tested different NDVI threshold values to determine which value led to the most effective binary classification. NDVI threshold values were increased between 0.2 and 0.8 by increments of 0.05. For example, we categorised NDVI data with values from -1 to 0.2 as non-greenspace and those with values from 0.2 to 1 as greenspace. We provided more details of the case study in online Supplementary Material Section 1. Results from the case study showed that the GISD30-derived greenspace classification had significant correlations with the NDVI-derived classifications at all thresholds. The highest correlation (0.772, $p < 0.001$) was found at an NDVI threshold of 0.5, indicating that the GISD30-derived greenspace classification is more likely to represent moderate to dense vegetation than sparse vegetation. This is because NDVI values increase with biomass and vegetation health. We linked each member's geocoded residential location at each data wave to the closest-in-time greenspace surface (see online Supplementary Material Section 2 for the temporal alignment of the greenspace data with CHDS data) and then computed mean values of pixels within circular buffering areas from the greenspace surfaces. This resulted in a time-variant greenspace availability measure for each member at 24 occasions across the lifecourse, with values closer to one indicating higher greenspace availability.

2.4. Covariates

2.4.1. Individual and family covariates

We selected a number of individual and family covariates from the CHDS database based on their theoretical relevance to greenspace availability. These covariates can be divided into two parts based on the time of measurement, including childhood covariates and adulthood covariates. We used childhood covariates to adjust the associations between childhood greenspace availability and mental health conditions in adolescence, which include three domains: a) individual characteristics (e.g. sex, ethnicity), b) parents' characteristics (e.g. maternal age, maternal education, father's occupational status, family composition), c) family functioning (e.g. parental relationship stability from birth to age 16 years, family living standards from age one to 10, residential moves from birth to age 16 years, parental mental health history, parental maladaptive behaviour). All childhood covariates were time-invariant, as they were either measured at a single time point or summarised over a certain period to construct an overall variable. We used adulthood covariates to adjust the associations between greenspace availability and mental health conditions in adulthood. They span three domains, including individual circumstances (e.g. highest education attainment, welfare dependency), family circumstances (e.g. whether living with partner, number of dependent children, residential moves), and lifestyle (e.g. tobacco use disorders, alcohol use disorders, illicit drug use disorders). All adulthood covariates were time-variant as they were measured and modelled at the same time as the mental health outcomes. We provided a list of all covariates and their full descriptions in the Supplementary Material Section 3.

2.4.2. Area-level covariates

We also included three area-level covariates, namely area-level SES, population density, and air pollution. These covariates are theoretically or empirically verified to correlate with greenspace availability and to mediate its association with mental health (Alcock et al., 2015; Dzhambov, Hartig, et al., 2018; Jarvis et al., 2021; Mouly et al., 2023). Similarly, all area-level covariates in childhood were time-invariant, while all area-level covariates in adulthood were time-variant. We measured childhood area-level SES from birth to age 16 years using a historical area-level deprivation metric, which was developed for 1981, 1986, and 1991 at Census Area Unit (CAU) level from census data (Deng, Campbell, et al., 2024). In this metric, quintile one (Q1) denotes the highest SES areas and quintile five (Q5) denotes the lowest SES areas. We counted the number of times when cohort members lived in lowest SES areas (Q5) to construct an overall indicator of area-level SES in childhood from birth to age 16. We measured adulthood area-level SES from age 18 to 40 years using NZ Deprivation Index (NZDep) in 1996, 2001, 2006, 2013, and 2018 (Atkinson et al., 2014, 2019; Salmond et al., 2007; Salmond & Crampton, 2002; Salmond et al., 1998). The NZDep is a widely used metric in NZ for evaluating area-level material and social deprivation derived from census data on nine or ten variables (Atkinson et al., 2019). We measured childhood air pollution by taking the average of annual black smoke estimates (in micrograms per cubic meter of air or $\mu g.m^{-3}$) from birth to age 10 years. Details regarding the historical air pollution measure can be found elsewhere (Hobbs et al., 2024). We measured adulthood air pollution exposure from age 21 to 40 using particulate pollution (PM_{10}) estimates (in micrograms per cubic meter of air or µg.m-3). These PM_{10} estimates were obtained from the Health and Air Pollution in NZ (HAPINZ) project (Fisher et al., 2007; Kuschel et al., 2012, 2022). We measured population density from birth to age 40 years using census data from years 1976 to 2018. We calculated population density by the number of privately occupied dwellings divided by the area of the geographical units. We further divided the calculated results into time-specific quartiles with quartile one being the least populated areas and quartile 4 being the most populated areas. We finally calculated the average population density from birth to age 16 years to provide an overall measure of the population density where the cohort members lived in childhood. All joins between area-level data and CHDS data followed the closest in time principle (see online Supplementary Material Section 2 for more details on the temporal alignment of area-level data with CHDS data). We calculated further details on these area-level covariates in online Supplementary Material Section 3. The directed acyclic graphs were used to visualise possible pathways for confounders (Textor et al., 2011) (online Supplementary Material Fig. S5 and Fig. S6).

2.5. Statistical analysis

2.5.1. Descriptive analysis

We computed mean (standard deviation (SD)) of greenspace availability from birth to age 16 years and from age 18 to 40 years, stratified by cohort members' characteristics and mental health conditions. We treated all characteristics and mental health conditions as categorical variables in descriptive analysis. We kept greenspace availability as original format in descriptive analysis, while standardised it to Z scores in formal statistical analyses.

2.5.2. Examining associations between childhood greenspace availability and adolescent mental health conditions

We employed Bayesian Relevant Lifecourse Exposure Model (BRLEM) to examine the associations between childhood greenspace availability and adolescent mental health conditions. The detailed methodology of BRLEM has been documented elsewhere (Madathil et al., 2018). This model examines the lifecourse effects of greenspace availability, measured across childhood, on mental health conditions in adolescence. The model also examines potential lifecourse hypotheses in the tested associations. Specifically, the BRLEM estimates relative weights for greenspace availability at different age stages in childhood using a Bayesian approach conditioned on a non-informative prior for weights and a weekly informative prior for lifecourse effect of the greenspace availability (Madathil et al., 2018). These relative weights represent the relative importance of greenspace availability at different ages for the presence of mental health conditions at age 16 years. We divided childhood (0–16 years) into six age periods, each with three waves of data. We standardised greenspace availability at each wave to time-specific Z scores and averaged non-missing values within each period to obtain a time-variant measure of mean greenspace availability across the six age periods. We tested 13 lifecourse hypotheses including: one accumulation (expected weights are 1/6 for all periods) hypothesis, six critical period hypotheses (one of the six expected weights are 1 and the other five are 0), and six sensitive periods hypotheses (one of the six expected weights are 0.7 and the other five are 0.06) (Armstrong et al., 2021; Kartiosuo et al., 2024; Madathil et al., 2018). We then calculated the differences between the distribution of the estimated weights and the expected weights under different lifecourse hypotheses using Euclidean distance (Madathil et al., 2018). The shortest distance identified the lifecourse hypothesis or a combination of different lifecourse hypotheses most supported by the data. We assessed model convergence using trace plots and Rhat values. We performed the modelling using "rstan' package version 2.32.6 (Stan Development Team, 2024) with R language version 4.2.2 (R Core Team, 2013). We adjusted the models by childhood covariates (see Supplementary Material Section 3 for covariate details). Further explanation of the BRLEM, along with relevant R code, can be found in online Supplementary Material Section 4.

2.5.3. Examining associations between greenspace availability and mental health in adulthood

We examined population-averaged associations between greenspace availability and mental health conditions in adulthood using a Generalised Estimating Equation (GEE) logistic regression modelling framework. We standardised greenspace availability at each wave to time-specific Z scores. We modelled mental health conditions (depressive symptoms, anxiety disorders, and suicidal ideation) at ages 18, 21, 25, 30, 35 and 40 years for the intervals 16–18, 18–21, 21–25, 25–30, 30–35, and 35–40 years as a function of each greenspace availability measure using the six waves of repeated-measures data simultaneously. We applied an unstructured correlation matrix to handle within-subject correlations over the six waves of repeated measures. We adjusted the models using both childhood and adulthood potential covariates (see Supplementary Material Section 3 for covariate details). All included childhood covariates were time-invariant, whereas adulthood covariates were time-variant in the model. We conducted all analyses using STATA 18. A significance level of $\alpha = 0.05$ was set to assess statistical significance.

2.5.4. Sample size and sample bias

The flowcharts of sample selection in the BRLEM and GEE models are provided in the Supplementary Material Section 5. The sample included in the BRLEM model consists of those with mental health conditions measured at age 16, all greenspace availability measures across six age periods from birth to age 16 years, all childhood covariates available (see Fig. S7). Therefore, the sample size in the BRLEM model was n = 929, representing 74.4% of the cohort members who survived to 16 (n = 1,248). To assess potential selection bias in this analysis, we compared the analysis sample in the BRLEM model with the surviving cohort members assessed at age 16 in terms of childhood characteristics. Online Supplementary Material Section 6 Table S4 indicates that the analysis sample in the BRLEM experienced more residential moves, had lower percentage of parental maladaptive behaviour, and had more experiences living in the most deprived areas during childhood, but there were no significant differences in other characteristics compared to the surviving members of the cohort assessed at age 16.

The sample included in the GEE model comprises those with at least one mental health condition measured from age 18 to 40 years, at least one greenspace availability measured during this period, and at least one measure available for each covariate during this period (see Fig. S8). The sample size in GEE model was n = 1,003 after adjustment, representing 82.1% of the cohort members surviving to 40 years (n = 1,221). Similarly, we compared the GEE model analysis sample with the surviving members of the cohort assessed at age 40 in terms of their childhood characteristics to examine potential selection bias. Online Supplementary Material Section 6 Table S5 shows that the GEE sample had a lower percentage of parental maladaptive behaviour than the surviving members at age 40, while no statistically significant differences were found across other childhood characteristics.

2.5.5. Sensitivity analysis

To address potential arbitrariness in the six-age-period division used in the BRLEM for the main analysis, we conducted a sensitivity analysis with a three-age-period division to examine associations between childhood greenspace availability within 1000 m and adolescent mental health outcomes. We divided childhood (0–16 years) into three age periods (0–4, 5–10, 11–16) and averaged greenspace availability within each period to obtain mean values. We tested seven lifecourse hypotheses including: one accumulation (expected weights are 1/3 for all periods) hypothesis, three critical period hypotheses (one of the three expected weights are 1 and the other two are 0), and three sensitive periods hypotheses (one of the three expected weights are 0.7 and the other two are 0.15). We kept all other BRLEM settings consistent with the main analysis. In addition, to increase the statistical power of the main analysis, we created an overall mental health measure by summing the depressive symptoms, anxiety disorders, and suicidal ideation variables. We then repeated the BRLEM to examine associations between childhood greenspace availability and overall mental health in adolescence. Additionally, we used a GEE negative binomial regression framework to test associations between greenspace availability and overall mental health in adulthood.

3. Results

3.1. Descriptive analysis

We calculated the mean (SD) of greenspace availability in childhood (from birth to age 16 years) and adulthood (from age 18 to 40 years) and then stratified them by CHDS childhood characteristics and mental health conditions (see online Supplementary Material Section 7). Overall, the average residential greenspace availability for all CHDS cohort members in childhood was 23.3% (SD = 24.1%) within 100m, 31.8% (22.7%) within 300m, 36.6% (21.8%) within 500m, 44.0% (21.1%) within 1000m, 48.6% (20.8%) within 1500m, 51.7% (20.4%) within 2000m, 56.1% (19.5%) within 3000m. Notably, cohort members with below-average greenspace availability in childhood tended to be of Māori ethnicity, from a single-parent family, low family living standards, reside in densely populated areas, and exposed to moderate levels of air pollution. In adulthood, the overall average residential greenspace availability for all CHDS cohort members was 22.4% (21.0%) within 100m, 29.4% (20.2%) within 300m, 33.6% (19.8%) within 50 m, 40% (19.5%) within 1000m, 44.0% (19.5%) within 1500m, 46.9% (19.5%) within 2000m, 51.2% (19.4%) within 3000m. Fig. 1 highlights an example of the greenspace data from 1985 to 2015 in the city centre of Christchurch, NZ where the CHDS cohort members were born.

3.2. Associations between childhood greenspace availability and adolescent mental health conditions

We used BRLEM models to examine the associations between greenspace availability in childhood from birth to age 16 and three mental health conditions in adolescence at age 16 years. We provided Trace plots and Rhat plots for unadjusted and adjusted models in online Supplementary Materials Section 8 to indicate that all models converged at the end of iterations. We also provided the Euclidean distance plots for testing the 13 lifecourse hypotheses in online Supplementary Materials Section 10. Table 1 presents results from unadjusted and adjusted models examining associations between childhood greenspace availability within a 1000m buffer and adolescent mental health outcomes. The results are reported using odds ratio (OR) and confidence interval (CI). In unadjusted models, higher greenspace availability in childhood was associated with a higher risk of depressive symptoms (OR [95 % CI] = 1.01 [0.79, 1.27]) and anxiety disorders (OR = 1.13 [0.92, 1.38]) but a lower risk of suicidal ideation (OR = 0.86 [0.68, 1.06]) at age 16 years. However, none of these associations were statistically significant, and the CIs were relatively wide. After adjusting for a range of individual, family, and area-level covariates, higher greenspace availability in childhood were associated with increased risks of depressive symptoms (OR = 1.04 [0.70, 1.48]), anxiety disorders (OR = 1.25 [0.90, 1.7]), and suicidal ideation (OR = 1.08 [0.77, 1.49]) in adolescence. Nevertheless, the CIs in the adjusted models were even wider, and the associations remained statistically nonsignificant. In addition, the 95% CIs of the relative importance of all six age stages were very broad, indicating a potential lack of statistical power to identify the best lifecourse hypothesis in this study sample. We provided results for buffer areas of 100m, 300m, 500m, 1500m, 2000m, and 3000m in online Supplementary Materials Section 9. Overall, the associations observed across these buffer sizes were consistent with those for the 1000m buffer in both magnitude and significance of effect sizes.

3.3. Associations between greenspace availability in adulthood and mental health in adulthood

We examined the associations between greenspace availability in adulthood from age 18 to age 40 and three mental health conditions from age 18 to age 40 using population averaged models. Table 2 shows the unadjusted and adjusted results for greenspace availability measured under various buffer sizes from 100m to 3000m. Before

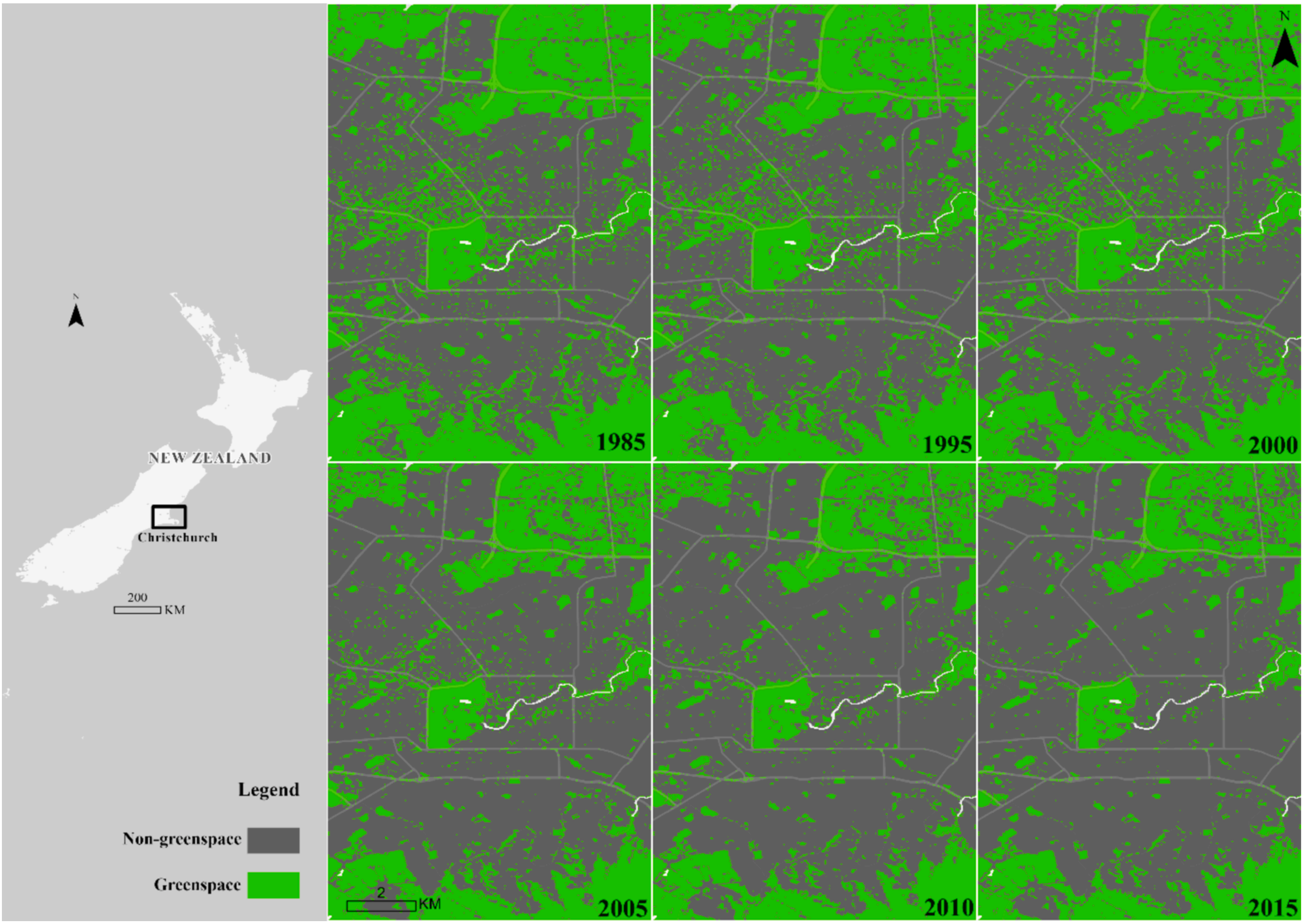

Fig. 1. Greenspace and non-greenspace classification from 1985 to 2015 derived from Global 30m Impervious-Surface Dynamic Dataset and the LCDB dataset (the panels illustrate examples from the city centre of Christchurch, New Zealand from 1985 to 2015, where the cohort members of the CHDS were born).

adjustment, an increase of one SD in greenspace availability within buffer areas of 500m, 1000m, 1500m, 2000m, 3000m was associated with 8% (OR = 0.92[0.86, 0.99]), 10% (OR = 0.90 [0.84, 0.97]), 11% (OR = 0.89 [0.82, 0.95]), 11% (OR = 0.89 [0.82, 0.95]), and 10% (OR = 0.90 [0.84, 0.97]) reduced risk of depressive symptoms in adulthood, respectively. After adjustment for individual, family, and area-level covariates, the associations at 500m, 1000m, and 3000m were fully attenuated, although they remained in the same direction as the unadjusted associations. In contrast, the associations at 1500m and 2000m remained statistically significant, with slightly wider CIs than in the unadjusted models. Specifically, a one SD increase in greenspace availability within 1500m and 2000m buffer areas was associated with 12% (OR = 0.88[0.77, 1.00]) and 13% (OR = 0.87[0.76, 0.99]) reduced risk of depressive symptoms in adulthood, respectively. Although these associations were significant, it should be noted that the upper limits of the 95% CIs are close to 1.00. For anxiety disorders, a one SD increase in greenspace availability was associated with a reduced risk across all buffer areas in adulthood, although none of these associations were statistically significant. The strongest effect was observed at the 500m buffer (OR = 0.95 [0.88, 1.03]), and the weakest effect was at the 100m buffer (OR = 0.97 [0.90, 1.05]). After adjusting for covariates, the associations remained in the same direction as the unadjusted associations but with slightly wider CIs, and they continued to be statistically insignificant. For suicidal ideation, a one SD increase in greenspace availability within buffer areas from 500m (OR = 0.98 [0.89, 1.09]) to 3000m (OR = 0.96 [0.86, 1.06]) was associated with a lower risk in adulthood in the unadjusted models. However, greenspace availability within 100m and 300m buffer areas did not show similar associations. After adjusting for covariates, the direction of the associations for 100m to 500m buffer areas reversed, suggesting that higher greenspace availability was associated with a higher risk of suicidal ideation, although these associations were not statistically significant. For buffer areas of 1000m to 3000m, the adjusted associations remained in the same direction as in the unadjusted models, with the largest effect size observed at the 1500m buffer (OR = 0.92 [0.77, 1.10]) after adjustment.

3.4. Sensitivity analyses

In the sensitivity analyses, increased greenspace availability in childhood was associated with elevated risks of depressive symptoms (1.08 [0.74, 1.53]), anxiety disorders (1.24 [0.89, 1.71]), and suicidal ideation (1.02 [0.72, 1.39]) in adolescence using three age periods (birth–4, 5–10, 11–16), although these associations had wide CIs and were not statistically significant (online Supplementary Materials Section 11). The associations between increased childhood greenspace availability and increased risks of overall mental health conditions in adolescence were observed across all buffer sizes, though these associations were non-significant and had wide CIs (online Supplementary Materials Section 12 Table S20-S26). In addition, before adjustment, associations between increased greenspace availability and decreased risks of overall mental health conditions in adulthood were observed across all buffer sizes, with significant associations at 1000m, 1500m, 2000m, and 3000m. However, these associations were all fully attenuated after adjustment (online Supplementary Materials Section 12

Table 1
Unadjusted and adjusted associations between childhood greenspace availability within circular buffer areas of 1000m and adolescent mental health outcomes, examined using Bayesian Relevant Lifecourse exposure logistic models.

	Depressive symptoms	Anxiety disorders	Suicidal ideation
Unadjusted			
Lifecourse effect	1.01 [0.79, 1.27]	1.13 [0.92, 1.38]	0.86 [0.68, 1.06]
Relative importance			
Birth–Age 1	17.05 % [0.63 %, 50.93 %]	16.33 % [0.53 %, 49.18 %]	13.95 % [0.31 %, 46.29 %]
Age 2–Age 4	16.65 % [0.51 %, 54.48 %]	17.64 % [0.50 %, 52.97 %]	17.50 % [0.56 %, 53.54 %]
Age 5–Age 7	16.24 % [0.39 %, 50.77 %]	17.08 % [0.44 %, 52.20 %]	16.19 % [0.43 %, 49.78 %]
Age 8–Age 10	16.31 % [0.45 %, 51.51 %]	17.48 % [0.56 %, 52.95 %]	16.92 % [0.54 %, 51.43 %]
Age 11–Age 13	16.77 % [0.50 %, 53.10 %]	15.42 % [0.58 %, 48.49 %]	16.95 % [0.54 %, 53.29 %]
Age 14–Age 16	16.97 % [0.61 %, 54.14 %]	16.05 % [0.53 %, 50.20 %]	18.50 % [0.59 %, 54.23 %]
Adjusted			
Lifecourse effect	1.04 [0.70, 1.48]	1.25 [0.90, 1.7]	1.08 [0.77, 1.49]
Relative importance			
Birth–Age 1	17.24 % [0.63 %, 52.19 %]	15.45 % [0.50 %, 48.34 %]	17.31 % [0.42 %, 53.16 %]
Age 2–Age 4	16.57 % [0.49 %, 49.71 %]	18.16 % [0.66 %, 54.51 %]	16.71 % [0.57 %, 51.09 %]
Age 5–Age 7	16.65 % [0.44 %, 50.74 %]	16.66 % [0.53 %, 51.17 %]	16.62 % [0.55 %, 52.47 %]
Age 8–Age 10	16.19 % [0.58 %, 50.83 %]	16.53 % [0.52 %, 51.62 %]	16.74 % [0.57 %, 52.84 %]
Age 11–Age 13	16.55 % [0.59 %, 50.84 %]	16.03 % [0.47 %, 47.94 %]	16.31 % [0.47 %, 51.10 %]
Age 14–Age 16	16.80 % [0.50 %, 52.29 %]	17.17 % [0.51 %, 50.95 %]	16.31 % [0.53 %, 52.07 %]

Note: Results are presented as Odds Ratio [95% Confidence Interval] for lifecourse effect and Mean [95% Confidence Interval] for relative importance.
The adjusted models are adjusted by sex, ethnicity, maternal age, maternal education, father's occupational status, family composition, parental relationship stability, family living standards, residential moves in childhood, parental mental health history, parental maladaptive behaviour, area-level SES, air pollution, and population density.

Table S27).

4. Discussion

This study used prospectively collected birth cohort data to investigate the associations between greenspace availability and mental health conditions which included depressive symptoms, anxiety disorders, and suicidal ideation. Specifically, this study examined the associations between greenspace availability in childhood (from birth to age 16 years) and mental health in adolescence (at age 16 years); and then examined the associations between greenspace availability and mental health in adulthood (from age 18 to 40 years). This study generated two key results. First, the associations between greenspace availability in childhood and mental health conditions in adolescence, as well as the lifecourse hypothesis supported, remain inconclusive due to the wide CIs of these associations. Second, the associations between greenspace availability and mental health conditions in adulthood are mixed, varying by buffer size and the type of mental health condition. Specifically, greenspace availability shows a protective effect for depressive symptoms in adulthood, with a one SD increase within 1500m and 2000m buffers associated with a 12% and 13% reduction in risk, respectively. However, this protective effect was not statistically significant for other buffer sizes and was not observed for anxiety disorders or suicidal ideation. By employing a spatial lifecourse epidemiology framework, the findings from this study may be useful to inform policies that aim to create a more health-promoting environment for mental health especially depressive symptoms in adulthood.

Table 2
Associations between greenspace availability and mental health outcomes in adulthood from age 18 to 40.

	Depressive symptoms	Anxiety disorders	Suicidal ideation
Unadjusted			
100 m	0.94 [0.87, 1.01]	0.97 [0.90, 1.05]	1.00 [0.91, 1.10]
300 m	0.93 [0.87, 1.00]	0.96 [0.89, 1.04]	1.00 [0.90, 1.10]
500 m	**0.92 [0.86, 0.99]** *	0.95 [0.88, 1.03]	0.98 [0.89, 1.09]
1000 m	**0.90 [0.84, 0.97]** **	0.96 [0.88, 1.04]	0.94 [0.85, 1.05]
1500 m	**0.89 [0.82, 0.95]** ***	0.95 [0.88, 1.03]	0.93 [0.84, 1.03]
2000 m	**0.89 [0.82, 0.95]** ***	0.96 [0.88, 1.04]	0.94 [0.84, 1.04]
3000 m	**0.90 [0.84, 0.97]** **	0.96 [0.89, 1.05]	0.96 [0.86, 1.06]
Adjusted			
100 m	0.98 [0.89, 1.09]	0.98 [0.88, 1.10]	1.02 [0.88, 1.16]
300 m	0.98 [0.88, 1.10]	0.95 [0.85, 1.07]	1.06 [0.91, 1.23]
500 m	0.98 [0.87, 1.10]	0.94 [0.82, 1.06]	1.05 [0.89, 1.24]
1000 m	0.92 [0.81, 1.05]	0.95 [0.82, 1.09]	0.95 [0.79, 1.14]
1500 m	**0.88 [0.77, 1.00]** *	0.95 [0.82, 1.10]	0.92 [0.77, 1.10]
2000 m	**0.87 [0.76, 0.99]** *	0.94 [0.82, 1.09]	0.93 [0.78, 1.12]
3000 m	0.89 [0.78, 1.02]	0.93 [0.81, 1.07]	0.96 [0.81, 1.14]

Note: Results are presented as Relative Risk Ratio [95% Confidence Interval].
* denotes p <= 0.05, ** denotes p <= 0.01, *** denotes p <= 0.001.
The models were adjusted by sex, ethnicity, maternal age, parental relationship stability, parental mental health history, highest educational attainment, whether live with partner, number of dependent children, welfare dependency, residential moves, tobacco use disorder, alcohol use disorder, illicit drug use disorders, area-level SES, air pollution (PM_{10}), and population density.

This study found that increased greenspace availability within 1500m to 2000m is significantly associated with a reduced risk of depressive symptoms in adulthood, after adjusting for individual, family, and area-level covariates from childhood and adulthood. It is important to note that these associations are tentative, as the 95% CIs are relatively wide, and the upper limit of the CIs is very close to the borderline. Despite this, these findings are consistent with the results from two *meta*-analysis studies on greenspace and mental health (Liu et al., 2023; Zhang et al., 2024), and longitudinal studies with adult participants (Alcock et al., 2014; Gonzales-Inca et al., 2022; Hystad et al., 2019). According to nature-based resilience theory, these beneficial effects of greenspace may be attributed to enhanced biological, psychological, and social resilience resources (White et al., 2023). In addition, this study found that the associations between greenspace availability and depressive symptoms in adulthood are sensitive to buffer size, with significant associations observed within buffer sizes of 1500m to 2000m. Some studies have found significant associations between greenspace and mental health at 3000m but not at 1000m (Bos et al., 2016), while others have identified significant associations at buffer sizes ranging from 100m to 500m without examining larger buffers (Dadvand et al., 2016; Gonzales-Inca et al., 2022). Different buffer sizes may correspond to different hypotheses. Smaller buffer sizes (under 1000m) often represent the immediate environment where greenspace may benefit mental health through psychological stress recovery. Larger, but not too large, buffer sizes (1500m to 2000m) typically represent the neighbourhood environment where individuals can access greenspace and engage in mental health-promoting activities such as physical and social activities (Markevych et al., 2017). Indeed, another systematic review study revealed that greenspace showed larger benefits for physical health at larger buffer sizes between 1000m and 2000m compared to smaller buffer sizes (Browning & Lee, 2017). Thus, the finding that greenspace within the 1500m to 2000m range significantly reduced depressive symptoms may suggest that the benefits provided by greenspace are more likely attributable to their capacity to encourage health-promoting behaviours such as physical activities. However, the 95% CI of the associations are close to the borderline, further research with larger sample size is needed to confirm this.

The present study did not find any significant associations between greenspace availability and anxiety disorders or suicidal ideation in adulthood. The findings regarding anxiety disorders align with a recent *meta*-analysis, which did not find significant associations between greenspace availability and anxiety, except in studies with very small sample sizes (Liu et al., 2023). However, other studies have reported significant associations in some specific adult populations including Australian women living in urban areas (Mouly et al., 2023) and individuals experiencing COVID-19 pandemic lockdowns (Pouso et al., 2021). Additionally, two nationwide cross-sectional studies in the Netherlands (Klompmaker et al., 2019; Maas et al., 2009) and at the city level in Auckland, NZ (Nutsford et al., 2013) also reported significant associations between greenspace availability and anxiety disorders. Another recent *meta*-analysis on greenspace and a range of psychiatric disorders found that all significant associations between greenspace and anxiety were revealed in studies using NDVI as the measure of greenspace (Zhang et al., 2024), which may explain the lack of associations between greenspace and anxiety disorders in the present study, even before adjusting for covariates. Regarding suicidal ideation, two ecological cross-sectional studies in England found no associations between greenspace availability or coverage and suicide rates among adults (Bixby et al., 2015; Mitchell & Popham, 2008), while two other ecological cross-sectional studies in the Netherlands (Helbich et al., 2018) and Japan (Jiang et al., 2021) reported the opposite findings. The underlying mechanisms linking greenspace availability to anxiety/suicidal ideation and depression may be different (Scheid & Wright, 2017). Given the limited evidence regarding the associations between greenspace availability, anxiety disorders, and suicidal ideation, particularly from longitudinal studies at the individual level, it is challenging to compare the findings of the present study with those of other studies. Future research with longitudinal designs at the individual level is needed to confirm the findings of the current study.

This study did not find any associations between childhood greenspace availability (from birth to age 16) and adolescent mental health (at age 16). This finding aligns with another longitudinal study involving similar age groups (Hartley et al., 2021) and is also consistent with another NZ study investigating maternal exposure to greenspace and its relationship with antenatal depression (Nichani et al., 2017). NZ is a country with a high amount of greenspace, as we found in descriptive analysis that cohort members had over 40 % of areas within 1000m to 3000m buffers covered by greenspace over the lifecourse, thus may lack variation in exposure relative to other countries internationally (Richardson et al., 2010). In contrast, a large-scale national study in Denmark, comprising more than 900,000 people, found that childhood residential greenspace measured by NDVI from birth to age 10 was protective against a range of psychiatric disorders in adolescence (age 13–19) (Engemann et al., 2019). Additionally, a prospective study found associations between cumulative greenspace availability, measured by average NDVI up to age 17, and depressive symptoms in adolescence and early adulthood (Bezold et al., 2018). As discussed above, studies using NDVI as the measures of greenspace are more likely to report significant results (Liu et al., 2023; Zhang et al., 2024). Compared to the binary measure of greenspace used in this study, NDVI may provide more detailed information on vegetation density and health, with higher values indicating denser and healthier vegetation. Due to the long period of follow-up, time-series and high-quality NDVI data across the whole NZ from late 1970's to 2010's are not possible. Despite the coarser greenspace measures, this study provides valuable insights into the temporal aspects of the associations between greenspace and mental health. In addition, it was unexpected to find that the associations between childhood greenspace and adolescent mental health conditions were positive in direction, although insignificant. This could be due to the small sample size and potential sample bias in this analysis, or to residual confounding factors (Grimes & Schulz, 2002). Furthermore, this study tested three types of lifecourse hypotheses, but the wide CIs in childhood for the relative importance of each age period provided little information to identify which hypothesis is supported by the data. Future research with refined greenspace measures is needed to better understand the associations between greenspace availability in childhood and adolescent mental health and to explore potential lifecourse hypotheses.

Perceptions, preferences, and use of greenspace may vary by age. Evidence suggests that adults tend to prefer forested areas, while children prefer greenspaces with recreational infrastructure (Arnberger et al., 2024; Müderrisoğlu & Gültekin, 2015). These recreational infrastructure features were not captured in our greenspace measure, potentially contributing to the null associations observed. In addition, older people tend to engage in more greenspace-related activities than younger people (Ode Sang et al., 2016). Children were less likely to visit greenspace to recover, relieve stress, or increase their ability to concentrate compared to the older age groups (Arnberger et al., 2024). These differences in greenspace perceptions, preferences, and usage by age groups may partly explain why significant associations were observed for greenspace in adulthood but not for adolescent mental health, underscoring the importance of considering such variations in future research.

This study has several notable strengths which improve the state of current scientific thought. First, and most importantly, this study applied a prospective birth cohort study design that reconstructed individuals' residential greenspace availability at address-level from birth to age 40 years, thus ensuring a clearer temporal relationship between exposure and outcome than is possible with a cross-sectional study design. By using a lifecourse perspective, this study also captures developmental changes and life transitions, providing insights into how early life greenspace availability impacts mental health across different stages of life. This study employed the novel BRLEM to test lifecourse hypotheses in the relationship between greenspace availability and mental health, though the statistical power was not enough. Second, the measure of greenspace availability considered individuals' relocation and the evolution of greenspace to minimise the misclassification of exposure (Hodgson et al., 2015). Third, greenspace availability within different sizes of buffer areas were measured, providing insights into the sensitivity of buffer sizes in the relationship between greenspace availability and mental health. Four, incorporating multiple mental health conditions into analysis can extend our understanding of how greenspace can impact different mental health conditions, some of which were rarely examined longitudinal studies in the literature (Mouly et al., 2023). Five, the novelty of using GISD30 as a proxy for greenspace and conducting a case study to validate its use as a proxy for greenspace in NZ provides potential ideas for future studies using data other than NDVI and land use as measures of greenspace. Six, we used a range of individual, family, and area-level covariates to adjust the associations between greenspace and mental health, some of which were rarely included in the literature such as parental mental health history. Accounting for these confounders is crucial for understanding the lifecourse impacts (Deng, McLeod, et al., 2024; Desjardins et al., 2023; Li et al., 2021).

Several limitations should be considered when interpreting the findings of this study. First, we only considered greenspace availability at residential locations, while individuals also spend time outside homes such as schools and workplaces (Campbell et al., 2021). Osa et al. (2024) found no significant longitudinal associations between residential greenspace exposure and anxiety, but significant associations were observed with greenspace at school. Second, the GISD30 product has different accuracy around the world (Zheng et al., 2023). This study only examined the quality of GISD30 for estimating greenspace in 2000, based on the assumption that GISD30 is a product of consistent quality over time. Third, our estimates of greenspace did not account for its quality, visits to greenspace, types, accessibility, and visibility of greenspace, which might be important factors in understanding the associations between greenspace and mental health (Houlden et al., 2018; Liu et al., 2023; Vanaken & Danckaerts, 2018; Vilcins et al., 2024; Wendelboe-Nelson et al., 2019; Zhang et al., 2021). For instance, our greenspace estimates treated all greenspace uniformly, without distinguishing between agricultural and urban greenspaces. In addition, different people may have different psychological response on greenspace, though most people feel pleasant and excited about greenspace, there are still some people who feel stressed in greenspace (Zhang, Amegbor, et al., 2022). Some studies found that associations with mental health were stronger for self-reported greenspace compared to objectively measured greenspace (Dzhambov, Hartig, et al., 2018; Dzhambov, Markevych, et al., 2018), indicating that objective measurements may not fully capture individuals' actual greenspace experiences. Fourth, the observed associations between greenspace availability and mental health may be influenced by selective migration. It is a longstanding debate in the field of health geography over whether healthier individuals are more likely to relocate to areas with better characteristics, such as higher greenspace coverage (Norman et al., 2005). However, this issue warrants exploration in future studies with a larger sample size, especially given NZ's highly mobile population (Marek et al., 2023). Fifth, we did not explore the associations between childhood greenspace availability and child mental health because we did not have mental health conditions measured in childhood. We also did not examine the associations between childhood greenspace availability and adult mental health because large sample attrition in adulthood would introduce selection bias in such investigations. In addition, we also did not examine whether move to greener areas or less greener areas has influence on later-life mental health (Belcher et al., 2024). However, these research questions are valuable to explore in future research. Additionally, while previous research has documented moderation effects by sex and SES (Astell-Burt et al., 2014; McEachan et al., 2016), our study did not investigate these due to limited statistical power. Exploring these effects in future research with larger samples would be valuable. Sixth, the cohort members in this study were born in the 1970 s, which may limit the generalisability of our findings to younger generations raised in an increasingly urbanised environment (Marek et al., 2020). Seventh, Although the expected weights assigned to the sensitive period hypotheses are based on available evidence and theoretical considerations, they are somewhat arbitrary and subjective. Last, the observational nature of this study design precludes making causal inferences about the relationship between greenspace availability and mental health.

Using a lifecourse perspective, this study may have important implications for policy aimed at age-specific interventions for adult depressive symptoms in NZ. Recently, a 3–30-300 greenspace rule was proposed in Spain, suggesting that every individual should see at least three trees from their home, have 30% tree canopy cover in their neighbourhood, and live no more than 300m from the nearest park or greenspace (Konijnendijk, 2023). However, our empirical study suggests that NZ adults might benefit from a larger range of greenspace availability from 1500m to 2000m. Additionally, acknowledging the wide CIs, we found that the effect estimates between greenspace availability within this range and depressive symptoms is comparable in magnitude to that of parental history of mental health problems, about half as strong as living with a partner or tobacco use, and about twice as strong as maternal age at birth. Further research is needed, but these findings suggest that increasing greenspace availability for adults in NZ could be an effective measure for mitigating depressive symptoms, as even a small effect estimate at the population level could have significant impacts, especially if a large portion of the population is exposed to the determinant in question (Ahern et al., 2008; McLaren, 2019; Rose, 1985; Wagner et al., 2024).

5. Conclusion

Using prospectively collected birth cohort data, this study examined the associations between greenspace availability and mental health conditions over the lifecourse. The findings suggest that increased greenspace availability may be associated with reduced risks of depressive symptoms in adulthood (ages 18–40), even after accounting for individual, family, and area-level covariates. These results align with previous evidence suggesting potential protective effects of greenspace on depressive symptoms. This study highlights the significance of employing a spatial lifecourse epidemiology framework to examine the long-term effects of environmental factors on health throughout an individual's life.

CRediT authorship contribution statement

B. Deng: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **J. Boden:** Writing – review & editing, Supervision, Methodology, Conceptualization. **N. Ye:** Writing – review & editing, Methodology, Conceptualization. **J. Morgenroth:** Writing – review & editing, Supervision, Methodology, Conceptualization. **M. Campbell:** Writing – review & editing, Supervision, Methodology, Conceptualization. **P. Eggleton:** Writing – review & editing, Investigation, Data curation. **G. McLeod:** Supervision, Methodology, Conceptualization. **M. Hobbs:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Acknowledgement

This project was part funded by a New Zealand Health Research Council Emerging Researcher First Grant (22/528). The CHDS age 40 assessment was supported by a Health Research Council of New Zealand Programme Grant [16/600]. Previous work has been supported by the National Child Health Research Foundation (Cure Kids), the Canterbury Medical Research Foundation and the New Zealand Lottery Grants Board. The first author is funded by the Accelerator PhD scholarship from the University of Canterbury. The publication process was supported by the Open Access funding and the Faculty of Health from the University of Canterbury. We also thank Professor Elena Moltchanova, University of Canterbury, for her expert advice on statistical analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.109223.

Data availability

The Christchurch Health and Development Study data are not freely available as we do not currently have ethical approval to upload these data to any repository and this prevents us from sharing this data in this way. However, data are available on request, subject to approval by the CHDS Director: chds.uoc@otago.ac.nz.

References

Abraham Cottagiri, S., Villeneuve, P.J., Raina, P., Griffith, L.E., Rainham, D., Dales, R., Peters, C.E., Ross, N.A., Crouse, D.L., 2022. Increased urban greenness associated with improved mental health among middle-aged and older adults of the Canadian Longitudinal Study on Aging (CLSA), 112587 *Environ. Res.* 206. https://doi.org/10.1016/j.envres.2021.112587.

Ahern, J., Jones, M.R., Bakshis, E., Galea, S., 2008. Revisiting Rose: Comparing the benefits and costs of population-wide and targeted interventions. *Milbank Q.* 86 (4), 581–600. https://doi.org/10.1111/j.1468-0009.2008.00535.x.

Alcock, I., White, M.P., Wheeler, B.W., Fleming, L.E., Depledge, M.H., 2014. Longitudinal effects on mental health of moving to greener and less green urban areas. *Environ. Sci. Tech.* 48 (2), 1247–1255. https://doi.org/10.1021/es403688w.

Alcock, I., White, M.P., Lovell, R., Higgins, S.L., Osborne, N.J., Husk, K., Wheeler, B.W., 2015. What accounts for 'England's green and pleasant land'? A panel data analysis of mental health and land cover types in rural England. *Landsc. Urban Plan.* 142, 38–46. https://doi.org/10.1016/j.landurbplan.2015.05.008.

Allen, J., Balfour, R., Bell, R., Marmot, M., 2014. Social determinants of mental health. *Int. Rev. Psychiatry* 26 (4), 392–407. https://doi.org/10.3109/09540261.2014.928270.

American Psychiatric Association. (1987). *Diagnostic and statistical manual of mental disorders: DSM-III-R.* (Third edition, revised.). American Psychiatric Association.

American Psychiatric Association. (1994). Diagnostic and statistical manual of mental disorders: DSM-IV (4th ed.). American Psychiatric Association Washington, DC.

Armstrong, M.K., Fraser, B.J., Hartiala, O., Buscot, M.-J., Juonala, M., Wu, F., Koskinen, J., Hutri-Kähönen, N., Kähönen, M., Laitinen, T.P., Lehtimäki, T., Viikari, J.S.A., Raitakari, O.T., Magnussen, C.G., 2021. Association of Non–High-Density Lipoprotein Cholesterol Measured in Adolescence, Young Adulthood, and Mid-Adulthood With Coronary Artery Calcification Measured in Mid-Adulthood. *JAMA Cardiol.* 6 (6), 661–668. https://doi.org/10.1001/jamacardio.2020.7238.

Arnberger, A., Eder, R., Allex, B., Wallner, P., Weitensfelder, L., Hutter, H.-P., 2024. Urban green space preferences for various health-related psychological benefits of adolescent pupils, university students and adults. *Urban For. Urban Green.* 98, Scopus. https://doi.org/10.1016/j.ufug.2024.128396.

Astell-Burt, T., Feng, X., 2019. Association of urban green space with mental health and general health among adults in Australia. JAMA Netw. Open 2 (7), e198209. https://doi.org/10.1001/jamanetworkopen.2019.8209.

Astell-Burt, T., Mitchell, R., Hartig, T., 2014. The association between green space and mental health varies across the lifecourse. A longitudinal study. J. Epidemiol. Community Health 68 (6), 578–583. https://doi.org/10.1136/jech-2013-203767.

Atkinson, J., Salmond, C., Crampton, P., 2014. NZDep2013 index of deprivation. https://www.otago.ac.nz/wellington/otago069936.pdf.

Atkinson, J., Salmond, C., Crampton, P., 2019. NZDep2018 Index of Deprivation. https://www.otago.ac.nz/wellington/otago730394.pdf.

Bao, W.W., Zhao, Y., Dadvand, P., Jiang, N., Chen, G., Yang, B., Huang, W., Xiao, X., Liang, J., Chen, Y., 2024. Urban greenspace and visual acuity in school children: A large prospective cohort study in China. *Environ. Int.* 184, 108423. https://doi.org/10.1016/j.envint.2024.108423.

Belcher, R.N., Murray, K.A., Reeves, J.P., Fecht, D., 2024. Socioeconomic deprivation modifies green space and mental health associations: A within person study, 109036 *Environ. Int.* 192. https://doi.org/10.1016/j.envint.2024.109036.

Bezold, C.P., Banay, R.F., Coull, B.A., Hart, J.E., James, P., Kubzansky, L.D., Missmer, S. A., Laden, F., 2018. The relationship between surrounding greenness in childhood and adolescence and depressive symptoms in adolescence and early adulthood. *Ann. Epidemiol.* 28 (4), 213–219. https://doi.org/10.1016/j.annepidem.2018.01.009.

Bixby, H., Hodgson, S., Fortunato, L., Hansell, A., Fecht, D., 2015. Associations between green space and health in English cities: An ecological, cross-sectional study. *PLoS One* 10 (3). https://doi.org/10.1371/journal.pone.0119495 e0119495.

Bos, E.H., Van der Meulen, L., Wichers, M., Jeronimus, B.F., 2016. A primrose path? Moderating effects of age and gender in the association between green space and mental health. *Int. J. Environ. Res. Public Health* 13 (5), 492. https://doi.org/10.3390/ijerph13050492.

Bowie, C., Beere, P., Griffin, E., Campbell, M., Kingham, S., 2013. Variation in health and social equity in the spaces where we live: A review of previous literature from the GeoHealth Laboratory. *N. Z. Sociol.* 28 (3), 164–191. https://doi.org/10.3390/ijerph14070675.

Browning, M., Lee, K., 2017. Within what distance does "greenness" best predict physical health? A systematic review of articles with GIS buffer analyses across the lifespan. *Int. J. Environ. Res. Public Health* 14 (7), 675. https://doi.org/10.3390/ijerph14070675.

Buchanan, M., Newton-Howes, G., Cunningham, R., McLeod, G.F.H., Boden, J.M., 2024. The role of social support in reducing the long-term burden of cumulative childhood adversity on adulthood internalising disorder. *Soc. Psychiatry Psychiatr. Epidemiol.* https://doi.org/10.1007/s00127-024-02674-6.

Campbell, M., Marek, L., Hobbs, M., 2021. Reconsidering movement and exposure: Towards a more dynamic health geography. *Geogr. Compass* 15 (6), e12566. https://doi.org/10.1111/gec3.12566.

Dadvand, P., Bartoll, X., Basagaña, X., Dalmau-Bueno, A., Martinez, D., Ambros, A., Cirach, M., Triguero-Mas, M., Gascon, M., Borrell, C., Nieuwenhuijsen, M.J., 2016. Green spaces and General Health: roles of mental health status, social support, and physical activity. *Environ. Int.* 91, 161–167. https://doi.org/10.1016/j.envint.2016.02.029.

de la Osa, N., Navarro, J.-B., Penelo, E., Valentí, A., Ezpeleta, L., Dadvand, P., 2024. Long-term exposure to greenspace and anxiety from preschool and primary school children, 102207 *J. Environ. Psychol.* 93. https://doi.org/10.1016/j.jenvp.2023.102207.

Deng, B., Campbell, M., McLeod, G.F., Boden, J., Marek, L., Sabel, C.E., Norman, P.D., Hobbs, M., 2024. Construction of a consistent historic time-series area-level deprivation metric for Aotearoa New Zealand. Population Review New Zealand. https://population.org.nz/wp-content/uploads/2024/10/NZPR-VOL-50_Deng-et-al_.pdf.

Deng, B., McLeod, G.F., Boden, J., Sabel, C.E., Campbell, M., Eggleton, P., Hobbs, M., 2024. The impact of area-level socioeconomic status in childhood on mental health in adolescence and adulthood: A prospective birth cohort study in Aotearoa New Zealand, 103246 *Health Place* 88. https://doi.org/10.1016/j.healthplace.2024.103246.

Desjardins, M.R., Murray, E.T., Baranyi, G., Hobbs, M., Curtis, S., 2023. Improving longitudinal research in geospatial health: an agenda, 102994 *Health Place* 80. https://doi.org/10.1016/j.healthplace.2023.102994.

Dzhambov, A., Hartig, T., Markevych, I., Tilov, B., Dimitrova, D., 2018. Urban residential greenspace and mental health in youth: different approaches to testing multiple pathways yield different conclusions. *Environ. Res.* 160, 47–59. https://doi.org/10.1016/j.envres.2017.09.015.

Dzhambov, A., Markevych, I., Hartig, T., Tilov, B., Arabadzhiev, Z., Stoyanov, D., Gatseva, P., Dimitrova, D.D., 2018. Multiple pathways link urban green-and bluespace to mental health in young adults. *Environ. Res.* 166, 223–233. https://doi.org/10.1016/j.envres.2018.06.004.

Elder, G.H., Johnson, M.K., Crosnoe, R., 2003. The Emergence and Development of Life Course Theory. In: Mortimer, J.T., Shanahan, M.J. (Eds.), Handbook of the Life Course. Springer US, pp. 3–19. https://doi.org/10.1007/978-0-306-48247-2_1.

Engemann, K., Pedersen, C.B., Arge, L., Tsirogiannis, C., Mortensen, P.B., Svenning, J.C., 2019. Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood. *Proc. Natl. Acad. Sci.* 116 (11), 5188–5193. https://doi.org/10.1073/pnas.1807504116.

Fergusson, D.M, Boden, J.M., Horwood, L.J., 2008. Exposure to childhood sexual and physical abuse and adjustment in early adulthood. Child Abuse Negl. 32 (6), 607–619. https://doi.org/10.1016/j.chiabu.2006.12.018.

Fergusson, D.M., Horwood, J.L., 2001. The Christchurch Health and Development Study: review of findings on child and adolescent mental health. *Aust. N. Z. J. Psychiatry* 35 (3), 287–296. https://doi.org/10.1046/j.1440-1614.2001.00902.x.

Fisher, G., Kjellstrom, T., Kingham, S., Hales, S., Shrestha, R., 2007. Health and air pollution in New Zealand. Special Edition: Pollution in the Urban Environment. 5 (2), 15–20.

Fergusson, D.M., Horwood, L.J., 2013. The Christchurch Experience: 40 Years of Research and Teaching (P. Joyce, G. Nicholls, K. Thomas, & T. Wilkinson, Eds.). University of Otago, Christchurch.

Giele, J., Elder, G., 1998. Methods of Life Course Research: Qualitative and Quantitative Approaches. SAGE Publications. https://doi.org/10.4135/9781483348919.

Gonzales-Inca, C., Pentti, J., Stenholm, S., Suominen, S., Vahtera, J., Käyhkö, N., 2022. Residential greenness and risks of depression: Longitudinal associations with different greenness indicators and spatial scales in a Finnish population cohort, 102760 *Health Place* 74. https://doi.org/10.1016/j.healthplace.2022.102760.

Goward, S., Arvidson, T., Williams, D., Faundeen, J., Irons, J., Franks, S., 2006. Historical record of Landsat global coverage. *Photogramm. Eng. Remote Sens.* 72 (10), 1155–1169. https://doi.org/10.14358/PERS.72.10.1155.

Grimes, D.A., Schulz, K.F., 2002. Bias and causal associations in observational research. *Lancet* 359 (9302), 248–252. https://doi.org/10.1016/S0140-6736(02)07451-2.

Harari-Kremer, R., Calderon-Margalit, R., Broday, D., Kloog, I., Raz, R., 2022. Exposure errors due to inaccurate residential addresses and their impact on epidemiological associations: Evidence from a national neonate dataset, 114032 *Int. J. Hyg. Environ. Health* 246. https://doi.org/10.1016/j.ijheh.2022.114032.

Hartley, K., Perazzo, J., Brokamp, C., Gillespie, G.L., Cecil, K.M., LeMasters, G., Yolton, K., Ryan, P., 2021. Residential surrounding greenness and self-reported symptoms of anxiety and depression in adolescents, 110628 *Environ. Res.* 194. https://doi.org/10.1016/j.envres.2020.110628.

Helbich, M., De Beurs, D., Kwan, M.-P., O'Connor, R.C., Groenewegen, P.P., 2018. Natural environments and suicide mortality in the Netherlands: A cross-sectional, ecological study. *The Lancet Planetary Health* 2 (3), e134–e139. https://doi.org/10.1016/S2542-5196(18)30033-0.

Hobbs, M., Atlas, J., 2019. Environmental influences on behaviour and health: A call for creativity and radical shifts in thinking within contemporary research. N. Z. Med. J. 132, 97–99. https://ir.canterbury.ac.nz/bitstream/10092/17766/3/Hobbs-FINAL.pdf.

Hobbs, M., Ahuriri-Driscoll, A., Kingham, S., Wiki, J., Marek, L., Dionisio, M., Curl, A., Schluter, P., Banwell, K., Mackenbach, J., 2022. A city profile of Ōtautahi Christchurch, 103481 *Cities* 121. https://doi.org/10.1016/j.cities.2021.103481.

Hobbs, M., Marek, L., McLeod, G.F., Woodward, L., Sturman, A., Kingham, S., Ahuriri-Driscoll, A., Epton, M., Deng, B., Campbell, M., Boden, J., 2024. Exploring the feasibility of linking historical air pollution data to the Christchurch Health and Development study: A birth cohort study in Aotearoa, New Zealand. Spatial and Spatio-Temporal Epidemiology. https://doi.org/10.1016/j.sste.2024.100675.

Hodgson, S., Lurz, P.W., Shirley, M.D., Bythell, M., Rankin, J., 2015. Exposure misclassification due to residential mobility during pregnancy. *Int. J. Hyg. Environ. Health* 218 (4), 414–421. https://doi.org/10.1016/j.ijheh.2015.03.007.

Houlden, V., Weich, S., Porto de Albuquerque, J., Jarvis, S., Rees, K., 2018. The relationship between greenspace and the mental wellbeing of adults: a systematic review. *PLoS One* 13 (9), e0203000. https://doi.org/10.1371/journal.pone.0203000.

Hystad, P., Payette, Y., Noisel, N., Boileau, C., 2019. Green space associations with mental health and cognitive function: results from the Quebec CARTaGENE cohort. Environ. Epidemiol. 3 (1). https://doi.org/10.1097/EE9.0000000000000040.

Jarvis, I., Gergel, S., Koehoorn, M., van den Bosch, M., 2020. Greenspace access does not correspond to nature exposure: Measures of urban natural space with implications for health research, 103686 *Landsc. Urban Plan.* 194. https://doi.org/10.1016/j.landurbplan.2019.103686.
Jarvis, I., Davis, Z., Sbihi, H., Brauer, M., Czekajlo, A., Davies, H.W., Gergel, S.E., Guhn, M., Jerrett, M., Koehoorn, M., Oberlander, T.F., Su, J., van den Bosch, M., 2021. Assessing the association between lifetime exposure to greenspace and early childhood development and the mediation effects of air pollution and noise in Canada: a population-based birth cohort study. Lancet Planet. Heath 5 (10), e709–e717. https://doi.org/10.1016/S2542-5196(21)00235-7.
Jia, P., 2019. Spatial lifecourse epidemiology. *The Lancet Planetary Health* 3 (2), e57–e59. https://doi.org/10.1016/S2542-5196(18)30245-6.
Jiang, W., Stickley, A., Ueda, M., 2021. Green space and suicide mortality in Japan: an ecological study, 114137 *Soc Sci Med* 282. https://doi.org/10.1016/j.socscimed.2021.114137.
Kartiosuo, N., Raitakari, O.T., Juonala, M., Viikari, J.S.A., Sinaiko, A.R., Venn, A.J., Jacobs, D.R., Urbina, E.M., Woo, J.G., Steinberger, J., Bazzano, L.A., Daniels, S.R., Magnussen, C.G., Rahimi, K., Dwyer, T., 2024. Cardiovascular risk factors in childhood and adulthood and cardiovascular disease in middle age. *JAMA Netw. Open* 7 (6), e2418148. https://doi.org/10.1001/jamanetworkopen.2024.18148.
Klompmaker, J.O., Hoek, G., Bloemsma, L.D., Wijga, A.H., van den Brink, C., Brunekreef, B., Lebret, E., Gehring, U., Janssen, N.A., 2019. Associations of combined exposures to surrounding green, air pollution and traffic noise on mental health. *Environ. Int.* 129, 525–537. https://doi.org/10.1016/j.envint.2019.05.040.
Konijnendijk, C.C., 2023. Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule. *J. For. Res.* 34 (3), 821–830. https://doi.org/10.1007/s11676-022-01523-z.
Kuschel, G., Metcalfe, J., Wilton, E., Guria, J., Hales, S., Rolfe, K., Woodward, A., 2012. Updated Health and air pollution in New Zealand study. https://environment.govt.nz/publications/updated-health-and-air-pollution-in-new-zealand-study-2012-summary-report/.
Kuschel, G., Metcalf, J., Berentson-Shaw, J., Hales, S., Atkinson, J., Woodward, A., 2022. Health and air pollution in New Zealand 2016 (HAPINZ 3.0): Volume 1–Finding and implications. https://environment.govt.nz/publications/health-and-air-pollution-in-new-zealand-2016-findings-and-implications/.
Landcare Research, 2018. LCDB v5.0—Land Cover Database Version 5.0. https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/.
Li, D., Menotti, T., Ding, Y., Wells, N.M., 2021. Life course nature exposure and mental health outcomes: a systematic review and future directions. *Int. J. Environ. Res. Public Health* 18 (10). https://doi.org/10.3390/ijerph18105146.
Liu, Z., Chen, X., Cui, H., Ma, Y., Gao, N., Li, X., Meng, X., Lin, H., Abudou, H., Guo, L., Liu, Q., 2023. Green space exposure on depression and anxiety outcomes: a meta-analysis. *Environ. Res.* 116303. https://doi.org/10.1016/j.envres.2023.116303.
Lu, D., Weng, Q., 2006. Use of impervious surface in urban land-use classification. *Remote Sens. Environ.* 102 (1–2), 146–160. https://doi.org/10.1016/j.rse.2006.02.010.
Maas, J., Verheij, R.A., de Vries, S., Spreeuwenberg, P., Schellevis, F.G., Groenewegen, P.P., 2009. Morbidity is related to a green living environment. *J. Epidemiol. Community Health* 63 (12), 967–973. https://doi.org/10.1136/jech.2008.079038.
Madathil, S., Joseph, L., Hardy, R., Rousseau, M.-C., Nicolau, B., 2018. A Bayesian approach to investigate life course hypotheses involving continuous exposures. *Int. J. Epidemiol.* 47 (5), 1623–1635. https://doi.org/10.1093/ije/dyy107.
Marek, L., Wiki, J., Campbell, M., Kingham, S., Sabel, C., Tomintz, M., Hobbs, M., 2020. Slipping under the radar: Worsened health outcomes in semi-urban areas of New Zealand. *N. Z. Med. J.* 133, 121–125.
Marek, L., Hills, S., Wiki, J., Campbell, M., Hobbs, M., 2023. Towards a better understanding of residential mobility and the environments in which adults reside: A nationwide geospatial study from Aotearoa New Zealand, 102762 *Habitat Int.* 133. https://doi.org/10.1016/j.habitatint.2023.102762.
Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., de Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., Lupp, G., Richardson, E.A., Astell-Burt, T., Dimitrova, D., Feng, X., Sadeh, M., Standl, M., Heinrich, J., Fuertes, E., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. *Environ. Res.* 158, 301–317. https://doi.org/10.1016/j.envres.2017.06.028.
McEachan, R.R.C., Prady, S.L., Smith, G., Fairley, L., Cabieses, B., Gidlow, C., Wright, J., Dadvand, P., van Gent, D., Nieuwenhuijsen, M.J., 2016. The association between green space and depressive symptoms in pregnant women: Moderating roles of socioeconomic status and physical activity. *J. Epidemiol. Community Health* 70 (3), 253–259. https://doi.org/10.1136/jech-2015-205954.
McLaren, L., 2019. In defense of a population-level approach to prevention: why public health matters today. *Can. J. Public Health* 110 (3), 279–284. https://doi.org/10.17269/s41997-019-00198-0.
Ministry of Health, 2023. Annual Data Explorer 2022/23: New Zealand Health Survey [Data File]. https://minhealthnz.shinyapps.io/nz-health-survey-2022-23-annual-data-explorer/.
Mitchell, R., Popham, F., 2008. Effect of exposure to natural environment on health inequalities: An observational population study. *Lancet* 372 (9650), 1655–1660. https://doi.org/10.1016/S0140-6736(08)61689-X.
Mouly, T.A., Mishra, G.D., Hystad, P., Nieuwenhuijsen, M., Knibbs, L.D., 2023. Residential greenspace and anxiety symptoms among Australian women living in major cities: a longitudinal analysis. *Environ. Int.* 108110. https://doi.org/10.1016/j.envint.2023.108110.
Müderrisoğlu, H., Gültekin, P.G., 2015. Understanding the children's perception and preferences on nature-based outdoor landscape. *Indoor Built Environ.* 24 (3), 340–354. https://doi.org/10.1177/1420326X13509393.
Nichani, V., Dirks, K., Burns, B., Bird, A., Grant, C., 2017. Green space and depression during pregnancy: results from the growing up in New Zealand study. *Int. J. Environ. Res. Public Health* 14 (9), 1083. https://doi.org/10.3390/ijerph14091083.
Norman, P., Boyle, P., Rees, P., 2005. Selective migration, health and deprivation: A longitudinal analysis. Soc. Sci. Med. 60 (12), 2755–2771. https://doi.org/10.1016/j.socscimed.2004.11.008.
Nutsford, D., Pearson, A.L., Kingham, S., 2013. An ecological study investigating the association between access to urban green space and mental health. *Public Health* 127 (11), 1005–1011. https://doi.org/10.1016/j.puhe.2013.08.016.
Ode Sang, Å., Knez, I., Gunnarsson, B., Hedblom, M., 2016. The effects of naturalness, gender, and age on how urban green space is perceived and used. *Urban For. Urban Green.* 18, 268–276. https://doi.org/10.1016/j.ufug.2016.06.008.
Pearce, J., Cherrie, M., Shortt, N., Deary, I., Ward Thompson, C., 2018. Life course of place: A longitudinal study of mental health and place. *Trans. Inst. Br. Geogr.* 43 (4), 555–572. https://doi.org/10.1111/tran.12246.
Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.-M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends Ecol. Evol.* 20 (9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011.
Piantadosi, S., Byar, D.P., Green, S.B., 1988. The ecological fallacy. *Am. J. Epidemiol.* 127 (5), 893–904.
Pouso, S., Borja, Á., Fleming, L.E., Gómez-Baggethun, E., White, M.P., Uyarra, M.C., 2021. Contact with blue-green spaces during the COVID-19 pandemic lockdown beneficial for mental health, 143984 *Sci. Total Environ.* 756. https://doi.org/10.1016/j.scitotenv.2020.143984.
R Core Team, 2013. R: A language and environment for statistical computing [Computer software]. Vienna, Austria. https://www.r-project.org/.
Richardson, E., Pearce, J., Mitchell, R., Day, P., Kingham, S., 2010. The association between green space and cause-specific mortality in urban New Zealand: An ecological analysis of green space utility. *BMC Public Health* 10 (1), 240. https://doi.org/10.1186/1471-2458-10-240.
Rose, G., 1985. Sick individuals and sick populations. *Int. J. Epidemiol.* 14 (1), 32–38. https://doi.org/10.1093/ije/14.1.32.
Salmond, C., Crampton, P., 2002. NZDep2001 Index of Deprivation User's Manual. Wellington School of Medicine and Health Sciences. https://www.otago.ac.nz/__data/assets/pdf_file/0031/318568/nzdep2001-index-of-deprivation-instruction-manual-020336.pdf.
Salmond, C., Crampton, P.R., Sutton, F., 1998. NZDep96: Index of deprivation. Health Services Research Centre, Victoria University of Wellington. https://www.otago.ac.nz/__data/assets/pdf_file/0033/318786/nzdep1996-index-of-deprivation-instruction-manual-020341.pdf.
Salmond, C., Crampton, P., Atkinson, J., 2007. NZDep2006 index of deprivation. Wellington School of Medicine and Health Sciences. https://www.otago.ac.nz/__data/assets/pdf_file/0027/317574/nzdep2006-index-of-deprivation-research-report-020348.pdf.
Scheid, T.L., Wright, E.R., 2017. *A Handbook for the Study of Mental Health.* Cambridge University Press.
Stan Development Team. (2024). *RStan: The R interface to Stan* [Computer software]. https://mc-stan.org/.
Sutcliffe, K., Ball, J., Clark, T.C., Archer, D., Peiris-John, R., Crengle, S., Fleming, T., 2023. Rapid and unequal decline in adolescent mental health and well-being 2012–2019: Findings from New Zealand cross-sectional surveys. *Aust. N. Z. J. Psychiatry* 57 (2), 264–282. https://doi.org/10.1177/00048674221138503.
Telfar, S., McLeod, G.F.H., Dhakal, B., Henderson, J., Tanveer, S., Broad, H.E.T., Woolhouse, W., Macfarlane, S., Boden, J.M., 2023. Child abuse and neglect and mental health outcomes in adulthood by ethnicity: Findings from a 40-year longitudinal study in New Zealand/Aotearoa, 106444 *Child Abuse Negl.* 145. https://doi.org/10.1016/j.chiabu.2023.106444.
Textor, J., Hardt, J., Knüppel, S., 2011. DAGitty: A Graphical Tool for Analyzing Causal Diagrams. *Epidemiology* 22 (5), 745. https://doi.org/10.1097/EDE.0b013e318225c2be.
Vanaken, G.J., Danckaerts, M., 2018. Impact of green space exposure on children's and adolescents' mental health: A systematic review. *Int. J. Environ. Res. Public Health* 15 (12), 2668. https://doi.org/10.3390/ijerph15122668.
Vilcins, D., Sly, P.D., Scarth, P., Mavoa, S., 2024. Green space in health research: an overview of common indicators of greenness. *Rev. Environ. Health* 39 (2), 221–231. https://doi.org/10.1515/reveh-2022-0083.
Wagner, C., Carmeli, C., Jackisch, J., Kivimäki, M., van der Linden, B.W., Cullati, S., Chiolero, A., 2024. Life course epidemiology and public health. *Lancet Public Health* 9 (4), e261–e269. https://doi.org/10.1016/S2468-2667(24)00018-5.
Wang, R., Yang, B., Yao, Y., Bloom, M.S., Feng, Z., Yuan, Y., Zhang, J., Liu, P., Wu, W., Lu, Y., Baranyi, G., Wu, R., Liu, Y., Dong, G., 2020. Residential greenness, air pollution and psychological well-being among urban residents in Guangzhou, China, 134843 Sci. Total Environ. 711. https://doi.org/10.1016/j.scitotenv.2019.134843.
Watkins-Martin, K., Bolanis, D., Richard-Devantoy, S., Pennestri, M.-H., Malboeuf-Hurtubise, C., Philippe, F., Guindon, J., Gouin, J.P., Ouellet-Morin, I., Geoffroy, M.C., 2022. The effects of walking in nature on negative and positive affect in adult psychiatric outpatients with major depressive disorder: a randomized-controlled study. *J. Affect. Disord.* 318, 291–298. https://doi.org/10.1016/j.jad.2022.08.121.
Wendelboe-Nelson, C., Kelly, S., Kennedy, M., Cherrie, J.W., 2019. A scoping review mapping research on green space and associated mental health benefits. *Int. J. Environ. Res. Public Health* 16 (12), 2081. https://doi.org/10.3390/ijerph16122081.

White, M.P., Hartig, T., Martin, L., Pahl, S., van den Berg, Wells, N.M., Costongs, C., Dzhambov, Elliott, L.R., Godfrey, A., Hartl, A., Konijnendijk, C., Litt, J.S., Lovell, R., Lymeus, F., O'Driscoll, C., Pichler, C., Pouso, S., Razani, N., van den Bosch, M., 2023. Nature-based biopsychosocial resilience: an integrative theoretical framework for research on nature and health. Environ. Int. 181, 108234. https://doi.org/10.1016/j.envint.2023.108234.

World Health Organization, 1993. Composite international diagnostic interview (CIDI), version 1.1. In: Composite International Diagnostic Interview (CIDI), Version 1.1.

World Health Organization, 2022. World mental health report: Transforming mental health for all. https://iris.who.int/bitstream/handle/10665/356119/9789240049338-eng.pdf?sequence=1.

Xie, B., Lu, Y., Zheng, Y., 2022. Casual evaluation of the effects of a large-scale greenway intervention on physical and mental health: a natural experimental study in China, 127419 *Urban For. Urban Green.* 67. https://doi.org/10.1016/j.ufug.2021.127419.

Younan, D., Tuvblad, C., Li, L., Wu, J., Lurmann, F., Franklin, M., Berhane, K., McConnell, R., Wu, A.H., Baker, L.A., Chen, J.C., 2016. Environmental determinants of aggression in adolescents: Role of urban neighborhood greenspace. *J. Am. Acad. Child Adolesc. Psychiatry* 55 (7), 591–601. https://doi.org/10.1016/j.jaac.2016.05.002.

Zhang, Z., Amegbor, P.M., Sigsgaard, T., Sabel, C.E., 2022. Assessing the association between urban features and human physiological stress response using wearable sensors in different urban contexts, 102924 *Health Place* 78. https://doi.org/10.1016/j.healthplace.2022.102924.

Zhang, X., Liu, L., Zhao, T., Gao, Y., Chen, X., Mi, J., 2022. GISD30: Global 30 m impervious-surface dynamic dataset from 1985 to 2020 using time-series Landsat imagery on the Google Earth Engine platform. Earth Syst. Sci. Data 14 (4), 1831–1856. https://doi.org/10.5194/essd-14-1831-2022.

Zhang, Y., Wu, T., Yu, H., Fu, J., Xu, J., Liu, L., Tang, C., Li, Z., 2024. Green spaces exposure and the risk of common psychiatric disorders: A meta-analysis, 101630 *SSM-Population Health* 25. https://doi.org/10.1016/j.ssmph.2024.101630.

Zhang, R., Zhang, C.Q., Rhodes, R.E., 2021. The pathways linking objectively-measured greenspace exposure and mental health: a systematic review of observational studies, 111233 *Environ. Res.* 198. https://doi.org/10.1016/j.envres.2021.111233.

Zheng, K., He, G., Yin, R., Wang, G., Long, T., 2023. A Comparison of Seven Medium Resolution Impervious Surface Products on the Qinghai–Tibet Plateau, China from a User's Perspective. *Remote Sens. (Basel)* 15 (9). https://doi.org/10.3390/rs15092366.