



Greenness and hospital admissions for cause specific mental disorders: multicountry time series study

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ABSTRACT

OBJECTIVES

To examine the association between exposure to greenness and hospital admissions for mental disorders, and to estimate greenness related hospital admissions under various greenness intervention scenarios.

DESIGN

Multicountry time series study.

SETTING

6842 locations in seven countries (Australia, Brazil, Canada, Chile, New Zealand, South Korea, and Thailand).

PARTICIPANTS

11.4 million hospital admissions for mental disorders, 2000-19.

MAIN OUTCOME MEASURES

Hospital admissions for all cause mental disorders and for six categories in relation to greenness (measured by the normalised difference vegetation index (NDVI)): psychotic disorders, substance use disorders, mood disorders, behavioural disorders, dementia, and anxiety. Associations were estimated using quasi-Poisson regression models, controlled for weather conditions, air pollutants, socioeconomic indicators, seasonality, and long term trends. Models were stratified by sex, age, urbanisation, and season. Hospital admissions were estimated under different greenness intervention scenarios.

RESULTS

During 2000-19, of hospital admissions related to mental health disorders, 30.8% (3 522 749 patients) were for psychotic disorders, 24.7% (2 821 860) for substance use disorders, 11.6% (1 325 305) for mood disorders, 7.4% (845 561) for behavioural disorders, 3.0% (348 149) for dementia, and 2.5% (283 914) for anxiety. A 0.1 increase in NDVI was associated with a 7% reduction in the risk of hospital admissions for all cause mental disorders (relative risk 0.93, 95% confidence interval (CI) 0.89 to 0.98) in pooled analyses. However, associations varied across countries and disorder types. Brazil, Chile, and Thailand showed consistent protective associations across most disorder categories, while modest adverse (ie, harmful) associations were observed in Australia and Canada for hospital admissions for all cause mental disorders and for several specific disorder categories. Exposure-response analyses showed a generally monotonic and approximately linear relation without clear thresholds. When limited to urban settings where associations were generally more consistent, an estimated 7712 (95% CI 6701 to 8726) hospital admissions for mental health disorders annually in urban areas were statistically attributable to observed greenness levels. Analysis by greenness intervention scenarios in urban areas suggested that a 10% increase in greenness was associated with reductions in hospital admissions for mental disorders ranging from ~1 per 100 000 in South Korea to ~1000 per 100 000 in New Zealand.

CONCLUSIONS

Greenness was statistically associated with lower risks of hospital admissions for mental disorders in several countries, particularly in urban settings. Some adverse associations were, however, observed, and findings were heterogeneous across contexts.

Introduction

Mental wellbeing is vital for humans to flourish but remains a global challenge, with mental disorders highly prevalent globally.¹ In 2021, the Global Burden of Disease study estimated that 1.1 billion people had mental disorders, contributing to 14.4% of the global disease burden.² Mental disorders are leading causes of disability and major risk factors for premature mortality,³ with associated economic and societal burden increasing across all levels of sociodemographic development.⁴

Environmental exposures substantially affect mental health. Urbanisation has transformed natural environments, reducing people's exposure to greenness

WHAT IS ALREADY KNOWN ON THIS TOPIC

Mental wellbeing remains a global challenge, with mental disorders highly prevalent worldwide

Environmental factors play an important role in mental health, with growing evidence suggesting that exposure to greenness might reduce the risk of mental disorders

Previous studies are limited to single country settings, short term exposures, or specific mental health outcomes, highlighting the need for large scale, multicountry research with comprehensive temporal and spatial analyses

WHAT THIS STUDY ADDS

Local greenness was associated with a 7% reduction in hospital admissions for all cause mental disorders, with stronger associations for substance use disorders (9%), psychotic disorders (7%), and dementia (6%)

Associations were strongest in urban areas, where an estimated 7712 hospital admissions for mental disorders annually were potentially preventable through greater exposure to greenness

The exposure-response relation was approximately linear, with no clear threshold

and increasing their contact with harmful conditions such as extreme heat,⁵ air pollution,⁶ and noise. These urban stressors have been linked to higher risks of adverse health outcomes,⁷ including psychiatric disorders.⁸ Environmental pollution, including air pollutants and other toxicants originating from urban sources, has also been associated with increased risks of anxiety, schizophrenia, and depression.^{9–10} Chronic exposure to noise can impair neurobiological processes, contributing to mental health issues.¹¹

Greenness is a modifiable and scalable feature of the built and natural environment that may support mental health. It can reduce exposure to environmental stressors such as air pollution, noise, and heat, while also promoting stress recovery, physical activity, and social interaction.¹² Although recent epidemiological studies have reported beneficial associations between residential greenness and mental wellbeing,^{13–18} findings remain mixed. Some studies have found no clear association,^{19–21} possibly because of differences in how greenness and mental health outcomes are measured and analysed. In addition, potential non-linear associations between greenness and health outcomes are often discussed¹³ but rarely explored in depth. These studies largely focused on a limited area, mainly regions in Europe,¹⁸ which may limit generalisability and applicability.

To address these gaps, we conducted a multinational study examining the association between greenness and hospital admissions for mental disorders across seven countries over two decades. We also investigated the shape of exposure-response relations and explored whether these associations have a threshold. In this study, we use the term greenness to refer broadly to the level of vegetative cover in each area. We aimed to provide robust, cross context evidence that can inform urban design and health policy to better protect mental health.

Methods

Data sources

We collected data on inpatient hospital admissions for mental disorders from 6842 locations in seven countries at the smallest geospatial unit available to us (see supplementary table S1). Data sources included 505 statistical areas level 2 in Australia (2000–19),²² 5570 municipalities in Brazil (2000–19),²³ 261 second level administrative divisions (census divisions) in Canada (2005–19),²⁴ 345 communes in Chile (2000–19),²⁵ 67 territorial authorities in New Zealand (2000–19),²⁶ 76 provinces and one special administrative area in Thailand (2000–19),²⁷ and nine provinces, six metropolitan cities, and two special cities across South Korea (2002–19).²⁸ Monthly data were aggregated by sex (female, male) and age groups (≤ 19 , 20–59, ≥ 60 years).

Hospital admissions were classified using ICD-10 (international classification of diseases, 10th revision) codes: all mental disorders (ICD-10: F00–F99) and six subtypes (dementia: F00–F03, substance use disorders: F10–F19, psychotic disorders: F20–F29,

mood disorders: F30–F39, anxiety disorders: F40–F48, and behavioural disorders: F40–F48). Only hospital admissions for all cause mental disorders were available for South Korea.

Population data were derived from WorldPop (2000–19) with a 1 km $\times$ 1 km resolution.²⁹ This dataset used a top-down approach and presents the world structured by sex and age groups (0–1 and in five years intervals up to ≥ 80). We adjusted the unconstrained data to align with country level population estimates from the United Nations World Population Prospects.³⁰ Based on the adjusted gridded data and location boundaries, we estimated the annual sex and age specific population count for each location.

Socioeconomic status was represented using gross domestic product (GDP) per capita and the Human Development Index. To calculate GDP per capita, we aggregated gridded GDP data and divided the results by population at each location annually (2000–19).³¹ We extracted Human Development Index values from a global subnational dataset,³² with 2015 values used uniformly owing to limited annual availability.

Healthcare access was measured using two indicators: average travel time to healthcare (by walking or motor vehicle) based on the Malaria Atlas Project,³³ and the number of healthcare facilities per 100 000 population based on OpenStreetMap data (<https://healthsites.io>). In addition, we calculated road density for each location using road network data from OpenStreetMap and used it as a spatial proxy for traffic related air pollution and noise exposure. All indicators were harmonised to the geographical units used for hospital admission data.

Local units were classified as urban, semi-urban, and rural areas according to degree of urbanisation by the Global Human Settlement Layer territorial units classification level 1.³⁴

Environmental exposure

We quantified greenness using the normalised difference vegetation index (NDVI), a widely utilised and reliable satellite derived metric for assessing the abundance of vegetation.^{35–36} NDVI measures the normalised difference between red and near infrared reflectance, indicating the density and vigour of vegetation. Values range from -1 to 1 , with very low values (≤ 0.1) representing barren areas such as rock, sand, water, and snow; moderate values (0.2 – 0.5) representing sparse vegetation such as shrubs and grasslands; and high values (≥ 0.6) representing dense vegetation. To assess medium term exposure to greenness, we utilised NDVI data from the MODIS (Moderate Resolution Imaging Spectroradiometer) Terra Vegetation Indices Monthly L3 Global data product.³⁷ This dataset provides monthly NDVI values globally at a spatial resolution of 1 km $\times$ 1 km. To focus exclusively on vegetated areas, we excluded zero and negative NDVI values, which correspond to water, cloud, and barren or non-vegetated regions. We then averaged monthly NDVI values within defined

geographical boundaries to represent medium term exposure levels for each location.

From a previous study, we sourced global daily average PM_{2.5} (particulate matter with a diameter of ≤ 2.5 μm) and daily maximum eight hour ozone levels at $0.25^\circ \times 0.25^\circ$ resolution.³⁸ We obtained weather indicators, including daily mean temperature ($^\circ\text{C}$), relative humidity (%), precipitation (mm), solar radiation (J/m^2), and pressure (hPa) at $0.25^\circ \times 0.25^\circ$ resolution from the European Centre for Medium-Range Weather Forecasts reanalysis version 5.³⁹ All air pollution and weather data were aggregated to monthly averages and linked to spatial units by population weighted averaging of grids within boundaries.

Statistical analysis

We used quasi-Poisson time series regression models to estimate the association between NDVI and hospital admissions for mental disorders for each country. Models adjusted for air pollutants (PM_{2.5}, ozone), weather variables (temperature, relative humidity, rainfall, pressure, ultraviolet B radiation), and socioeconomic indicators (GDP per capita, Human Development Index). Non-linear relations for air pollution and weather variables were modelled using natural cubic splines (three degrees of freedom). Long term trends were adjusted using a natural spline function of time, with three degrees of freedom for each 10 years, and seasonality was controlled by adding month categories.⁴⁰ We included population size at location level as an offset.

Analyses were stratified by sex, age group, urbanisation level, and season. We defined seasons using a temperature based classification for each location: the warm season (four warmest months), cold season (four coldest months), and intermediate period (remaining four months). Results were expressed as relative risks with 95% confidence intervals (CIs) for hospital admissions per 0.1 increase in NDVI.

To examine non-linear relations and determine greenness thresholds, we replaced the linear NDVI term with a natural spline (three degrees of freedom) in the model, then plotted exposure-response curves with predicted hospital admission counts and 95% CIs. We compared country specific models using the quasi-bayesian information criterion, with lower values indicating better fit.

We conducted several sensitivity analyses to evaluate the robustness of our findings. Firstly, we tested the temporal alignment between exposure to greenness and mental health outcomes by replacing the current month greenness with lagged exposures, using two, three, and four month moving averages. Secondly, to explore the potential influence of residential self-selection (that is, whether wealthier people disproportionately reside in greener areas), we stratified the analysis by local socioeconomic status using quarters of the Human Development Index.

To assess potential residual confounding in our time series analysis, we applied a negative control exposure approach (see supplementary method 1.1).

To assess the impact of unmeasured environmental confounders, we introduced road density as a proxy for traffic related air pollution and noise exposure. We also conducted additional models adjusting for healthcare access, including travel time to the nearest facility and density of healthcare infrastructure.

All analyses were conducted separately for each country and mental disorder category. We pooled country level estimates using a random effect meta-analysis with maximum likelihood estimation.

Estimation of greenness related hospital admissions

We estimated the number of hospital admissions and fractions of mental health related hospital admissions statistically attributable to exposure to greenness, referred to as greenness related hospital admissions, across different settings (urban, semi-urban, rural). These estimates reflect both protective (negative) and adverse (positive) associations and were calculated using methods adapted from previous work.⁴¹

For each location, month, and greenness level scenario, we estimated the attributable fraction of hospital admissions using country and cause specific exposure-response coefficients and the difference between the observed greenness level and a specified counterfactual greenness value. The number of greenness related hospital admissions was then derived by multiplying the attributable fraction by the corresponding number of hospital admissions. We obtained total greenness related hospital admissions by summing across time points and locations. The country specific attributable fractions were computed by dividing the total number of greenness related hospital admissions by the total number of hospital admissions over the study period. Supplementary method 1.2 provides further details and related calculations.

We applied this method in two ways. We estimated greenness related hospital admissions using the observed greenness level compared to a counterfactual scenario defined as the minimum NDVI observed across all locations in each country. We then evaluated greenness related hospital admissions under two hypothetical greenness intervention scenarios: a uniform increase in greenness across all locations by 1%, 5%, and 10% relative to location specific original greenness level, and a targeted intervention increasing greenness in areas of low baseline greenness (bottom 25th centile) to the 75th centile within each country.

Analyses were performed using R (v4.2.2). Original maps were created in ArcGIS (v10.8.2).

Patient and public involvement

Patients and members of the public were not involved in the design, conduct, reporting, or dissemination plans of our research because it was a secondary analysis of existing routinely collected data, with no direct contact with patients. We acknowledge the value of patient and carer input and will consider incorporating

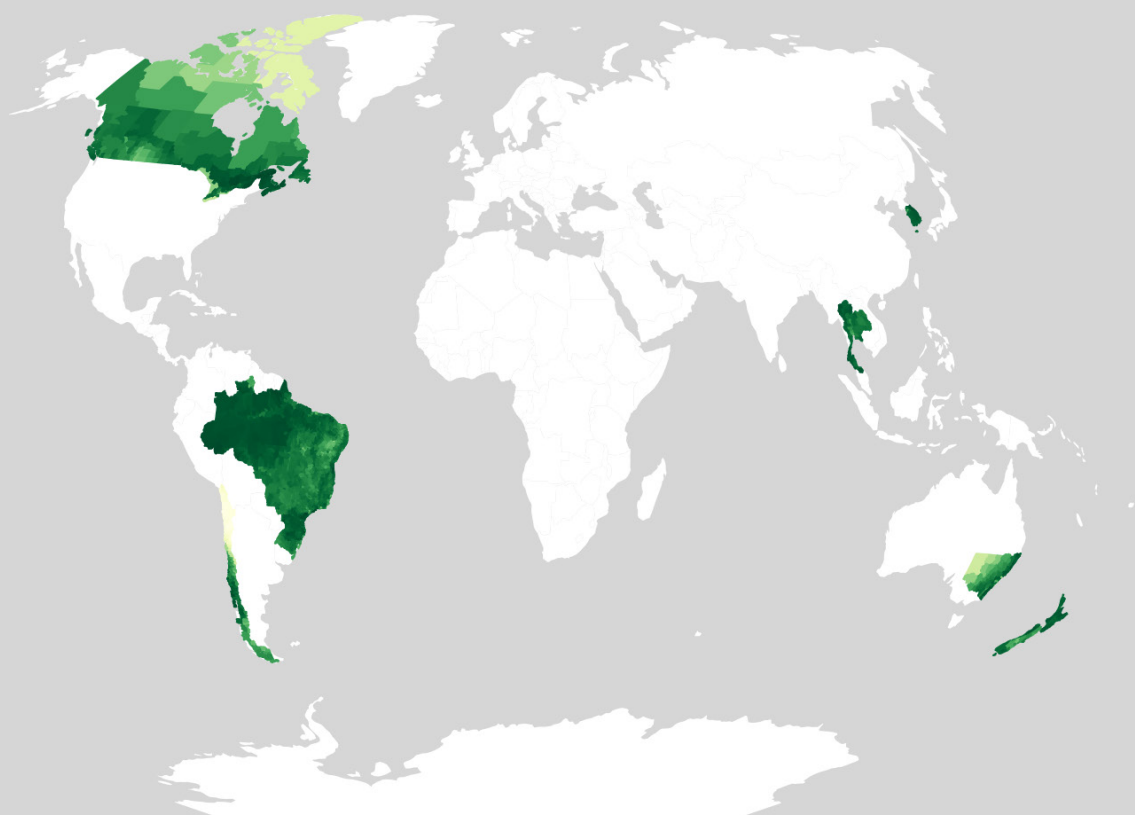
Geographical distribution of study areas and yearly maximum greenness (NDVI) across seven countries



Maps showing all included locations and their average annual maximum NDVI values across Australia (505 in NSW), Brazil (5570), Canada (261), Chile (345), New Zealand (67), Thailand (77), and South Korea (17)

This figure presents the spatial distribution of all included study locations ($n = 6842$) and their average annual maximum NDVI from 2000 to 2019. Locations coloured by NDVI values. NDVI was categorised into seven bins ranging from <0.30 (low greenness) to >0.80 (high greenness)

0.07  0.87



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NDVI=normalised difference vegetation index

Fig 1 | Geographical distribution of study areas and yearly maximum greenness according to normalised difference vegetation index (NDVI) across seven countries. An interactive version of this graphic is available at <https://public.flourish.studio/visualisation/24600082/>

qualitative data and participatory approaches in future work when feasible.

Results

Our study analysed 11.4 million hospital admissions for mental disorders across seven countries from 2000 to 2019. The primary reasons for mental health related hospital admissions were psychotic disorders (30.8%; 3 522 749 patients), substance use disorders (24.7%;

2 821 860), mood disorders (11.6%; 1 325 305), behavioural disorders (7.4%; 845 561), dementia (3.0%; 348 149), and anxiety (2.5%; 283 914). Males generally had higher hospital admission counts across all countries except in Thailand. Most hospital admissions (>60%) occurred among individuals aged 20-59 years. Psychotic and substance use disorders accounted for the largest shares of cause specific hospital admissions across all countries (see supplementary table S2).

Supplementary table S2 also provides descriptive statistics on environmental exposures, including greenness, air pollution, weather conditions, GDP per capita, and Human Development Index.

The mean NDVI values varied considerably across countries. New Zealand exhibited the highest mean greenness (NDVI=0.72), whereas Canada had the lowest (NDVI=0.49) (fig 1). Seasonal variations in exposure to greenness between 2000 and 2019 showed contrasting patterns by hemisphere. In countries in the northern hemisphere (Canada, South Korea, and Thailand), peak greenness occurred in July and August, showing pronounced seasonality. Conversely, countries in the southern hemisphere (Brazil, Australia, New Zealand, and Chile) showed less pronounced seasonal variation, with peak greenness typically occurring in February (see supplementary figure S1).

Hospital admissions for mental disorders associated with greenness

Figure 2 shows that a 0.1 increase in NDVI was associated with a 7% reduction in the risk of hospital

admissions for all cause mental disorders (relative risk 0.93, 95% CI 0.89 to 0.98). Stronger associations were observed for substance use disorders (0.91, 0.87 to 0.95), psychotic disorders (0.93, 0.87 to 1.00), dementia (0.94, 0.89 to 0.98), and anxiety (0.97, 0.94 to 0.99). Associations for behavioural disorders (0.98, 0.88 to 1.08) and mood disorders (0.98, 0.91 to 1.06) were weaker and not statistically significant in the pooled analysis.

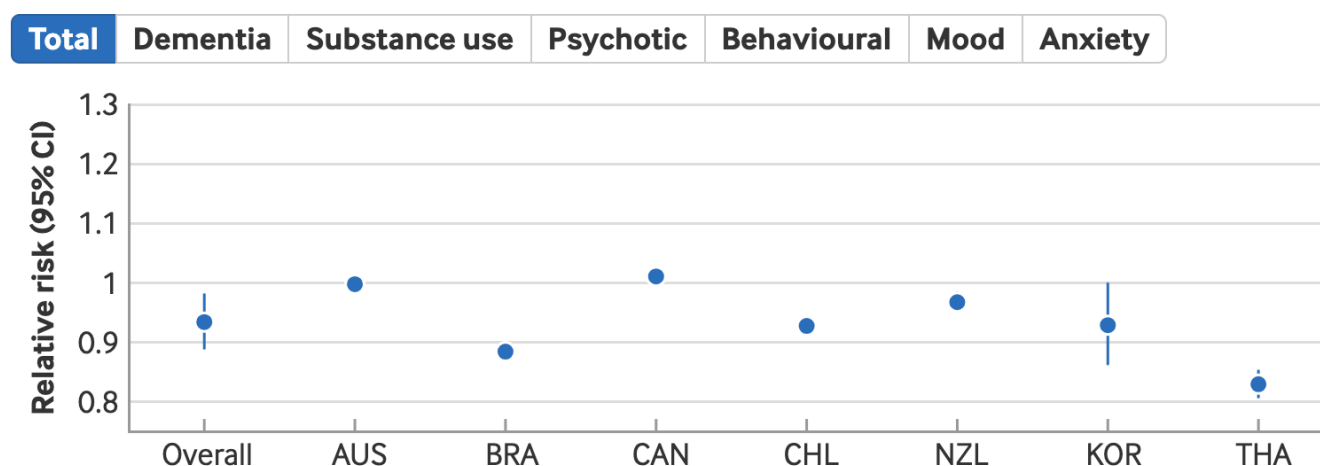
While many country specific associations reflected a protective pattern, others were null or even adverse. For example, Brazil, Chile, and Thailand exhibited consistently protective associations across most disorder categories. In South Korea, where data on cause specific hospital admissions were unavailable, greenness was associated with a lower risk of hospital admissions for all cause mental disorders (relative risk 0.93, 0.86 to 1.00). In contrast, Australia showed slightly positive associations for mood disorders (1.06, 1.06 to 1.07) and behavioural disorders (1.22, 1.88 to 1.25), and no significant association for all cause hospital admissions (1.00, 0.99 to 1.00). Similarly, in Canada, greenness was associated with modestly

Overall and country specific relative risks of hospital admissions for mental disorders associated with exposure to greenness



Pooled and country level estimates of the association between NDVI based greenness and hospital admissions for all mental disorders combined and six specific diagnostic categories, shown as relative risks with 95% confidence intervals

Relative risks are shown per 0.1 unit increase in NDVI, adjusted for air pollution, weather, socioeconomic status, seasonality, and temporal trends



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NDVI=normalised difference vegetation index

AUS=Australia; BRA=Brazil; CAN=Canada; CHL=Chile; NZL=New Zealand; KOR=South Korea;

THA=Thailand

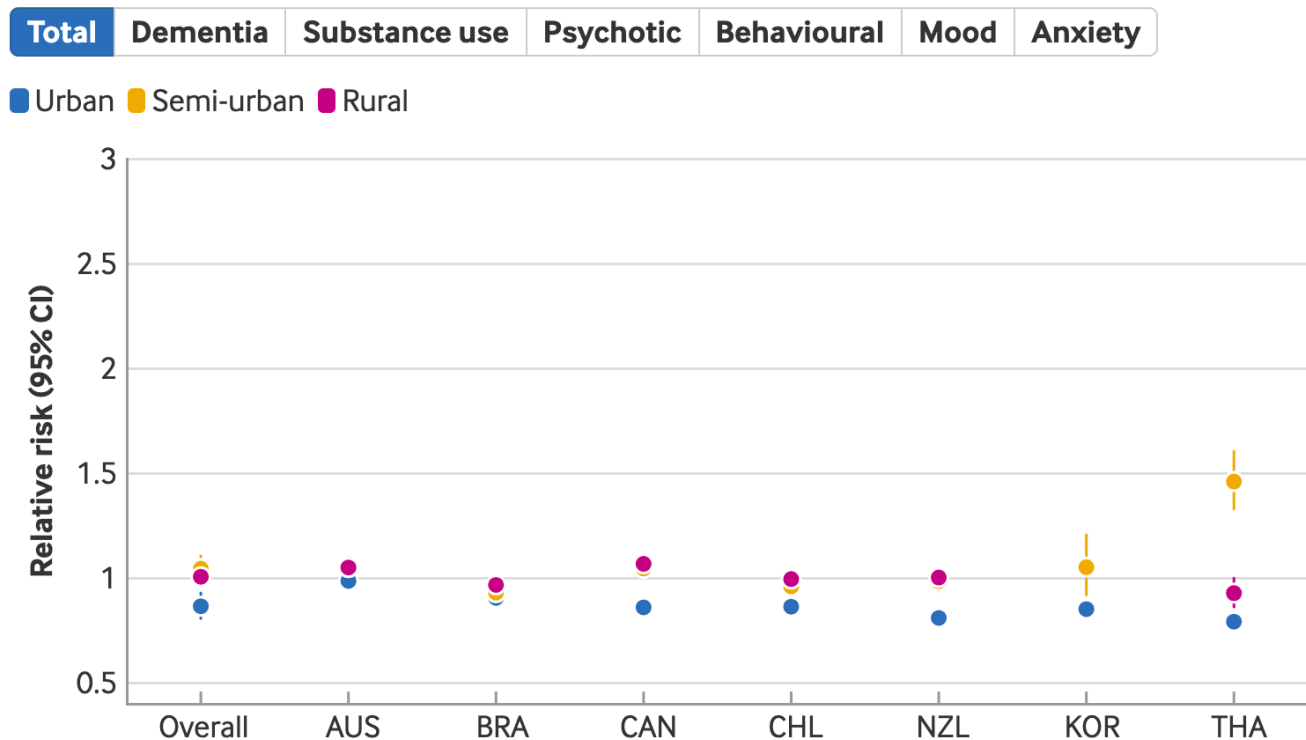
Fig 2 | Overall pooled estimates and country specific relative risks of all cause and cause specific hospital admissions for mental disorders associated with exposure to greenness. An interactive version of this graphic is available at <https://public.flourish.studio/visualisation/24633056/>

Associations between greenness and hospital admissions for mental disorders by urbanisation category



Relative risks of all cause and cause specific hospital admissions for mental disorders associated with greenness exposure (NDVI), stratified by urban, semi-urban, and rural areas across seven countries

This figure presents relative risks and 95% confidence intervals for the association between a 0.1 unit increase in NDVI and risk of hospital admission. Each panel represents a diagnostic category (eg, total, dementia, anxiety), with results shown for overall pooled estimates and seven countries, stratified by urbanisation level. The models adjust for air pollution, weather, socioeconomic status, seasonality, and temporal trends. Note: Only data on all cause hospital admissions were available for South Korea



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NDVI=normalised difference vegetation index; CI=confidence interval

AUS=Australia; BRA=Brazil; CAN=Canada; CHL=Chile; NZL=New Zealand; KOR=South Korea;

THA=Thailand

Fig 3 | Overall pooled estimates and country specific relative risk of cause specific hospital admissions for mental disorders associated with exposure to greenness in different urbanisation categories (urban, semi-urban, and rural). An interactive version of this graphic is available at <https://public.flourish.studio/visualisation/24630923/>

increased risks for mood disorders (1.13, 1.12 to 1.14), psychotic disorders (1.05, 1.03 to 1.06), behavioural disorders (1.05, 1.03 to 1.07), and all cause mental disorders (1.01, 1.00 to 1.02).

The protective associations were most evident in urban areas (fig 3). In these settings, greenness was associated with a 13% reduction in hospital

admissions for all cause mental disorders (0.87, 0.81 to 0.93). Country specific results showed protective associations across most disorder categories. For example, the relative risk for hospital admissions for all cause mental disorders in urban areas was 0.79 (0.76 to 0.82) in Thailand, 0.81 (0.80 to 0.82) in New Zealand, 0.85 (0.81 to 0.89) in South Korea, 0.86 (0.84

Density plot and exposure-response curve



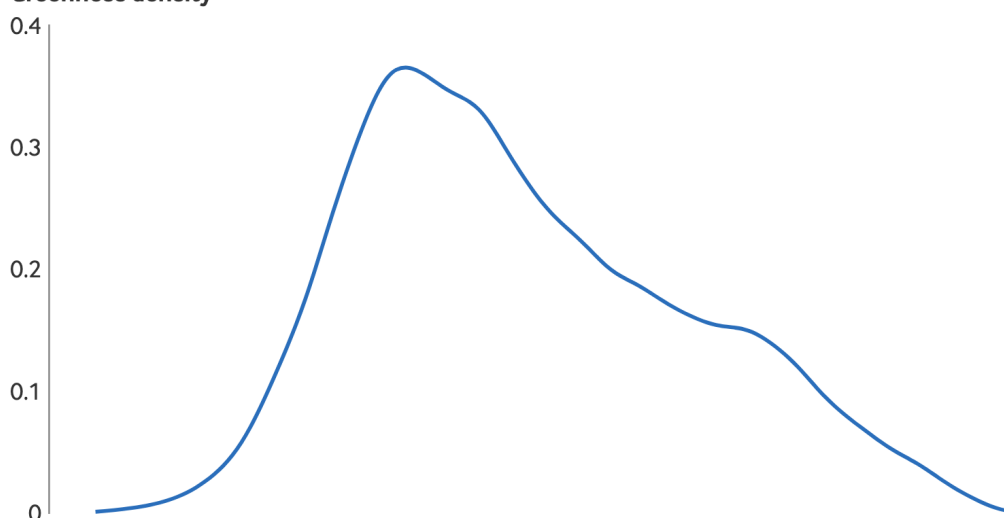
Exposure-response relation between NDVI based greenness and hospital admissions for mental disorders in urban areas across seven countries, with overlay of NDVI density distribution (upper panel)

Upper panel: NDVI density plots indicate the distribution of observed greenness levels across all urban locations in each country

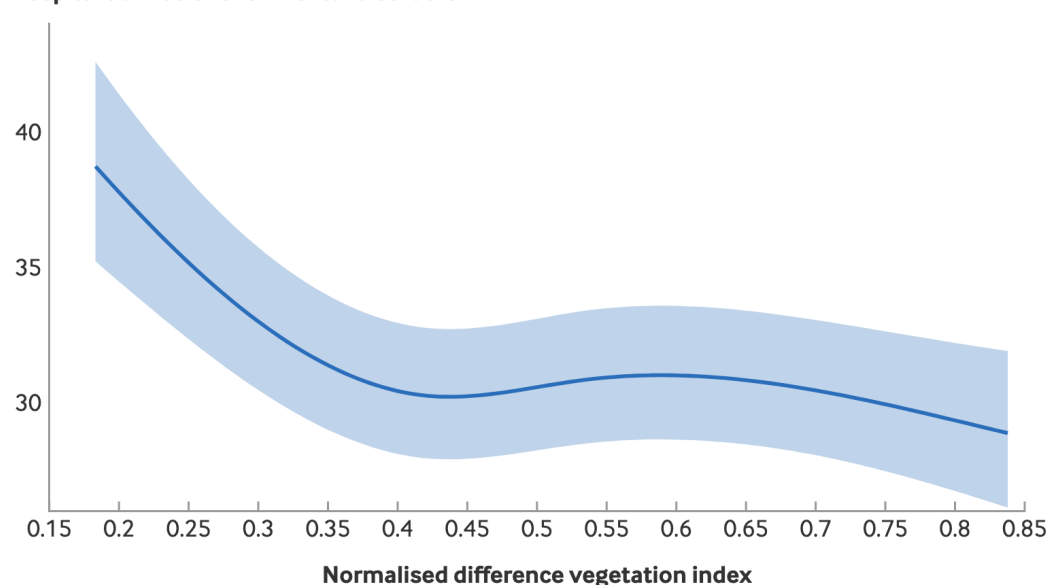
Lower panel: The curve and shaded area show the estimated hospital admissions for mental disorders (95% confidence intervals) associated with NDVI, modelled using a natural cubic spline (three degrees of freedom) and adjusted for air pollution, weather, socioeconomic status, seasonality, and temporal trends

Australia Brazil Canada Chile New Zealand Thailand South Korea

Greenness density



Hospital admissions for mental disorders



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NDVI=normalised difference vegetation index; CI=confidence interval

Fig 4 | Exposure-response relation between greenness and hospital admissions for mental disorders in urban areas across seven countries, with overlay of distribution of greenness density (upper panel). Greenness was modelled using a natural spline function with three degrees of freedom. An interactive version of this graphic is available at <https://public.flourish.studio/visualisation/24598550/>

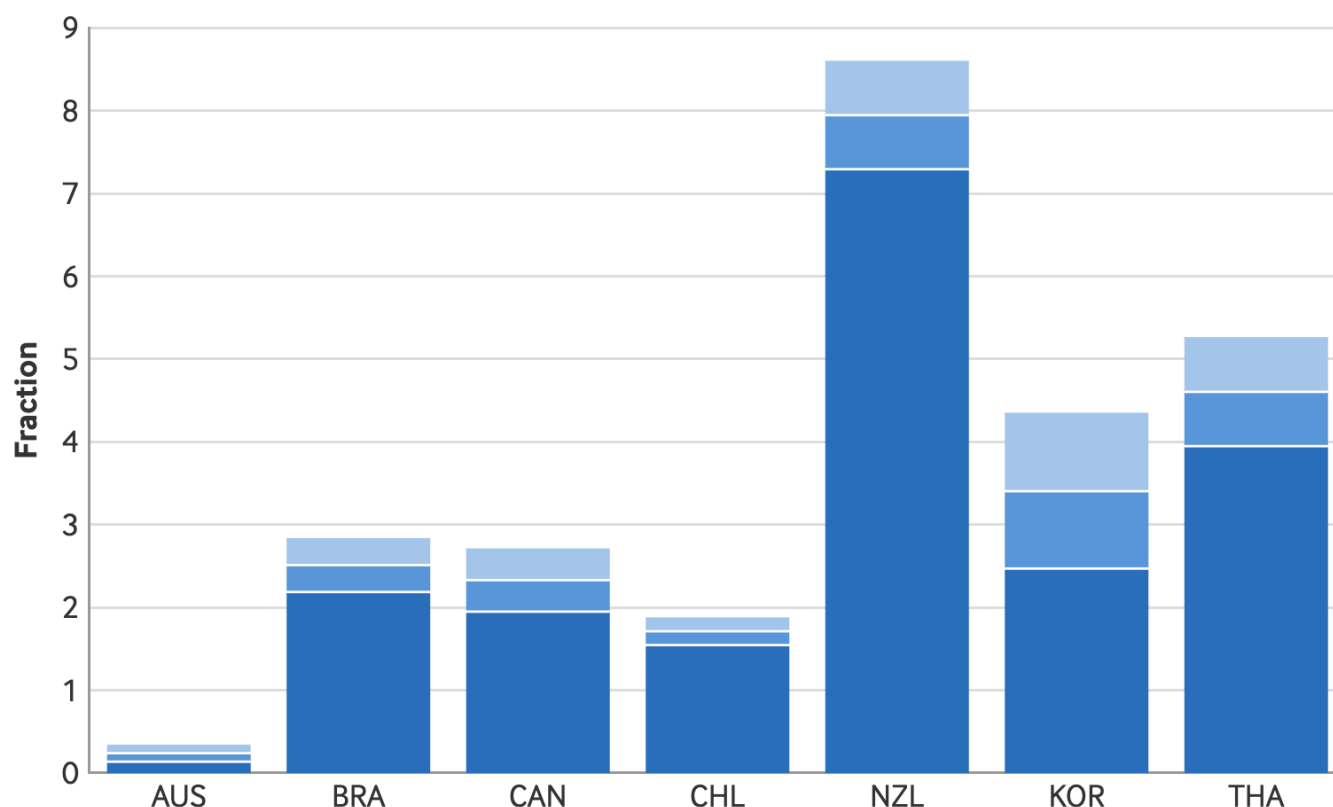
Country and cause specific fractions of hospital admissions for mental disorders statistically attributable to exposure to greenness



Estimated proportion of hospital admissions for total and cause specific mental disorders associated with current levels of greenness (NDVI) in urban areas across seven countries

Total Dementia Substance use Psychotic Behavioural Mood Anxiety

■ Fraction below 95% CI ■ Fraction between lower 95% CI and point estimate
■ Fraction between point estimate and upper 95% CI



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NDVI=normalised difference vegetation index; CI=confidence interval

AUS=Australia; BRA=Brazil; CAN=Canada; CHL=Chile; NZL=New Zealand; KOR=South Korea; THA=Thailand

Fig 5 | Country and cause specific fractions of hospital admissions for mental disorders statistically attributable to greenness in urban areas. An interactive version of this graphic is available at <https://public.flourish.studio/visualisation/24597203/>

to 0.88) in Canada, 0.86 (0.85 to 0.88) in Chile, 0.91 (0.89 to 0.92) in Brazil, and 0.99 (0.98 to 0.99) in Australia.

In semi-urban areas, the associations were more mixed. In Canada, greenness was associated with a higher risk of hospital admissions for mood disorders (1.18, 1.15 to 1.20), while in Chile, protective associations were still observed (0.93, 0.91 to 0.94).

In rural settings, results also varied. For instance, in Australia, greenness was associated with higher risks of hospital admissions for substance use disorders (1.06, 1.04 to 1.07), whereas protective associations were observed in rural Brazil (0.95, 0.93 to 0.96).

Seasonal patterns were also observed in urban areas (see supplementary figure S2). In Brazil, Chile, Thailand, and New Zealand, the protective effects of

Table 1 | Greenness related hospital admissions for cause specific mental disorders in urban locations for each country during study period

Australia	Brazil	Canada	Chile	New Zealand	South Korea*	Thailand	Overall
Study period	2001-19	2005-19	2001-19	2000-19	2002-19	2015-19	2015-19
Hospital admissions annually							
All cause mental disorders	150 (85 to 214)	719 (601 to 837)	328 (296 to 360)	1213 (1113 to 1313)	20 (15 to 26)	605 (519 to 691)	7712 (6701 to 8726)
Anxiety	-78 (-114 to -42)	50 (30 to 71)	23 (12 to 34)	145 (111 to 179)	NA	10 (6 to 14)	NA
Behavioural disorders	-139 (-153 to -124)	24 (19 to 29)	3 (2 to 4)	26 (18 to 33)	NA	3 (2 to 4)	NA
Dementia	6 (3 to 10)	93 (79 to 108)	7 (5 to 9)	85 (69 to 100)	NA	3 (0 to 6)	NA
Mood disorders	-181 (-214 to -147)	642 (331 to 958)	68 (60 to 75)	385 (345 to 425)	NA	34 (23 to 46)	NA
Psychotic disorders	251 (236 to 267)	1186 (826 to 1548)	95 (85 to 104)	279 (237 to 322)	NA	228 (179 to 276)	NA
Substance use disorders	159 (135 to 184)	1148 (965 to 1331)	46 (36 to 57)	148 (119 to 177)	NA	279 (249 to 309)	NA
Attributable fractions (%)							
All cause mental disorders	0.24 (0.14 to 0.34)	2.51 (2.19 to 2.84)	1.71 (1.55 to 1.88)	7.95 (7.29 to 8.60)	3.40 (2.47 to 4.35)	4.60 (3.95 to 5.27)	2.65 (2.31 to 3.00)
Anxiety	-0.72 (-0.39 to -1.05)	8.67 (6.89 to 10.48)	1.22 (0.66 to 1.79)	8.42 (6.45 to 10.43)	NA	3.12 (1.92 to 4.34)	NA
Behavioural disorders	-4.99 (-4.47 to -5.50)	3.63 (2.35 to 4.92)	1.13 (0.73 to 1.54)	9.68 (6.93 to 12.51)	NA	6.47 (3.87 to 9.15)	NA
Dementia	0.65 (0.26 to 1.03)	5.28 (0.62 to 10.20)	1.75 (1.18 to 2.32)	8.18 (6.70 to 9.69)	NA	1.56 (0.03 to 3.11)	NA
Mood disorders	-0.94 (-0.77 to -1.11)	2.34 (1.21 to 3.48)	1.16 (1.03 to 1.29)	9.63 (8.64 to 10.63)	NA	2.71 (1.81 to 3.63)	NA
Psychotic disorders	3.28 (3.08 to 3.48)	1.48 (1.03 to 1.93)	2.68 (2.41 to 2.94)	7.45 (6.32 to 8.60)	NA	5.01 (3.95 to 6.08)	NA
Substance use disorders	1.13 (0.96 to 1.31)	2.46 (2.07 to 2.85)	1.13 (0.87 to 1.40)	5.58 (4.50 to 6.67)	NA	6.40 (5.71 to 7.09)	NA

NA=not available.

*Hospital admissions for cause specific mental disorders were not available.

greenness were stronger during the cold season, with risk reductions ranging from 5% to 17%. In contrast, in Canada the strongest association was observed in the warm season, where a 0.1 increase in NDVI was associated with a 23% reduction in risk of hospital admissions for mental disorders. No significant seasonal patterns were found in rural and semi-urban areas (see supplementary figures S3 and S4).

Stratifications by age and sex showed no meaningful effect modification (see supplementary figure S5). Stratification by Human Development Index quarters showed mixed patterns across countries, with no clear trend, indicating stronger associations in higher or lower Human Development Index categories (see supplementary figure S6).

Several sensitivity analyses largely supported the main findings. Firstly, lagged exposure to greenness using two, three, and four month moving averages produced results similar to those from the main models. In Chile and Australia, longer lag periods were associated with slightly stronger protective effects (see supplementary figure S7). Secondly, the residual confounding of our main models was not statistically significant (see supplementary table S3). Finally, adjustment for road density (as a proxy for traffic related air pollution and noise), and additional adjustment for healthcare access indicators (travel time to the nearest facility and facility density), resulted in minimal change to the main models (see supplementary table S4).

Non-linear associations

In urban locations, exposure-response curves showed a generally monotonic downward association between greenness and hospital admissions for all cause mental disorders, with risks decreasing steadily as NDVI increased (fig 4). Linear models provided a better fit in Canada, South Korea, and Thailand, while spline models (three degrees of freedom) fit better in Australia, Brazil, Chile, and New Zealand (see supplementary table S5). For example, in Australia, a change in NDVI from 0.2 to 0.4 was associated with a reduction in the risk of hospital admissions for mental disorders by about 10%, with further reductions found as NDVI values increased beyond 0.6. Despite statistical evidence of non-linearity, the overall exposure-response relation remained directionally consistent, with no clear threshold or inflection point identified.

Stratified analyses by NDVI thirds (see supplementary figure S8) further supported these findings. In Brazil, Canada, New Zealand, and Thailand, stronger protective associations were observed in higher thirds of greenness, although no distinct threshold or plateau effect was identified.

Greenness related hospital admissions

During the study period, an estimated 1213 (95% CI 1113 to 1313) hospital admissions for all cause mental disorders annually in New Zealand were statistically associated with exposure to greenness,

corresponding to 7.95% (95% CI 7.29% to 8.60%) of hospital admissions in urban locations. The annual number and proportion of greenness related hospital admissions for mental disorders were 20 (95% CI 15 to 16, 3.40%) in South Korea, 605 (519 to 691, 4.60%) in Thailand, 719 (601 to 837, 2.33%) in Canada, 4677 (4072 to 5285, 2.51%) in Brazil, 328 (296 to 360, 1.71%) in Chile, and 150 (85 to 214, 0.24%) in Australia (fig 5, table 1).

Cause specific attributable fractions varied by country and type of mental disorder. For example, in New Zealand, exposure to greenness was associated with a reduction in annual anxiety related hospital admissions of 145 (95% CI 111 to 179), while in Australia, exposure to greenness was associated with an increase of 78 (42 to 114) in such admissions (fig 5, table 1).

We also evaluated the potential impact of greenness intervention scenarios in urban areas (see supplementary table S6). For example, a 10% increase in greenness was associated with reductions in hospital admissions for mental disorders ranging from ~1 per 100 000 in South Korea to ~1000 per 100 000 in New Zealand.

Discussion

This study examined the association between exposure to greenness and mental health, utilising data on hospital admissions from seven countries across in both northern and southern hemispheres and diverse geographical, climatic, and urbanisation contexts. We observed significant associations between higher levels of greenness and reduced risks of hospital admissions for all cause mental disorders, psychotic disorders, substance use disorders, anxiety, and dementia. Our findings indicate a monotonic, approximately linear exposure-response relation, with no clear threshold.

Previous epidemiological studies showed mixed results, with statistical significance varying by study and context. Some studies have shown the mental health benefits of exposure to greenness, particularly in reducing the risks of anxiety,⁴²⁻⁴⁴ mood disorders,^{42 44 45} and psychotic disorders,^{17 46 47} and higher scores on mental health and vitality scales.⁴⁸ The protective associations observed for behavioural disorders, substance use disorders, and dementia in some countries in this study extend these findings. Most previous studies on greenness and mental disorders have been conducted in developed regions, with Europe accounting for the largest share, followed by north America. By including data from Thailand, Brazil, Chile, New Zealand, and South Korea, our study broadens the understanding of these associations in less studied regions.

Urban-rural comparisons revealed heterogeneity in the association between greenness and mental health. Protective associations were more consistent in urban settings, where green spaces are typically more structured, accessible, and integrated into the built environment. In contrast, rural regions are characterised by vast, less structured natural

environments, including forests and agricultural land. The organised green spaces in rural areas may be more heterogeneous in quality and accessibility.⁴⁹ These variations might affect how residents engage with green spaces, which, in turn, could have an influence on their mental health.

Our findings suggest seasonal differences in the associations between greenness and hospital admissions for mental disorders. Climate and weather conditions play a crucial role in how green spaces are used and perceived. In tropical or temperate regions such as Brazil, Chile, and Thailand, where temperatures remain relatively stable throughout the year, greenness showed stronger associations during the “cold season.” This could be because landscapes remain green during the cooler months, and milder temperatures may make green space more appealing, encouraging outdoor activities that benefit mental health. In countries with stronger seasonal changes, such as Canada, greenness has a more important impact during the warmer months, when the landscape is greener and outdoor activities are more feasible. In Australia and New Zealand, where outdoor recreation is a prominent part of the culture, the mental health benefits of greenness may not show strong seasonal fluctuations. In addition, the overall impact of greenness on mental health might be reduced by better access to mental healthcare and preventive services.

A recent study in Canada modelled the non-linear association between greenness and depression scales using cubic spline regression. The exposure-response curve was largely linear, with slight non-linear inverse patterns emerging when NDVI values exceeded 0.8.¹⁶ In another study, from Shanghai, China, machine learning algorithms were used to assess the impact of exposure to green spaces on psychological stress. The study found that green spaces had a positive effect on reducing stress, but the effect diminished once exposure to green spaces exceeded a threshold of 0.35.¹³ In contrast, several other studies conducted in different contexts, such as the Netherlands,^{21 50} Italy,⁵¹ Canada,⁵² and China⁴⁷ did not observe statistically significant non-linear associations. Some of these studies addressed non-linearity by comparing different fourths or 10ths of greenness (eg, the highest versus the lowest fourth).^{21 46 47 52} The variability in findings suggests that the evidence on thresholds remains inconclusive, varies by population, landscape type, and exposure context, and may be difficult to detect in ecological data.

Public health relevance and implications

Our findings suggest that a considerable proportion or rate of hospital admissions for mental disorders may be associated with exposure to greenness and could potentially be reduced through greening interventions under realistic scenarios. These mental health benefits may also bring broader economic and social advantages, including reduced healthcare costs, less strain on health systems, improved workplace productivity, and enhanced community wellbeing.⁵³

Although this study is based on ecological time series data, the implications for exposure to greenness at individual and household level are increasingly relevant. Evidence suggests that even small scale or passive interactions with vegetation, such as viewing greenery from a window, tending to indoor plants, or greening private balconies and yards, can support mental wellbeing.⁵⁴

Strengths and limitations of this study

This study has several strengths, including its large sample size, use of harmonised statistical methods across diverse settings, cause specific models, and exploration of seasonality and non-linear patterns. However, several limitations should be acknowledged. Data on hospital admissions were sourced from multiple countries, introducing uncertainties owing to differences in the management of mental health systems. Our outcome measure of inpatient hospital admissions for mental disorders captures people with more severe mental health conditions requiring inpatient care but excludes a substantial proportion of milder, subclinical, or untreated mental health conditions managed in outpatient or community settings. As such, our findings underestimate the full burden of mental health and do not reflect the broader spectrum of psychological distress in relation to greenness. As this study was observational, residual confounding cannot be excluded, although findings remained unchanged after additional adjustment for road density and healthcare access indicators. Although NDVI does not account for qualitative aspects of greenness, such as access, safety, or biodiversity, it serves as a valuable ecological indicator of overall presence of vegetation in the environment. Our NDVI based exposure metric captures the broader environmental greenness, including vegetated surroundings that may be experienced visually or incidentally, and is thus relevant even in the absence of direct access to green spaces. However, future research should aim to explore the differential effects of various types of green spaces, such as parks or forests, on mental health outcomes,⁵⁵ and focus on assessing the quality and accessibility of green spaces. While our study does not provide individual level guidance, it highlights the public health value of greening strategies at neighbourhood scale and underscores the need for future studies on local greening and individual level outcomes. Future research should also explore how greenness related interventions could be incorporated into individual care plans. This includes evaluating the feasibility and effectiveness of social prescribing of exposure to green spaces. Lastly, differences in geographical units across countries may introduce variation owing to differences in the size and structure of administrative units. We used the finest resolution available and adjusted for population and location level covariates, but differences in geographical units remain a source of potential heterogeneity.

Conclusion

This multicountry ecological study highlights the complex and context specific association between exposure to greenness and hospital admissions for mental disorders. While greenness was statistically associated with lower risks of hospital admissions for several mental disorder disorders, particularly in urban settings and in Brazil, Chile, and Thailand, some adverse or null associations were observed, including modestly increased risks in Australia and Canada. The heterogeneity across countries, seasons, and types of mental disorders underscores the need for locally tailored approaches when evaluating the mental health implications of environmental greenness. These findings could inform future research and public health planning related to environmental determinants of mental health.

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Ethical approval: This study was approved by Monash University Human Research Ethics Committee (project ID 29141).

Data sharing: Data for weather indicators, greenness, global population, and urban-rural classifications are available for free from the European Centre for Medium-Range Weather Forecasts reanalysis version 5 (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>), Moderate Resolution Imaging Spectroradiometer vegetation index products (<https://modis.gsfc.nasa.gov/data/dataproduct/mod13.php>), WorldPop (<https://www.worldpop.org/catalog/>), and Global Human Settlement Layer (<https://human-settlement.emergency.copernicus.eu/>), respectively. Analysis codes are available from the corresponding authors on request and will be shared on https://github.com/pipty/Green_Mental.

Transparency: The lead authors (YG and SL) affirm that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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- Steel Z, Marnane C, Iranpour C, et al. The global prevalence of common mental disorders: a systematic review and meta-analysis 1980-2013. *Int J Epidemiol* 2014;43:476-93. doi:10.1093/ije/dyu038
- Ferrari AJ, Santomauro DF, Aali A, et al. GBD 2021 Diseases and Injuries Collaborators. Global incidence, prevalence, years lived with disability (YLDs), disability-adjusted life-years (DALYs), and healthy life expectancy (HALE) for 371 diseases and injuries in 204 countries and territories and 811 subnational locations, 1990-2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024;403:2133-61. doi:10.1016/S0140-6736(24)00757-8
- GBD 2019 Mental Disorders Collaborators. Global, regional, and national burden of 12 mental disorders in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet Psychiatry* 2022;9:137-50. doi:10.1016/S2215-0366(21)00395-3
- Arias D, Saxena S, Verguet S. Quantifying the global burden of mental disorders and their economic value. *EclinicalMedicine* 2022;54:101675. [https://www.thelancet.com/journals/eclinm/article/PIIS2589-5370\(22\)00405-9/fulltext](https://www.thelancet.com/journals/eclinm/article/PIIS2589-5370(22)00405-9/fulltext). doi:10.1016/j.eclinm.2022.101675
- Perkins-Kirkpatrick SE, Lewis SC. Increasing trends in regional heatwaves. *Nat Commun* 2020;11:3357. doi:10.1038/s41467-020-16970-7
- Wang S, Gao S, Li S, Feng K. Strategizing the relation between urbanization and air pollution: Empirical evidence from global countries. *J Clean Prod* 2020;243:118615doi:10.1016/j.jclepro.2019.118615.
- Romanello M, Napoli CD, Green C, et al. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *Lancet* 2023;402:2346-94. doi:10.1016/S0140-6736(23)01859-7
- Ventriglio A, Torales J, Castaldelli-Maia JM, De Berardis D, Bhugra D. Urbanization and emerging mental health issues. *CNS Spectr* 2021;26:43-50. doi:10.1017/S1092852920001236
- Tota M, Karska J, Kowalski S, et al. Environmental pollution and extreme weather conditions: insights into the effect on mental health. *Front. Psychiatry* 2024;15 (cited 6 May 2025). www.frontiersin.org/journals/psychiatry/articles/10.3389/fpsy.2024.1389051/full
- Guo J, Garshick E, Si F, et al. Environmental Toxicant Exposure and Depressive Symptoms. *JAMA Netw Open* 2024;7:e2420259. doi:10.1001/jamanetworkopen.2024.20259
- Hahad O, Kuntic M, Al-Kindi S, et al. Noise and mental health: evidence, mechanisms, and consequences. *J Expo Sci Environ Epidemiol* 2025;35:16-23. doi:10.1038/s41370-024-00642-5
- Ye T. Green space and health in children. 2024 (cited 7 May 2025). https://bridges.monash.edu/articles/thesis/Green_space_and_health_in_children/26518600/1
- Zhang T, Wang L, Zhang Y, Hu Y, Zhang W. Assessing the nonlinear impact of green space exposure on psychological stress perception using machine learning and street view images. *Front. Public Health* 2024;12 (cited 6 May 2025). www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2024.1402536/full
- Geary RS, Thompson D, Mizen A, et al. Ambient greenness, access to local green spaces, and subsequent mental health: a 10-year longitudinal dynamic panel study of 2-3 million adults in Wales. *Lancet Planet Health* 2023;7:e809-18. doi:10.1016/S2542-5196(23)00212-7
- Slawsky ED, Hajat A, Rhew IC, et al. Neighborhood greenspace exposure as a protective factor in dementia risk among U.S. adults 75 years or older: a cohort study. *Environ Health* 2022;21:14. doi:10.1186/s12940-022-00830-6
- Abraham Cottagiri S, Villeneuve PJ, Raina P, et al. Increased urban greenness associated with improved mental health among middle-aged and older adults of the Canadian Longitudinal Study on Aging (CLSA). *Environ Res* 2022;206:112587. doi:10.1016/j.envres.2021.112587
- Engemann K, Svenning JC, Arge L, et al. Natural surroundings in childhood are associated with lower schizophrenia rates. *Schizophr Res* 2020;216:488-95. doi:10.1016/j.schres.2019.10.012
- Wendelboe-Nelson C, Kelly S, Kennedy M, Cherrie JW. A Scoping Review Mapping Research on Green Space and Associated Mental Health Benefits. *Int J Environ Res Public Health* 2019;16:2081. doi:10.3390/ijerph16122081
- Zagnoli F, Filippini T, Jimenez MP, Wise LA, Hatch EE, Vinceti M. Is Greenness Associated with Dementia? A Systematic Review and Dose-Response Meta-analysis. *Curr Environ Health Rep* 2022;9:574-90. doi:10.1007/s40572-022-00365-5
- Yoo EH, Roberts JE, Eum Y, Li X, Konty K. Exposure to urban green space may both promote and harm mental health in socially vulnerable neighborhoods: A neighborhood-scale analysis in New York City. *Environ Res* 2022;204:112292. doi:10.1016/j.envres.2021.112292
- Helbich M, O'Connor RC, Nieuwenhuijsen M, Hagedoorn P. Greenery exposure and suicide mortality later in life: A longitudinal register-based case-control study. *Environ Int* 2020;143:105982. doi:10.1016/j.envint.2020.105982
- Lam MK. How good is New South Wales admitted patient data collection in recording births? *Health Inf Manag* 2011;40:12-9. doi:10.1177/183335831104000302
- Nakamura-Pereira M, Mendes-Silva W, Dias MAB, Reichenheim ME, Lobato G. Sistema de Informações Hospitalares do Sistema Único de Saúde (SIH-SUS): uma avaliação do seu desempenho para a identificação do near miss materno. [The Hospital Information System of the Brazilian Unified National Health System: a performance evaluation for auditing maternal near miss.] *Cad Saude Publica* 2013;29:1333-45. doi:10.1590/S0102-311X2013000700008
- Amua JE, Molodianovitch K, Carbone S, et al. Development and validation of a hospital frailty risk measure using Canadian clinical administrative data. *CMAJ* 2023;195:E437-48. doi:10.1503/cmaj.220926
- Departamento de Estadísticas e Información de Salud. <https://deis.minsal.cl/>
- National Minimum Dataset. (hospital events) - Health New Zealand. Te Whatu Ora (cited May 2025).: <https://www.tewhatuora.govt.nz/for-health-professionals/data-and-statistics/nz-health-statistics/national-collections-and-surveys/collections/national-minimum-dataset-hospital-events>
- Wen B, Kliengchuay W, Suwanmanee S, et al. Association of cause-specific hospital admissions with high and low temperatures in Thailand: a nationwide time series study. *Lancet Reg Health West Pac* 2024;46:101058. [https://www.thelancet.com/journals/lanwpc/article/PIIS2666-6065\(24\)00052-X/fulltext](https://www.thelancet.com/journals/lanwpc/article/PIIS2666-6065(24)00052-X/fulltext). doi:10.1016/j.lanwpc.2024.101058

- 28 Lee J, Lee JS, Park SH, Shin SA, Kim K. Cohort Profile: The National Health Insurance Service-National Sample Cohort (NHIS-NSC), South Korea. *Int J Epidemiol* 2017;46:e15.
- 29 Lloyd CT, Chamberlain H, Kerr D, et al. Global spatio-temporally harmonised datasets for producing high-resolution gridded population distribution datasets. *Big Earth Data* 2019;3:108-39. doi:10.1080/20964471.2019.1625151
- 30 United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects, 2019. <https://population.un.org/wpp/> (accessed 9 May 2022).
- 31 Kumm M, Kosonen M, Masoumzadeh Sayyar S. Downscaled gridded global dataset for gross domestic product (GDP) per capita PPP over 1990-2022. *Sci Data* 2025;12:178. doi:10.1038/s41597-025-04487-x
- 32 Kumm M, Taka M, Guillaume JHA. Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015. *Sci Data* 2018;5:180004. doi:10.1038/sdata.2018.4
- 33 Weiss DJ, Nelson A, Vargas-Ruiz CA, et al. Global maps of travel time to healthcare facilities. *Nat Med* 2020;26:1835-8. doi:10.1038/s41591-020-1059-1
- 34 Schiavina M, Melchiorri M, Pesaresi M, et al. GHSL Data Package 2023. JRC Publications Repository, 2023 (cited 24 Jan 2025). <https://publications.jrc.ec.europa.eu/repository/handle/JRC133256>
- 35 Pan N, Feng X, Fu B, Wang S, Ji F, Pan S. Increasing global vegetation browning hidden in overall vegetation greening: Insights from time-varying trends. *Remote Sens Environ* 2018;214:59-72. doi:10.1016/j.rse.2018.05.018.
- 36 Ye T, Xu R, Huang W, et al. Billions of people exposed to increasing heat but decreasing greenness from 2000 to 2022. *Innovation (Camb)* 2025;6:100870. doi:10.1016/j.xinn.2025.100870
- 37 Didan K. MODIS/Terra Vegetation Indices Monthly L3 Global 1km SIN Grid V061 [Data set]. 2021 (cited 6 May 2025) <https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod13a3-061>
- 38 Xu R, Ye T, Yue X, et al. Global population exposure to landscape fire air pollution from 2000 to 2019. *Nature* 2023;621:521-9. doi:10.1038/s41586-023-06398-6
- 39 Hersbach H, Bell B, Berrisford P, et al. The ERA5 global reanalysis. *Q J R Meteorol Soc* 2020;146:1999-2049. doi:10.1002/qj.3803.
- 40 Damasceno da Silva RM, Andreotti Dias M, Rodrigues Ferreira Barbosa V, Jablinski Castelhanos F, James P, Requia WJ. Greenness and Hospitalization for Cardiorespiratory Diseases in Brazil. *Environ Health Perspect* 2024;132:67006. doi:10.1289/EHP13442
- 41 Xu R, Ye T, Huang W, et al. Multi-Country Multi-City Collaborative Research Network. Global, regional, and national mortality burden attributable to air pollution from landscape fires: a health impact assessment study. *Lancet* 2024;404:2447-59. doi:10.1016/S0140-6736(24)02251-7
- 42 Astell-Burt T, Feng X. Association of Urban Green Space With Mental Health and General Health Among Adults in Australia. *JAMA Netw Open* 2019;2:e198209. doi:10.1001/jamanetworkopen.2019.8209
- 43 Nutsford D, Pearson AL, Kingham S. An ecological study investigating the association between access to urban green space and mental health. *Public Health* 2013;127:1005-11. doi:10.1016/j.puhe.2013.08.016
- 44 Beyer KMM, Kaltenbach A, Szabo A, Bogar S, Nieto FJ, Malecki KM. Exposure to neighborhood green space and mental health: evidence from the survey of the health of Wisconsin. *Int J Environ Res Public Health* 2014;11:3453-72. doi:10.3390/ijerph110303453
- 45 Generaal E, Hoogendijk EQ, Stam M, et al. Neighbourhood characteristics and prevalence and severity of depression: pooled analysis of eight Dutch cohort studies. *Br J Psychiatry* 2019;215:468-75. doi:10.1192/bjp.2019.100
- 46 Chang HT, Wu CD, Wang JD, Chen PS, Wang YJ, Su HJ. Green space structures and schizophrenia incidence in Taiwan: is there an association? *Environ Res Lett* 2020;15:094058. doi:10.1088/1748-9326/ab91e8
- 47 Song J, Liang Y, Xu Z, et al. Built environment and schizophrenia re-hospitalization risk in China: A cohort study. *Environ Res* 2023;227:115816. doi:10.1016/j.envres.2023.115816
- 48 van den Berg M, van Poppel M, van Kamp I, et al. Visiting green space is associated with mental health and vitality: A cross-sectional study in four European cities. *Health Place* 2016;38:8-15. doi:10.1016/j.healthplace.2016.01.003
- 49 Lin Y, Shui W, Li Z, et al. Green space optimization for rural vitality: Insights for planning and policy. *Land Use Policy* 2021;108:105545. doi:10.1016/j.landusepol.2021.105545.
- 50 Bloemsma LD, Wijga AH, Klompmaaker JO, et al. Green space, air pollution, traffic noise and mental wellbeing throughout adolescence: Findings from the PIAMA study. *Environ Int* 2022;163:107197. doi:10.1016/j.envint.2022.107197
- 51 Asta F, Michelozzi P, Cesaroni G, De Sario M, Davoli M, Porta D. Green spaces and cognitive development at age 7 years in a Rome birth cohort: The mediating role of nitrogen dioxide. *Environ Res* 2021;196:110358. doi:10.1016/j.envres.2020.110358
- 52 Paul LA, Hystad P, Burnett RT, et al. Urban green space and the risks of dementia and stroke. *Environ Res* 2020;186:109520. doi:10.1016/j.envres.2020.109520
- 53 Wolf KL, Measells MK, Grado SC, Robbins AST. Economic values of metro nature health benefits: A life course approach. *Urban For Urban Green* 2015;14:694-701 doi:10.1016/j.ufug.2015.06.009.
- 54 Bratman GN, Anderson CB, Berman MG, et al. Nature and mental health: An ecosystem service perspective. *Sci Adv* 2019;5:eaax0903. doi:10.1126/sciadv.aax0903
- 55 Akpinar A, Barbosa-Leiker C, Brooks KR. Does green space matter? Exploring relationships between green space type and health indicators. *Urban For Urban Green* 2016;20:407-18. doi:10.1016/j.ufug.2016.10.013

Supplementary information: Methods, tables S1-S5, figures S1-S8, and additional references