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# Association between residential greenness and severe psychological distress and the moderating role of 'stay-at-home' status: a population-based cross-sectional study during the COVID-19 pandemic in Japan

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## ABSTRACT

**Objective** There is a need for public health strategies to address the negative psychological consequences of the COVID-19 pandemic, and the role of residential green exposure has gained prominence, particularly in the context of the 'new normal' and the prevailing 'stay-at-home' policies. This study aimed to evaluate the association between residential greenness and severe psychological distress during the COVID-19 pandemic in Japan. We also investigated the association stratified by 'stay-at-home' status, a proxy for exposure to residential greenness.

**Methods and analysis** We used data from a population-based cohort study conducted in Utsunomiya City, Japan. Residential greenness was measured by the normalised difference vegetation index (NDVI) averaged over circular buffers around residence. Severe psychological distress was defined as a Kessler Psychological Distress Scale (K6) score ≥13. 'Stay-at-home' status was categorised as either 'not stay-at-home' (individuals working outside the home or self-employed) or 'stay-at-home' (working from home or not working), based on the working status. Logistic regression analysis was performed to examine the association between residential greenness and severe psychological distress.

**Results** A total of 615 participants were analysed. Among the 'stay-at-home' group, an IQR increase in NDVI was inversely associated with severe psychological distress (100 m buffer: OR=0.27, 95% CI 0.10 to 0.77; 250 m buffer: OR=0.26, 95% CI 0.10 to 0.69; 500 m buffer: OR=0.33, 95% CI 0.11 to 0.95). However, no significant association was observed for the 'not stay-at-home' group.

**Conclusion** Residential greenness was a protective factor for severe psychological distress among the 'stay-at-home' group, who were assumed to have spent more time in their residence.

### WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Previous evidence suggests that higher residential greenness is associated with better mental health; however, few studies have examined the potential of residential greenness as a protective factor for mental health problems during the COVID-19 pandemic.

### WHAT THIS STUDY ADDS

⇒ Based on a population-based study conducted in Japan between June and July 2020, we found that residential greenness was a protective factor for severe psychological distress among the 'stay-at-home' individuals, who were assumed to have spent more time in their residence.

### HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Developing better environment for residential greenness may provide countermeasures against deterioration of mental health due to 'stay-at-home' policies.

## INTRODUCTION

The COVID-19 pandemic has witnessed a surge in mental health issues,[1–3] with social isolation being one of the contributing factors. Measures such as social distancing, home confinement, quarantine or isolation[3] have been implemented to curb the spread of COVID-19, leading to increased social isolation and subsequent mental health challenges. Moreover, economic burden is known to be a trigger for deterioration of mental health,[1] and the impact of the COVID-19 pandemic on individuals' financial well-being, including income loss and financial

strain, has been linked to the manifestation of depressive symptoms.[4] Conflicting messages from authorities and overabundance of information about COVID-19 may have also contributed to an increased risk of mental illness.[1 5] Against this backdrop, researchers[1 2] and health officials[6] have underscored the critical importance of promptly developing and implementing public health interventions to address mental health issues during the COVID-19 pandemic.

Existing evidence suggests that higher residential greenness is associated with better mental health[7–9] and that greenspaces could be a potential protective factor for mental health problems induced by home confinement.[10] Online surveys conducted in Japan,[11] Italy[12] and Bulgaria[13] have indicated that both subjective indoor and outdoor greenness were positively associated with better mental health during the COVID-19 pandemic. However, it is important to note that these studies have faced a significant limitation in the form of common source bias, primarily stemming from self-reported questionnaires.[14] Only a limited number of studies have examined the relationship between objectively measured residential greenness in proximity to homes and the mental health status during the COVID-19 pandemic.[15]

Notably, individual factors can potentially modify these associations. Roberts *et al*[16] discovered that the link between neighbourhood social characteristics and depressive symptoms was more pronounced among individuals who were non-working or working from home compared with those who worked outside the home. They speculated that individuals who spent more time in their residences would be more influenced by the residential environment.[16] During the COVID-19 pandemic, due to social distancing policies like the 'stay-at-home' policy, people have been encouraged to work remotely and minimise outdoor activities, except for essential purposes.[17] In this context, increased exposure to residential greenness may serve as a protective factor for mental health problems, particularly for individuals working from home.

This study aimed to examine the association between objectively measured residential greenness around the home and severe psychological distress during the COVID-19 pandemic in Japan. In particular, we used 'stay-at-home' status as a proxy for intensity of exposure to residential greenness and examined whether working status moderated the association.

## METHODS

### Participants

This study used data from the Utsunomiya COVID-19 seROprevalence Neighbourhood Association (U-CORONA) study, a population-based cohort study conducted in Utsunomiya City, Japan.[18] The objective of U-CORONA study was to estimate the seroprevalence of SARS-CoV-2 and other physical and mental health conditions among the general population during the COVID-19 pandemic in Japan. Utsunomiya City, as of 2020, is home to an estimated population of around 510 000 individuals residing in approximately 220 000 households.[19] The city encompasses a diverse landscape, encompassing both urban and rural areas, and accommodates a wide range of households, including those with children as well as elderly residents. We considered Utsunomiya City to be a representative area of a typical Japanese city and hence making it a suitable location for conducting this study. The flow chart of sampling is presented in figure 1. Briefly, invitations containing self-administered questionnaires were distributed to a total of 2290 citizens, including 1973 adults aged 18 years or older and 317 children below the age of 18 years. These invitations were sent to 1000 randomly selected households from the basic resident registry of Utsunomiya City. Of the recipients, 753 individuals from 333 households (649 adults and 104 children) responded to the invitations and actively participated in this face-to-face study, resulting in a participation rate of 32.9%. The participants visited the study site, Kuramochi Clinic Interpark, a general practitioner clinic in Utsunomiya City, between June 14 and July 5, 2020, following the conclusion of the first wave of the pandemic. They completed the questionnaires and submitted them during their visit. It is noteworthy that Utsunomiya City was under a state of emergency, declared by the Japanese government, from April 16 to May 14, 2020.[20] People were urged to stay at home, except for essential activities, although it was not mandatory.

We excluded children (n=104) from the analysis since severe psychological distress was only assessed for adults. Additionally, we excluded adults with missing values for either severe psychological distress or 'stay-at-home' status (n=34), resulting in an analytical sample of 615 participants from 314 households.

We calculated the required sample size as follows: we assumed that the prevalence of severe psychological distress was 0.07–0.1[21 22] and that the OR of depression for an IQR increase in residential greenness measured by the normalised difference vegetation index (NDVI) was 0.4–0.6.[23] Using a two-tailed test with a significance level of 0.05 and a statistical power of 80%, a sample size of 534 was obtained. Expecting a dropout rate of 10%, a sample size of 588 or larger was estimated to be sufficient. Background characteristics of the study participants differed from those of the adult non-participants in age (51.3 vs 53.7 years old, respectively, p=0.012), presence of cohabitants (88.1% vs 81.0%, respectively, p<0.001) and residential district (centre, east and south: 38.2%, 40.2% and 21.6% vs 32.1%, 39.7% and 28.3%, respectively, p=0.003) (online supplemental table 1). This study conforms to the Strengthening the Reporting of Observational Studies in Epidemiology statement.[24]

### Residential greenness

Residential greenness was characterised by the NDVI, which was calculated according to land surface reflectance of near-infrared (NIR) and visible red (RED)

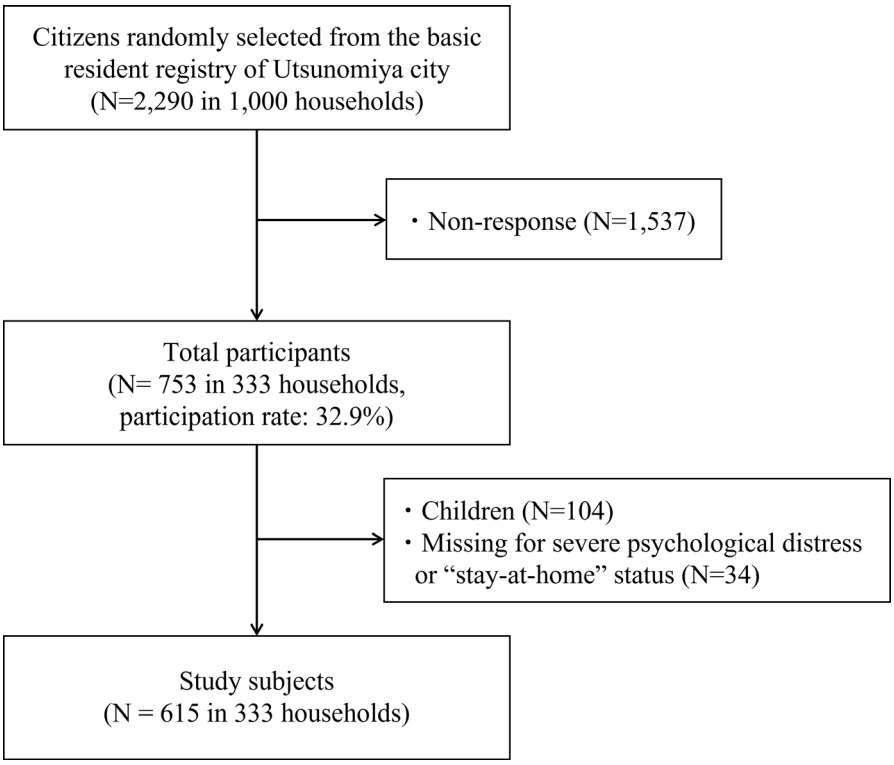


**Figure 1** Flow chart of sampling.

radiation obtained from satellite data.[25] Healthy green vegetation reflects more near-infrared radiation and absorbs more visible red radiation when compared with unhealthy vegetation or non-vegetated land. NDVI is calculated based on the following formula: NDVI = (NIR – RED) / (NIR+RED). NDVI ranges from −1 to 1, with higher values indicating more greenness. Spectral data captured from Landsat 8 Operational Land Imager at 30 m × 30 m resolutions on 1 August 2019 were downloaded from the website of National Institute of Advanced Industrial Science and Technology.[26] We selected cloud-free summertime images because NDVI exhibits its maximum and highest level of geographical variance in summer.[27] NDVI was averaged over circular buffers of 100 m, 250 m, 500 m and 1000 m around each residential location because these distances have been frequently used in previous studies.[27 28] Home address of each participant was extracted from the basic resident registry of Utsunomiya City and geocoded based on ArcGIS Online World Geocoding Service (ESRI, Redlands, California, USA), Google Earth (Google, Mountain View, California, USA), Itsumo Navi Labo (ZENRIN DataCom, Tokyo, Japan) and Blue Map (ZENRIN, Fukuoka, Japan).

### Severe psychological distress

Severe psychological distress was assessed through self-reporting by using the validated Kessler Psychological Distress Scale (K6).[29] Respondents were asked how often they had felt (1) nervous, (2) hopeless, (3) restless or fidgety, (4) so depressed that nothing could cheer you up, (5) that everything was an effort and (6) worthless during the past 30 days. Responses were provided on a 5-point Likert scale (0=none of the time; 1=a little of the time; 2=some of the time; 3=most of the time; 4=all of the time), which resulted in total scores ranging from 0 to 24. We used the Japanese version of K6, which had been validated and is considered reliable for the Japanese population.[30] Severe psychological distress was defined as a total score of 13 or higher, following the original work by Kessler *et al*[29] and a randomised controlled trial that investigated the impact of greening intervention on self-reported mental health.[31]

### Covariates

Individuals who were working from home or not working were categorised as the 'stay-at-home' group, based on a previous study conducted by Roberts *et al*.[16] Conversely, individuals who were working outside the home or were self-employed were classified as the 'not stay-at-home' group. Covariates including age, sex, presence or absence of cohabitants, residential district, presence or absence of comorbidities, education (junior/senior high school, vocational school and university/higher), working status and household income (Japanese yen (JPY) 0–<4 million, JPY 4–<8 million and JPY +8 million) were assessed. Information on age, sex, presence or absence of cohabitants and residential district were based on the basic resident registry of Utsunomiya City. Residential district was categorised into centre, east and south areas, based on the police jurisdiction of Utsunomiya City.[32] Other variables were assessed via a self-rated questionnaire. Comorbidities include seasonal allergy, asthma, cardiological disease, renal disease, immune disease, diabetes, cancer, arthritis, epilepsy/convulsion, gastroenteric disease,

dermatological disease, mental disease, alcohol/drug abuse, intellectual disabilities, autism spectrum disorder, learning disabilities and tuberculosis.

### Statistical analysis

Logistic regression analysis was performed to examine the association between residential greenness and severe psychological distress. The model was adjusted for age, sex, presence or absence of cohabitants, residential district, presence or absence of comorbidities, education, working status and household income. The variance inflation factors were found to be low, indicating the absence of multicollinearity concerns even when residential districts and greenness were included simultaneously in the model (online supplemental table 2). Furthermore, we tested whether 'stay-at-home' status moderated the association between residential greenness and severe psychological distress using interaction terms between residential greenness and 'stay-at-home' status. Stratified analysis according to the 'stay-at-home' status was further conducted.

Unit non-response was accounted for by non-response weighting.[33] Probability of response was predicted by logistic regression based on individual data from the basic resident registry, including age, sex, distance to the clinic where the survey was conducted, residential district and number of cohabitants.[32] Non-response weights were subsequently obtained as the inverse of the predicted probabilities of response and applied to logistic regression analysis.

There were missing values in education (2.3%) and household income (11.7%). These variables were handled with multiple imputation. Fifty imputed datasets were created, and estimates obtained from each imputed dataset were combined using Rubin's rules.[34] For sensitivity analysis, complete case analysis excluding data with missing values was performed. Furthermore, we further refined the sample by including only employed individuals and stratifying the analysis based on whether they worked outside the home or from home. In the imputed dataset analysis, models were adjusted for age, sex and presence or absence of cohabitants: to avoid violation of positivity, residential district, presence or absence of comorbidities, education and household income were not included. Finally, to examine a wider range of psychological distress, we defined moderate psychological distress as the total K6 scores of 9 or higher[30] and conducted the same analysis as a sensitivity analysis. All analyses were conducted using STATA 15 (Stata Corp, College Station, Texas, USA). Two-sided p values less than 0.05 were regarded as statistically significant.

### Patient and public involvement

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research.

## RESULTS

The characteristics of study participants in the complete dataset are presented in table 1. We identified 14 (2.6%) participants with severe psychological distress. Participants with severe psychological distress were younger than those without (38.6 vs 51.4 years old, p=0.005). Furthermore, the proportion of participants living with cohabitants was lower among those with severe psychological distress compared with those without distress (64.3% vs 87.8%, p=0.024).

The associations between residential greenness and severe psychological distress in imputed dataset are displayed in table 2. In the crude models, the associations between NDVI and severe psychological distress were not significant for any of the NDVI values averaged over circular buffers of 100 m, 250 m, 500 m or 1000 m. In the models adjusted for age, sex, comorbidities, cohabitants, residential district, education, 'stay-at-home' status and household income, the associations between NDVI and severe psychological distress were also non-significant for NDVI values within 100 m, 250 m, 500 m or 1000 m buffers.

The association between residential greenness and severe psychological distress in imputed dataset, stratified by 'stay-at-home' status, is shown in table 3 and illustrated in figure 2. For the 'stay-at-home' group, an IQR increase in NDVI was inversely associated with severe psychological distress (NDVI 100 m buffer: OR=0.27, 95% CI 0.10 to 0.77; NDVI 250 m buffer: OR=0.26, 95% CI 0.10 to 0.69; NDVI 500 m buffer: OR=0.33, 95% CI 0.11 to 0.95). For NDVI 1000 m buffer, an IQR increase in NDVI was also inversely associated with severe psychological distress, although the associations were not statistically significant (OR=0.43, 95% CI 0.14 to 1.31). In contrast, no significant association was observed for the 'not stay-at-home' group (p value for the interaction: 0.006, 0.011, 0.042 and 0.212 for NDVI 100 m, 250 m, 500 m and 1000 m, respectively).

For sensitivity analysis, complete case analysis (n=546) was also performed. The results were almost identical to those obtained from the imputed dataset. The associations between NDVI and severe psychological distress were not significant for NDVI averaged over 100 m, 250 m, 500 m and 1000 m buffers in both crude and adjusted models (online supplemental table 3). The associations between NDVI and severe psychological distress stratified by 'stay-at-home' status are shown in online supplemental table 4. For the 'stay-at-home' group, higher NDVI values showed protective effect on severe psychological distress: an IQR increase in NDVI was inversely associated with severe psychological distress (NDVI 100 m buffer: OR=0.24, 95% CI 0.07 to 0.86; NDVI 250 m buffer: OR=0.21, 95% CI 0.07 to 0.61; NDVI 500 m buffer: OR=0.30, 95% CI 0.09 to 0.95). For NDVI 1000 m buffer, an IQR increase in NDVI was also inversely associated with severe psychological distress, although the association was not statistically significant (OR=0.40, 95% CI 0.11 to 1.41).

**Table 1** Characteristics of study participants in the complete dataset (N=546)*

| | K6 score ≤12 (n=532) | K6 score ≥13 (n=14) | |
|---|---|---|---|
| | N (%) or mean±SD | N (%) or mean±SD | P value† |
| Age (years) | 51.4±16.8 | 38.6±16.8 | 0.005 |
| Sex | | | 0.058 |
| Female | 274 (51.5) | 11 (78.6) | |
| Male | 258 (48.5) | 3 (21.4) | |
| Comorbidities‡ | | | 0.251 |
| Absent | 159 (29.9) | 2 (14.3) | |
| Present | 373 (70.1) | 12 (85.7) | |
| Cohabitants | | | 0.024 |
| Absent | 65 (12.2) | 5 (35.7) | |
| Present | 467 (87.8) | 9 (64.3) | |
| Residential district | | | 0.690 |
| Centre | 197 (37.0) | 4 (28.6) | |
| East | 219 (41.2) | 6 (42.9) | |
| South | 116 (21.8) | 4 (28.6) | |
| Education | | | > 0.999 |
| Junior/senior high | 206 (38.7) | 6 (42.9) | |
| Vocational | 131 (24.6) | 3 (21.4) | |
| University or higher | 195 (36.7) | 5 (35.7) | |
| 'Stay-at-home' status | | | 0.854 |
| Not 'stay-at-home' | 298 (56.0) | 9 (64.3) | |
| Working outside the home§ | 254 (47.7) | 8 (57.1) | |
| Self-employed§ | 44 (8.3) | 1 (7.1) | |
| 'Stay-at-home' | 234 (44.0) | 5 (35.7) | |
| Working from home¶ | 64 (12.0) | 2 (14.3) | |
| Not working¶ | 170 (32.0) | 3 (21.4) | |
| Household income | | | 0.087 |
| JPY 0–<4 million | 154 (28.9) | 8 (57.1) | |
| JPY 4–<8 million | 230 (43.2) | 3 (21.4) | |
| JPY +8 million | 148 (27.8) | 3 (21.4) | |
| NDVI 100 m | 0.186±0.073 | 0.166±0.051 | 0.309 |
| NDVI 250 m | 0.199±0.078 | 0.185±0.057 | 0.526 |
| NDVI 500 m | 0.209±0.084 | 0.195±0.065 | 0.516 |
| NDVI 1000 m | 0.218±0.082 | 0.206±0.068 | 0.589 |

*Logistic regression analysis was performed based on the imputed dataset (n=615).
†Statistical tests performed: Fisher's exact test for sex, comorbidities, cohabitants, residential district, education, working status and household income; t-test for age and NDVI.
‡Comorbidities assessed: seasonal allergy, asthma, cardiovascular disease, renal disease, immune disease, diabetes, cancer, arthritis, epilepsy/convulsion, gastroenteric disease, dermatological disease, mental disease, alcohol/ drug abuse, intellectual disabilities, autism spectrum disorder, learning disabilities and tuberculosis.
§Those working outside the home or those self-employed were categorised into the 'not stay-at-home' group.
¶Those working from home or those not working were categorised into the 'stay-at-home' group.
JPY, Japanese yen; K6, Kessler Psychological Distress Scale; NDVI, normalised difference vegetation index.

Similar associations were observed when we refined the sample by including only employed individuals (n=366) (online supplemental table 5). For the 'working from home' group, higher NDVI values were inversely associated with severe psychological distress (NDVI 100 m buffer: OR=0.11, 95% CI 0.03 to 0.43; NDVI 250 m buffer: OR=0.38, 95% CI 0.15 to 0.94). For NDVI 500 m and 1000 m buffers, an increase in NDVI was also inversely

**Table 2** Association between residential greenness (NDVI) and severe psychological distress (K6 score ≥13) in the imputed dataset (n=615)

| | Crude model | | Adjusted model* | |
|---|---|---|---|---|
| | OR (95% CI)† | P value | OR (95% CI)† | P value |
| NDVI 100 m‡ | 0.71 (0.38 to 1.31) | 0.267 | 0.77 (0.44 to 1.34) | 0.352 |
| NDVI 250 m‡ | 0.82 (0.43 to 1.58) | 0.560 | 0.86 (0.46 to 1.60) | 0.627 |
| NDVI 500 m‡ | 0.82 (0.41 to 1.66) | 0.582 | 0.83 (0.42 to 1.66) | 0.597 |
| NDVI 1000 m‡ | 0.85 (0.41 to 1.75) | 0.657 | 0.85 (0.41 to 1.75) | 0.655 |

*Adjusted for age, sex, comorbidities, cohabitants, residential district, education, 'stay-at-home' status and household income.
†OR and 95% CI were estimated for an IQR increment in NDVI.
‡Average NDVI values within circular buffers of 100 m, 250 m, 500 m and 1000 m of each residential location were used.
K6, Kessler Psychological Distress Scale; NDVI, normalised difference vegetation index.

associated with severe psychological distress, although the associations were not statistically significant (NDVI 500 m buffer: OR=0.41, 95% CI 0.15 to 1.08; NDVI 1000 m buffer: OR=0.45, 95% CI 0.17 to 1.16).

The same trend was observed when we reset the cut-off value for total K6 scores to 8/9. An increase in NDVI was inversely associated with moderate psychological distress, although the associations were not statistically significant (NDVI 250 m buffer: OR=0.88, 95% CI 0.44 to 1.78; NDVI 500 m buffer: OR=0.84, 95% CI 0.40 to 1.74; NDVI 1000 m buffer: OR=0.93, 95% CI 0.48 to 1.79) (online supplemental table 6).

## DISCUSSION

This study was one of the pioneering efforts to investigate the association between objectively measured residential greenness and severe psychological distress during the COVID-19 pandemic. Our findings reveal an inverse association between residential greenness and severe psychological distress among individuals who likely spent more time at home. Importantly, by employing objective measurements of residential greenness, this study avoids the common source bias that affected previous research relying on self-reported questionnaires to assess mental health in relation to subjective greenness.[14]

Several mechanisms have been suggested to explain the positive impact of residential greenness on mental health,[9 35] including: (a) stress recovery and attention restoration through exposure to green spaces; (b) a healthier environment with reduced air pollution and noise levels; and (c) increased opportunities for physical activity and social interaction. It is worth noting that social isolation and loneliness have been linked to heightened inflammation[36 37] which, in turn, is associated with poorer mental health outcomes.[38] Mental health has emerged as a crucial concern during the COVID-19 pandemic, primarily due to the impact of social distancing measures that have limited opportunities for physical activity and social interaction.[2] However, our findings indicate that even amidst 'stay-at-home' policies, residential green spaces have demonstrated positive effects on mental well-being when viewed from home.

The conventional assessment of the residential environment has faced considerable criticism.[39] One aspect that has often been overlooked is exposure misclassification, as many studies have failed to consider the variability in individual exposure to residential greenness. Furthermore, studies examining the link between residential greenness and mental health have predominantly assumed that individuals remain fixed at specific locations, such as their residence.[40 41] In reality, however, individuals are exposed to a variety of environments beyond their residential areas, including their work and leisure environments.[40 42] Individual factors, such as employment status, can result

**Table 3** Association between residential greenness (NDVI) and severe psychological distress (K6 score ≥13) in the imputed dataset (n=615), stratified by the 'stay-at-home' status

| Buffer size for NDVI | OR (95% CI) | | P for interaction |
|---|---|---|---|
| | Not stay-at-home | Stay-at-home | |
| 100 m | 0.91 (0.47 to 1.79) | 0.27 (0.10 to 0.77) | 0.006 |
| 250 m | 0.98 (0.44 to 2.19) | 0.26 (0.10 to 0.69) | 0.011 |
| 500 m | 0.94 (0.37 to 2.37) | 0.33 (0.11 to 0.95) | 0.042 |
| 1000 m | 0.92 (0.33 to 2.59) | 0.43 (0.14 to 1.31) | 0.212 |

All models adjusted for age, sex, comorbidities, cohabitants, residential district, education, and household income.
OR and 95% CI were estimated for an IQR increment in NDVI.
K6, Kessler Psychological Distress Scale; NDVI, normalised difference vegetation index.

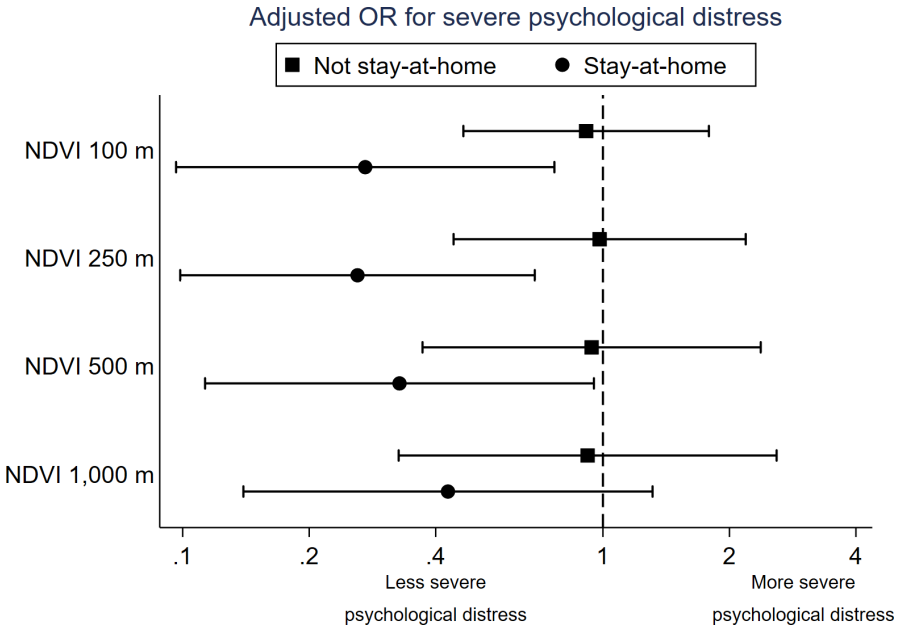


**Figure 2** Diagram for the association between residential greenness (NDVI) and severe psychological distress (K6 score ≥13) in the imputed dataset (n=615), stratified by the 'stay-at-home' status. All models were adjusted for age, sex, comorbidities, cohabitants, residential district, education and household income. OR and 95% CI were estimated for an IQR increment in NDVI and illustrated on a log scale. Solid squares and solid circles refer to the 'not stay-at-home' group (those working outside the home or those self-employed) and the 'stay-at-home' group (those working from home or those not working), respectively. Solid lines indicate 95% CI. Average NDVI values within circular buffers of 100 m, 250 m, 500 m and 1000 m of each residential location were used. K6, Kessler Psychological Distress Scale; NDVI, normalised difference vegetation index.

in varying levels of exposure to the neighbourhood. For instance, a study by Perchoux *et al*[39] revealed that unemployed individuals had smaller activity spaces compared with those who were employed. The authors speculated that the observed trend among unemployed residents indicated greater confinement to their residences and limited opportunities to travel beyond their immediate neighbourhoods.[39] Individuals who had higher levels of exposure to residential greenness were more likely to be influenced by the surrounding environment near their homes. As a result, the 'stay-at-home' group, who experienced greater confinement to their residences, may have experienced an amplified exposure to residential greenness. In contrast, the 'not stay-at-home' group would have maintained a similar level of exposure to residential greenness.

Significant associations were observed between NDVI and severe psychological distress for the 'stay-at-home' group within the 100 m, 250 m and 500 m buffers, while no significant associations were found for the 1000 m buffers. Previous studies have indicated that areas beyond 300–400 m buffers around the home are less frequently visited compared with those within this range.[43 44] Additionally, another study highlighted that the distance of 250 m approximately represents the extent of people's visual surroundings from their homes.[45] Moreover, Gascon *et al*[9] highlighted that if the relationship between residential greenness and mental health operates through attention restoration achieved by simply viewing green spaces, individuals residing in proximity to green spaces are likely to experience more beneficial effects. The findings from these studies suggest that smaller buffer sizes may better capture the restorative influences of residential greenness. Consistent with these previous studies, our results also suggest that smaller buffer distances around the home may better represent the restorative influences, as individuals can still benefit from the view of residential greenness even when staying at home.

Nonetheless, several limitations to this study should be noted. First, although NDVI is widely used as a measure of residential greenness in epidemiological studies, it does not take into account the specific types of vegetation present.[28] The effects of residential greenness on mental health may differ depending on the types of vegetation. For example, Astell-Burt and Feng[46] found that exposure to tree canopy was associated with better mental health, while exposure to grass was linked to poorer mental health outcomes. Our study did not consider the geographic variation in vegetation, which may have resulted in non-differential misclassification of exposure and potentially underestimated the associations between residential greenness and mental health.

Second, there is a possibility of misclassification in determining 'stay-at-home' status. We used 'stay-at-home' status as a proxy for the intensity of exposure to residential greenness, as suggested by previous studies.[16 39] Nevertheless, we acknowledge that our measure of exposure may not have captured all the locations where participants had been, which could have led to underestimating the association between residential greenness and mental

health. To address this limitation, the utilisation of more advanced technologies such as the global positioning system could offer a means to capture the detailed daily activities of study participants.[47]

Third, when comparing the study participants to the non-participating adults, we observed that the non-participants tended to be older, residing in peripheral areas and living alone. These groups may have experienced less peer pressure, resulting in lower motivation to participate in the study. Furthermore, individuals who chose not to participate may have had poorer mental health and resided in areas with less residential greenness. As a result, there is a possibility that this could have led to an underestimation of the association between residential greenness and mental health status. To address this issue, non-response weights were applied to the logistic regression models, aiming to account for potential biases caused by non-participation.

Fourth, the observed association between residential greenness and severe psychological distress does not necessarily represent a causal relationship due to the cross-sectional nature of the study design. To overcome this limitation, a longitudinal study is warranted.

Fifth, severe psychological distress was assessed by a self-administered questionnaire. The presence of stigma surrounding mental illness may have influenced participants to report lower scores on the mental health questionnaire due to social-desirability bias. However, since this bias represents non-differential misclassification of the outcome, it would lead to an underestimation of the associations (towards the null).

Sixth, there is a possibility of some unmeasured confounding factors remaining in the analysis. We lack information regarding the participants' mental health status prior to the COVID-19 pandemic, which could potentially affect both their mental health status and their living environment during the pandemic, serving as a potential confounder. Additionally, another study indicated that parents with young children may have faced specific challenges during the pandemic, such as increased stress levels or concerns for the future.[15] These parents may have sought out environments more suitable for childcare, potentially leading to a relocation to areas with greater green space. However, we did not account for the presence or absence of young children in our analysis.

Finally, the vegetation composition and characteristics can vary across different regions, which means the protective effect of residential greenness measured by NDVI may differ from one region to another. Therefore, it is important to validate our results through studies conducted in diverse geographic locations to establish generalisability and ensure the broader applicability of our findings.

Notwithstanding these limitations, the findings from this study hold policy implications. Amidst the COVID-19 pandemic, nature-based social prescribing has been proposed as an approach to foster social connectedness and promote mental well-being.[7] However, the implementation of such strategies has been challenging due to restrictions on outdoor activities and social interactions. Despite these circumstances, our study revealed that residential greenness around the home served as a protective factor for poor mental health status, particularly for individuals who were more confined to their residences as a result of social distancing policies. These findings highlight the potential significance of residential green spaces in supporting mental well-being even in situations where social interactions are limited.

There is an urgent need to establish preparation and response plans for public health interventions targeting mental health issues during the COVID-19 pandemic.[1 2 6] Furthermore, the development of improved residential green spaces around homes can potentially serve as a protective factor for the deterioration of mental health not only during the current pandemic but also in future pandemics. It is worth noting that a heightened burden of mental health problems is expected even in the post-pandemic era.[48] The question of whether residential greenness will continue to function as a protective factor for mental health in the post-COVID era remains unanswered, presenting a research opportunity for future longitudinal studies.

In conclusion, we found that objectively measured residential greenness around the home can be a protective factor for severe psychological distress among individuals who likely spent more time at home during the COVID-19 pandemic. Further research is warranted to investigate the quality of residential greenness, along with more comprehensive information on individuals' activities.

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