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Effects of tree canopy on psychological distress: A repeated cross-sectional study before and during the COVID-19 epidemic

Chang Zhang [a,b], Cheng Wang [a,b,1], Chao Chen [c,1], Liyuan Tao [d,*], Jiali Jin [a,b], Ziyan Wang [e], Baoquan Jia [a,b]

[a] Research Institute of Forestry, Chinese Academy of Forestry, Beijing, 100091, China
[b] Key Laboratory of Tree Breeding and Cultivation and Urban Forest Research Centre, National Forestry and Grassland Administration, Beijing, 10091, China
[c] National Clinical Research Center for Mental Disorders (Peking University Sixth Hospital/Institute of Mental Health) and the Key Laboratory of Mental Health, Ministry of Health (Peking University), Beijing, 100191, China
[d] Research Center of Clinical Epidemiology, Peking University Third Hospital, Beijing, China
[e] Department of Landscape Architecture, School of Architecture, Tsinghua University, Beijing, 100084, China

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ABSTRACT:

Background: During the COVID-19 epidemic period, people showed a stronger connection to the environment within their communities. Although tree canopy in residential areas has been shown to positively affect psychological distress, it is not clear whether the COVID-19 epidemic played a role in this process. Elucidation of the relationship between tree canopy and the impact on psychological distress during the COVID-19 epidemic could provide valuable information as to the best methods to help individuals cope with urban mental stress events.
Methods: A total of 15 randomly selected residential areas of Beijing were enrolled in this repeated cross-sectional study. A total of 900 residents were included in the two-waves of the investigation (450 residents per wave) before and during the COVID-19 epidemic (i.e., May 2019 and May 2020). Psychological distress was estimated using the 12-question General Health Questionnaire (GHQ-12). Tree canopy coverage (TCC) was measured through visual interpretation based on the 2013 data sources (World View 2 satellite imagery of Beijing urban areas with a resolution of 0.5 m). The demographic characteristics, distance to the nearest surrounding green or blue space, residential area house price, household density, and construction year were also collected in this study. A multivariate logistic regression, relative risk due to interaction (RERI), and synergy index (SI) were used to explore the relationships among tree canopy, COVID-19, and psychological distress.
Results: The negative impact of the COVID-19 epidemic on mental health was significant, with the prevalence of psychological distress increased 7.84 times (aOR = 7.84, 95% CI = 4.67–13.95) during the COVID-19 epidemic period. Tree canopy coverage in the group without psychological distress was significantly higher than that of the psychologically distressed group (31.07 ± 11.38% vs. 27.87 ± 12.97%, P = 0.005). An increase in 1% of TCC, was related to a 5% decrease in the prevalence of psychological distress (aOR = 0.95, 95% CI = 0.93–0.98). An antagonism joint action between tree canopy and the COVID-19 epidemic existed (RERI = 1.09, 95% CI = 0.72–1.47; SI = 0.16, 95% CI = 0.05–0.52), and persisted enhancing only in medium (26.45%–33.21%) and above TCC level. Correlation of GHQ items and TCC significantly differed between the COVID-19 non-epidemic and epidemic periods, with the effects of tree canopy on GHQ-12 items covering topics, such as social function and depression, presumably absent because of epidemic limitations.
Conclusions: This study indicates that the COVID-19 epidemic harmed mental health and verified the positive effects of residential tree canopy on psychological distress in Beijing. We suggest paying more attention to residents in areas of low TCC and dealing with psychological distress caused by public health stress events based on tree canopy strategies.

* Corresponding author.
E-mail addresses: zhangchang_caf@caf.ac.cn (C. Zhang), wch8361@163.com (C. Wang), chenchaojames@163.com (C. Chen), tendytly@163.com (L. Tao), jiali_jin@126.com (J. Jin), ziyanw93@163.com (Z. Wang), jiabaoquan2006@163.com (B. Jia).
[1] These authors contributed equally to this work.

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1. Introduction

Urban residents are vulnerable to public health stress events, with the adverse impacts on mental health considered risk factors for psychological distress, resulting in overall poor mental health, anxiety, depression, stress, and somatic complaints (Jokela et al., 2020; Pope et al., 2015). As it is likely the most acute public health stress in a generation, the COVID-19 epidemic attracting global attention has had a large negative impact on the mental health of urban residents. Recent research has shown that 53.3% of individuals studied exhibited anxiety in response to COVID-19 events or information (including 9.6% exhibiting extreme anxiety) and the rate of depression in studied individuals reached 48.3% (Yi et al., 2020). Moreover, anxiety and depression in response to the COVID-19 epidemic has been observed among large-city dwellers (Chen et al., 2020; Qianyi et al., 2020). Thus, the need to explore effective methods to improve the mental health of urban residents and protect the public from psychological distress caused by stress events is urgent.

Connection with nature to recuperate from stress, depression, and anxiety can be beneficial (Kondo et al., 2015; Vujcic et al., 2017). Several studies have indicated that a residential areas' green space is significantly associated with residents' mental health (Victoria et al., 2018), with higher levels of green space exposure associated with better mental well-being (Berg et al., 2010; Boers et al., 2018; Bos et al., 2016; Gascon et al., 2018; Weimann et al., 2015). Additionally, a dose–response relationship between the positive attributes of residential greenness and psychological distress has also been identified (Alcock et al., 2014; Astell-Burt et al., 2014; Pope et al., 2015; Triguero-Mas et al., 2015).

Tree canopy coverage (TCC) has increasingly been used to describe an urban residential areas' level of greenness, not only measuring the amount of green space in accordance with other indicators, i.e., the proportion of green land (expressed as the Normalized Difference Vegetation Index; NDVI), but also the qualities and functional features of shade (Tabatabaie et al., 2019), which supports the physical (Bjork et al., 2008; Sugiyama et al., 2008), social (Liu et al., 2019), and visual (Vemuri et al., 2011) benefits to residents' mental health. Related studies have reported, but insufficiently emphasized, these effects on reducing psychological distress in residential areas, which is noteworthy for residents facing the stress events. Moreover, the tree canopies described in these studies were extracted using various spatial scales, i.e., LSOA, census district, and postcode centroid buffer (Labib et al., 2020; Victoria et al., 2018), all of which do not entirely reflect the range of residential areas in China. Thus, evidence of the positive effects of residential tree canopy on psychological distress still need to be provided for Chinese residential areas.

During the COVID-19 epidemic period, implementation of prevention and home quarantine policies extended whole-day, continuous exposure to the tree canopy and involved relatively restricted physical activities in public spaces. As such, previous studies examining relationships between mental health and tree canopy are unable to provide accurate evidence that explain the results of this complex situation. Thus, clarifying the influence of residential tree canopy on mental health under the COVID -19 period is important to assist in the exploration of interventions based on the residential tree canopy, and can also provide a reference for improving residents' ability to cope with psychological distress that occur in response to urban stress events.

During the COVID-19 epidemic, Beijing adopted prevention and control measures in urban residential areas. Residents primarily stayed within residential areas, and rarely went into public for activities, which provided samples that were under continuous stimulation from the residential tree canopy. This study selected Beijing urban residents as research subjects, and separately collected data in the same residential areas during the COVID-19 epidemic and non-epidemic periods. Residential greenness and mental health were measured by TCC and the GHQ-12, respectively, to assess the following hypotheses: 1) tree canopy has a positive effect on residents' mental health, with the risk of psychological distress being reduced with higher TCC; 2) the COVID-19 epidemic has a negative impact on the mental health of residents; 3) there is an interaction between the tree canopy and COVID-19 epidemic on the mental health; and 4) the COVID-19 epidemic has altered the effect of tree canopy on different items of the GHQ-12. Verifying these hypotheses could help to assess the impact of the COVID-19 epidemic on the mental health of Beijing urban residents, potentially allowing for differentiated prevention and intervention methods based on the tree canopy of residential areas.

2. Methods

2.1. Study design and sampling

This study was a repeated cross-sectional study. First, the TCC of residential areas in Beijing, based on the visual interpretation results of Liu et al. (2019), was divided into three levels by K-means clustering, i.e., 1 = low (13.7%–22.3%), 2 = medium (26.45%–33.21%), and 3 = high (38.06%–54.06%). Then, five residential areas were randomly selected in each of the three levels, for a total of 15 residential areas selected as research plots (Fig. 1). Next, residents were convenience sampled from these 15 residential areas in two waves (May 2019 and May 2020), with different residents sampled in each wave. For both waves, we ensured that the number of valid residents for each residential area reached 30, for a total number of 450 valid residents per wave.

The on-site interception investigation followed the principle of absolute voluntariness and was conducted anonymously. Participants included in this study must have lived in these residential areas for more than two years, and have quarantine experience, i.e., living in residential areas for more than one month during the COVID-19 epidemic period. A total of 900 valid mental health data samples were collected from the residential areas during the study period, i.e., the COVID-19 non-epidemic period (May 2019) and the epidemic period (May 2020). This study was approved by the Ethical Committee of Peking University Third Hospital and conducted in accordance with the Helsinki Declaration. Informed consent was obtained from all participants during the questionnaire survey.

2.2. Indices

TCC: We used TCC to measure the greenness of residential areas, calculated as the ratio of the area covered by tree canopy to the total residential area. TCC is not the same as NDVI (Dadvand et al., 2016; Triguero-Mas et al., 2017), proportion of area that is green space (Astell-Burt et al., 2014; Houlden et al., 2017), as it not only describes the general level of vegetation (Luck et al., 2011), but also the size of shaded space provided by trees, which is considered to have an impact on residents' behavior, feelings, and outlook, being extremely important to mental health (Jiang et al., 2014; Markevych et al., 2017).

This study used previously reported visual interpretation results of TCC in Beijing residential areas (Xiuping, 2017). As these results were based on 2013 images (2013 World View 2 satellite imagery, with a resolution of 0.5 m, of Beijing urban areas was used as a data source after geometric and orthographical correction), we checked the age of trees in each residential area and found that almost all of the trees observed

were in the adult stage. Thus, the change in tree canopy due to growth since 2013 was small. Furthermore, during the survey, we asked local residents if there had been any issues with tree damage in their areas since 2013, with no such events reported. Therefore, the tree canopy of each residential area appeared to be well-protected, making the visual interpretation suitable for this study.

Distance to the nearest surrounding green space: Green space around the residential area, i.e., outside the residential area boundary, has an impact on resident's mental health, and the closer the green space, the more obvious the positive influence (Berg et al., 2010; Dadvand et al., 2016). Thus, we obtained the Euclidean distance to the nearest surrounding green space in ArcGIS to describe the green spaces around residential areas (Dzhambov et al., 2018a), and divided them into three groups, i.e., 1, 2, and 3 (0–500, 500−1,000, and ≥1000 m, respectively).

Distance to the nearest surrounding blue space: Although researchers have not reached a consensus on the significance of blue space on mental health (Grellier et al., 2017; Mireia et al., 2015), it is still considered to have an effect in a manner similar to green space (Dzhambov et al., 2018b), with people living closer to blue spaces being thought to have better mental health (Völkera et al., 2018). Sometimes the blue space was measured as a part of the green space (Gascon et al., 2018), thus, in order to know the separate influence of green space and blue space, we also identified the nearest blue space outside the residential areas in ArcGIS, obtained its minimum linear distance to the residential area, and divided the data into three groups, i.e., 1, 2, and 3 (0–500, 500−1,000, and ≥1000 m, respectively).

Residential area conditions: Several characteristics of residential areas, such as house prices (Wei et al., 2021) and house density (Wei et al., 2021) have an impact on the mental health of residents. Thus, we obtained information regarding house price, construction year, and number of households (https://bj.ke.com/). The average house value in 2019 was used as the house price, while household density was calculated by number of households/residential area × 100, with the residential area being read by ArcGIS based on the residential area boundary. Finally, the construction year was represented as a subtraction from 2019.

Residents' mental health: Psychological distress was measured by the 12-question General Health Questionnaire (GHQ-12) (Goldberg and Williams, 1988). This measure included the following items: (1) Lost sleep, (2) Under strain, (3) Able to concentrate, (4) Play a useful part, (5) Able to face problems, (6) Making decisions, (7) Unable to overcome difficulties, (8) Reasonably happy, (9) Enjoy day-to-day activities, (10) Feeling unhappy, (11) Losing confidence, and (12) Thinking of self as worthless. For the negatively worded items, the response options were: "less than usual-no more than usual-more than usual-much more than usual." For the positively worded items the response options were: "more than usual-same as usual-less than usual-much less than usual" (Stochl et al., 2016). Each response of the Likert scale was coded as "0-0-1-1" with 0 and 1 representing without and with clinical significance, respectively. Higher sums indicated worse mental health. A previously described dichotomous outcome was used to denote the presence or absence of psychological distress: 0 = No psychological distress (i.e., good mental health, GHQ-12 sum score 0–3), 1 = psychological distress (i.e., poor mental health, GHQ-12 sum score 4–12) (Jokela et al., 2020).

The GHQ-12 is one of the most commonly used mental health measure tools in green space research field (Bosh, 2017; Victoria et al., 2018). Furthermore, the GHQ-12 had demonstrated cross-cultural validity and reliability (Hartig et al., 2014). In this study, the Chinese version of the GHQ-12 (MingYuan and YanLing., 2015) was used. The Cronbach's α coefficient was 0.893.

2.3. Statistical analyses

In this study, we analyzed the difference between psychological distress (i.e., poor mental health) and no-psychological distress (i.e., absence of mental health issues) at the single factor level. Numerical variables, i.e., residential areas' house price, construction year, household density, and TCC were analyzed by two-sample t-tests, while categorical variables, i.e., age, gender, COVID-19 epidemic status, and distance to the nearest surrounding blue and green spaces, were analyzed with the chi-square or Fisher exact tests to determine statistical significance, with two-sided P-value < 0.05 considered as threshold.

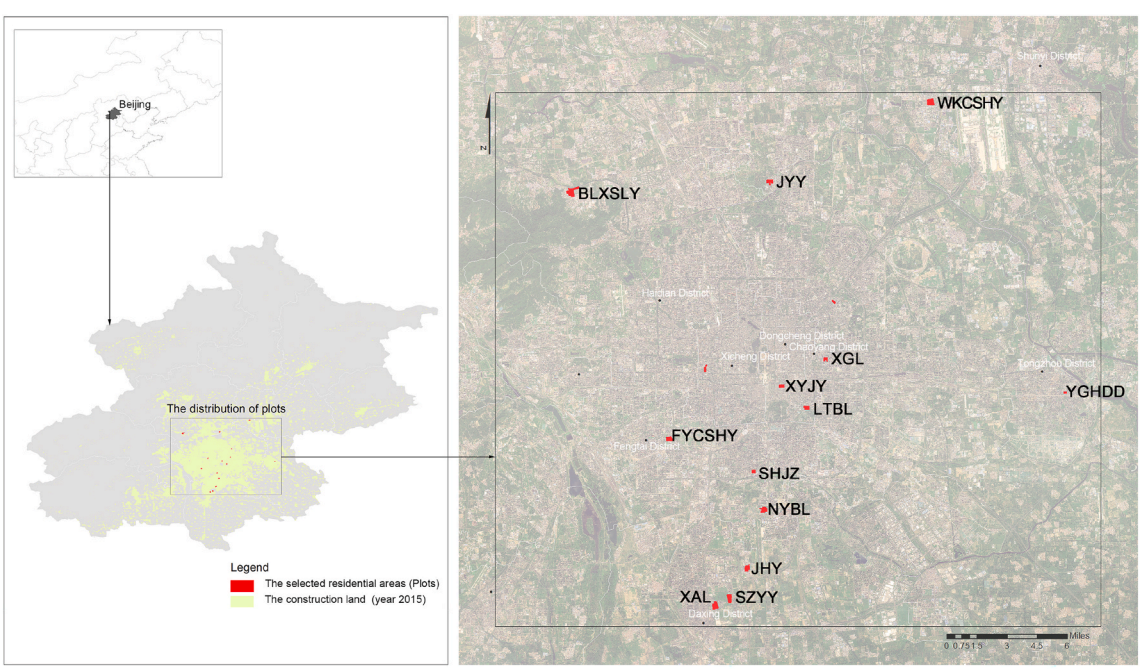

Fig. 1. Location of the research plots.

Multivariate logistic regression was used to analyze the relationship between mental health and the variables. First, we used the tolerance and variance inflation factor (VIF) to test collinearity among the variables, with tolerance > 0.1 and VIF < 10 considered as no collinearity. Then, a stepwise logistic regression model was constructed. We developed two models to compare the positive effects of tree canopy on resident mental health during the COVID-19 epidemic and non-epidemic periods. Model 1 was the logistic regression of mental health and all selected variables, and Model 2 added the interactive effect of tree canopy and COVID-19 epidemic to Model 1. The ROC curve was used to test the models, and an area under the curve (AUC) value > 0.75 was considered significant (see Fig. A.1 for AUC values). The relative risk due to interaction (RERI) and the synergy index (SI) (Richardson and Kaufman, 2009) were used to explore the interaction between tree canopy and COVID-19 on mental health. The 95% confidence interval of RERI and SI, with values between 0 and 1 were considered statistically significant, while an SI > 1 indicated synergy and an SI < 1 indicated a lack of synergy.

Moreover, to improve our understanding of the tree canopy's influence on various psychological distress items, we analyzed the relationship between them. We calculated the Spearman correlation coefficients between TCC and the GHQ-12 items for the COVID-19 non-epidemic and epidemic periods separately, with $P < 0.05$ (two-sided) set as the statistical significance threshold. Additionally, the bootstrap method was used to calculate differences between periods, calculating confidence intervals by the adjusted bootstrap percentile method (Kabacoff, 2015).

Data analyses and visualization were performed with R, version 3.6.2 (R core team, Vienna, Austria) mainly using the "stas" (Rteam et al., 2014), "boot" (Canty and Ripley, 2015), "epiR" (Stevenson et al., 2021) and "ggplot2"(Wickham, 2016) packages.

3. Results

3.1. Sample description

A total of 900 residents were included in analyses, with 450 residents per period (the COVID-19 non-epidemic and epidemic period). The gender (male: 227 vs. 226, female: 223 vs 224) and age (young: 206 vs. 207, middle-aged: 192 vs 193, elderly: 52 vs 50) observed were almost identical between the non-epidemic and epidemic periods.

Among the 900 samples, 50.3% (n = 453) were male and 49.7% (n = 447) were female. The proportion of young people (15–40 years old, n = 413), middle-aged people (41–65 years old, n = 385), and elderly people (>65 years old, n = 102) was 45.9%, 42.8%, and 11.3%, respectively, which was similar to the Beijing population age structure (Beijing, 2020). Sample characteristics are shown in Table 1.

3.2. Mental health of residents and factors

The prevalence of psychological distress was 13.0% (117/900, 95% CI: 10.8%–15.2%) in the total population, the prevalence of psychological distress was 3.8% (17/450, 95% CI: 2.0%–5.5%) and 22.2% (100/450, 95% CI: 18.4%–26.1%) in the COVID-19 non-epidemic and epidemic period, respectively. The COVID-19 epidemic increased the proportion of GHQ positive individuals, and the difference was statistically significant ($P < 0.001$).

Tree canopy coverage of the no-psychological distress group was significantly higher than that of the psychological distress group (31.07 ± 11.38% vs. 27.87 ± 12.97%, $P = 0.005$). The prevalence of psychological distress in the low, medium, and high TCC group was 17.0% (95% CI: 12.7%–21.3%), 10.0% (95% CI: 6.6%–13.4%), and 12.0% (95% CI: 8.3%–15.7%), respectively. Moreover, house price was significantly different between groups ($P < 0.01$). Age, gender, residential area's household density, and construction year did not differ between the psychological distress and no-psychological distress groups ($P > 0.05$).

Table 1
Difference between the psychological distress and no-psychological distress groups.

	No-Psychological distress (n = 783)	Psychological distress (n = 117)	t/χ2	*P*
Gender			0.108	0.750
Male	392 (86.5)	61 (13.5)		
Female	391 (87.5)	56 (12.5)		
Age (years)			2.817	0.245
15–40	355 (86.0)	58 (14.0)		
40–65	334 (86.8)	51 (13.2)		
> 65	94 (92.2)	8 (7.8)		
COVID-19 epidemic			66.058	<0.001
Non-epidemic period (2019/05)	433 (96.2)	17 (3.8)		
Epidemic period (2020/05)	350 (77.8)	100 (22.2)		
Residential area's TCC (%)	31.07 ± 11.38	27.87 ± 12.97	2.527	0.013
Low residential TCC	249	51	6.897	0.032
Medium residential TCC	270	30		
High residential TCC	264	36		
Distance to nearest surrounding green space			0.075	0.963
≤ 500 m	469 (86.5)	71 (13.5)		
500–1000 m	210 (87.9)	30 (12.1)		
≥ 1000 m	104 (87.5)	16 (12.5)		
Distance to nearest surrounding blue space			8.024	0.018
≤ 500 m	324 (90.0)	36 (10.0)		
500–1000 m	211 (87.9)	29 (12.1)		
≥ 1000 m	248 (82.7)	52 (17.3)		
Residential area's house price (ten thousand CNY)	6.34 ± 2.94	7.19 ± 3.46	−2.507	0.013
Residential area's household density (per household/100 m^2)	1.99 ± 0.75	1.97 ± 0.72	0.325	0.746
Residential area's construction year (a subtraction from 2019)	25.55 ± 16.20	23.35 ± 14.90	1.474	0.142

Note: Continuous and categorical variables were respectively indicated as mean ± standard deviation and n (%) and tested by independent *t*-test or Chi-square test as appropriate.

The prevalence of psychological distress significantly increased with distance to the nearest surrounding blue space, i.e., 10.3%, 11.7%, and 17.3% for <500 m, 500−1000 m, and ≥1000 m, respectively. However, this trend did not appear with the distance to the nearest surrounding green space. Details on the psychological distress and no-psychological distress samples are shown in Table 1.

3.3. Multivariate analyses of tree canopy, COVID-19, and interaction with psychological distress

According to the logistic regression results (Table 2), Model 1 (AUC = 0.761), which included all of the selected variables, TCC (aOR = 0.95, 95% CI = 0.93–0.98), COVID-19 epidemic (aOR = 7.84, 95% CI = 4.67–13.95), house price (aOR = 1.98, 95% CI = 1.05–3.70), and household density (aOR = 0.18, 95% CI = 0.07–0.47), were significantly associated with psychological distress. With a TCC increase of 1%, decreasing the risk of psychological distress by 0.05. Furthermore, the

Table 2
Results of logistic regression.

Variables	Model 1			Model 2		
	aOR	95% CI	*P*	aOR	95% CI	*P*
TCC (%)	0.95	0.929–0.980	<0.001	0.61	0.460–0.745	<0.001
COVID-19 epidemic (Yes vs. No)	7.84	4.671–13.950	<0.001	0.07	0.008–0.455	0.009
Residential area's household density (per household/100m^2)	0.18	0.070–0.470	<0.001	0.33	0.123–0.882	0.028
Residential area's house price (ten thousand CNY)	1.98	1.050–3.696	0.033	–	–	–
Tree canopy & Epidemic	–	–	–	1.26	1.140–1.461	<0.001

Note: aOR: adjusted odds ratio. Table 2 exhibits the stepwise regression results. Model 1 was the logistic regression of psychological distress and all selected variables, and Model 2 added the interactive effect of tree canopy and the COVID-19 epidemic to Model 1. "Tree canopy & Epidemic" indicated the interaction variable between TCC and COVID-19 epidemic. In addition, only significant variables are shown in Table 2.

COVID-19 epidemic period increased the odds of psychological distress by 7.84 times when compared to the non-COVID-19 period. Model 2 (AUC = 0.788) included the interaction term between TCC and COVID-19 epidemic, showing a significant effect of the tree canopy and the COVID-19 epidemic on mental health (aOR = 1.26, 95% CI = 1.14–1.46). The relative excess risk due to interaction (RERI) was 1.09 (95% CI = 0.72–1.47) and the synergy index (SI) was 0.16 (95% CI = 0.05–0.52), indicating that the COVID-19 epidemic and tree canopy had an antagonistic joint action.

In general, the prevalence of psychological distress was higher during the epidemic period. In both the COVID-19 non-epidemic and epidemic periods, there was a negative correlation between the prevalence of psychological distress and tree canopy. Increasing the TCC apparently reduced the prevalence of psychological distress. Moreover, at medium (26.45%–33.21%) and high TCC (>38.06%), the decrease during the COVID-19 epidemic period was larger than that in the non-epidemic period, reaching the largest at the high TCC (>38.06%) level. It was indicated that the antagonistic effects of tree canopy on reducing the risk of psychological distress were enhanced during the COVID-19 epidemic period, but only beyond medium TCC level, with the most obvious effects at the high TCC level (Fig. 2).

3.4. Correlation of tree canopy and GHQ-12 items

Exploring the correlation of TCC and GHQ-12 items, there were considerable differences of correlation coefficients between the two periods (Table 3). Entire correlation coefficients significantly reduced during the COVID-19-epidemic period, and several previously significant negative correlation coefficients developed into the positive ones, although not remarkably i.e., Able to concentrate (G3), Play a useful part (G4), Unable to overcome difficulties (G7), Reasonably happy (G8), Unhappy (G10), and Losing confidence (G11), with their correlation coefficients decreasing by more than 0.20. This indicates that the effects of TCC against those GHQ-12 items were presumably absent during the COVID-19-epidemic.

4. Discussion

4.1. Overall mental health status

The prevalence of psychological distress was 13.0% (117/900) in the total population, which was within the range of a previously reported psychological distress empirical value, i.e., 5%–27% (Pope et al., 2015). However, the prevalence of psychological distress strongly reached 22.2% (100/450) in the COVID-19 epidemic period, almost 5 times that of the non-epidemic period, which was much higher than the most previous GHQ outcomes (see Table A.1), as well as the average adult level in China (14.97%, measured by The Kessler Psychological Distress Scale) (Li et al., 2019). Therefore, this result indicated that the COVID-19 epidemic had a strong negative impact on the mental health of residents, and to some extent, could reflect that urban residents may be more vulnerable to public health events.

4.2. Influence of TCC on mental health

Results indicate that, in Beijing, residential areas' green space is beneficial to residents' mental health (details see Table A.2). In the current study, individuals with high psychological distress (27.87 ± 12.97%) had significantly lower residential TCC than that of individuals reporting no-psychological distress (31.07 ± 11.38%). Residents living

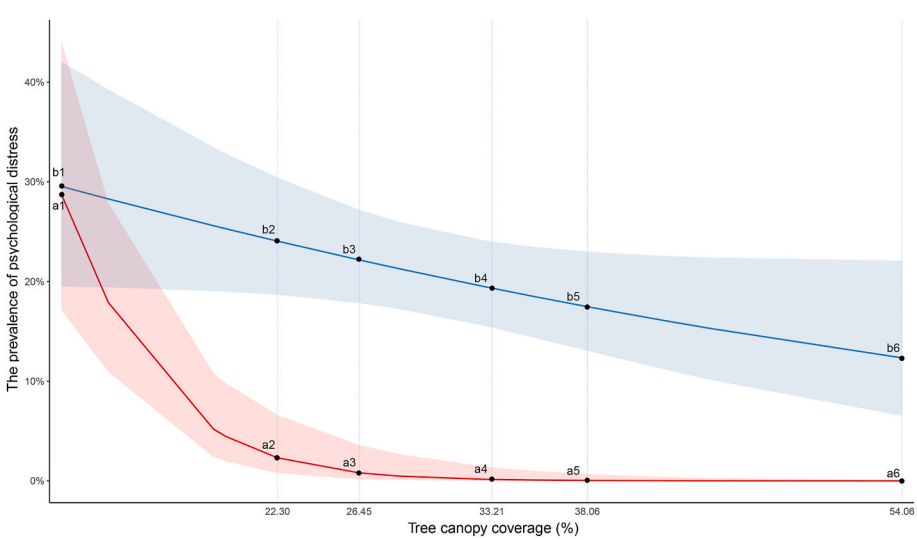

Fig. 2. Shows the interactive effect of the COVID-19 epidemic and TCC on prevalence of psychological distress. Red and blue represent May 2019 (COVID-19 non-epidemic period) and May 2020 (COVID-19 epidemic period), respectively, and shaded areas show the 95% confidence interval. The vertical dash line of x-axis was 22.3%, 26.45% and 33.21%, 38.06% represented the baselines for low, medium, and high residential TCC, respectively. The psychological distress prevalence of a1 subtracting a2 represents the (all possible) decrease in the low TCC level during non-epidemic period, which was obviously much higher than that of b1 subtracting b2 during the epidemic period. In the same way, in the medium TCC level, the decrease (a3 subtracting a4) during the non-epidemic period was lower than the decrease (b3 subtracting b4) during epidemic period. While at the high TCC level, the decrease (a5 subtracting a6) during the non-epidemic period was lower than that (b5 subtracting b6) in the epidemic period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Correlation coefficients of TCC and GHQ-12 items in each period.

Items	COVID-19 epidemic		Difference	95% CI
	No	Yes		
G1: Lost sleep^{-}	−0.280**	−0.111*	−0.169	−0.271, −0.065
G2: Under strain^{-}	−0.283**	−0.108*	−0.174	−0.281, −0.075
G3: Able to concentrate^{+}	−0.299**	0.037	−0.336	−0.447, −0.248
G4: Play a useful part^{+}	−0.243**	0.045	−0.288	−0.394, −0.171
G5: Able to face problems^{+}	−0.244**	−0.032	−0.212	−0.332, −0.099
G6: Making decisions^{+}	−0.231**	−0.009	−0.222	−0.343, −0.104
G7: Unable to overcome difficulties^{-}	−0.252**	0.005	−0.257	−0.369, −0.147
G8: Reasonably happy^{+}	−0.192**	0.011	−0.203	−0.328, −0.076
G9: Enjoy day-to-day activities^{+}	−0.259**	−0.095*	−0.164	−0.277, −0.060
G10: Feeling unhappy^{-}	−0.259**	0.008	−0.267	−0.370, −0.166
G11: Losing confidence^{-}	−0.244**	0.014	−0.258	−0.366, −0.159
G12: Thinking of self as worthless^{-}	−0.206**	−0.008	−0.198	−0.319, −0.075

Two-sided $P < 0.01$, * Two-sided $P < 0.05$. Items with "$^{-}$" were the negatively worded items, scored "0-0-1-1" as the response options: "less than usual-no more than usual-more than usual-much more than usual". Items with "$^{+}$" were the positively worded items, scored "0-0-1-1" as the response options: "more than usual-same as usual-less than usual-much less than usual".

in residential areas with less tree canopy may need more attention paid to their mental health, as there is the possibility that psychiatric patients may live in neighborhoods with lower amounts of green space (Boers et al., 2018).

While in our study, a 1% increase of TCC could decrease the prevalence of psychological distress by 0.05 based on the overall study population. However, this relationship was not simply an inversely linear proportion (Tosevski and Milovancevic, 2006; Verheij et al., 2008). The medium TCC level appeared to be the critical range (26.45%–33.21%) in COVID-19 non-epidemic period. Below this, a slight increase TCC yielded a considerable decrease of the prevalence of psychological distress. But beyond this, the same increase added only a minimal decrease of psychological distress prevalence. This kind of relationship, which also appears between tree cover and landscape preference (Jiang et al., 2014), might be a common aspect of the benefit of tree canopy to welfare. While the increase of psychological distress prevalence observed in the epidemic period could not be completely removed, it could be reduced by the antagonistic effects from tree canopy, which provides supporting evidence for the nature-based strategies to ameliorate the damage caused by public health stress events (Kondo et al., 2015; Vujcic et al., 2017). As the dose–response relationship was identified in the negative interaction effects, the inverse relationship progressively increased in low, medium, and high TCC levels. Hence, we propose a reference for residential area's TCC to exceed the medium level, i.e., 26.45%–33.21% (better than 33.21%, but at least above 26.45%), to help lower the prevalence of psychological distress, and help residents better cope with the next public stress event.

4.3. Correlations between TCC and psychological distress items

As expected, the mechanism responsible for the impact of green spaces on mental health involves several mediators and/or moderators, which interact with each other and compose several indirect regulatory pathways (see Table A.2 for details of previous pathway items). We suspect environmental annoyance relief, green exercise, physical actives, window view, and social cohesion acted on resident's psychological distress, and owing to epidemic limitations, some of these elements were weakened, so that the entire effects of tree canopy on psychological distress shrank. However, the variation was observed in each of the psychological distress items.

Higher TCC implies more greenness, with increased shade space for residential compounds, forming comfortable and secure places for supporting interpersonal neighbor communication, social activities, and physical actives, which improve the resilience of social communication (Campbell et al., 2016), and increases the opportunities for establishing deep social networks (Smith and Christakis, 2008), which improves social support and provides good social relationships (Jennings and Bamkole, 2019). With good social support, a person might more easily overcome difficulties (G7) and establish self-confidence (G11), so that the individual feels that he/she is playing a useful part in things (G4). In addition, physical activity has always been considered the highest contributing factor to the effects of green space on mental health, with more physical activity resulting in higher stress reduction (G2), relief of somnipathy (G1) (Choi et al., 2018), regulation of emotions, and improving attention (Han, 2017). With these benefits, a person might have no barriers to feeling reasonably happy (G8), be less likely to be unhappy or depressed (G10), and be able to better concentrate on whatever he/she is doing (G3). However, the opportunities for residents to visit green spaces to carry out physical activities or social interaction greatly decreased in the COVID-19 epidemic period. Therefore, the ability of tree canopy to influence these items was likely reduced.

Without obvious tree cover changes during the COVID-19 epidemic period, the advantages gained from tree canopy (Dimitrova and Dzhambov, 2017), such as avoiding noise annoyance, may have been weakened, but possibly still existed, promoting a restorative quality (Von Lindern et al., 2016) to alleviate sleep disorders (G1) (Tiesler et al., 2013). Furthermore, the number of visible trees and canopy seen from windows alleviates unhappiness (G10) arising from a prolonged stay at home (Ko et al., 2020; Shuqing et al., 2019). The more tree canopy around the residence, the more likely green canopy scenery could be seen from residents' home, allowing for more benefits during the epidemic period, which may be one of the key reasons for antagonism of tree canopy that was observed. However, further studies of this subject are needed. Additionally, carrying out alternative or optimized incentive measures by applying the current results outlining the variation of the effects on psychological distress items during the epidemic period is required to help individuals better handle stress events.

4.4. Residential area conditions

The house density of residential areas in our study was significantly associated with psychological distress (aOR = 0.18), with higher density being associated with a higher risk of anxiety and stress (Chen et al., 2020). A lower density implies more TCC or potential TCC, which could support more physical activities and social communication at present or in the future, making great contributions to reducing the psychological distress of residents. Interestingly, we also found that higher house prices also resulted in a higher prevalence of psychological distress (aOR = 1.98). Although several studies have reported higher house prices being associated with a greener living environment, no such pathway was observed that high housing prices of the residential area, which indicates high TCC, led to a decline in mental health. Because the housing prices of residential areas in Beijing are not simply positively

correlated with the dwelling environment, but also benefit from school, traffic, and other factors. Conversely, higher housing prices usually indicate greater economic and working pressures, which would have a negative impact on mental health (Wei et al., 2021). Thus, house prices is not an appropriate independent predictor of mental health.

4.5. Strengths and limitations

To our knowledge, this was the first study that comprehensively considered the impact of the COVID-19 epidemic and residential tree canopy on mental health through a repeat cross-section in fixed residential areas, containing data from the non-epidemic period of May 2019 and the COVID-19 epidemic period of May 2020. While the limitation of convenience sampling does exist, we adopted two separate cohorts with similar gender (male: 227 vs. 226, female: 223 vs 224), age (young:206 vs. 207, middle-aged:192 vs 193, elderly: 52 vs 50) in the non-epidemic and epidemic periods, filling the gap of a longitudinal cohort (Weimann et al., 2015).

Unfortunately, we did not find any apparent difference in overall psychological distress by gender or age. In other studies (also using the GHQ-12), no significant difference in psychological distress by gender was reported (Pope et al., 2015), but most found that the green space impacts on mental health varied with gender, age, or the interaction of gender and age (Astell-Burt et al., 2014; Dadvand et al., 2016; Maas et al., 2009; Matilda et al., 2015; Triguero-Mas et al., 2015). A reasonable explanation was that the different age or gender population groups had different amounts of exposure or participation in residential green spaces (Annerstedt et al., 2012). However, while our study population experienced similar reduction of green space visitation during the home quarantine period, we were unable to determine their usual exposure time in residence, which limited us to analyze the inapparent psychological distress variation of gender or age by the possible previous exposure mechanism. Moreover, as the usual exposure time may have also been insufficient for the surrounding green space, evidence from the regression results to reflect the distinct influence of inner residential green space and surrounding green space to mental health made little sense. While we found that proximity to blue space lowered the prevalence of psychological distress, this association was not conclusive considering the regression results. Therefore, the role of blue space in mental health warrants further study (Grellier et al., 2017).

Additionally, this study also lacked other demographic information, including occupation, income, and basic physical health, which prevented conduction of additional demographic cross analyses. Moreover, we found GHQ-12 items reflecting social function varied between the epidemic and non-epidemic periods, which could seemingly be explained by mediators and/or moderators, such as social support. However, we lacked the first-hand data of participants' psychosocial status, i.e., investigation though the SSRS (Social Support Rating Scale) or FES-CV (Family Environment Scale Chinese Version), that we could not quantify the actual psychosocial benefits of TCC. Future studies on this topic will focus more on psychosocial factors. Finally, this study used the GHQ-12 to estimate psychological distress. However, this scale is unable to answer whether the group without psychological distress was happy or not. Further research should add targeted scales to address this issue.

5. Conclusion

This study aimed to analyze the comprehensive influence of the COVID-19 epidemic and TCC on the mental health of residents in Beijing. Psychological distress (mental health) was estimated according to the GHQ-12 and TCC was used as an index to measuring green space on the spatial scale of the residential area. The results showed that: 1) more tree canopy in residential areas corresponded with a lower prevalence of psychological distress, with a 1% increase of TCC associated with a 0.05 decrease in the prevalence of psychological distress (aOR = 0.95); 2) the prevalence of psychological distress increased 7.84 times (aOR = 7.84) during the COVID-19 epidemic period; 3) for residential areas with less TCC, a slight increase of TCC yielded a considerable decrease of psychological distress prevalence; however, the reduction of distress associated with the epidemic was weak; similarly, in areas with a medium TCC level (26.45%–33.21%) and above, the increase of TCC added only a minimal decrease of psychological distress prevalence; yet the ability to ameliorate stress associated with the epidemic was enhanced; 4) the overall correlation between TCC and psychological distress shrank, and, owing to epidemic limitations, the effects of TCC against being unable to concentrate, play a useful part, being unable to overcome difficulties, reasonably happy, unhappiness, and loss of confidence was presumably absent. We suggest paying closer attention to residents in areas with low TCC and consider dealing with psychological distress owing to stress events based on the residential tree canopy strategies.

Author contributions

Chang Zhang: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Funding acquisition, Cheng Wang: Conceptualization, Data curation, Supervision and Project administration, Chao Chen: Writing – review & editing, Liyuan Tao: Methodology, Writing – review & editing, Visualization, Jiali Jin: Writing – review & editing, Ziyan Wang: Writing – review & editing, Baoquan Jia: Conceptualization, Data curation, All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

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

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Appendix A. The information and overview of study residential areas

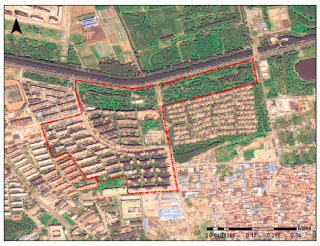
1- WKCSHY/Shunyi District

Tree canopy coverage:42.06

2-JYY/Cangping District

Tree canopy coverage:35.33

3- BLXSLY/Haidian District



Tree canopy coverage:54.06

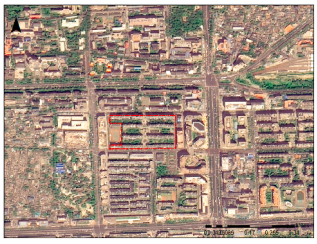
4- XGL/Chaoyang District

Tree canopy coverage:26.45

5-XCGJ/Chaoyang District

Tree canopy coverage:19.67

6-XYJY/Dongcheng District

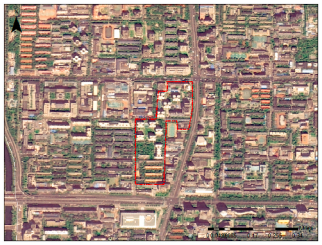


Tree canopy coverage:11.31

7-LTBL/Dogncheng District

Tree canopy coverage:32.78

8- SLH/Xicheng District



Tree canopy coverage:38.91

9- FYCSHY/Fengtai District

Tree canopy coverage:33.21

10- HSJZ/Fengtai District

Tree canopy coverage:11.31

11- NYBL/Fengtai District

Tree canopy coverage:32.78

12- JHY/Daxing District

Tree canopy coverage:44.32

13- XAL/Daxing District

Tree canopy coverage:38.06

14- SZYY/Daxing District

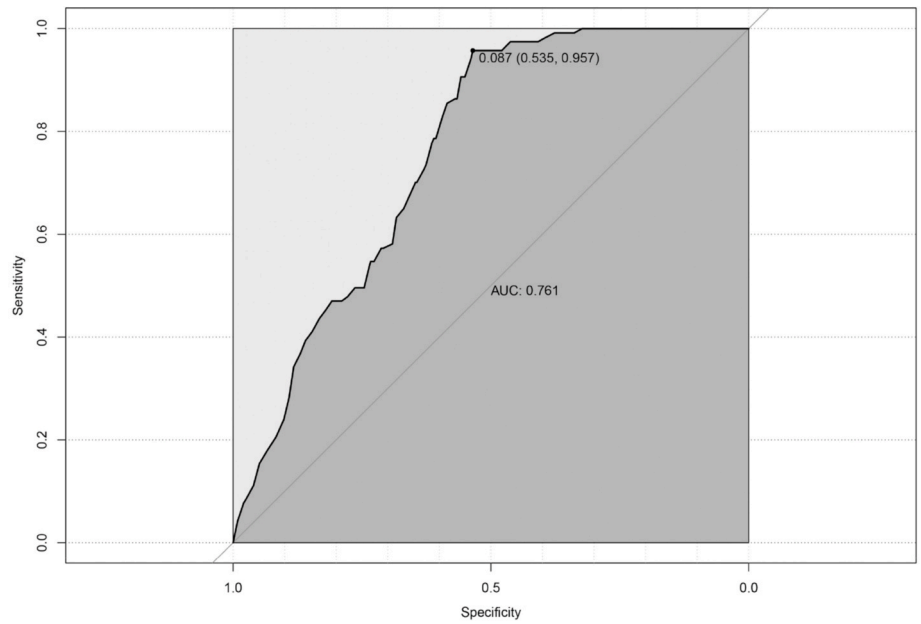
Tree canopy coverage:13.7

15-YGHDD/Tongzhou District

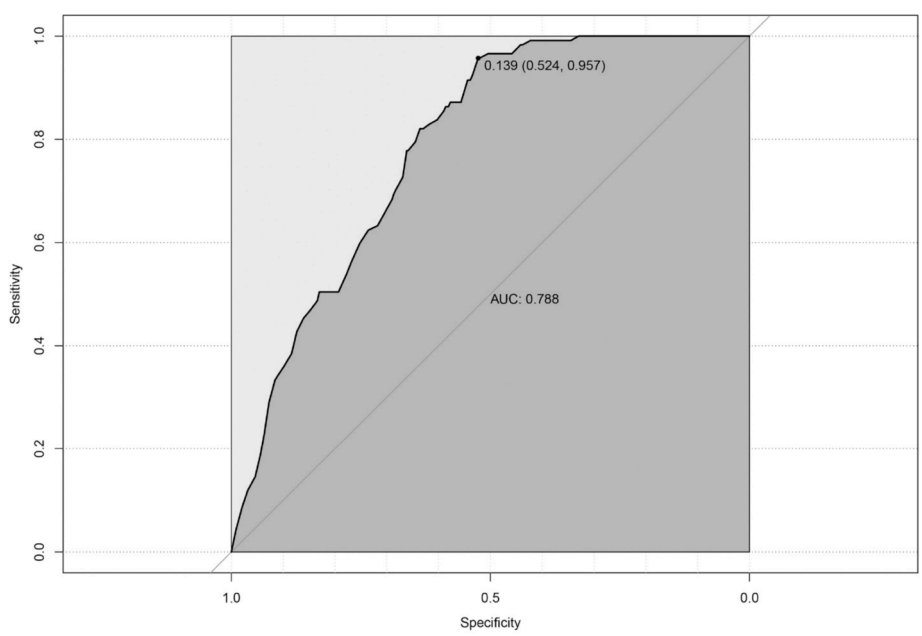
Tree canopy coverage:22.3

Note: The tree canopy coverage value shown in Appendix A were Jia's visual interpretation results based on 2013 images (World View 2 satellite imagery with a resolution of 0.5 m of Beijing urban areas), which we used in our study analysis. While the pictures of each plot in Appendix A were 2019 image (resolution of 2 m) for overviewing the study residential areas and their boundaries.

Appendix B. The ROC curve of regression models



(a)



(b)

Fig. A.1. The ROC curve of Model 1 (a) and Model 2 (b)

Appendix C. Summaries of related previous studies

Table A.1
A brief summary of previous studies about the GHQ-12 (12-items General Health Questionnaire) outcomes in residential areas.

Author, Year, Country	Study Design	Population Size	GHQ-12 outcomes	GHQ-12 Criteria
Astell-Burt et al. (2014), UK	Longitudinal cohort	6540	The prevalence of poor mental health for male: 17.6%, 15.7%, 16.0%, and for female:24.6%, 23.4%, 23.6% in low, moderate, high green land, respectively.	dichotomization
Bosch et al., 2012, Sweden.	Cross-sectional	24,945	The prevalence of poor mental health was 16.4% (year 1999),	dichotomization

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Table A.1 (*continued*)

Author, Year, Country	Study Design	Population Size	GHQ-12 outcomes	GHQ-12 Criteria
Bosch, 2015, Sweden	Longitudinal cohort	9230	The prevalence of poor mental health was 15.8% (year 2005)	dichotomization
Maas, 2009, Netherland	Cross-sectional	10,089	Risk of psychopathology (poor mental health) was 22.6%	dichotomization
Triguero-Mas et al. (2015), Spain	Cross-sectional	8793	Risk of poor mental health was 11.96%	dichotomization
Pope et al., 2015, UK	Cross-sectional	1680	The prevalence of psychological distress (poor mental health) was 22.7%.	dichotomization
Weimann et al., 2015, Sweden.	Longitudinal cohort	9444	The prevalence of poor mental health was 18%	dichotomization

Notes: All these studies' individuals were aged >15 years.

Table A.2
A brief summary of previous studies about the effects of residential areas' greenspace/ pathway items on mental/ Wellbeing

Author, Year, Country/ Region	Study Design/Study population/model	Mental/Wellbeing (measurement)	Greenspace/Pathway Items (measurement)	Main Findings
Residential greenspace				
Astell-Burt et al. (2014), UK	longitudinal design/ 65,407/Multilevel linear regression	Mental health (GHQ-12)	Residence green and natural land cover	Male before mid-adulthood and older women with a moderate availability of green space had better mental health
Berg et al. (2010), Netherlands	Cross-Sectional/4529/ Multilevel regression	Mental health (GHQ-12); Stressful events (LTE-Q)	Greenness (within 1 km and 3 km buffer around a respondent's home)	Green space can provide a buffer against the negative health impact of stressful life events, and the farther ones is particularly important.
Jiang et al., 2014, USA	cross-sectional/314/Linear regression	Preference of street scenes (questionaries)	Tree cover density (two dose–response curves: aerial and eye-level measures way).	For low tree cover streets, a slight increase in tree cover yielded a considerable increase in preference. But for streets with moderate or high tree cover, the same increase added only a slight increase in landscape preference.
Boers et al. (2018), Netherlands	Cross-Sectional/623/ Multivariate regression	Psychiatric health (inpatient days in psychiatric department)	Green and blue space (the amount of green and blue space within 300 m buffer around residence)	Compared to the general population, psychiatric patients had a significantly lower amount of green space in their neighborhood.
Elisabeth et al., 2016, Netherlands	Cross-sectional/4924/ Regression models	Psychopathology (DASS); Quality of life (MANSA)	Greenness (1 km and 3 km around the 4-digit postal code residence)	Effect of greenspace on psychopathology was significant for male, youngest/oldest age women, who could use it within 3 km buffer.
Gascon et al. (2018), Spain.	Cross-Sectional/958/ Logistic regression	Mental health (anxiety, depressive, medication use)	Green and blue space (NDVI, green land cover and access of 100 m/300 m/ 500 m buffer)	There is a potential protective role of green spaces on mental health (anxiety and depression) in adults.
Pope et al., 2015, UK	Cross-sectional/1680/ Multivariable logistic regression	Mental health: Psychological distress (GHQ-12)	Accessibility and Sufficiency of green spaces	green spaces were significantly associated with reduced psychological distress, and a dose–response relationship was identified.
Weimann et al., 2015, Sweden.	Longitudinal design/9444/ Logistic multilevel (random intercept)	General health (questions); Mental health (GHQ-12)	Exposure-assessment neighborhood greenness	Benefits of increased greenness was among the lowest prognostic good general health.
Green vision/Window view				
Du et al., 2021, China.	Cross-Sectional/647/linear multiple regression	Health and well-being (questions)	Vegetation configuration (photos)	The impact of vegetation configuration on public health and well-being varies with the type of urban green space, and visiting greenspace can release stress and relax.
Han (2017), Taiwan	Cross-sectional/116: adapted to PAR-Q/ ANOVAs	Emotions (POMS-SF); attention (the Wechsler Memory Scale)	Visible greenness rate (photos); Physical exercise level (Actigraph)	Low level physical activity for just 15 min in a relatively natural setting can improve emotions and attention.
Ko et al., 2020, USA	Randomized crossover/86/ Permutation tests	Emotion (questionnaire)	Window view	Windows with a green view have a positive impact on attention restoration, stress reduction.
Shuqing et al., 2019, China	Randomized crossover/60/ Descriptive statistics	Mental health (DSB, STAI-S)	Window view	Window scape of greenspace has healing effects on human health.
Vemuri et al. (2011), USA	Cross-Sectional/4880/ Multivariate logistic regression	Neighborhood and individual life satisfaction (self-assessed questions)	Greenness (Tree canopy cover); Tree vision (trees from window); Social capital index (questions)	For neighborhoods, access to a clean natural environment always contributes to higher satisfaction, and for individuals, higher incomes contribute to higher levels of satisfaction.
Residential environment annoyance/physical activities/social cohesion				
Ambrey, 2016, Australia.	Cross-sectional/6082/ logistic regression	Life satisfaction (self-assessed questions); Mental health (SF-36); Psychological distress (K10)	Greenspace (the amount of greenspace in Census Collection District); Physical activity (international Physical Activity Questionnaire)	Exposure to neighborhood greenness is positively associated with mental wellbeing. Promotion of walking, facilitation of social cohesion and satisfaction separately mediated the greenness' protective effect.

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Table A.2 (*continued*)

Author, Year, Country/ Region	Study Design/Study population/model	Mental/Wellbeing (measurement)	Greenspace/Pathway Items (measurement)	Main Findings
Annerstedt et al. (2012), Sweden.	Cross-sectional/24,945/ Logistic regression	Mental health (GHQ-12);	Green qualities (a gold standard of 5-degree assessment); Physical activity (questionnaire)	The higher the daily greenspace exposure, the higher the physical activity level and the better the overall health (including physical, mental, and social health).
Berg et al., 2019, Spain, UK, Netherlands, Lithuania.	Cross-sectional/3748, 2972 for mental health; 2960 for vitality/ Multilevel linear regression (random intercept)	Mental health (SF-36, nervousness and depression items, energy and fatigue items); Loneliness (UCLA loneliness scale)	Visits to green space (self-assessed questions); Physical activity (SQUASH); Social cohesion (social cohesion and trust scale)	Daily NE commuting was associated with better mental health.
Berg et al.,2017, Spain, UK, Netherlands, Lithuania.	Cross-sectional/1628/ Linear and logistic multilevel models (random intercept)	Cognitive function (CTT); Loneliness (UCLA loneliness scale); Mental health (SF-36)	Greenness (NDVI of 100 m/300 m/500 m Residence buffers); Physical activity (SQUASH); Social cohesion (Social cohesion and trust scale); Traffic noise/ air pollution (questions).	Time spent visiting green space contributes indirectly to mental health and vitality, but the associations between them still need other mediators to explain.
Bjork et al. (2008), Sweden.	Cross-sectional/24,819/ Regression models	Neighborhood satisfaction (SF-36)	Greenspace (5-degree assessment of residence 300 m buffer); Physical activity (questionnaire)	Green spaces were associated with general health and mental health, especially for female and residents of non-densely populated areas. In addition, access to blue spaces was associated with more social support.
Campbell et al., 2016, USA	Mixed method/618/ Descriptive statistics	Enjoyment (interviews)	Greenspace physical activities (questionnaire)	Greenspace producing vital cultural ecosystem services that help to strengthen social resilience.
Catharine Ward Thompson, 2016, UK	cross-sectional/406/ Correlated Component Regression	Stress (PSS); Mental wellbeing (SWEMWBS); Overall health (single item question)	Physical activity, Social wellbeing, Access to Green Space (self-reported); Green space (percentage area of green space within community boundaries).	The amount and access to green space in the neighborhood were significant predictors of stress. Physical activity in winter months, and views from the home were predictors of general health.
Choi et al. (2018), korea	Control trial/63 Korean college students./	Vigor (perceived stress) and Fatigue (sleep duration); stress (BEPSI)	Social activities and physical exercise (IPAQ-SF)	Residences recreational greenspace was strongly associated with neighborhood satisfaction and physical activity for women.
Dimitrova and Dzhambov (2017)	Cross-sectional/43,636/ Multivariate logistic regression	self-rated health (5- category question)	Residential environment annoyance (noise/air quality)	Promoting exposure to urban greenspace might alleviate the adverse effects of environmental pollution.
Dzhambov et al., 2018a, Bulgaria	Cross-sectional/399/Mixed linear models (random intercept)	Mental health (GHQ-12)	Residential greenspace (NDVI, tree cover density, distance to the nearest greenspace); Availability to greenspace.	Restorative quality associating with physical activity and social cohesion, mediated the relationship between NDVI and mental health.
Dzhambov et al., 2018b, Bulgaria	Cross-sectional/720/ Structural equation modelling	Mental health (GHQ-12);	Residential green-and blue space (NDVI, tree cover density, distance to the nearest green-and blues pace); Environment annoyance (traffic noise/ air pollution)	more Residential greenspace supports better mental health through several indirect pathways with serial components, including restorative quality, physical activity, social cohesion.
Dzhambov et al., 2018a, 2018b, Bulgaria	Cross-sectional/399/ Linear regression models	Mental health (GHQ-12)	Residential greenspace (NDVI, tree cover density, distance to the nearest greenspace); Environment annoyance (traffic noise/air pollution)	Road traffic noise has negative effect on mental health, which was medicated by higher recreational quality in greener environment.
Liu et al. (2019), China	Cross-sectional/1029/ Structural Equation Modelling	Mental wellbeing (WHO-5); Satisfaction (self-assessed questions).	Neighborhood greenness (NDVI of 1 km buffer); Stress, Walking Behavior, Social cohesion, Perceived pollution (self-assessed questions)	The farther the residential distance to natural outdoor environment the longer CTT completing time.
Shanahan, 2016, Australia	Cross-sectional/1538/ Generalized linear regression	Mental health (Depression, Anxiety and Stress scale); Physical health (blood pressure); Social health (questions).	Nature intensity (vegetation cover); Nature dose (Nature Relatedness scale, self-report)	The amount and access to green space in the neighborhood were significant predictors of stress. Physical activity in winter months, and views from the home were predictors of general health.
Sugiyama et al. (2008), Australia.	Cross-sectional/1895 walk without assistance/ Stepwise logistic regression	Physical and mental health (SF-12)	Perceived neighborhood greenness (Neighborhood Environment Walkability Scale); Physical activity (the International Physical Activity Questionnaire); Social coherence (self-assessed questions).	Physical activity is more positively associated with wellbeing than greenspace.
Tiesler et al. (2013), German	Cross-sectional/872/ Logistic regression models	sleeping problems and other emotions (SDQ)	Road traffic noise levels at home	physical activity has positive effect on reducing sedentary behavior, stress levels, sleep problem.
Triguero-Mas et al. (2015), Spain	Cross-sectional/8793/ Logistic regression	General health (SF-36); Perceived risk of poor mental health (GHQ-12)	Residence greenness (NDVI of 300 m buffer); Access to green/blue spaces; Social support (DUFSS); Physical activity (Welsh Heart Health Survey)	Residence surrounding greenness was statistically significantly tied to better mental health, and the relationships were stronger for males, younger people.
Triguero-Mas et al. (2017), Spain;	Cross-sectional/406/ Poisson regression	Psychological wellbeing (SF-36); Lack of somatization (4DSQ); Sleep	Residence greenness (NDVI of 300 m buffer); Exposure (the presence of	Reduced risk of poor mental health for women, through a significant

(*continued on next page*)

Table A.2 (*continued*)

Author, Year, Country/ Region	Study Design/Study population/model	Mental/Wellbeing (measurement)	Greenspace/Pathway Items (measurement)	Main Findings
United Kingdom; The Netherlands; Lithuania.		quality (questions); Stress (question);	green or blue spaces within residence 50 m buffer); Social cohesion (5-item social cohesion and trust scale); Physical activity (CalFit-recorded)	interaction effect between physical activity and access to greenspace with more natural qualities.
Von Lindern et al. (2016), Austria	Cross-sectional/572/ Structural equation models	restorative quality (PRS); satisfaction (survey); mental health (GHQ)	Residential environment annoyance (traffic noise/air pollution)	Traffic-related exposures reduce the effects of the living environment's restorative qualities.
Wilma L. Zijlema, 2018,	Cross-sectional/3599 participants/Multilevel analyses	Mental health (SF-36)	Amount of neighborhood NE commuting and quality (self-reported questions); Active commuting (SQUASH)	Nature dose encompassing the duration and frequency of experiences. A dose-response showed positive associations between nature dose and mental illnesses reduction.
Zhang et al., 2018, China.	Cross-sectional/1003/ Structural Equation Modelling	Physical health (SF-36, items 1, 4, and 7); Mental health (WHO-5); Social health (Social Cohesion and Trust Scale, Social Wellbeing Scale and SSL-I).	Physical activity (metabolic equivalents); Exposure (Vegetation coverage of 1000 m buffer around each stay point and 500 m buffer for travel routes).	Perceived neighborhood greenness was strongly associated with mental health, and this relationship was partly accounted for by recreational walking and social coherence.

Notes: The meaning of abbreviation. **DASS**: Depression Anxiety Stress Scale; **SF-36:** 36-items Short-Form Health Survey; **SF-12:**12-items Short-Form Health Survey; **GHQ-12:** 12-items General Health Questionnaire; **DUFSS:** Duke-UNC Functional Social Support; **4DSQ:** Four-Dimensional Symptom Questionnaire; **WHO-5:** World Health Organization's Five Well-Being Indexes; **SSL-I**: Social Support List-Interactions; **K10**: Kessler Psychological Distress Scale; **LTE-Q:** List of Threatening Experiences; **CTT:** Color Trails Test; **SQUASH:** Short Questionnaire to Assess Health-enhancing Physical Activity. **UCLA:** Loneliness Scale; **PAR-Q**: Physical Activity Readiness; **NDVI**: Normalized Difference Vegetation Index.

References

Alcock, I., et al., 2014. Longitudinal effects on mental health of moving to greener and less green urban areas. Environ. Sci. Technol. 48, 1247–1255.

Annerstedt, M., et al., Green qualities in the neighbourhood and mental health – results from a longitudinal cohort study in Southern Sweden, 2012. BMC Publ. Health 12, 337–349.

Astell-Burt, T., et al., 2014. The association between green space and mental health varies across the lifecourse. A longitudinal study. J. Epidemiol. Community Health 68, 578–583.

Beijing, S.B.o., 2020. Beijing Statistical Yearbook 2020. China Statistics Press.

Berg, A.E.v. d., et al., 2010. Green space as a buffer between stressful life events and health. Soc. Sci. Med. 70, 1203–1210.

Bjork, J., et al., 2008. Recreational values of the natural environment in relation to neighbourhood satisfaction, physical activity, obesity and wellbeing. J. Epidemiol. Community Health 62, 221–228.

Boers, S., et al., 2018. Does residential green and blue space promote recovery in psychotic disorders? A cross-sectional study in the province of utrecht, The Netherlands. Int. J. Environ. Res. Publ. Health 15, 2195–2203.

Bos, E.H., et al., 2016. A primrose path? Moderating effects of age and gender in the association between green space and mental health. Int. J. Environ. Res. Publ. Health 13, 492–500.

Bosh, M.v. d., Sang, A.O., 2017. Urban natural environment as natural-based solution for improved public health-a systematic review of reviews. Environ. Res. 158, 373–384.

Campbell, L.K., et al., 2016. A social assessment of urban parkland: analyzing park use and meaning to inform management and resilience planning. Environ. Sci. Pol. 62, 34–44.

Canty, A., Ripley, B., 2015. Boot: Bootstrap R (S-Plus) Functions. R Package Version 1.3-23.

Chen, Z., et al., 2020. Mental health status among residents in Hubei province during novel coronavirus disease epidemic: an online survey. Chin. J. Public Health 36, 11–14.

Choi, J.Y., et al., 2018. Effects of a physical activity and sedentary behavior program on activity levels, stress, body size. and Sleep in Sedentary Korean College Students 32, 1–9.

Dadvand, P., et al., 2016. Green spaces and General Health: roles of mental health status, social support, and physical activity. Environ. Int. 91, 161–167.

Dimitrova, D.D., Dzhambov, A.M., 2017. Perceived access to recreational/green areas as an effect modifier of the relationship between health and neighbourhood noise/air quality: results from the 3rd European Quality of Life Survey (EQLS, 2011 – 2012). Urban For. Urban Green. 23, 54–60.

Dzhambov, A.M., et al., 2018a. Multiple pathways link urban green- and bluespace to mental health in young adults. Environ. Res. 166, 223–233.

Dzhambov, A.M., et al., 2018b. Residential greenspace might modify the effect of road traffic noise exposure on general mental health in students. Urban For. Urban Green. 34, 233–239.

Gascon, M., et al., 2018. Long-term exposure to residential green and blue spaces and anxiety and depression in adults: a cross-sectional study. Environ. Res. 162, 231–239.

Goldberg, D., Williams, P., 1988. A Users' Guide to the General Health Questionnaire. NFER-Nelson, Windsor,UK.

Grellier, J., et al., 2017. BlueHealth: a study programme protocol for mapping and quantifying the potential benefits to public health and well-being from Europe's blue spaces. Bmj Open 7, 188–198.

Han, K.-T., 2017. The effect of nature and physical activity on emotions and attention while engaging in green exercise. Urban For. Urban Green. 24, 5–13.

Hartig, T., et al., 2014. Nature and health. Annu. Rev. Publ. Health 35, 207–228.

Houlden, V., et al., 2017. A cross-sectional analysis of green space prevalence and mental wellbeing in England. BMC Publ. Health 17, 460–469.

Jennings, V., Bamkole, O., 2019. The relationship between social cohesion and urban green space: an avenue for health promotion. Int. J. Environ. Health Res. 16, 452–468.

Jiang, B., et al., 2014. A dose of nature: tree cover, stress reduction, and gender differences. Landsc. Urban Plann. 132, 26–36.

Jokela, M., et al., 2020. Specific symptoms of the General Health Questionnaire (GHQ) in predicting persistence of psychological distress: data from two prospective cohort studies. J. Psychiatr. Res.

Kabacoff, R., 2015. R in action: data analysis and graphics with R. Manning Publications Co.

Ko, W.H., et al., 2020. The impact of a view from a window on thermal comfort, emotion, and cognitive performance. Build. Environ. 10, 79–108.

Kondo, M.C., et al., 2015. Nature-based strategies for improving urban health and safety. J. Urban Health 92, 800–814.

Labib, S.M., et al., 2020. Spatial dimensions of the influence of urban green-blue spaces on human health a systematic review. Environ. Res. 180.

Li, W., et al., 2019. Status and influencing factors of mental health among adult residents in China. Chin. J. Public Health 35, 579–582.

Liu, Y., et al., 2019. Neighbourhood greenness and mental wellbeing in Guangzhou, China: what are the pathways? Landsc. Urban Plann. 190, 103602.

Luck, G.W., et al., 2011. Relations between urban bird and plant communities and human well-being and connection to nature. Conserv. Biol. J. Soc. Conserv. Biol. 25, 816–826.

Maas, J., et al., 2009. Social contacts as a possible mechanism behind the relation between green space and health. Health Place 15, 586–595.

Markevych, I., et al., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317.

Matilda, V.D.B., et al., 2015. Moving to serene nature may prevent poor mental health—results from a Swedish longitudinal cohort study. Int. J. Environ. Res. Publ. Health 12, 7974–7989.

MingYuan, Z., YanLing, H., 2015. Handbook of Psychiatry Department Scales. Hunan Science and Technology Press, Hunan.

Mireia, G., et al., 2015. Mental health benefits of long-term exposure to residential green and blue spaces: a systematic review. Int. J. Environ. Res. Publ. Health 12, 4354–4379.

Pope, D., et al., 2015. Quality of and access to green space in relation to psychological distress: results from a population-based cross-sectional study as part of the EURO-URHIS 2 project. Eur. J. Publ. Health 35–38.

Qianyi, L., et al., 2020. An online investigation of mental health status of 857different status identities in Guangdong province during the outbreak of COVID-19. China. J. Psychinatrys 53, 190–197.

Richardson, D.B., Kaufman, J.S., 2009. Estimation of the relative excess risk due to interaction and associated confidence bounds. Am. J. Epidemiol. 169, 756–760.

Rteam, R., et al., 2014. R: a language and environment for statistical computing. Computing 14, 12–21.

Shuqing, H., et al., 2019. The healing landscape of the living room: a study of the health benefits of interior design and windowscape through virtual reality technology. N. Archit. 5, 23–28.

Smith, K.P., Christakis, N.A., 2008. Social networks and health. Annu. Rev. Sociol. 34, 405–429.
Stevenson, M., et al., 2021. epiR: Tools for the Analysis of Epidemiological Data. R Package Version 2.0.19.
Stochl, J., et al., 2016. An evaluation of computerized adaptive testing for general psychological distress: combining GHQ-12 and Affectometer-2 in an item bank for public mental health research. BMC Med. Res. Methodol. 16.
Sugiyama, T., et al., 2008. Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social interaction explain the relationships? J. Epidemiol. Community Health 62, e9–e15.
Tabatabaie, S., et al., 2019. A study of perceived nature, shade and trees and self-reported physical activity in denver. Int. J. Environ. Res. Publ. Health 16, 3604–3618.
Tiesler, C.M.T., et al., 2013. Exposure to road traffic noise and children's behavioural problems and sleep disturbance: results from the GINIplus and LISAplus studies. Environ. Res. 123, 1–8.
Tosevski, D.L., Milovancevic, M.P., 2006. Stressful life events and physical health. Curr. Opin. Psychiatr. 19, 184–189.
Triguero-Mas, M., et al., 2015. Natural outdoor environments and mental and physical health: relationships and mechanisms. Environ. Int. 77, 35–41.
Triguero-Mas, M., et al., 2017. Natural outdoor environments and mental health Stress as a possible mechanism. Environ. Res. 159, 629–638.
Vemuri, A.W., et al., 2011. A tale of two scales: evaluating the relationship among life satisfaction, social capital, income, and the natural environment at individual and neighborhood levels in metropolitan baltimore. Environ. Behav. 43, 3–25.
Verheij, R.A., et al., 2008. Urban—rural health differences and the availability of green space. Eur. Urban Reg. Stud. 15, 307–316.
Victoria, et al., 2018. The relationship between greenspace and the mental wellbeing of adults: a systematic review. PloS One 13, 71–106.
Völkera, S., et al., 2018. Do perceived walking distance to and use of urban blue spaces affect self-reported physical and mental health? Urban For. Urban Green. 29, 1–9.
Von Lindern, E., et al., 2016. Traffic-related exposures, constrained restoration, and health in the residential context. Health Place 39, 92–100.
Vujcic, M., et al., 2017. Nature based solution for improving mental health and well-being in urban areas. Environ. Res. 158, 385–392.
Wei, G., et al., 2021. Impact of house price growth on mental health: evidence from China - ScienceDirect. SSM - Population Health 13, 100696.
Weimann, H., et al., 2015. Effects of changing exposure to neighbourhood greenness on general and mental health: a longitudinal study. Health Place 33, 48–56.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer, New York, NY, USA.
Xiuping, L., 2017. A study on urban forest structure and urban tree canopy of residential areas and public institutions in Beijing urban area. Chinese Acad. Fores.
Yi, W., et al., 2020. The relationship between media exposure and mental health problems during COVID-19 outbreak. Fudan Univ. J. Med. Sci. 47, 174–179.