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Original article

Casual evaluation of the effects of a large-scale greenway intervention on physical and mental health: A natural experimental study in China

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ABSTRACT

Many cross-sectional studies have supported the health benefits of urban greenways. However, the causal relationship between urban greenway intervention and residents' physical and mental health remains unclear. Furthermore, the potential dose-response effect by distance to a greenway intervention remains unknown. This study explored the impact of a large-scale urban greenway intervention (construction of a 102-km-long East Lake Greenway in Wuhan, China) on the health outcomes of residents by using a natural experimental research design. We collected data before and after the intervention (in 2016 and 2019, respectively) from 1,020 participants living within a 5-km street-network distance from the entrances of this greenway. The average age of the participants was approximately 50, and most of them were married. More than half of the participants were female, currently employed, and had received a college education or above. Mixed-effects difference-in-difference (DID) models were used while controlling for individual and neighbourhood covariates. The results showed that the East Lake Greenway had a positive effect on the self-reported mental health of residents who lived within 2 km, and these benefits decreased with distance. The physical health benefit was insignificant. To increase the health benefits of urban greenways, more effort should be made to improve the accessibility of greenways and the surrounding environment. We also advocate that future natural experiments should explore the distance-varying dose-response effect of green space interventions on health outcomes.

1. Introduction

It has been projected that more than 70 % of the world population will live in cities by 2050 (United Nations, 2018). Concurrent with rapid global urbanization, people have fewer opportunities to contact nature (Parra-Saldivar et al., 2020). The shrinkage of urban green spaces may lead to exacerbated air pollution, traffic noise, and physical inactivity and therefore harm residents' physical and mental health (Klompmaker et al., 2019; Lachowycz and Jones, 2011; Wolch et al., 2014). Given the important role of urban green spaces in influencing public health, green space intervention has attracted increasing attention from government officials and researchers (Frank et al., 2019; Kestens et al., 2019). It is believed that creating new and improving existing urban green spaces could facilitate residents' healthy behaviours, reduce stress, and promote social interactions, thereby providing long-term health benefits at the population level (Badland and Schofield, 2005; Panter et al., 2019).

Greenways are linear, landscaped, and traffic-calm pathways for pedestrians and/or cyclists and usually connect parks and other public open spaces (Gobster, 1995; Moore and Shafer, 2011). Creating or retrofitting urban greenways has been recognized as one of the most effective green space intervention strategies (Branas et al., 2011; Humphreys et al., 2016). Urban greenways provide a continuous and safe environment for prolonged walking, cycling and exercise, thus encouraging people to maintain active lifestyles (Fitzhugh et al., 2010). Furthermore, some evidence also shows that performing physical activities in accessible urban greenways may increase exposure to nature and social interaction (Jaszczak et al., 2018; Shafer et al., 2000), thereby increasing the physical and mental health benefits.

Although there is consensus regarding the health benefits of greenways, most evidence comes from cross-sectional research, which is

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observational and may lead to spurious findings (Coutts, 2008; Hartig, 2008; Wu et al., 2018). It is difficult to establish causal relationships from cross-sectional studies because the observed greenway-health associations may be alternatively explained by other factors linking to both greenway accessibility and health outcomes. For instance, cross-sectional studies are prone to residential self-selection bias, which means that a person who prefers an active lifestyle may move to a neighbourhood with accessible greenways.

Aware of such potential limitations of cross-sectional studies, researchers have increasingly advocated natural experimental research design (Kuo and Sullivan, 2001; Ulrich et al., 1991). Natural experimental studies are of high value in establishing causation because of their longitudinal design (before and after intervention) and use of comparison groups (treatment groups vs. control group) (West and Shores, 2015; Zhang et al., 2019). However, to date, the majority of natural experimental studies have focused on the effect of urban greenways on physical activity improvement (Chen et al., 2017; Zuniga-Teran et al., 2019), and little research attention has been given to the physical and mental health benefits of greenways (Dallat et al., 2013; Keith, 2016; West and Shores, 2011).

Furthermore, most studies investigating the health impacts of greenway interventions used a single distance threshold to define greenway exposure (i.e., intervention vs. control group) (Hunter et al., 2019), which may lead to inconsistent findings because of a lack of consensus regarding appropriate distance threshold selection (Frank et al., 2019).

Dose-response estimation, which seeks to determine how the health benefits of a greenway vary for residents with different distances from a greenway, may help address this limitation (Jiang et al., 2014, 2015a, b; Shanahan et al., 2016). For instance, by evaluating the changes in physical activity and sedentary behaviour of residents living 100 m to 500 m from a greenway, Frank et al. (2019) determined the distance decay effect of a greenway intervention. Nevertheless, little is known about the distance-based dose-response effect on physical and mental health, especially for a large-scale greenway intervention.

Moreover, previous natural experimental studies on green space and health may fail to control for neighbourhood-level environments (Evenson et al., 2005; Pazin et al., 2016). Some cross-sectional studies have indicated that the effects of green space on residents' health may be stratified by the neighbourhood environment (Abildso et al., 2007; Zuniga-Teran et al., 2019). For example, it was suggested that residents who lived in neighbourhoods with higher perceived walkability reported more physical activity in the greenway (Zhu et al., 2019). To what extent greenway interventions impact residents' health outcomes across surrounding neighbourhoods with different attributes has not been sufficiently explored.

Last, most natural experimental studies of greenway intervention were conducted in low- or medium-density cities in developed counties, and the effectiveness of greenway intervention in high-density cities in developing countries is still unclear. Cities in developing countries, such as China, have undergone rapid and dense urban development (Yang et al., 2020). The consequent severe deterioration in the urban environment poses serious health challenges and has created an urgent need for green space interventions (Li et al., 2016). Despite the boom in urban greenway projects in China in recent years, longitudinal evidence on greenways' health benefits remains scarce. Considering the differences in the built environment and social contexts between developing and developed countries, a natural experimental study examining the impact of a greenway intervention on residents' physical and mental health in a high-density urban context in China is warranted to provide insights for urban planners and policymakers.

To address the abovementioned research gaps, we employ a natural experimental study design to explore the impact of a large-scale greenway intervention on changes in residents' physical and mental health status in Wuhan, China.

2. Literature review

2.1. Green space and health associations in cross-sectional studies

Existing cross-sectional studies on green space have extensively demonstrated its health benefits. The findings have mainly focused on three aspects. First, green spaces have a positive association with physical activity across the socioeconomic spectrum (Hunter et al., 2015; Twohig-Bennett and Jones, 2018). Increased physical activity level was associated with multiple green space indicators, including the accessibility, quantity, and quality of the green spaces (Jones et al., 2009; Twohig-Bennett and Jones, 2018).

Second, some studies support positive associations between green space and a wide range of physical health outcomes. For example, beneficial associations between green space and mortality and self-reported physical health have been reported (Mitchell et al., 2011; Richardson et al., 2010). The proximity of green space is associated with a lower risk of cardiovascular disease mortality and diabetes (Gascon et al., 2016; Ngom et al., 2016) and better sleep quality (Astell-Burt et al., 2013).

Third, another stream of research investigates the associations between green space and mental health outcomes, including mental fatigue (such as cognitive performance) (Browning and Rigolon, 2019; Dadvand et al., 2015; Jiang et al., 2015a, b), mental stress (Corraliza and Collado, 2011), depressive symptoms (Reklaitiene et al., 2014), anxiety (Nutsford et al., 2013), hyperactivity/inattention and peer relationship problems (Markevych et al., 2014). As one review found, most studies have reported a positive association between green space and a lower risk of mental health problems (Gascon et al., 2015).

Overall, cross-sectional research provides a considerable amount of evidence on the health benefits of green space. However, due to the difficulty of exploring temporal relationships using cross-sectional designs, inferences regarding causal relationships have been restricted. For example, residential self-selection bias cannot be excluded from the observed associations (Zang et al., 2019). It is uncertain whether proximity to green space causes better health outcomes or whether healthier people with active lifestyles choose to live in places with more green spaces.

2.2. Greenway interventions and health outcomes in natural experimental studies

To address the limitations of cross-sectional research designs, natural experimental studies have been advocated as a new research front (Kuo and Sullivan, 2001; Twohig-Bennett and Jones, 2018). Natural experimental studies collect longitudinal data (pre- and postintervention) for the intervention group (people who were exposed to an intervention) and control group (people who were not exposed to such intervention). By comparing the longitudinal changes in health outcomes of the intervention and control groups, the causal claim regarding health changes can be improved. The effects of endogeneity, e.g., self-selection bias, can also be minimized, as the intervention is less related to the residents' personal variables (Leatherdale, 2018a).

Most natural experimental studies on greenways have primarily focused on physical activity outcomes. For example, Fitzhugh et al. (2010) reported an increased physical activity level after a greenway was retrofitted. Similarly, the improvement of a greenway exerted a positive effect on walking and cycling time in other studies (Hirsch et al., 2017; Sahlqvist et al., 2013). Additional studies have demonstrated the inverse effect of greenway interventions on sedentary behaviour, indicating that greenway interventions may facilitate population-level healthy behaviour changes (Brownson et al., 2000; Dallat et al., 2013).

However, few studies have directly investigated the health benefits of greenway interventions. A recent review of six natural experimental studies focusing on greenways and trails revealed that none of them explored the intervention effect on physical or mental health outcomes

(Hunter et al., 2019). A natural experimental study focusing on neighbourhood-level green space improvement, which included greenway development as one of the green intervention measures, reported no significant effect of green space improvement on general health (Droomers et al., 2016a).

2.3. Pathways between greenway interventions and health outcomes

Researchers have identified several potential causal pathways through which greenway interventions improve residents' physical and mental health outcomes: stimulating physical activity, increasing exposure to green space, and facilitating social cohesion (Branas et al., 2011; Droomers et al., 2016b; West and Shores, 2011). First, urban greenways stimulate physical activity (Akpinar, 2016; Auchincloss et al., 2019; Xie et al., 2021). Achieving adequate physical activity, which has been acknowledged as a public health priority (Heath et al., 2012), is beneficial to reducing the risk of obesity and cardiovascular diseases (Akpinar, 2017; Benjamin et al., 2019; Lachowycz and Jones, 2011) and generates mental health benefits (Thompson Coon et al., 2011).

Second, increasing exposure to green space has been recognized as a pathway linking greenway interventions to mental health benefits (Hunter et al., 2019). Some studies have documented that visiting green spaces has a restorative effect on mental health (Lachowycz and Jones, 2013; Ojala et al., 2019). Stress reduction theory (SRT) suggests that exposure to green space reduces mental stress and evokes positive emotions (Ulrich et al., 1991). Moreover, attention restoration theory (ART) indicates that exposure to vegetation diverts people's attention while simultaneously reducing cognitive fatigue (Kaplan and Kaplan, 1989). The above evidence suggests that exposure to green space may reduce nearby residents' stress and mental fatigue and provide mental health benefits (Chaney and Stones, 2019; de Brito et al., 2020).

Third, facilitating social cohesion (e.g., a high degree of social interaction, community participation, and strong place attachment) is the third pathway (Forrest and Kearns, 2001). The presence of urban green spaces, including greenways, provided accessible public open space for residents with different social backgrounds to meet, share, and interact (Keith, 2016), which could help to build stronger social bonds between individuals (Liu et al., 2019; Peters et al., 2010). Urban green space of good quality also enables residents to build positive emotional connections with the environment, therefore helping develop place attachment (Chang et al., 2020). A cohesive neighbourhood is an essential precursor for engagement in collective physical activities such as walking, cycling, and receiving social support from neighbours (Broyles et al., 2011; Peters et al., 2010). Empirical evidence indicates that social cohesion is an important underlying mediator behind the relationship between green space and residents' physical and mental well-being (Liu et al., 2020; Maas et al., 2009).

2.4. Moderating factors

Some factors may moderate the relationship between greenway intervention and health outcomes. Evidence is emerging that individual characteristics, greenway features, and the surrounding environment are related to the magnitude of the health benefits produced by greenway interventions (Huston et al., 2003; Xiong et al., 2019). Regarding individual factors, multiple sociodemographic characteristics, such as age, gender, income, and education, moderate the impacts of a greenway on health outcomes (Starnes et al., 2011). For example, Brownson et al. (2000) documented that females and those with low income and education levels report higher increased walking frequency after the development of a greenway.

Some studies have found that greenway features, namely, greenway design, service facilities, and the quality of the natural environment, influence people's preferences and greenway usage and thus determine whether the health benefits of a greenway intervention meet expectations (Abildso et al., 2007; Gobster, 1995). Hence, a high-quality landscape and sufficient supporting facilities, such as parking areas and restrooms, encourage people to participate in greenway activities (Chen et al., 2017; Corazon et al., 2019; Dorwart, 2015; Xiong et al., 2019), thereby generating greater health benefits.

The built environment surrounding the greenway not only affects accessibility to the greenway (Xiong et al., 2019) but also affects the baseline health status of the residents who would be potential users of the greenway (Sampson et al., 2002). For example, residents living in neighbourhoods with higher perceived walkability are more likely to engage in physical activities in the greenway (Abildso et al., 2007). Residential proximity and density, which reflect the population aggregation level near the greenway, are positively related to the intensity of greenway use (Zhu et al., 2019). Moreover, a higher degree of mixed land use around the greenway may provide more potential destinations for residents, which in turn has a positive impact on greenway usage, especially for active travel purposes (Liu et al., 2016). Additionally, a recent study found that parks near greenways may 'dilute' visits, thus decreasing greenway usage (Liu et al., 2018). In summary, the built environment of the surrounding area could play an important role in the health outcomes of residents living nearby by facilitating greenway use.

2.5. Our study

To address the research gaps summarized in the introduction, we used a natural experimental study design to explore the causal effects of a greenway intervention on nearby residents' mental and physical health.

We also propose a comprehensive conceptual framework to capture the potential impact of greenway interventions on changes in health outcomes (Fig. 1). Specifically, greenway intervention directly stimulates the greenway usage of nearby residents, thereby increasing their physical activity, green space exposure, and social cohesion and ultimately improving their physical and mental health. Additionally, the individual, greenway, and surrounding built environment factors moderate the pathways through which greenway interventions impact the health outcomes of residents.

This study extends previous research in three respects. First, it is one of the front natural experimental studies exploring the effect of a large-scale greenway intervention on physical health and mental health simultaneously. Second, it offers insight into the research design of natural experiments by considering the dose-response effect of greenway exposure and controlling the neighbourhood-level covariates. Third, it provides longitudinal evidence of the health effects of a greenway intervention in a dense urban context from a developing country.

3. Study design

3.1. Study sites and sampling

The construction of the East Lake Greenway in Wuhan, China, presented an opportunity to investigate the health impact of greenways using a natural experimental design (Fig. 2). Two waves of surveys were conducted before and after East Lake Greenway construction. As the largest city in the economic and political centre of central China, Wuhan is undergoing rapid urbanization. Rapid urbanization has drastically reconfigured the built environment, e.g., green spaces. The East Lake Greenway was converted from a pedestrian-unfriendly traffic artery across East Lake to a traffic-free natural corridor. Connecting various scenic spots and public facilities around East Lake, this 102-km greenway provides residents not only various kinds of greening settings (e.g., parks and forests) but also the chance to contact blue space (He et al., 2021). The first 28.7-km phase of the greenway was constructed in 2016, and the 74-km second phase was constructed in 2017.

Two waves of surveys were conducted in 2016 and 2019. First,

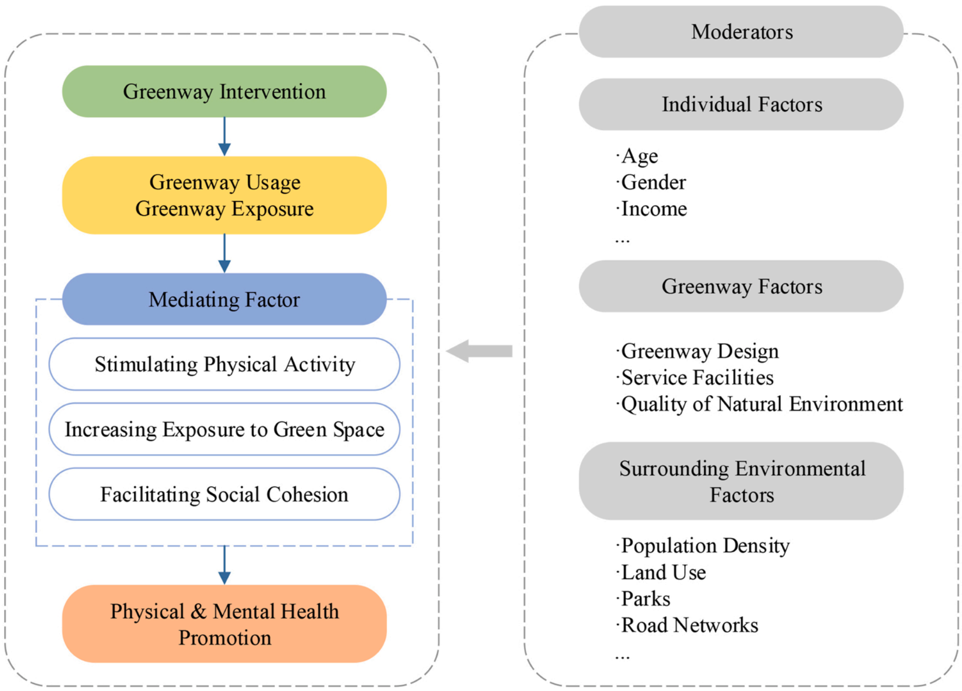

Fig. 1. Conceptual framework of the relationship between greenway interventions and health outcomes.

before the greenway intervention, a baseline survey was carried out in April 2016. Second, after the greenway intervention, we conducted a follow-up survey with the same participants in April 2019 to ensure the same seasonality of both surveys. The greenway was open to the public in December 2016, and our participants had a total 28-month intervention exposure until the follow-up survey. Questions specifically involving the respondents' individual factors were asked only in the baseline survey.

The study neighbourhoods and participants were selected using a three-stage sampling process. In the first stage, 0–1, 1–2, 2–3, 3–4, and 4–5 km street-network buffers were created with the three main entrances of the East Lake Greenway, namely, the Yikeshu entrance, the Liyuan entrance, and the Ma'anshan Forest Park entrance, as the reference points (Fig. 2). The five distance bands, rather than one single distance threshold, were used to explore the potential dose-response effect of greenway intervention on health outcomes. By comparing the health effect for residents living with varying distances to the greenway, we may identify the potential distance-sensitive effect of greenway intervention.

We selected 5 km as the maximum distance for sampling participants based on previous studies focusing on large-scale greenway interventions (Astell-Burt et al., 2016; Merom et al., 2003b). Moreover, neighbourhood-, city- and regional-level greenways in China are built according to service areas of 5 min (500 m), 15 min (1 km), and 45 min (5 km), respectively (Liu et al., 2016). The East Lake greenway is a regional-level, large-scale greenway that attracts many residents far away from the greenway with its natural and cultural scenery. Therefore, the 5-km street-network buffer was chosen in this study.

In the second stage, 52 neighbourhoods (*Xiaoqu* in Chinese) were selected and geocoded based on the principle of sampling equal numbers of higher socioeconomic status (higher-SES) and lower-SES neighbourhoods in each buffer. The average housing price within the neighbourhood was used as an SES proxy because real estate makes up the majority of household wealth in China (Li and Wu, 2014). The cut-off value separating higher-SES neighbourhoods from lower-SES neighbourhoods was set at 20,000 CNY/m^2 according to the median housing price in the districts (Wuchang District and Hongshan District) where the sampled neighbourhoods are located in (China Index Academy, 2016). In addition, the higher-SES neighbourhoods in the 0–1 km buffer were oversampled because the housing prices in the neighbourhoods near East Lake are generally higher than the median.

Finally, a total of 2,331 participants living in the 52 neighbourhoods were randomly selected for a face-to-face interview with trained research assistants as the baseline survey. The participants in the 0–1 and 1–2 km buffers were oversampled because they were more likely to be affected by this greenway intervention. The selected participants of the baseline survey who were willing to participate in a second interview were contacted again in 2019. Ultimately, 1,020 participants engaged in the second wave, and the retention rate was 43.8 %.

3.2. *Measures*

3.2.1. *Physical and mental health*

Physical and mental health outcomes were measured using the 12-item Chinese Short-Form Health Survey (SF-12), which assesses health outcomes in eight dimensions, including physical functioning, role-physical, body pain, general health, vitality, social functioning, role-emotional, and mental health (Ware, 2001). The Chinese SF-12 has been validated for the Chinese population (Lam et al., 2005; Shou et al., 2016). Both the physical component score (PCS) and mental component score (MCS) were calculated to represent physical health and mental health, respectively (Frankenthal et al., 2014; Kocalevent et al., 2013). Higher scores represent better health status.

3.2.2. *Neighbourhood environment*

This study adapted the 5Ds framework to capture the built environment characteristics at the neighbourhood level (Ewing and Cervero, 2010). The five categories of measures are (1) density (building density, residential density), (2) diversity (land use mix), (3) distance to transit (bus stop density and metro station density), (4) destination (park density), and (5) design (road density and intersection density). We created a 500 m street network buffer from the centroid of each neighbourhood to measure the neighbourhood environment variables. All the factors selected in the analysis passed the multicollinearity test (variance inflation factor value <4). Additionally, the average household income of the neighbourhood was used to define neighbourhood

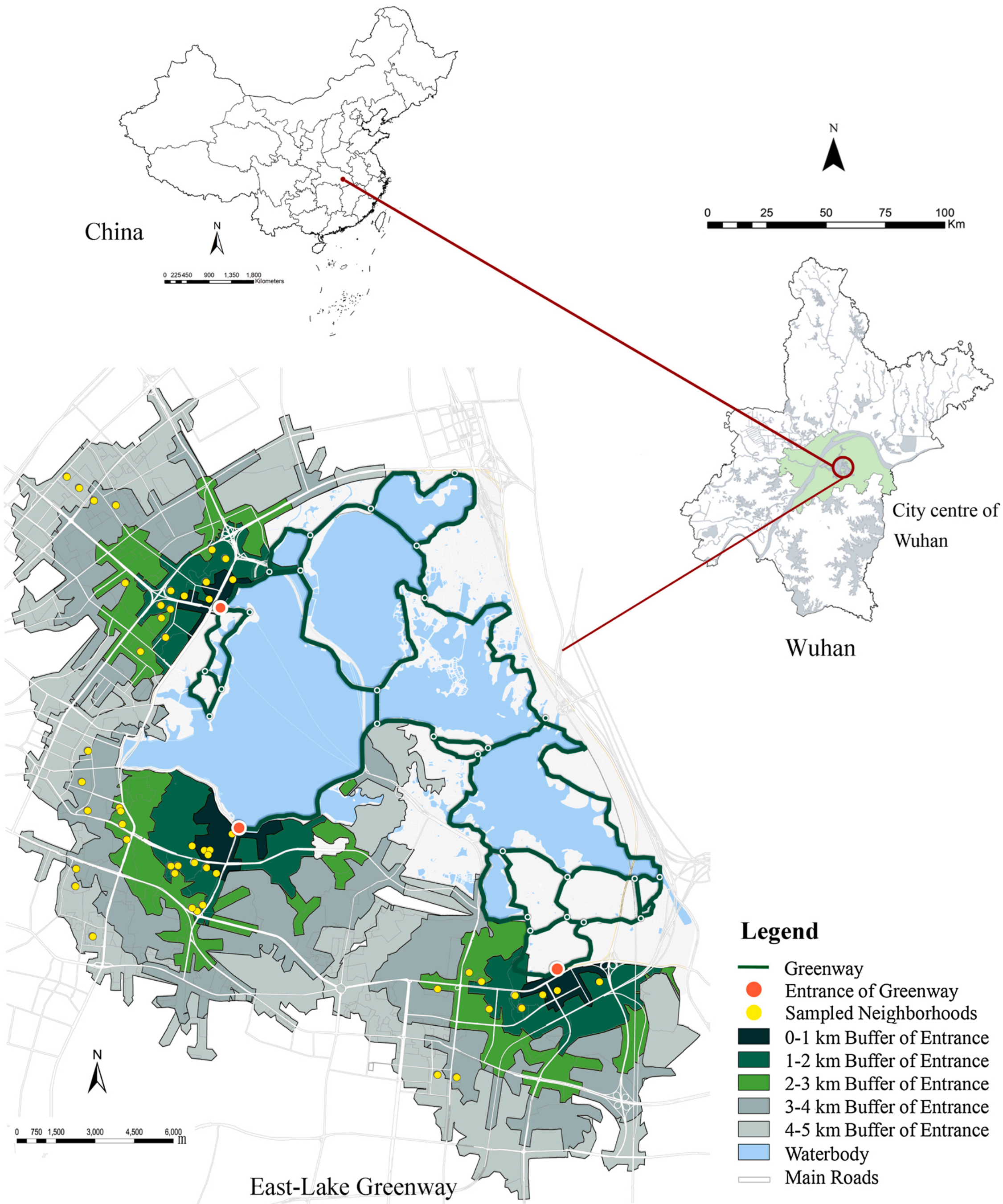

Fig. 2. The location of the East Lake Greenway and sampled neighbourhoods.

SES as a categorical variable (high vs. low). All the built environment variable measurements were carried out in ArcGIS 10.5.

3.2.3. Individual characteristics

The individual characteristics of the participants included their socioeconomic and demographic characteristics (i.e., age, gender, annual household income, marital status, education, and employment status).

3.3. Statistical analysis

3.3.1. Greenway exposure definition

In this study, we used two different methods to measure greenway exposure. First, a categorical measure with a threshold distance of 2 km was used to define the intervention and control groups. The residents living within 2 km of the greenway were treated as the intervention group, and those within 2–5 km were treated as the control group. Although the selection of the threshold distance for a comparable large-scale greenway has not been determined in previous research, some studies provide a reference for defining the exposure. For example, in a natural experimental study of a new 16.5-km trail, researchers defined residents within 1.5 km as the intervention group and those within 1.5–5 km as the control group (Merom et al., 2003a). Similarly, West and Shores (2015) defined residents living within 1 mile (1.61 km) of a 1.93 mile (3.11 km) greenway as the intervention group and those living between 2 and 3 miles of the greenway as the control group. In particular, a study in Wuhan reported that residents choose to visit large-scale green infrastructure when it is within 1.8 km; otherwise, they may be more inclined to choose neighbourhood green spaces instead (Xie et al., 2018). Because the East Lake greenway is a large-scale greenway with a length of 102 km, which is longer than any greenway reported in previous natural experimental studies (Merom et al., 2003b; West and Shores, 2015), we used the 2-km threshold distance.

Second, a continuous graded measure (1, 2, 3, 4, and 5 km) was used to define exposure to the greenway to explore the potential dose-response effect. For example, residents living in the 0−1 km buffer zone constituted the 1 km distance group, those living in the 1−2 km buffer zone constituted the 2 km group, and so on for the 3, 4, and 5 km groups.

3.3.2. A two-step analysis

Paired t-tests were used to determine the differences in the participants' health scores between the baseline and follow-up periods. Furthermore, a mixed-effect difference-in-difference (DID) regression model was run to examine the effect of greenway exposure on changes in physical health and mental health over time, with multilevel models to represent individuals nested in neighbourhoods. DID models can be used to estimate the effect of a specific intervention (e.g., greenway intervention in this study) by comparing the changes in outcomes over time between the intervention group and control group (Leatherdale, 2018b; Singer et al., 2003).

A two-step analysis with three DID models in each step was designed to estimate the effect size of greenway exposure on the physical score and mental score when different exposure measurement methods were used.

For the first step, in model (1), the determinants "exposure" and "time" and the interaction term "*Exposure*Time*" were included in the mixed-effect linear analysis. Because the neighbourhoods were not randomly selected in this study, the sampled participants might be subject to large variations in neighbourhood characteristics such as SES. To avoid this problem, individual and neighbourhood covariates were further added to models (2) and (3).

$$PCS_{ij}(or\ MCS_{ij}) = \beta_0 + \beta_1 Exposure_{ij} + \beta_2 Time_{ij} + \beta_3 Exposure_{ij}*Time_{ij} + (\varepsilon_{ij} + \mu_{ij}) \quad (1)$$

$$PCS_{ij}(or\ MCS_{ij}) = \beta_0 + \beta_1 Exposure_{ij} + \beta_2 Time_{ij} + \beta_3 Exposure_{ij}*Time_{ij} + \beta_4 Individual_{ij} + (\varepsilon_{ij} + \mu_{ij}) \quad (2)$$

$$PCS_{ij}(or\ MCS_{ij}) = \beta_0 + \beta_1 Exposure_{ij} + \beta_2 Time_{ij} + \beta_3 Exposure_{ij}*Time_{ij} + \beta_4 Individual_{ij} + \beta_5 Neighborhood_j + (\varepsilon_{ij} + \mu_{ij}) \quad (3)$$

where $PCS_{ij}(or\ MCS_{ij})$ is the physical score or mental score of participant *i* in *j*; β_1 captures the net difference between participants in the intervention group and the control group; β_2 captures the net physical score and mental score difference between participants before and after the greenway intervention; and β_3 captures the difference-in-differences estimate of the impact of greenway intervention on changes in health outcomes, i.e., the difference in the outcome in the intervention group before and after intervention minus the difference in the outcome in the control group before and after treatment. Moreover, ε_{ij} represents the individual-level error term, and μ_{ij} represents the neighbourhood-level error term. $Individual_{ij}$ and $Neighborhood_j$ denote the individual covariates and neighbourhood covariates, respectively. If β_3 is statistically significant in model (1), greenway intervention affects the changes in participants' physical and mental health. Moreover, if β_3 remains statistically significant in models (2) and (3), this reflects that the nonrandom assignment of the participants does not affect the original model results.

For the second step, the dose-response effect of the greenway intervention on the physical score and mental score was examined using a continuous measure of greenway exposure (1 km, 2 km, 3 km, 4 km, and 5 km). Model 4 was a basic DID model, similar to Model 1. Models 5 and 6 were based on Model 4 with individual and neighbourhood covariates added, respectively. The magnitudes of β_3 in the three above models can be used to examine how the intervention effect of the greenway changed with increasing distance to the greenway. All of the analyses were conducted using R (version 3.6).

4. Results

4.1. Descriptive statistics

Table 1 summarizes the descriptive statistics for the changes in physical and mental health from baseline to follow-up and the individual characteristics and neighbourhood environment at baseline. Specifically, the average physical score in the intervention, control and overall groups decreased significantly from baseline to follow-up. In addition, the Mental Score in the intervention group increased significantly, from 52.01 (SD = 7.40) to 52.49 (SD = 7.27), while the Mental Score in the control group did not change significantly (53.67 vs. 53.46).

Overall, the average age of our participants was 50.8, similar to the Wuhan population. There were slightly more female participants (56.6 %), and the majority of participants were married (83.5 %). More than half of the participants received a college education or above (50.3 %) and were currently employed (55.9 %).

On average, the participants in the intervention group were slightly younger than those in the control group (50.1 vs. 52.8), had higher household income (203.8 vs. 197.8), and were less likely to receive college education or above (49.5 % vs. 52.5 %). There were proportionally fewer females in the intervention group than in the control group (55.6 % vs. 59.2 %).

Regarding the neighbourhood environment, the number of parks was higher for the intervention group than for the control group. However, most of the built environment variables, including building density, land use mix, street intersection density, and number of bus stops, did not differ significantly between the intervention and control groups, reflecting that the neighbourhood environment of the intervention group corresponded closely to that of the control group.

4.2. Effects of the large-scale greenway intervention on physical and mental health

Table 2 shows the regression results for the first step of the analysis, which measured greenway exposure as a binary variable (intervention vs. control). Model 1 tested the effect of the greenway intervention on the physical score and mental score unadjusted for individual and neighbourhood covariates. The results revealed a significantly positive effect of the greenway intervention on the mental score but not on the physical score. In particular, the estimates of the interaction item (exposure*time) on Mental Score remained significant after adjusting for the individual and neighbourhood covariates in Models 2 and 3.

Regarding the covariates, age was significantly associated with the physical score and the mental score, while household income was positively related only to the physical score. Regarding the neighbourhood covariates, the number of bus stops was the only significant covariate for both the physical score and the mental score.

Table 3 shows the regression results for the second step of the analysis, which measured greenway exposure as a continuous variable. The results in Model 4 reveal that the interaction term (exposure*time) was negatively associated with Mental Score, suggesting that the effect of the greenway intervention on changes in Mental Score decreased with increasing distance from residential location to the greenway. Furthermore, the effect size of the interaction item on Mental Score did not significantly change after incrementally adjusting for the individual and neighbourhood covariates in Models 5 and 6. Fig. 3 shows the dose-response effect of the greenway intervention on changes in mental health by distance in Model 6, which implies that the effect decreases by distance. However, the effect of the greenway intervention on the physical score remains insignificant.

Table 1
Characteristics of the participants and the greenway and neighbourhood environments (n = 1020).

Variables	0–1 km	1–2 km	2–3 km	3–4 km	4–5 km	Intervention group	Control group	Overall
	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%
Physical score								
At baseline	50.89(8.07)	50.12(7.36)	50.68(8.41)	49.28(9.30)	46.47(7.85)	50.55(7.77)	49.04(8.71)	50.18(8.04)
At follow-up	49.91(8.35)	49.07(8.22)	48.94(9.34)	49.08(9.24)	46.14(8.06)	49.54(8.30)	48.22(9.03)	49.21(8.50)
Changes in PCS	−0.98(3.80)***	−1.05(4.26)***	−1.73(4.58)***	−0.19 (1.84)	−0.33(1.60)	−1.01(4.01)***	−0.82(3.21)***	−0.96(3.82)***
Mental score								
At baseline	52.59(7.41)	51.27(7.33)	53.89(8.03)	51.05(6.91)	56.63(6.60)	52.01(7.40)	53.67(7.57)	52.43(7.47)
At follow-up	53.27(7.05)	51.49(7.44)	53.85(8.88)	50.86(6.98)	56.15(7.07)	52.49(7.27)	53.46(8.03)	52.73(7.48)
Changes in MCS	0.67(3.34)***	0.23(3.28)	−0.03(4.53)	−0.19 (1.52)	−0.47(1.44)**	0.48(3.32)***	−0.21(3.03)	0.31(3.26)**
Individual factors								
Age	49.4 (16.4)	51.1 (16.2)	51.6 (15.4)	52.3 (14.3)	54.9 (16.8)	50.1 (16.3)	52.8 (15.4)	50.8 (16.1)
Gender (% female)	60.1 %	49.9 %	57.7 %	62.1 %	58.6 %	55.6 %	59.2 %	56.6 %
Education (% ≥college)	46.6 %	53.1 %	60.8 %	48.3 %	47.1 %	49.5 %	52.5 %	50.3 %
Employment (% employed)	54.1 %	64.5 %	48.5 %	41.4 %	54.3 %	58.6 %	47.5 %	55.9 %
Marital status (% married)	85.4 %	82.4 %	81.4 %	80.5 %	84.3 %	84.1 %	81.6 %	83.5 %
Household income ('000 CNY/ year)	218.4 (200.9)	185.0 (204.3)	280.8 (599.8)	134.7 (85.9)	161.2 (198.4)	203.8 (202.9)	197.8 (392.6)	202.3 (263.1)
Neighbourhood characteristics								
Building density	0.18 (0.06)	0.19 (0.05)	0.21 (0.07)	0.25 (0.12)	0.20 (0.04)	0.18 (0.05)	0.22 (0.09)	0.19 (0.06)
Land-use mix	1.64 (0.45)	1.76 (0.45)	1.85 (0.25)	1.38 (0.38)	1.57 (0.31)	1.69 (0.45)	1.61 (0.37)	1.67 (0.43)
Street intersection density	7.40 (2.31)	5.71 (0.97)	6.02 (1.20)	5.63 (0.86)	7.26 (0.43)	6.66 (2.03)	6.23 (1.13)	6.55 (1.86)

Note: The individual factors and the neighbourhood characteristics of selected participants were investigated in the baseline survey. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2
Regression estimates of the PCS and MCS changes due to greenway exposure, which was measured as a binary variable (intervention vs. control) (total n = 1020).

	Physical score			Mental score		
Model predictors	Model 1 beta (95 % CI)	Model 2 beta (95 % CI)	Model 3 beta (95 % CI)	Model 1 beta (95 % CI)	Model 2 beta (95 % CI)	Model 3 beta (95 % CI)
Greenway exposure (int. vs. control)	0.170 (-0.027, 0.366)	0.067 (-0.106, 0.240)	0.085 (-0.100, 0.271)	−0.280 (-0.516, -0.048)*	−0.243 (-0.471, 0.020)*	−0.087 (-0.358, 0.186)
Time	−0.099 (-0.156, -0.042)***	−0.099 (-0.156, -0.042)***	−0.099 (-0.156, -0.042)***	−0.028 (-0.081, 0.025)	−0.028 (-0.081, 0.025)	−0.028 (-0.081, 0.025)
Greenway exposure* Time	−0.023 (-0.089, 0.042)	−0.023 (-0.089, 0.042)	−0.023 (-0.089, 0.042)	0.092 (0.030, 0.154)**	0.092 (0.030, 0.154)**	0.092 (0.030, 0.154)**
Individual factors						
Age		−0.533 (-0.583, -0.483)***	−0.537 (-0.588, 0.487)***		0.330 (0.274, 0.386)***	0.331 (0.275, 0.388)***
Gender (female vs. male)		0.022 (-0.077, 0.122)	0.023 (-0.076, 0.124)		−0.040 (-0.152, 0.072)	−0.035 (-0.146, 0.077)
Education (≥college vs. others)		−0.057 (-0.163, 0.050)	−0.069 (-0.174, 0.040)		−0.092 (-0.211, 0.029)	−0.072 (-0.192, 0.048)
Employment (employed vs. not)		0.091 (-0.017, 0.199)	0.087 (-0.021, 0.194)		−0.044 (-0.165, 0.077)	−0.050 (-0.170, 0.071)
Marital status (married vs. others)		0.019 (-0.114, 0.152)	0.019 (-0.115, 0.150)		0.078 (-0.071, 0.227)	0.081 (-0.067, 0.230)
Household income		0.072 (0.022, 0.122)**	0.077 (0.027, 0.129)**		−0.002 (-0.059, 0.055)	−0.002 (-0.058, 0.057)
Neighbourhood characteristics						
Building density			0.046 (-0.028, 0.118)			0.032 (-0.061, 0.125)
Land-use mix			0.028 (-0.063, 0.122)			−0.087 (-0.218, 0.045)
Street intersection density			0.006 (-0.073, 0.082)			0.032 (-0.077, 0.135)
Greenery density			−0.083 (-0.192, 0.021)			0.029 (-0.109, 0.161)
Number of parks			0.016 (-0.106, 0.133)			−0.037 (-0.191, 0.121)
Number of bus stops			0.094 (0.010, 0.172)*			−0.134 (-0.233, -0.028)*
Neighbourhood SES (high vs. low)			−0.071 (-0.217, 0.075)			0.090 (-0.123, 0.283)

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3
Regression estimates of the physical and mental health changes due to greenway exposure, which was measured as a continuous variable (1-5 km) (total n = 1020).

	Physical score			Mental score		
Model predictors	Model 4 beta (95 % CI)	Model 5 beta (95 % CI)	Model 6 beta (95 % CI)	Model 4 beta (95 % CI)	Model 5 beta (95 % CI)	Model 6 beta (95 % CI)
Greenway exposure	−0.149 (-0.240, -0.058)**	−0.087 (-0.169, -0.005)*	−0.103 (-0.188, -0.012)	0.159 (0.055, 0.262) **	0.131 (0.031, 0.230) *	0.078 (-0.039, 0.192)
Time	−0.116 (-0.145, -0.088)***	−0.116 (-0.145, -0.088)***	−0.116 (-0.145, -0.088)***	0.041 (0.014, 0.068) **	0.041 (0.014, 0.068) **	0.041 (0.014, 0.068)
Greenway exposure* Time	0.020 (-0.009, 0.048)	0.020 (-0.009, 0.048)	0.020 (-0.009, 0.048)	−0.048 (-0.074, -0.021)***	−0.048 (-0.074, 0.021)***	−0.048 (-0.074, -0.021)**
Individual factors						
Age		−0.531 (-0.581, -0.481)***	−0.535 (-0.586, -0.485)***		0.329 (0.273, 0.385) ***	0.331 (0.276, 0.388)***
Gender (female vs. male)		0.023 (-0.077, 0.122)	0.023 (-0.076, 0.123)		−0.038 (-0.150, 0.074)	−0.035 (-0.146, 0.077)
Education (≥college vs. others)		−0.054 (-0.159, 0.053)	−0.065 (-0.170, 0.043)		−0.091 (-0.210, 0.030)	−0.072 (-0.191, 0.049)
Employment (employed vs. not)		0.091 (-0.017, 0.198)	0.086 (-0.021, 0.194)		−0.048 (-0.169, 0.073)	−0.051 (-0.171, 0.070)
Marital status (married vs. others)		0.017 (-0.116, 0.150)	0.018 (-0.115, 0.149)		0.077 (-0.072, 0.226)	0.081 (-0.067, 0.229)
Household income		0.069 (0.019, 0.119) **	0.076 (0.025, 0.128) **		−0.001 (-0.058, 0.056)	−0.002 (-0.058, 0.057)
Neighbourhood characteristics						
Building density			0.056 (-0.019, 0.127)			0.034 (-0.059, 0.128)
Land-use mix			0.024 (-0.068, 0.117)			−0.090 (-0.219, 0.040)
Street intersection density			−0.006 (-0.084, 0.073)			0.033 (-0.078, 0.138)
Greenery density			−0.080 (-0.188, 0.025)			0.030 (-0.108, 0.162)
Number of parks			0.009 (-0.109, 0.124)			−0.041 (-0.193, 0.114)
Number of bus stops			0.090 (0.006, 0.167) *			−0.135 (-0.234, -0.030)*
Neighbourhood SES (high vs. low)			−0.089 (-0.235, 0.060)			0.089 (-0.127, 0.285)

Note: PCS represents physical health, and MCS represents mental health.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

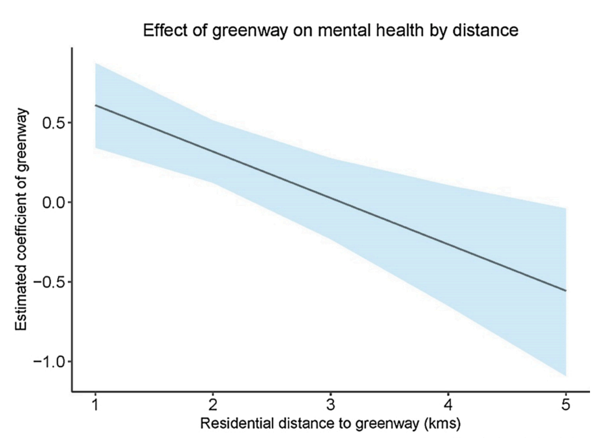

Fig. 3. Dose-response effect of the greenway intervention on changes in mental health. The effect of greenway intervention decreases with distance from residential location to the greenway.

Similar to the results in the first step, age was significantly associated with mental score, and household income was significantly associated with physical score. The number of bus stops was still the only neighbourhood covariate linked to both the physical score and mental score.

5. Discussion

In this study, we employed a natural experimental research design to explore the causal effect of a large-scale greenway intervention on the self-reported physical and mental health status of residents living within a 5-km street-network distance of the East Lake Greenway in Wuhan, China. Furthermore, the dose-response effect of the greenway intervention on health outcomes by distance was explored.

5.1. Main findings

First, our study demonstrated the causal relationship between a large-scale greenway intervention and changes in the mental health of residents after controlling for individual and neighbourhood covariates. Similar findings have been found in several studies assessing the benefits of urban green space interventions on mental well-being (Grilli et al., 2020) and decreased psychological distress (Park et al., 2011). The findings are supported by theoretical consensus that exposure to nature can improve mental health by invoking involuntary attention and reducing cognitive fatigue (Kaplan, 1995; Ulrich et al., 1991). In other words, natural elements can deliver mental health benefits (Gritzka et al., 2020; Wolf et al., 2020). Therefore, the East Lake Greenway intervention, including both green and blue spaces, has substantial and prolonged mental health benefits.

Second, in contrast, the greenway intervention in our study was not associated with changes in residents' physical health status. The participants in our study tended to be older, and their general physical health and mobility may decrease with age (Pleson et al., 2014). Therefore, the positive physical health benefits produced by greenway intervention may be largely offset by the natural ageing of our participants. Our results also showed that both the intervention group and control group had decreased physical health during the study period. In addition, similar results were also found in previous longitudinal studies, suggesting that factors not captured in the study may have contributed to decreased physical health status (Thompson et al., 2019).

Third, the dose-response estimation showed that the mental health benefit deceases by distance, and the residents living within 2 km had positive mental health changes. This finding supports the critical role of greenway proximity in health promotion (Abildso et al., 2007; Dennis et al., 2020). The effective distance in this study is longer than those in other smaller-scale greenway studies. For example, the effective distance threshold in Frank et al. (2019)'s study was 300 m for a 2 km route greenway. However, despite the large scale of the 102-km greenway interventions, the spatial reach of the population receiving such benefits was still limited. To optimize health benefits, improving the accessibility of greenways should be highlighted to encourage the use of greenways from residents living in wider surrounding areas. For example, the connection between surrounding neighbourhoods and greenways could be enhanced by improving street connectivity, public transportation, and the land use mix (Coutts, 2008).

5.2. Strengths and limitations

In this study, we contribute to previous natural experimental research in several respects. First, we used dose-response estimation to explore the distance-decay effect of greenway intervention. The majority of existing natural experimental studies used a single distance threshold to measure greenway exposure as a binary variable (intervention vs. control group) (Fitzhugh et al., 2010; Tully et al., 2013). However, the geographic scale of the optimal distance threshold for green space intervention could be affected by numerous factors, such as the greenway location, type, and environmental context (Frank et al., 2019). Hence, an arbitrary distance threshold may not be able to capture distance-varying effects of a green space intervention, thus leading to inconsistent conclusions. To minimize such bias, dose-response estimation might help future natural experimental studies capture the fine-grained spatial reach of the health benefits of green space interventions.

Second, the scale of the East Lake Greenway intervention is notably larger than those of the greenway interventions in other natural experiments. This large-scale greenway intervention, implemented by the local government, is projected to provide broadened health benefits because it can be accessed freely by the general public (Ward Thompson et al., 2016). Meanwhile, given the heavy financial cost of such a large intervention, its cost-effectiveness warrants attention. Although greenway planning is now widespread in China and over 163 cities had initiated municipal greenway construction by 2016 (Liu, 2017), little academic attention has been given to the evaluation of greenways' potential health impacts. Thus, our study provided valuable evidence on the health effect of a rare large-scale urban greenway intervention.

In addition, our study yielded important insight into the sensitivity of natural experimental studies by controlling for neighbourhood covariates. Because a fully controlled experiment with participants randomly assigned to the greenway intervention and control groups is infeasible, residential self-selection of individuals based on their preferences with respect to the neighbourhood built and social environment may induce bias in assessing the observed causal relationship between green space interventions and changes in health outcomes (James et al., 2015). How to minimize residential self-selection bias has been extensively discussed in the literature (Barnett et al., 2017; Boone-Heinonen et al., 2010). A natural experimental study investigating the relationship between the built environment and suicide death in Hong Kong sampled rent-only public housing communities, where public housing flats were largely randomly assigned to low-income individuals or families; hence, such a research design reduces the self-selection bias (Jiang et al., 2021). In our study, we alternatively controlled for potential neighbourhood covariates to reduce such bias. Although the results showed that nonrandom assignment did not have a significant impact on the estimation of health benefits, controlling for neighbourhood environment covariates should be considered in future natural experimental research on green space interventions.

This study has several limitations. First, we measured only self-reported physical and mental health rates, which are subject to recall bias. Objective measures of physical and mental health are needed in future studies. Second, this study highlighted the health outcomes due to an urban greenway intervention, but the mechanism was not fully explored in our study. Future longitudinal research should explore the causal pathway from urban greenway intervention to health outcomes. Third, we used dose-response estimation to explore the optimal distance thresholds, with graded measures of distance. Future studies could use a dose-response curve to establish a relationship with larger sample sizes across different distances. Fourth, we only conducted one follow-up investigation. To better understand the temporal changes in health outcomes, multiple follow-ups covering a wider range of exposure times are needed in future studies. Finally, it would be worthwhile to collect greenway usage data and explore their association with greenway exposure and health outcomes, which may provide more evidence of changes in health outcomes associated with greenway interventions.

6. Conclusion

This study provided longitudinal evidence based on a natural experiment conducted near the East Lake Greenway in Wuhan, China. The results show that the large-scale urban greenway intervention produced mental health benefits for urban residents. The results also demonstrate a clear distance-decay effect of this intervention on changes in the mental health of residents, and the large-scale greenway promoted the mental health of residents living within 2 km of the greenway. However, the greenway did not affect residents' physical health status in this study. To improve the health of urban residents in China, more efforts should be made to increase the provision and accessibility of urban greenways. In particular, urban planners and government officials should improve the neighbourhood environment to encourage greenway usage.

Author statement

Bo Xie: Methodology, Investigation, Writing - Original Draft. **Yi Lu:** Conceptualization, Writing - Review & Editing. **Yiling Zheng:** Software, Formal analysis.

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Declaration of Competing Interest

The authors report no declarations of interest.

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