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Large-scale greenway exposure reduces sedentary behavior: A natural experiment in China

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ABSTRACT

As a global public health problem, sedentary behavior has attracted more and more attention. Although numerous studies have demonstrated many benefits of green spaces to health, causal evidence on how green spaces affect people's sedentary behavior is scarce. This study used a natural experiment to evaluate the impact of greenway intervention on sedentary behavior. Two waves of data were collected in 2016 and 2019 (before and after the intervention) at East Lake Greenway (102-km-long) in Wuhan, China, with 1020 participants in 52 neighborhoods. We adopted three major methods to evaluate the impact of greenway intervention on sedentary behavior, including Propensity Score Matching and difference-in-difference (PSM-DID) method (with both individual and neighborhood variables to match samples), continuous treatment DID method (with distance to the greenway as the continuous treatment), and mediation analysis (with moderate to vigorous physical activity or MVPA, and walking time as the mediator). The results revealed that the greenway intervention significantly reduced participants' sedentary time and the intervention has a distance decay effect. The closer to the greenway, the greater decrease in sedentary time after the greenway opening. Furthermore, we found that MVPA and walking time mediate the impact of the greenway intervention on the change in sedentary behavior. The effect of greenway intervention was more beneficial for those under the age of 60, those who were employed, or those who were married. Our findings provided robust evidence that exposure to urban greenways affects sedentary behavior and such green infrastructures help protect public health in high-density urban areas.

1. Introduction

1.1. *Sedentary behavior and public health*

Sedentary behavior has emerged as a global public health concern due to its association with several diseases like diabetes, obesity, and cardiometabolic risks (Aggio et al., 2015; Motomura et al., 2022; O'Donoghue et al., 2016; Storgaard et al., 2013; Wu et al., 2023a,b). It is defined as "any waking behavior characterized by an energy expenditure ≤1.5 METs while in a sitting or reclining posture" (Sedentary Behaviour Research, 2012), including sitting, vehicle operation, computer use, and television watching (Koster et al., 2012). Studies have confirmed that those who meet moderate to vigorous physical activity (MVPA) guidelines don't necessarily reduce the sedentary time (Park et al., 2020; Storgaard et al., 2013) and sedentary behavior is associated with related diseases regardless of an individual's physical activity levels (Kim et al., 2022; Rhodes et al., 2012). These findings implied the independence of sedentary behavior from MVPA and suggested the need for distinct interventions to reduce sedentary behavior. Therefore, it is crucial to investigate sedentary behavior itself.

According to a 2021 report, Chinese employees have an average daily sitting time of 9.4 h, with 73.9% engaging in more than 8 h sitting per day. Similar patterns are observed in other countries worldwide. For instance, Korean adults have an average 8.3 h sedentary time daily, Japanese have 5.3 h, and Americans have 7.7 h. Europeans spend 40% of their leisure time on watching TV (Kitayama et al., 2021; Park et al., 2020; Patterson et al., 2018). Moreover, studies found that the average daily sedentary time for older adults is more than 9 h, equal to 65–80% of their waking hours (Harvey et al., 2015; Shibata et al., 2019).

Sedentary behavior can cause great harm to our health. It affects

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lipid and glucose metabolism and atherosclerosis, as a result, leads to cardio-metabolic related diseases (Hamilton et al., 2007; Patterson et al., 2018). With aging, sedentary behavior may lead to sarcopenia and muscle atrophy, which in turn contributes to increased mortality in nonalcoholic fatty liver disease patients (Golabi et al., 2020; Kerr and Booth, 2022). Evidence has also shown that each hour increment in sedentary time was associated with an 11% and 18% increased risk of all-cause and cardiovascular disease mortality, respectively (Owen et al., 2010; Patterson et al., 2018). Sedentary behavior not only affects human health but also leads to substantial social costs. According to a study in Canada, annual healthcare costs associated with sedentary behavior contribute approximately 1.6% to the overall healthcare burden, i.e., roughly 2.2 billion Canadian dollars in 2021 (Chaput et al., 2023). Studies from other countries (Finland, France, UK, etc.) have also shown similar findings (Leonie et al., 2019; Noël Racine et al., 2022; Päivi et al., 2022).

Hence, reducing sedentary behavior is not only beneficial for our health but also helpful in alleviating the burden on healthcare systems. The World Health Organization 2020 guidelines also emphasize the importance of reducing sedentary time across all age groups and replacing it with any level of physical activity (Fiona et al., 2020).

Many studies have found a link between green space and sedentary behavior (Aggio et al., 2015; Benjamin-Neelon et al., 2019; Fernández-Barrés et al., 2022; Frank et al., 2019; Loder and van Poppel, 2020; Storgaard et al., 2013). However, evidence from natural experiments is scarce, which limits causal inferences between sedentary behavior and greenspaces. Second, it is unclear how the effect of greenspace on sedentary behavior varies with distance and whether there are possible mediators between them. Exploring these potential pathways is essential for understanding the underlying mechanisms between greenspace interventions and sedentary behavior. Hence, this study used a natural experiment to evaluate the impact of a large-scale greenway intervention on sedentary behavior.

1.2. *Literature review*

1.2.1. *Greenspace and sedentary behavior*

The determinants of sedentary behavior can be classified into three categories: individual, interpersonal, and environmental factors according to the socio-ecological model (O'Donoghue et al., 2016; Rhodes et al., 2012). Individual factors include lifestyle, physical activity, age, gender, attitudes and perceptions, educational levels, and income. Interpersonal factors involve marital status, number of children, social norms, and cohesion. Environmental factors, including physical environment (e.g., street lighting, benches), public transport facilities, and neighborhood safety, have recently aroused increasing interest from urban planners and researchers (Anthony et al., 2015; Astell-Burt et al., 2014a,b; Cerin et al., 2021; Chandrabose et al., 2022; Chen et al., 2022a, b; Epstein et al., 2006; Liu et al., 2023).

Urban public greenspace, as a critical component of urban open space and natural environment, is vital in reducing sedentary behavior (Aggio et al., 2015; Benjamin-Neelon et al., 2019; Loder and van Poppel, 2020; Storgaard et al., 2013). Greenspace encourages physical activities by providing safe and accessible spaces and may simultaneously reduce sedentary behavior (Chong et al., 2019). Several studies have found that increasing the availability and density of greenspaces (e.g., the proportion, number, or area of greenspaces within specific buffers) correlates with reduced sedentary time. Staying longer in greenspaces is also associated with less sedentary time (Benjamin-Neelon et al., 2019; García de Jalón et al., 2021; Sanders et al., 2015). In addition, less sedentary behavior was observed in recreational areas (e.g., zoo, playground) and agricultural green spaces (e.g., grassland, orchard) than in parks (Jansen et al., 2017).

However, most studies employed a cross-sectional design, limiting causal inferences between sedentary behavior and greenspaces (O'Donoghue et al., 2016). The association observed in cross-sectional design studies may be susceptible to bias from unmeasured confounders or measurement errors (Leatherdale, 2019). Hence, natural experiments are often recommended to address these limitations. Furthermore, most studies have been conducted in low-or-medium-density cities in developed countries, including the US, Australia, and Denmark (Aggio et al., 2015; Loder and van Poppel, 2020; Storgaard et al., 2013). Evidence is, however, very scarce in developing countries, e.g., China. Due to the differences in motorization levels and physical demands of different types of work between developed and developing countries, residents may have different physically active levels (Dumith et al., 2011). Hence, the impact of greenspace interventions on residents' sedentary behavior remains unclear in developing countries.

1.2.2. *Relationship between distance to greenspace and sedentary behavior*

Several studies have explored the relationship between participants' distance to greenspace and sedentary behavior. Some studies found that proximity to greenspace is associated with less sedentary time. For example, children residing more than a 20-min walking distance from green spaces exhibited over 2 h more sedentary time compared to those living within a 5-min walking distance (Aggio et al., 2015). However, conflicting findings were reported in other studies (Fernández-Barrés et al., 2022; Koohsari et al., 2020; Veitch et al., 2016), where no significant associations were observed between sedentary behavior and the proximity to the nearest green spaces. This inconsistency in evidence might be due to that the impact of greenspaces on sedentary behavior becomes apparent only beyond a certain distance threshold (Kaczynski et al., 2009). Notably, in these studies, the distance to greenspaces was predominantly within 1000 m of participants' homes, a range that may not be sufficient to discern significant changes in sedentary behavior (West and Shores, 2011).

Only one study examined the distance decay effect of greenspace intervention on sedentary behavior through a natural experiment (Frank et al., 2019). Utilizing a difference-in-difference analysis with multiple distance thresholds, the study revealed that the effect of greenspace intervention on sedentary behavior works best for those living within 300 m of the greenway. However, it's important to note that this study employed a binary variable for the treatment and control groups, failing to capture the fine-grained distance decay effect of greenspace interventions (Craig et al., 2017). For example, even within the same treatment group (within the 300 m distance threshold), spatial heterogeneity in the impact of greenspace intervention may exist.

1.2.3. *Heterogeneity of greenspace intervention effect*

Several studies have demonstrated that the impact of greenspace intervention on sedentary behavior varies among different demographic groups. For example, unemployed individuals are more affected by the availability of green spaces than employed people (Storgaard et al., 2013). Gender differences are also observed, where boys in greener environments show reduced weekend television viewing, while such an effect is not evident among girls (Sanders et al., 2015). Among college students, sedentary behavior is more likely to be influenced by the perceived greenness in nearby neighborhoods rather than the greenness on the university campus (Loder and van Poppel, 2020). It should be noted that these studies predominantly focus on the sedentary behavior of children and younger adults (Aggio et al., 2015; Benjamin-Neelon et al., 2019; Fernández-Barrés et al., 2022). The heterogeneity in other age groups and some other individual sociodemographic factors, such as SES, education, and gender, remains to be explored.

1.3. *Major research gaps*

Although the link between urban greenspaces and sedentary behavior is well established, several research gaps hinder a comprehensive understanding of this relationship.

First, few studies used natural experiments to examine the relationship between greenspace and sedentary behavior, which limits the causal inferences between them. Natural experiments enable researchers to discern causality by comparing outcomes between a treatment and control group before and after intervention (Hunter et al., 2015). It can provide robust and reliable evidence and is essential to evaluate large-scale population health interventions (Craig et al., 2017). Although natural experiments have been widely used to evaluate the relationship between physical activity and environmental interventions (Benton et al., 2021; Tester and Baker, 2009; Wu et al., 2023b; Xie et al., 2021), there is only one such experiment assessing the relationship between greenspace and sedentary behavior (Frank et al., 2019).

In addition, most natural experiment studies on greenspace interventions haven't controlled for the self-selection bias. Although the DID model can control for the observed and unobserved differences and avoid the omitted variable bias (Craig et al., 2017), residential self-selection bias may still exist because the ideal approach is to compare outcomes between individuals who are randomly assigned to treatment group and control group (Caliendo and Kopeinig, 2008). However, in urban studies, random assignments are not feasible. Using natural experiment research design may introduce differences between the two groups. For example, individuals who like doing outdoor activities may choose to reside near green spaces. As a result, their frequency of outdoor activities may increase (Boone-Heinonen et al., 2010). This phenomenon, termed as residential self-selection (Cao et al., 2009), can introduce bias. In a natural experiment, if there are more people having preferences for greenspace in the treatment group than in the control group, it will lead to a misestimation of the net effect of greenspace intervention because we cannot distinguish whether it is due to the intervention or the individual preferences (Craig et al., 2017).

Second, the relationship between distance to greenspace and sedentary behavior has not been fully understood. Although several natural experiment studies have investigated the distance decay effect of greenspace intervention using multiple distance thresholds (Frank et al., 2019) or graded distance measures (He et al., 2022; Xie et al., 2021) to define participants' exposure to greenspace, these methods have limitations. The multiple distance threshold method means the participants are binarily divided into multiple sets of treatment and control groups with different threshold distances (e.g., 100 m, 200 m, 300 m). The graded distance measure method categorizes participants based on their distance to greenspace (e.g., 0–1 km, 1–2 km) (Xie et al., 2021). Although these methods are better than the method of using a single distance threshold in earlier studies, they still did not capture the fine-grained patterns of the changes in participants' exposure to greenspace by distance. For example, even in the same distance threshold, i.e., within 1–2 km, the greenspace exposure of participants (treatment intensity in the DID model) may be different. Continuous treatment, as commonly used in economics and agriculture studies to measure treatment intensity in DID models (Adorno et al., 2007; Callaway et al., 2021; Kassie et al., 2014; Nunn and Qian, 2011), presents an opportunity to evaluate the variation in exposure more comprehensively. Although distance is often used as a continuous variable to investigate the distance decay effect in transportation and geography cross-sectional studies (Krizek et al., 2007; Larsen and El-Geneidy, 2011; Prins et al., 2014), it has rarely been used in natural experiment studies on greenspace. In a recent study, the distance to the greenway was used as the measure of greenspace exposure (Wang et al., 2023b). Therefore, employing distance as a continuous treatment intensity is a viable approach to exploring the distance decay effect in natural experiments.

Third, the possible mechanism between sedentary behavior and greenspace intervention remains unclear. Many studies have shown that access to green space could promote physical activity, including both walking and MVPA (Astell-Burt et al., 2014a; Feng et al., 2021; Frank et al., 2019; He et al., 2021). This is due to that green spaces are likely to offer a safe, comfortable, and appealing setting for physical activity (Almanza et al., 2012). However, the evidence on whether increasing in physical activity is linked to reduced sedentary behavior remains inconsistent. On one hand, some studies showed that interventions to increase physical activity do not reduce sedentary behavior (Aittasalo et al., 2012; Andersen et al., 2013). For example, in a study designed to increase physical activity among office workers, it was found that workers' physical activity increased, but their sedentary time did not significantly decrease (Gilson et al., 2009). In addition, people who increase their physical activity levels may become more sedentary because they are satisfied with achieving a certain amount of physical activity levels (Prince et al., 2014). On the other hand, some other studies revealed that people who increase their time in physical activity (either LPA or MVPA) often reduce their sedentary time (Harding et al., 2015; Siddique et al., 2015). For instance, one study found that participants' light physical activity increased as time spent watching television decreased (Raynor et al., 2013). This is likely because people tend to redistribute time between physical activity and sedentary activity.

The inconsistency in the empirical findings may be explained by different contexts in terms of the scale of interventions, urban settings, and social norms. Considering that this study focused on a high-quality and large-scale greenway, we tend to believe that our participants are more likely to reallocate sedentary time to MVPA or walking. Therefore, we assume that increasing physical activity mediates the relationship between greenspace interventions and reducing sedentary behavior.

1.4. *The present research*

Our study addresses these gaps through a natural experiment approach, investigating the impact of a greenway intervention on changes in sedentary behavior. Two waves of data were collected in 2016 and 2019 (before and after the intervention) at East Lake Greenway in Wuhan, China, with 1020 participants in 52 neighborhoods. The East Lake Greenway was operated in 2017 when the former vehicle roads were transformed into a 102-km-long greenway. This greenway includes dedicated bicycle lanes, pedestrian pathways, extensive service amenities, and beautiful scenery. It is a typical example of a greenway intervention to promote public health in China.

First, we assessed the effect of greenway exposure across various distance thresholds (e.g., 500 m, 1000 m, 1500 m, etc.) to identify the most appropriate exposure range (treatment group). Second, we employed the Propensity Score Matching-Difference-in-Differences (PSM-DID) method to evaluate the net effect of the greenway intervention on sedentary behavior, effectively addressing self-selection bias in standard DID models. Third, we applied the DID model with a continuous treatment, the distance to the greenway, to explore the distance decay effect of the greenway intervention. This approach allows for a nuanced analysis of how the greenway intervention's impact varies with distance. Fourth, we conducted mediation analysis to investigate whether increased MVPA or walking time mediates the relationship between the greenway intervention and changes in sedentary behavior. Lastly, we examined the heterogeneity of the greenway's impact on participants. To our best knowledge, our study is one of the few natural experiments in evaluating the effects of large-scale greenway interventions on sedentary behavior in China.

2. Methods

2.1. *Study sample and data collection*

2.1.1. *Study site and survey*

The East Lake (Donghu in Chinese), located in Wuhan, a city in central China, is China's largest urban lake (Fig. 1). The East Lake Greenway is in the East Lake. To improve Wuhan's urban ecosystem and increase its tourism potential, the local government has built a 102-km vehicle-free greenway in the East Lake. The East Lake Greenway is the longest greenway around the lake in the urban core area in China. It is also selected as the pilot project for improved urban public space by UN-Habitat (UN-Habitat, 2016).

The greenway was transformed from the original village roads and

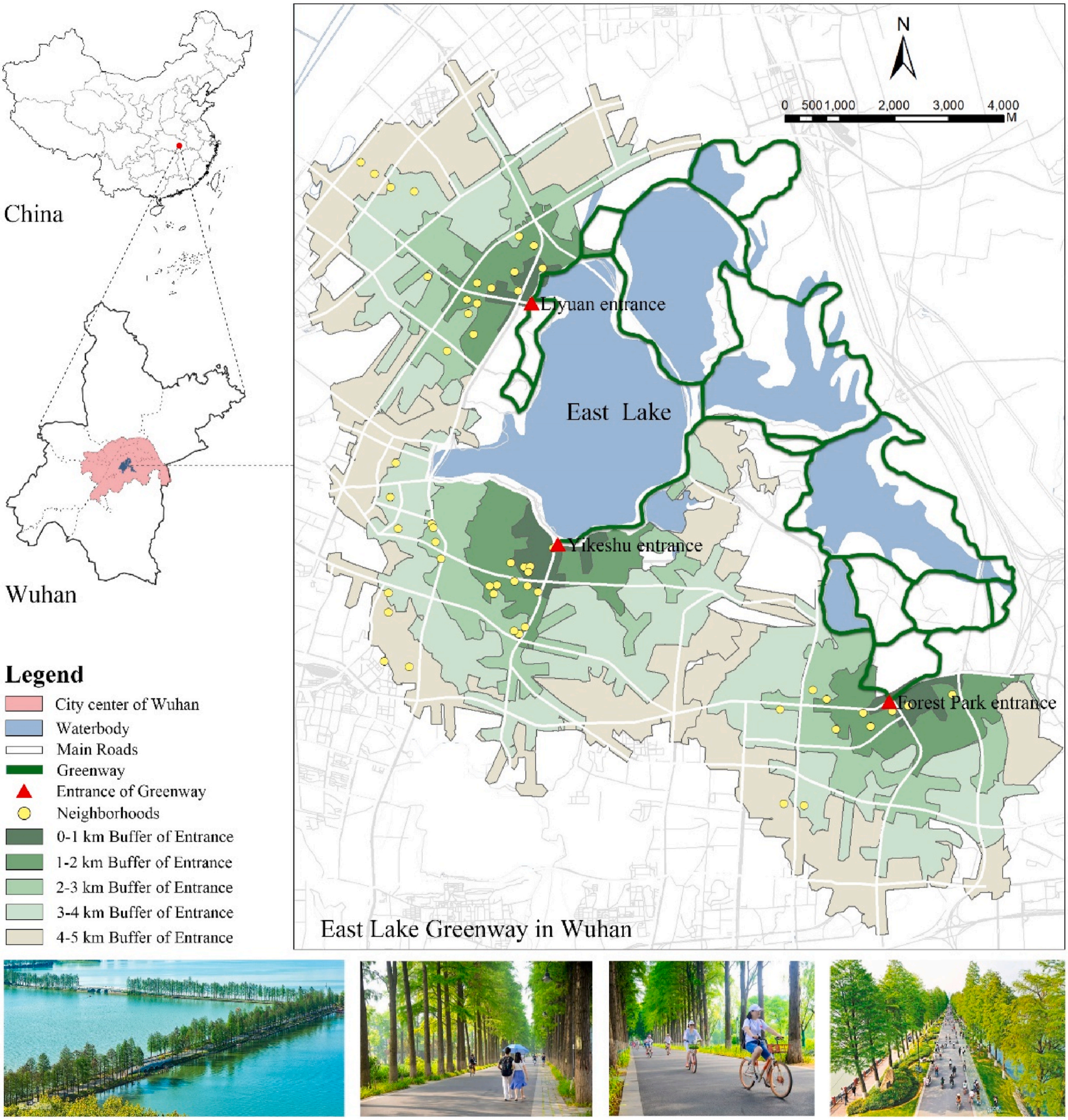

Fig. 1. Locations of the East lake greenway in Wuhan.

vehicle roads. The first phase of the greenway is 28 km long and was completed in December 2016. The second phase of the greenway is 74 km long and was completed in December 2017 (Xie et al., 2021). The greenway connects various scenic spots around East Lake (such as parks, wetlands, historic sites, etc.) through multiple paths and it integrates many urban functions such as sightseeing, leisure, sports, and fitness. Overall, this large-scale project provides a unique opportunity to study the health benefits of large-scale green space interventions.

This study conducted a baseline survey in April 2016 before the greenway reconstruction, followed by a subsequent survey in April 2019. Participants had approximately two and a half years of exposure to the greenway during the post-intervention survey. The baseline and follow-up questionnaires included consistent inquiries regarding participants' sedentary behavior. Additionally, individual variables, such as age, gender, education level, and others, were documented during the baseline survey.

2.1.2. *Sampling and participants*

The selection of research neighborhoods and participants employed several criteria (Xie et al., 2021). First, the participants were chosen within a 5 km distance threshold from three main entrances of the greenway: the Liyuan entrance, the Yikeshu entrance, and the Forest Park entrance (Fig. 1). This distance criterion has been used in several studies to assess exposure to large-scale greenspace research (Jenna and

David, 2015; Merom et al., 2003; Thomas et al., 2016). The service distance of city-level greenways (such as East Lake Greenway) is also planned to be 4–5 km in China (Liu et al., 2016). Second, 52 neighborhoods (Xiaoqu in Chinese) were selected with an equal distribution of high-SES and low-SES communities based on average house prices. Third, the number of individuals interviewed in each neighborhood was proportionate to the total population residing there. The participants within the 2 km distance buffer were oversampled, given their higher likelihood of being influenced by the greenway intervention (Xie et al., 2022).

Over 4000 residents were contacted in the baseline survey, and 2331 valid responses were collected. Those participants who did not attend the second wave were excluded from the analysis. Hence, the total sample size was 1020 participants in the baseline and follow-up surveys, with a retention rate of 43.8%.

2.2. Variable measures

2.2.1. Sedentary behavior

The International Physical Activity Questionnaire (IPAQ-SF12) is a reliable tool for assessing sedentary behavior and physical activity (Craig et al., 2003). It has been widely used by many other similar studies (Bauman et al., 2011; Bergier et al., 2012; Tomioka et al., 2011). In this study, sedentary behavior was evaluated by the IPAQ question: “In the past seven days, how much time, on average, did you spend on sitting per day, including lying or sitting while working, visiting relatives and friends, reading, watching TV, or playing on the computer?” The average time spent sitting in minutes per day over the past seven days was recorded as the outcome of sedentary behavior in both the baseline and follow-up surveys.

2.2.2. Mediators

MVPA was measured by another two IPAQ questions: (1) “How many days in the last week did you engage in moderate/vigorous physical activities for at least 10 min at a time?” and (2) “On one of these days, how much time did you usually spend engaging in moderate/vigorous physical activities?” MVPA includes moderate and vigorous physical activity. Moderate physical activity covers walking with heavy objects (such as grocery shopping or carrying children), cleaning, manual car washing, swimming at normal speed, cycling at normal speed, etc. Vigorous physical activity includes swimming quickly, climbing hills, hip-hop, riding a bicycle quickly, playing ball, etc. The outcome of the MVPA was calculated as the average duration of moderate and vigorous physical activity in minutes per day.

Walking was also assessed by two IPAQ questions: (1) “How many days have you ever walked for at least 10 min in the past seven days?” and (2) “How long did you, on average, spend on walking per day during the past seven days?” Walking time includes walking at work, at home, from one place to another, for entertainment or leisure. The outcome of walking was calculated as the average walking time in minutes per day in the previous seven days.

2.2.3. Personal factors

In the baseline survey (April 2016), participants were asked about their age, gender (male vs. female), marital status (married vs. other), employment status (employed or not), level of education (college or above vs. below college), and annual household income.

2.2.4. Neighborhood environment

All built environment variables of the sampled neighborhoods were collected within a 500 m street-network buffer centered on the housing estate in the baseline period (Xie et al., 2021). The street-network buffers were generated using data from the Wuhan Land Resources and Planning Information Center. We included the variables of building density, land-use mix, street intersection density, number of parks, bus stops, and neighborhood SES within the 500 m buffer. The land-use mix was calculated by the Shannon diversity index. Street intersection density was measured by the density of intersections where three or more roadway segments meet. Neighborhood SES was determined based on the average housing price (Moudon et al., 2011), approximately 20,000 CNY/ m^2, in Wuhan’s urban center in 2016. Accordingly, high-SES and low-SES neighborhoods refer to those with housing price $\geq$ 20,000 CNY/ m^2 and $<$ 20,000 CNY/ m^2, respectively (Xie et al., 2022).

2.3. Statistical analysis

We conducted a series of analysis to explore the impact of greenway intervention on sedentary behavior, mainly including the following steps (Fig. 2).

First, we defined treatment and control groups with multiple distance thresholds to identify the optimal spatial scale for assessing the impact of the greenway intervention. Second, we applied the mixed-effects difference-in-difference (DID) regression models to examine the effect of greenway intervention on changes in sedentary behavior. In this step, we further applied the propensity score matching and difference-in-differences (PSM-DID) method to handle the self-selection bias in the DID method. Third, we investigated the distance decay effect of the greenway intervention on sedentary behavior by using a continuous treatment (distance to the greenway) in the DID model. In addition, we computed the difference in sedentary time of an individual before and after the intervention, and then employed a multilevel linear model to examine its association with distance which is an alternative analytical approach to further investigate the distance decay effect of the greenway intervention on sedentary behavior. Fourth, we applied the mediation analysis to explore the possible pathway (MVPA or walking time, respectively) between the greenway intervention and sedentary behavior. Fifth, we explored the heterogeneous impact of the greenway intervention on participants using the mixed-effects DID regression model.

Analysis 1: t-tests with multiple distance thresholds

Previous natural experiments on greenspace interventions have utilized various distance thresholds, ranging from 100 m to several kilometers (Frank et al., 2019; He et al., 2021; West and Shores, 2011). However, the suitable distance threshold for this extensive greenway remains undefined. Hence, we created a set of dichotomous variables based on the distance thresholds to define the treatment and control groups, including 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m (Benton et al., 2016). For instance, in the case of the 500 m threshold, participants residing within 500 m of the greenway constituted the treatment group, while those residing beyond 500 m comprised the control group. Subsequently, we employed paired t-tests and independent samples t-tests to examine the differences in sedentary behavior before and after the greenway intervention in the treatment and control groups.

Analysis 2: PSM-DID models with multiple distance thresholds

The basic DID model is Model (1), as shown below. We included the fixed effects of individual factors and neighborhood characteristics variables, making it less susceptible to confounding bias, as shown in Models (2) & (3). We also added the random effects for subjects and neighborhoods in the DID models for sample clustering at the neighborhood level (Craig et al., 2017).

$$Sedentary\ behavior_{ijt} = \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_{it} + \beta_3 Treatment_{ij} * Time_{it} + \left(\varepsilon_{ij} + \mu_j\right) \quad (1)$$

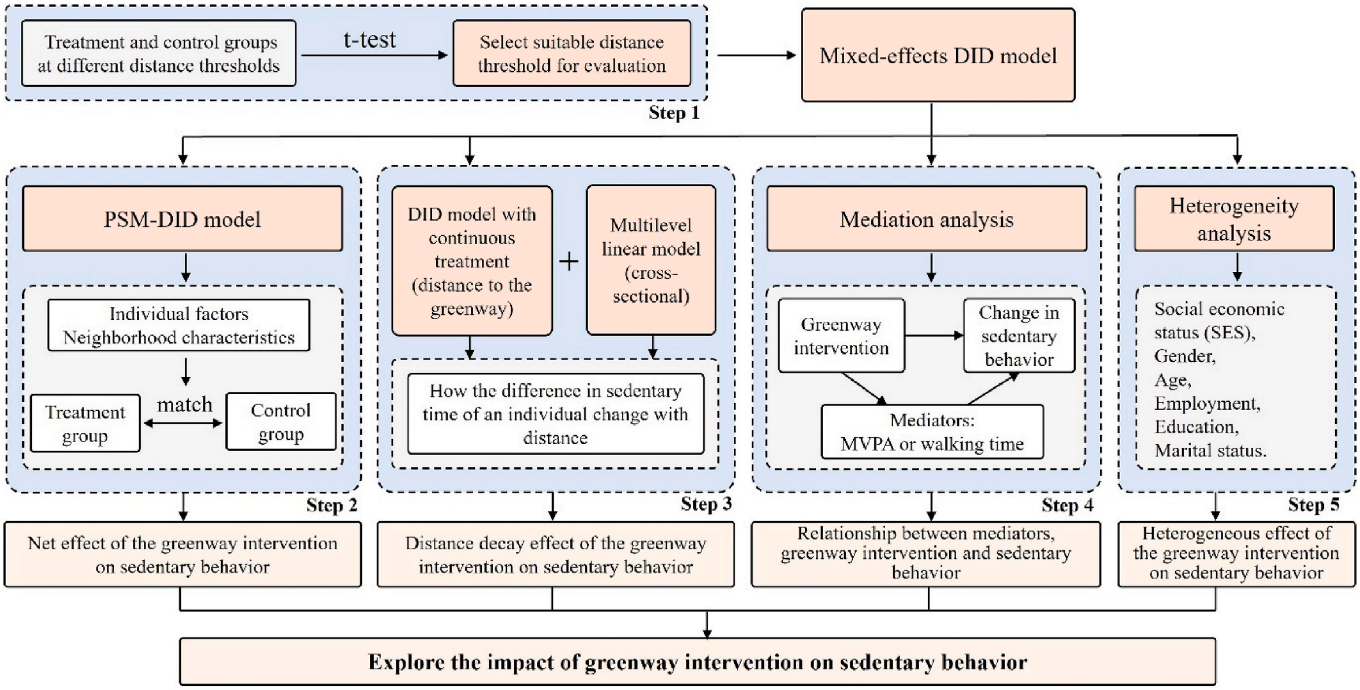

Fig. 2. Analytical approach for the study.

$$\textit{Sedentary behavior}_{ijt} = \beta_0 + \beta_1 \textit{Treatment}_{ij} + \beta_2 \textit{Time}_{it} + \beta_3 \textit{Treatment}_{ij} * \textit{Time}_{it} + \beta_4 \textit{Individual}_{ij} + \left(\varepsilon_{ij} + \mu_j\right) \tag{2}$$

$$\textit{Sedentary behavior}_{ijt} = \beta_0 + \beta_1 \textit{Treatment}_{ij} + \beta_2 \textit{Time}_{it} + \beta_3 \textit{Treatment}_{ij} * \textit{Time}_{it} + \beta_4 \textit{Individual}_{ij} + \beta_5 \textit{Neighborhood}_j + \left(\varepsilon_{ij} + \mu_j\right) \tag{3}$$

where $\textit{Sedentary behavior}_{ijt}$ is the sedentary behavior of participant i in neighborhood j and in time t. $\textit{Treatment}_{ij}$ is a binary variable of participants' greenway exposure (treatment vs. control) and β_1 shows the net difference between participants with or without exposure to the greenway. $\textit{Time}_{it}$ is a binary variable of the greenway intervention (before vs. after) and β_2 represents the net difference in sedentary behavior between the baseline and follow-up periods. $\textit{Treatment}_{ij} * \textit{Time}_{it}$ is an interaction term indicating the effect of the greenway exposure on participants based on the change of time period and β_3 reflects the net effect of the greenway intervention. $\textit{Individual}_{ij}$ is a set of individual covariates and $\textit{Neighborhood}_j$ is a set of neighborhood characteristics covariates. ε_{ij} and μ_j are the individual-level and neighborhood-level error terms, respectively.

Then, we applied the propensity score matching and difference-in-differences (PSM-DID) method to handle the self-selection bias in the DID method. The PSM-DID method, a combination of the PSM and DID method, has been used in several studies (Fan and Zhang, 2021; Wang et al., 2019; Xu et al., 2018). On one hand, the DID method can control for the observed and unobserved differences, but it may have self-selection bias due to the nonrandom assignment of samples. On the other hand, the PSM method is often used to address the nonrandom assignment of treatments by matching samples in the treatment and control groups (Cao and Schoner, 2014; Elizabeth, 2010; Wang et al., 2023a). Hence, the PSM-DID method is more effective than the standard DID method in evaluating the impact of greenway intervention on sedentary behavior.

Both individual factors and neighborhood characteristics variables were employed to match participants in the treatment and control groups. The individual factors include age, gender, and income. The neighborhood characteristics include building density and the number of bus stops. We used the command 'matchit' with the options 'distance (logit)', 'method (nearest)', 'ratio (1)', and 'caliper (0.02)', to perform matching in R. Standardized mean differences (SMD<0.15) of propensity scores were used to examine the balance of the matched samples (Elizabeth, 2010; Rubin, 2001; Zhao et al., 2021). Then, we used the matched samples to estimate the effect of the greenway intervention on sedentary behavior. Similar to the DID models, Model (4) was the basic model of the PSM-DID method. Models (5) and (6) included the fixed effects of individual factors and neighborhood characteristics variables. The estimated interaction terms revealed the net effect of greenway intervention in the PSM-DID method (Caliendo and Kopeinig, 2008).

Analysis 3: DID models with a continuous treatment

Third, we used a continuous treatment, participants' walking distance from their homes to the nearest entrance of the greenway, in the DID model. It is employed to investigate the distance decay effect of the greenway intervention. Most empirical research used DID with a binary treatment (treatment vs. control group), assuming that the control group participants are unaffected by the greenway intervention (Frank et al., 2019). However, the impact of the greenway does not abruptly cease beyond a specific distance threshold. Instead, the intervention may exhibit a "dose-response" effect, wherein its influence is more significant in areas proximal to the greenway than those farther away (Callaway et al., 2021). The DID with continuous treatment allows for capturing more nuanced variations of greenway intervention intensity, and it has been used in many economic and medical studies (Jason et al., 2019; Nunn and Qian, 2011). Consistent with previous DID models, we incorporated the fixed effects of individual factors and neighborhood characteristics variables in models (7), (8), and (9).

$$\textit{Sedentary behavior}_{ijt} = \beta_0 + \beta_1 \textit{Distance}_{ij} + \beta_2 \textit{Time}_{it} + \beta_3 \textit{Distance}_{ij} * \textit{Time}_{it} + \beta_4 \textit{Individual}_{ij} + \beta_5 \textit{Neighborhood}_j + \left(\varepsilon_{ij} + \mu_j\right) \tag{9}$$

where $\textit{Distance}_{ij}$ is a continuous variable of participants' walking distance from their homes to the nearest entrance of the greenway, which is calculated by 1000 m as a unit. β_1 shows the effect of the distance on participants' sedentary behavior. $\textit{Distance}_{ij} * \textit{Time}_{it}$ is an interaction

Table 1
Descriptive statistics of sedentary behavior, individual factors, and neighborhood characteristics at different distance thresholds (n = 1020).

Variables	0–0.5 km	0–1 km	0–1.5 km	0–2 km	0–2.5 km	0–3 km	Overall
	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%	Mean (SD)/%
Sedentary behavior							
Sedentary time at baseline (min/day)	247.80 (124.10)	299.95 (149.27)	293.94 (147.58)	289.78 (143.41)	290.97 (143.43)	291.35 (143.12)	287.72 (141.57)
Sedentary time at follow-up (min/day)	232.20 (124.92)	286.19 (141.61)	282.99 (140.64)	280.62 (137.87)	282.41 (138.08)	283.24 (137.96)	281.12 (137.18)
Changes in sedentary time (min/day)	−15.60 (76.18)	−13.76 (76.81) ***	−10.95 (72.76) ***	−9.16 (66.87) ***	−8.56 (65.23) ***	−8.11 (64.04) ***	−6.60 (61.52) ***
Individual factors							
Age	51.56 (15.07)	50.73 (16.08)	50.67 (16.46)	50.06 (16.31)	50.09 (16.18)	50.14 (16.05)	50.78 (16.14)
Gender (% male)	46	42.05	44.12	44.51	43.61	44	43.43
Education (% ≥ college)	32	45.32	48.38	50.12	50.87	51	50.29
Employment (% employed)	64	54.90	58.26	58.67	57.32	57	55.88
Marital status (% married)	80	85.74	85.17	83.80	82.88	82.88	83.52
Household income (in 1000 CNY)	185.60 (170.31)	220.91 (186.62)	209.96 (209.16)	201.91 (202.20)	210.41 (276.23)	209.08 (272.96)	202.28 (263.05)
Neighborhood characteristics							
Building density	0.15 (0.05)	0.18 (0.05)	0.18 (0.05)	0.18 (0.05)	0.18 (0.06)	0.19 (0.06)	0.19 (0.06)
Land-use mix	2.01 (0.01)	1.64 (0.46)	1.64 (0.46)	1.68 (0.44)	1.67 (0.45)	1.68 (0.44)	1.66 (0.43)
Street intersection density	6.36 (0.62)	7.51 (2.31)	6.92 (2.21)	6.63 (2.01)	6.53 (1.97)	6.53 (1.93)	6.55 (1.85)
Number of parks	0.38 (0.49)	0.27 (0.44)	0.27 (0.44)	0.45 (0.82)	0.41 (0.80)	0.39 (0.79)	0.35 (0.75)
Number of bus stops	3.14 (1.47)	2.74 (1.76)	2.59 (1.59)	2.93 (2.32)	2.80 (2.28)	2.79 (2.24)	2.65 (2.18)
Neighborhood SES (% with high SES)	38	73.13	61.15	61.09	60.37	60.88	59.01
Number of participants	50 (4.9%)	428 (41.9%)	587 (57.5%)	784 (76.9%)	853 (83.6%)	900 (88.2%)	1020

Notes: The participants' individual factors and neighborhood characteristics were gathered at the baseline survey. Paired t-tests were conducted for the difference between sedentary time at baseline and follow-up period in different distance thresholds.
$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

term, indicating how the sedentary time changes with distance due to the greenway intervention and β_3 reflects the net effect size of the greenway intervention.

As an alternative analytical approach, we computed the difference in sedentary time for an individual before and after the intervention and employed a multilevel linear model to examine its association with distance. The model is as follows.

$$\Delta Sedentary\ behavior_{ij} = \beta_0 + \beta_1 Distance_{ij} + \beta_2 Individual_{ij} + \beta_3 Neighborhood_j + \left(\varepsilon_{ij} + \mu_j\right) \tag{10}$$

where $\Delta Sedentary\ behavior_{ij}$ is the difference values of sedentary time of a participant i in neighborhood j before and after the intervention. $Distance_{ij}$ represents participants' walking distance from their homes to the nearest entrance of the greenway and β_1 shows the effect of the distance on participants' sedentary behavior changes.

Analysis 4: mediation analysis

Fourth, we applied the mediation analysis to investigate the possible pathways (MVPA or walking time) between the greenway intervention and sedentary behavior. We tested the two mediators respectively. Mediation analysis is a reliable method to help explain the process or mechanism by which one variable influences another (MacKinnon et al., 2007). It is desirable for longitudinal data and has been widely used in psychology and program evaluation (VanderWeele, 2016). In this model, we hypothesized that the greenway intervention caused the increase in participants' MVPA or walking time, and the increased MVPA or walking time, in turn, reduced participants' sedentary behavior. The equations are as follows (11).

$$\begin{aligned} Sedentary\ behavior_{ijt} &= \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_{it} + \beta_3 Treatment_{ij} * Time_{it} + \beta_4 Individual_{ij} + \beta_5 Neighborhood_j + \left(\varepsilon_{ij} + \mu_j\right) \\ Mediator_{ijt} &= \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_{it} + \beta_3 Treatment_{ij} * Time_{it} + \beta_4 Individual_{ij} + \beta_5 Neighborhood_j + \left(\varepsilon_{ij} + \mu_j\right) \\ Sedentary\ behavior_{ijt} &= \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_{it} + \beta_3 Treatment_{ij} * Time_{it} + \beta_4 Mediator_{ijt} + \beta_5 Individual_{ij} + \beta_6 Neighborhood_j + \left(\varepsilon_{ij} + \mu_j\right) \end{aligned} \tag{11}$$

where $Mediator_{ijt}$ is the MVPA or walking time of participant i in neighborhood j and in time t.

Analysis 5: heterogeneity analysis

Fifth, we explored the heterogeneous impact of the greenway intervention on participants using the mixed-effects DID regression model (Model 3). We mainly explored the heterogeneity of the treatment effect on neighborhood SES, gender, age, employment, education, and marital status.

3. Results

3.1. Descriptive statistics of participants

Table 1 demonstrates the descriptive statistics of participants' sedentary time, individual factors, and neighborhood characteristics across various distance thresholds. The overall sedentary time was reduced after the greenway construction during the follow-up period. The mean sedentary time was highest at the 1 km distance threshold at the baseline and follow-up periods.

Regarding individual factors and neighborhood characteristics, the

Table 2
Difference test based on Sedentary behavior (n = 1020).

Treatment group					Control group					Treatment-Control
Distance (km)	N (%)	Before (1)	After (2)	Difference (3) = (2)–(1)	Distance (km)	N (%)	Before (4)	After (5)	Difference (6) = (5)–(4)	Difference in difference (7) = (3)–(6)
0–0.5	4.9	247.8	232.2	−15.6	>0.5	95.1	289.7	283.6	−6.1**	−9.4
0–1	41.9	299.9	286.1	−13.7***	>1	58.1	278.8	277.4	−1.4	−12.3**
0–1.5	57.5	293.9	282.9	−10.9***	>1.5	42.5	279.2	278.6	−0.6	−10.2**
0–2	76.9	289.7	280.6	−9.1***	>2	23.1	280.8	282.7	1.9	−11.1**
0–2.5	83.6	290.9	282.4	−8.5***	>2.5	16.4	271.1	274.5	3.4	−11.9***
0–3	88.2	291.3	283.2	−8.1***	>3	11.8	260.5	265.2	4.7	−12.8**

Notes: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ (Paired *t*-test and Independent Samples *t*-test).
Distance: the distance to the greenway. N: the number of samples.

average participants' age was 50.78 years. There were more female participants than male (56.57% vs. 43.43%). More than half of the participants received a college education or above (50.29%). Most participants were married (83.52%), and similar numbers of high-SES and low-SES neighborhoods were investigated (59% vs. 41%).

3.2. *Sedentary behavior characteristics*

Table 2 presents the t-test results between the treatment and control groups at different distance thresholds. The differences in sedentary time before and after the intervention in the treatment and control groups were shown in columns (3) and (6), respectively. The difference-in-difference results, displayed in column (7), became statistically significant when the distance threshold exceeded 0.5 km. It suggested that the impact of the greenway intervention may extend over a broader range.

The distance threshold defined as 1 km or above was suitable. In these distance thresholds, the difference of sedentary time was significant in the treatment group but insignificant in the control group. It indicates that the treatment group was affected by the intervention while the control group was not, meeting our hypothesis.

3.3. *PSM-DID analysis*

3.3.1. *Result of DID analysis*

Table 3 presents the results of mixed-effects DID regression models in multiple distance thresholds. After adjusting for the covariates of individual factors and neighborhood characteristics, models of different distance thresholds showed that greenway intervention had a negative effect on sedentary behavior except for the 0.5 km distance threshold. It revealed that the East Lake Greenway intervention did reduce the sedentary time of participants in multiple distance thresholds.

The estimated interaction term (Treatment × Time) showed that the effect of greenway intervention was more significant at the 1 km and 1.5 km distance threshold ($p < 0.01$). Given the similarity between the DID results for the 1 km and 1.5 km distance thresholds, we choose the 1 km threshold for subsequent analyses. Results for the 1.5 km distance threshold can be found in the appendix.

3.3.2. *PSM-DID analysis*

Table 4 compares the results of mixed-effects DID and PSM-DID regression models using the 1 km distance threshold in all models. The coefficient for the interaction term (Treatment × Time) remained negatively significant in the PSM-DID models (4, 5, 6) after controlling the covariates. It revealed that the effect of greenway intervention on sedentary behavior was relatively robust after matching samples, which was consistent with the primary DID analysis.

In the standard DID analysis, the interaction term (Treatment × Time) was significant with an effect size of −0.036, indicating that participants' sedentary time decreased by 0.036 SD (standard deviation) in the treatment group than the control group after the greenway's opening.

Compared to the DID method, the effect size of the greenway intervention slightly decreased in the PSM-DID method (from 0.036 to 0.032). This minor decrease may be attributed to residential self-selection bias. Hence, the standard DID method might slightly overestimate the effect of greenway intervention on sedentary behavior.

3.4. *The distance decay effect of the greenway intervention*

3.4.1. *Results of continuous treatment DID models*

Table 5 presents the results of DID models with a continuous

Table 3
Multiple distance thresholds of exposures in mixed-effects DID regression models.

Model predictors	0–0.5 km	0–1 km	0–1.5 km	0–2 km	0–2.5 km	0–3 km
	(1)	(2)	(3)	(4)	(5)	(6)
	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)
Treatment	−0.069 (−0.105, 0.014)	0.045 (−0.023, 0.109)	0.040 (−0.021, 0.099)	0.036 (−0.033, 0.094)	0.047 (−0.015, 0.105)	0.047 (−0.012, 0.108)
Time	−0.022 (−0.035, −0.008) **	−0.005 (−0.022, 0.012)	−0.002 (−0.023, 0.018)	0.007 (−0.021, 0.034)	0.012 (−0.021, 0.045)	0.017 (−0.022, 0.056)
Treatment × Time	**−0.011 (−0.029, 0.008)**	**−0.036 (−0.058, −0.013)** **	**−0.033 (−0.058, −0.008)** **	**−0.039 (−0.069, −0.007)** *	**−0.042 (−0.078, −0.006)** *	**−0.046 (−0.087, −0.004)** *
Control Variables:						
Individual factors	Yes	Yes	Yes	Yes	Yes	Yes
Neighborhood characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2040	2040	2040	2040	2040	2040
R^2	0.905	0.905	0.905	0.905	0.905	0.904

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

Table 4
Mixed-effects DID regression models and PSM-DID regression models.

Model predictors	DID model			PSM-DID model		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)
Treatment	0.051 (−0.027, 0.126)	0.066 (−0.002, 0.134)	0.045 (−0.023, 0.109)	0.001 (0.005, 0.007)	0.026 (0.031, 0.033)	0.005 (0.005, 0.007)
Time	−0.005 (−0.022, 0.012)	−0.005 (−0.022, 0.012)	−0.005 (−0.022, 0.012)	0.005 (0.005, 0.006)	0.005 (0.005, 0.006)	0.005 (0.005, 0.006)
Treatment × Time	**−0.036 (−0.058,−0.013) ****	**−0.036 (−0.058,−0.013) ****	**−0.036 (−0.058,−0.013) ****	**−0.032 (−0.032,−0.031) ****	**−0.032 (−0.032,−0.031) ****	**−0.032 (−0.032,−0.031) ****
Control Variables:						
Individual factors	No	Yes	Yes	No	Yes	Yes
Neighborhood characteristics	No	No	Yes	No	No	Yes
N	2040	2040	2040	1334	1334	1334
R^2	0.904	0.904	0.905	0.929	0.930	0.931

Notes: *p < 0.05, **p < 0.01, ***p < 0.001.

Table 5
Mixed-effects DID regression models of sedentary behavior with a continuous treatment.

Model predictors	Model 7		Model 8		Model 9	
	Beta (95%CI)	Standardized Beta (95% CI)	Beta (95%CI)	Standardized Beta (95% CI)	Beta (95%CI)	Standardized Beta (95% CI)
Distance	−7.313 (−16.183, 1.671)	−0.059 (−0.131, 0.013)	−5.088 (−13.191, 3.084)	−0.041 (−0.106, 0.025)	−6.670 (−13.972, 0.749)	−0.054 (−0.112, 0.006)
Time	−15.999 (−22.582, −9.415) ***	−0.057 (−0.081, −0.033) ***	−15.999 (−22.582, −9.415) ***	−0.057 (−0.081, −0.033) ***	−15.999 (−22.582, −9.415) ***	−0.057 (−0.081, −0.033) ***
Distance × Time	**5.81 (2.468, 9.151) *****	**0.047 (0.020, 0.074) *****	**5.81 (2.468, 9.151) *****	**0.047 (0.020, 0.074) *****	**5.81 (2.468, 9.151) *****	**0.047 (0.020, 0.074) *****
Control Variables:						
Individual factors	No	No	Yes	Yes	Yes	Yes
Neighborhood characteristics	No	No	No	No	Yes	Yes
N	2040	2040	2040	2040	2040	2040
R^2	0.904	0.904	0.904	0.904	0.905	0.905

Notes: *p < 0.05, **p < 0.01, ***p < 0.001.

treatment (Models 7, 8, and 9). The interaction term (Distance × Time) was significant in all models. The standardized coefficient for the effect size of the interaction term was 0.047, indicating that the effect of greenway intervention on daily sedentary time increased by 0.047 SD (standard deviation) as their distance to the greenway increased by one SD. The unstandardized coefficient for the effect size was 5.81, meaning that participants' daily sedentary time increased by 5.81 min for every 1000 m away from the greenway due to the greenway intervention. This finding suggests that the greenway's impact on residents' sedentary behavior diminishes with distance. In other words, the closer to the greenway, the greater decrease in sedentary time. It indicated a distance decay effect of the greenway intervention on sedentary behavior.

The effect size of interaction terms remained significant and stable (Models 8 and 9) after adjusting for the individual and neighborhood covariates.

3.4.2. Changes in sedentary time by distance

To further verify the distance decay effect of the greenway, we investigated how changes in sedentary time (before and after the intervention) varied with distance using a multilevel linear model (Model 10). The effect size of it was 0.084, indicating that the difference in sedentary time increased by 0.084 SD as the distance increased one SD away from the greenway. Fig. 3 further showed the relationship between the difference in sedentary time and the participant's distance to the greenway. Notably, the negative starting point of the difference values in the plot indicates that the closer to the greenway, the greater reduction in sedentary time. In addition, beyond a certain distance, the difference in sedentary time turned positive, signifying an increase in participants' sedentary time after the greenway intervention. This shift might indicate that individuals residing farther from the greenway may not benefit from the greenway, and the rise in sedentary time could potentially be attributed to aging factors (Rhodes et al., 2012).

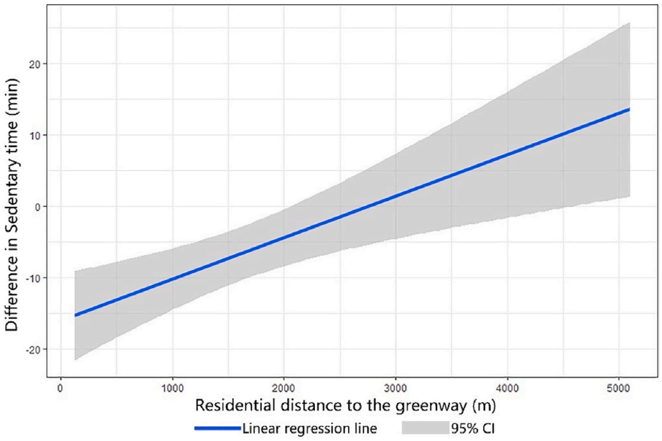

Fig. 3. The difference in sedentary time before and after the greenway construction varies with distance.

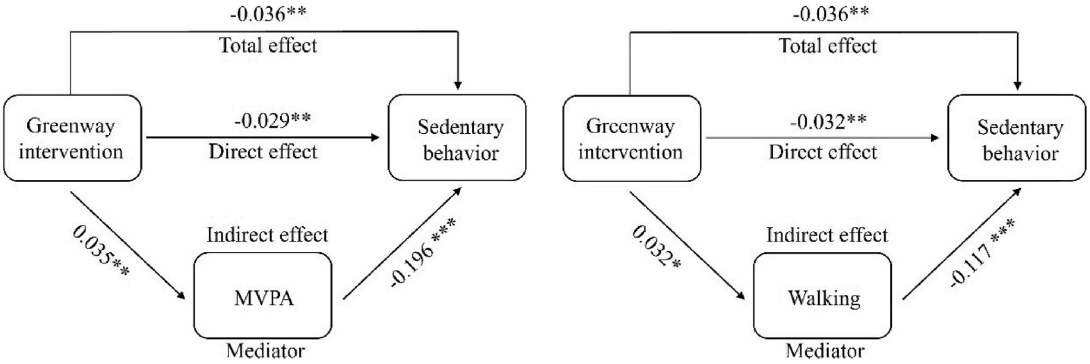

Fig. 4. Conceptual framework of the mediating analysis of MVPA and walking on the relationship between greenway intervention and sedentary behavior.

Table 6
Analysis of MVPA and walking as mediators between greenway intervention and sedentary behavior.

Model predictors	Total effect	Mediator		Mediation analysis		Proportion mediated
	Sedentary behavior (1)	MVPA (2)	Walking (3)	Sedentary behavior (4)	Sedentary behavior (5)	
MVPA				−0.196 (−0.239,−0.155) ***		0.191 (0.143, 0.231) **
Walking					−0.117 (−0.154,−0.077) ***	0.104 (0.023, 0.154) *
Treatment × Time	−0.036 (−0.058,−0.013) **	0.035 (0.012, 0.056) **	0.032 (0.004, 0.058) *	−0.029 (−0.051,−0.007) **	−0.032 (−0.054,−0.010) **	
Control Variables:						
Individual factors	Yes	Yes	Yes	Yes	Yes	
Neighborhood characteristics	Yes	Yes	Yes	Yes	Yes	
Observations	2040	2040	2040	2040	2040	
R^2	0.905	0.914	0.864	0.904	0.907	

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

3.5. *Mechanism analysis*

3.5.1. *Mediation analysis*

We hypothesized that increasing MVPA or walking time mediated the relationship between greenspace interventions and reducing sedentary behavior. The mediation analysis results are presented in Fig. 4 and Table 6. It showed that the greenway intervention and MVPA were negatively related to sedentary behavior. Notably, the effect size of the greenway intervention was reduced in the mediation analysis (Table 6 column 4) compared to that in total effect (Table 6 column 1) (0.029 vs. 0.036). This suggested that MVPA partially mediated the impact of the greenway on sedentary behavior. Additionally, walking time also showed a partial mediating effect.

3.5.2. *Heterogeneity of the treatment effect*

Table 7 presents the results of mixed-effects DID regression analysis on different groups of people. It revealed a negative effect of greenway intervention on sedentary behavior, especially for those under the age of 60, those who were employed, or those who were married, compared with their counterparts.

4. Discussion

4.1. *Main findings*

This study employed a natural experiment approach to explore the impact of a large-scale greenway intervention on participants' sedentary behavior in Wuhan, China. The results showed that the greenway intervention significantly reduced participants' sedentary time, and the intervention has a distance decay effect, the closer to the greenway, the greater decrease in sedentary time. MVPA and walking time are the mediators between greenway intervention and sedentary behavior. In addition, the effect of greenway intervention was more beneficial for those under 60 years old, employed people, and married people.

4.1.1. *Greenway intervention on sedentary behavior changes*

Although several studies have explored the relationship between greenspace and sedentary behavior, this study is one of the few natural experiments investigating the relationship between greenspace and sedentary behavior in a high-density city in China. The results showed that the greenway intervention significantly decreased participants' sedentary behavior, even after we examined the net effect with the PSM-DID method. This finding aligns well with previous cross-sectional and natural experiment studies (Benjamin-Neelon et al., 2019; Fernández-Barrés et al., 2022; Frank et al., 2019; Storgaard et al., 2013).

Although the effect of greenway intervention on sedentary behavior was significant at most distance thresholds, it was insignificant at the 0.5 km distance threshold. One explanation is that the effect of the greenway cannot be detected within the 500 m distance threshold, which is consistent with findings from a US city greenway study (West and Shores, 2011). It suggests that the greenway's impact may start to work after a certain distance, and a 500 m distance is not far enough to detect significant changes in behaviors in such a large-scale greenway (Kaczynski et al., 2009). This finding also strengthened the results from a Canadian two-kilometer-long greenway study (Frank et al., 2019), where the reduction in sedentary time was most significant at a 300 m distance threshold rather than 100 m or 200 m.

The effect of greenway intervention was most significant at the 1 km and 1.5 km distance thresholds, which is longer than the distance thresholds in a Canadian greenway study (Frank et al., 2019). This divergence may be due to the scale and quality of the greenway intervention. The project in Canada was a 2 km long greenway, and the effect was greatest at the 300 m distance threshold. In comparison, this study's greenway is 102 km long and its effective distance threshold was up to

Table 7
Mixed-effects DID regression analysis of stratified individual factors.

Model predictors	Neighborhood SES		Gender		Age		Employment		Education		Marital status	
	Low	High	Male	Female	Age<60	Age $\geq$ 60	Employed	Unemployed	College or above	Bellow college	Married	Other
Treatment × Time	−0.033 (−0.133, 0.067)	−0.033 (−0.067, 0.001)	−0.021 (−0.051, 0.008)	−0.047 (−0.137, 0.042)	**−0.056 (−0.088, −0.025)** ***	0.002 (−0.022, 0.027)	**−0.043 (−0.076, −0.009)** *	−0.027 (−0.126, 0.071)	−0.007 (−0.031, 0.015)	−0.062 (−0.156, 0.032)	**−0.042 (−0.068, −0.017)** **	−0.001 (−0.372, 0.371)
Control Variables:												
Individual factors	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Neighborhood characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	836	1204	886	1154	1310	730	1140	900	1026	1014	1704	336
R^2	0.106	0.888	0.925	0.149	0.876	0.959	0.881	0.240	0.687	0.209	0.897	0.343

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

1.5 km. This finding could offer valuable insights for greenway planning and the implementation of the '15-min life circle' planning concept (roughly 1.2 km circle) in China. Additionally, it supports the case that such green infrastructures can protect public health in high-density areas.

4.1.2. *Distance decay effect of greenway intervention*

Although previous studies have explored the distance decay effect of greenspace, they usually apply multiple distance thresholds (Frank et al., 2019) or graded distance measures (He et al., 2022; Xie et al., 2021) to define participants' exposure to the greenspace. These methods remain limited in capturing more variation in treatment intensity. This paper extends the methodological development by using the continuous variable (i.e., distance) to measure greenway intervention intensity. The results showed a clear "dose-response" relationship between the greenway intervention and sedentary behavior changes. This finding extended the evidence about the relationship between greenspace and sedentary behavior and gave us a deeper understanding of how proximity to greenway affects sedentary behavior. Specifically, the results showed that participants' daily sedentary time increased by 5.81 minutes for every 1000 meters away from the greenway due to the greenway intervention. It indicated a distance decay effect where the impact of greenway intervention on sedentary behavior decreases with distance.

4.1.3. *The possible mechanism between greenway and sedentary behavior*

Little is known about the mechanisms underlying the associations between green space and sedentary behavior. The results showed that both MVPA and walking time are partial mediators, namely, participants' sedentary behavior is affected not only by the direct effect of greenway intervention but also by the indirect effect of the changes in individual's MVPA and walking time. One possible explanation for this mechanism is that the greenway provides a safe and comfortable environment, encouraging participants to engage in MVPA or walking within or near the greenway, and simultaneously discouraging sedentary behavior (Chong et al., 2019). Under this circumstance, the design features of the greenway may also play an important role in reducing sedentary behavior. For example, a study in Taiwan has found that greenways with better path quality, higher seating quality, and better viewing qualities increase people's frequency and duration of physical activities (Chang, 2020). Greenways that have unique design features (such as curving of the trail) and make people feel safe can attract older adults to conduct more activities (Dorwart, 2015). In addition, adequate supporting facilities, such as parking lots, restrooms, etc., can also encourage people to engage in physical activities on greenways (Chen et al., 2017; Xie et al., 2022).

Another possible mechanism of green space influencing sedentary behavior may be that green space provides open spaces for social interaction and collective activities, thereby reducing residents' sedentary time (Dadvand and Nieuwenhuijsen, 2019). This aspect warrants further exploration to gain a deeper understanding of how social and community factors contribute to the relationship between green space and sedentary behavior.

In addition, it is worth noting that some other factors, e.g., sociocultural factors, may shape an individual's perception of greenways and subsequently influence changes in sedentary behavior. Sociocultural factors, including crime rates, government policies, and social attitudes, can influence individuals' use of green spaces (Lachowycz and Jones, 2013). For example, if people live within a community with a high crime rate, they will be reluctant to go out, thus affecting the use of surrounding green spaces (Ambrey and Shahni, 2017). Besides, government policies and social attitudes can also influence individuals' perceptions of nature and thus influencing the use of green spaces (Bell et al., 2014). For example, after the Japanese government promoted the "Taking in the forest atmosphere" campaign in 1982, green spaces have become more and more popular among Japanese (Tsunetsugu et al., 2010). Similarly, in Norway, the prevailing cultural norm of interacting with nature makes people more willing to visit forests and green spaces (Skår, 2010). Future research can examine more about the impact of socio-cultural factors on greenway use.

4.1.4. Heterogeneity of the greenway effect

The effect of greenway intervention on sedentary behavior was beneficial among different groups of people. The result showed that the effect of greenway intervention is significant among those under 60 years old while insignificant among those over 60 years old. Interestingly, in this study, individuals under 60 years old exhibited longer sedentary time than their older counterparts. One possible explanation is that individuals under 60 years old may be more drawn to the environment and spend more time outdoors due to the greenway intervention. Consequently, the greenway intervention may have a larger marginal effect on reducing sedentary time for individuals under 60 years old compared to those over 60 years old.

Furthermore, employed individuals were more affected by the greenway intervention than their unemployed counterparts, contrary to the findings in a Denmark study where unemployed individuals were more influenced by the availability of green space (Storgaard et al., 2013). Additionally, married individuals were found to be more affected by the greenway intervention than those who were not. Several studies have found that married people usually sit less, while those who are single usually sit more (Ishii et al., 2013; Van Dyck et al., 2012). The willingness of married individuals to walk together and spend more time in the greenway may contribute to the greater impact of the greenway on their sedentary behavior.

4.2. Planning implications

First, it is important to improve the accessibility of urban greenways. The results of this study showed that people who live close to greenways are more affected by the intervention than those who live further away. Hence, it is advisable for planners to optimize the location of greenway entrances and public transportation facilities. Additionally, they should enhance the connectivity of urban greenways and nearby neighborhoods and other green spaces to increase the usage of greenways.

Second, planners should pay attention to promoting equity in greenway use. The study has found that the effects of greenway intervention are heterogeneous; for example, the effect is weak for socially disadvantaged groups, i.e., older adults and the unemployed. Therefore, it is crucial to prioritize the needs of socially disadvantaged groups when planning large-scale greenway projects. For instance, enhancing the walkability and safety of streets surrounding greenways, optimizing barrier-free design at greenway entrances, and incorporating age-friendly design elements into greenways can significantly increase the usage of greenways by these specific groups.

4.3. Limitations

Our study has several limitations. First, the data on sedentary behavior relied on self-reporting, which is subjective and may introduce the potential for recall bias and social desirability bias. More objective data measurements on sedentary behavior, such as wearable activity monitors (accelerometers and portable GPS), are recommended. This can provide more accurate and reliable information on overall sedentary time, and how their sedentary time accumulates (Healy et al., 2011), subsequently overcoming the self-reporting bias. Second, we only used the built environment data at baseline and did not examine whether there were changes in built environment attributes, e.g., participants' exposure to playgrounds, NDVI, and other green spaces. In addition, the participants' distance to the greenway may be influenced due to the entrance changes after the intervention. Future research can characterize green space exposure based on individual travel routes to accurately reflect individual differences. Third, this paper used total sitting time as a proxy for sedentary behavior without distinguishing between different types of sedentary behavior. This simplification might overlook nuanced relationships between greenway intervention and specific sedentary activities (Kim et al., 2013; Rhodes et al., 2012; Stamatakis et al., 2014). Future research could delve into the distinct impacts of greenways on various types of sedentary behavior, such as TV viewing time, reading time, computer time, or total sitting time. Fourth, although we have controlled for many confounders, such as the individual covariates and neighborhood characteristics, some unmeasured confounding variables may also lead to biased results. For example, individual-level factors (e.g., individual preference for outdoor recreation, perceived stress levels and tiredness) are also found to be associated with sedentary behavior (O'Donoghue et al., 2016; Rhodes et al., 2012).

5. Conclusion

This study employed a natural experiment approach to explore the impact of a large-scale greenway intervention on participants' sedentary behavior in Wuhan, China. This study revealed the important role of green space intervention on residents' health in the context of China's rapid urbanization and contributed to causal evidence on how green spaces reduce residents' sedentary behavior. There are four main findings.

1) The mixed-effects DID models revealed that the greenway intervention significantly reduced participants' sedentary time.
2) The continuous DID models showed that the closer to the greenway, the greater decrease in sedentary time. This analysis also revealed that changes in daily sedentary time increased by approximately 5.81 min for every 1000 m away from the greenway due to the greenway intervention.
3) Mediation analysis showed that both MVPA and walking time mediate the link between the greenway intervention and changes in sedentary behavior.
4) The effect of greenway intervention was more beneficial for those under the age of 60, those who were employed, or those who were married compared with their counterparts.

These findings provide robust evidence that exposure to greenways reduces sedentary behavior. It also suggests that such large-scale green infrastructures can protect public health, particularly in high-density cities.

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Ethics approval

Ethical approval for the study was obtained prior to this study from the Research Committee of City University of Hong Kong (No. H000691). All participants provided written informed consent.

CRediT authorship contribution statement

Zhenhua Li: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Yi Lu:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Bo Xie:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yihao Wu:** Writing – review & editing.

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.

Data availability

The data that has been used is confidential.

Appendix

Table 4A
Mixed-effects DID regression models and PSM-DID regression models (1.5 km distance threshold).

Model predictors	DID			PSM-DID		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)	Standardized Beta (95%CI)
Treatment	0.028 (−0.049, 0.104)	0.034 (−0.034, 0.104)	0.040 (−0.021, 0.099)	0.009 (0.012, 0.013)	0.020 (0.023, 0.025)	0.003 (0.002, 0.004)
Time	−0.002 (−0.023, 0.018)	−0.002 (−0.023, 0.018)	−0.002 (−0.023, 0.018)	0.011 (0.010, 0.011)	0.011 (0.010, 0.011)	0.011 (0.010, 0.011)
Treatment × Time	−0.033 (−0.058,−0.008) **	−0.033 (−0.058,−0.008) **	−0.033 (−0.058,−0.008) **	−0.031 (−0.032,−0.030) *	−0.031 (−0.032,−0.030) *	−0.031 (−0.032,−0.030) *
Control Variables:						
Individual factors	No	Yes	Yes	No	Yes	Yes
Neighborhood characteristics	No	No	Yes	No	No	Yes
N	2040	2040	2040	1334	1334	1334
R^2	0.904	0.904	0.905	0.929	0.930	0.931

Notes: *p < 0.05, **p < 0.01, ***p < 0.001.

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