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Urban greenery cushions the decrease in leisure-time physical activity during the COVID-19 pandemic: A natural experimental study

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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic and related social distancing measures have altered the daily lifestyles of people worldwide. Although studies on this disease are emerging rapidly, less is known about the impacts of COVID-19 and urban greenery on leisure-time physical activity, which is critical to maintain health for urban residents during the pandemic. In this study, we used a natural experimental research design to identify whether urban greenery cushions the decrease in leisure-time physical activity caused by the pandemic and related social distancing measures in a high-density city. The two-wave physical activity data (before and during the pandemic) were collected for urban residents in neighborhoods with high or low levels of greenery. The results of difference-in-differences model suggest that urban greenery mitigated the decrease in physical activity during the pandemic. People who lived in greener neighborhoods experienced a lesser decrease in the leisure-time physical activity level than those who lived in less green neighborhoods. Additionally, people who lived in greener neighborhoods experienced increased levels of physical activity related to visits to country parks during the pandemic. These findings suggest that urban green spaces play a significant role in shaping physical activity and providing a refuge for the public during crises. Our study is among the first to investigate the impact of urban greenery on pandemic-induced changes in leisure-time physical activity in densely populated Asian cities, and our findings shed light on the potential protective role of urban greenery on public health during the COVID-19 pandemic and beyond.

1. Introduction

Since the initial outbreak in late December 2019, severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), the causative pathogen of coronavirus disease 2019 (COVID-19), has spread to at least 180 countries and regions and infected more than 126 million persons worldwide as of March 2021 (World Health Organization, 2020, 2021). Most epidemiological experts agree that interventions such as population-wide social distancing measures remain most effective to contain the spread of SARS-CoV-2 (Giordano et al., 2020; Koo et al., 2020; Prem et al., 2020). Such measures can considerably reduce an individual's opportunities to move outside of their home, thus limiting the spread of the virus. Accordingly, numerous countries have implemented various social distancing measures.

Despite their effectiveness, these measures may have collateral negative effects on other dimensions of health in the targeted populations. Particularly, it is very difficult to maintain an adequate level of physical activity under pandemic-related restrictive measures (Brooks et al., 2020). The initiation of such measures implies a radical change in the lifestyles of population members because opportunities to engage in outdoor physical activities, such as walking, running, hiking, and even climbing staircases, have been greatly reduced by bans on social gatherings, gym or park closures, or total lockdown orders.

The importance of regular physical activity for both physical and mental health has been well established. The World Health Organization (WHO) suggests that adults should perform at least 150 min of

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moderate-intensity aerobic physical activity or at least 75 min of vigorous-intensity aerobic physical activity per week (World Health Organization, 2010). Adequate physical activity and exercise can reduce the risks of certain diseases, such as diabetes, hypertension, cardiovascular disease, and respiratory diseases (Haskell et al., 2009; Kokkinos, 2012; Warburton et al., 2006). Furthermore, regular physical activity may be particularly beneficial for health during the COVID-19 pandemic. First, a regular physical activity habit can reduce the risk of SARS-CoV-2 infection and limit the damage caused by COVID-19 (Chen et al., 2020). Second, the widespread nature of the COVID-19 pandemic, uncertain prognoses, unfamiliar isolation policies, financial losses, and conflicting messages have induced considerable levels of fear, worry, depression, and anxiety among the public (Pfefferbaum and North, 2020; Torales et al., 2020). Continued and increased engagement in physical activity is recommended to cope with pandemic-related stress, consistent with previous studies that proved the likely significant role of physical activity in the management of mental health diseases, especially depression and anxiety (Fox, 1999; Paluska and Schwenk, 2000).

Physical activity performed in a green space may have additional physical and mental health benefits compared with physical activity in an indoor environment (Maas et al., 2008; Richardson et al., 2013). Here we define the green space as the vegetated area, combined areas of trees, parks, forests, or gardens (Almanza et al., 2012; Bastian et al., 2012). The superior health benefits of physical activity conducted in a green space may be explained by two reasons. First reason is related to the stress recovery theory and attention restoration theory, which suggest that green space may contribute to recovery from stress and attention fatigue (Kaplan, 1995). The second reason is the synergy effect between physical activity and exposure to nature; empirical studies have shown that when compared with built-up settings, natural settings induced more positive affective, cognitive, and physiological responses (Mitchell, 2013; Van den Berg et al., 2007).

Closures of green spaces during the COVID-19 pandemic may have reduced residents' opportunities to perform physical activity. In British Columbia, Canada, most provincial parks were closed in March in response to the call for increased action to address the COVID-19 pandemic, and similar actions were also taken in New York and Hong Kong (Parks, 2020; Leisure and Cultural Services Department, 2020; New York City Department of Parks and Recreation, 2020). These closures may have enhanced the issues faced by populations in high-density cities relative to those in low-density cities because the former has fewer alternative venues where they can engage in outdoor physical activities.

In summary, strong evidence supports green spaces promote physical activity levels and health during normal times. However, less is known about whether green spaces can increase physical activity or at least slow the decline in physical activity during a pandemic. We aim to explore the following questions: 1) What are the changes in leisure-time physical activity for people who live in greener or less green neighborhoods respectively during the pandemic than before? 2) More importantly, whether the urban greenery is related to the change in leisure-time physical activity during the global pandemic or not.

2. Literature review

2.1. The negative effects of social distancing measures on health

Social distancing measures are widely accepted approaches to slow down virus transmission by reducing human-to-human contact. However, these measures may have unintended negative consequences, including reduced physical activity, increased stress, and exacerbated health conditions. One review identified the adverse impacts of psychological effects reported during a quarantine, including post-traumatic stress symptoms, confusion, and anger (Brooks et al., 2020). Other stressors identified during the pandemic included the long-term quarantine duration, infection fears, frustration, boredom, inadequate supplies, inadequate information, financial losses, and stigma associated with a positive infection or loss of freedom (Bao et al., 2020; Druss, 2020). Furthermore, a long-term stay-at-home order may lead to reduced physical activity levels and prolonged sedentary behaviors such as sitting, reclining, or lying down (Ho et al., 2020). This long-term physical inactivity leads to increased risks of cardiovascular and cancer mortality, type 2 diabetes, and the potential exacerbation of chronic health conditions (Owen et al., 2010; Patterson et al., 2018).

Several reviews have provided strong evidence of the effects of physical inactivity on different health risks across different age groups (Bize et al., 2007; Janssen and LeBlanc, 2010; Reiner et al., 2013; Stone et al., 1998; Taylor et al., 2004). Regarding children and adolescents, strong evidence supports the relationship between the time spent in sedentary behavior and obesity (Rey-López et al., 2008; Tremblay et al., 2011), and moderate evidence suggests links with blood pressure and total cholesterol levels in children (Gopinath et al., 2012; Ullrich-French et al., 2010). In adults, strong evidence supports associations of sedentary behavior with all-cause mortality, fatal and non-fatal cardiovascular disease, type 2 diabetes, and metabolic syndrome (Chau et al., 2015; Patterson et al., 2018; Schmid et al., 2015). In addition, moderate evidence supports a link between sedentary behavior and ovarian, colon, and endometrial cancer incidence rates (Kerr et al., 2017). Independently, long-term physical inactivity leads to mental illnesses, such as anxiety and depression (Bonnet et al., 2005; Rebar et al., 2015; Siddiqui et al., 2014).

2.2. Urban greenery and physical activity

Recent evidence supports various built environment characteristics affect physical activity behaviors (Handy et al., 2002; Saelens and Handy, 2008; Smith et al., 2017). In particular, urban greenery is an important contributor to physical activity and health outcomes (Richardson et al., 2013). Exposure to urban greenery in neighborhoods generates significant health benefits, including reduced mental stress, improved physical health outcomes, and decreased chronic disease risks (Kardan et al., 2015; Stigsdotter et al., 2010). In urban settings, accessible green spaces offer places for urban-dwelling residents to perform exercise or recreational activities. In an international study conducted in multiple cities, a significant and positive correlation was observed between the number of parks and the level of physical activity (Schipperijn et al., 2017). Positive associations have been identified between physical activity and the proximity, access, size, quantity, and quality of urban green spaces (Coombes et al., 2010; Klompmaker et al., 2018; Zhang et al., 2017). For example, access to a large, attractive urban green space is associated with more frequent walking (Astell-Burt et al., 2014). In another study, people who lived in the greenest quintile neighborhood had a higher odds of achieving the recommended amount of physical activity than those living in the least green quintile neighborhood (Mytton et al., 2012). Evidence regarding the effect of exposure to street-level greenery on physical activity has emerged in recent years. Researchers have noted that higher exposure to greenery at the street level increases the odds and total time of engagement in physical activity (Lu et al., 2019; Yang et al., 2019, 2020).

However, inconsistent findings have also been reported (Hillsdon et al., 2006; Schipperijn et al., 2013), and researchers have attributed such inconsistency to the cross-sectional study design, which is prone to several biases such as those related to the residential self-selection of residents. It is important to improve the quality of evidence regarding the associations between physical activity and the built environment, especially urban green spaces, as environments are constantly changing in ways that may have positive or negative long-term effects on whole populations. Moreover, such research may elucidate the long-term consequences of urban planning and design practices.

2.3. Natural experiments

Although many studies have found the link between urban greenery and physical activity, most have relied on a cross-sectional research design. Randomized controlled trials (RCTs) are often recommended to mitigate confounding effects and isolate treatment effects (Kabisch et al., 2011). However, large-scale RCTs remain impractical in urban planning or public health research. In recent years, natural experimental studies have been advocated strongly and preferentially for providing rigorous evidence about the potential associations between the built environment and physical activity (Kärmeniemi et al., 2018). Natural experiments have a long history in public health research, and the most famous example is John Snow's study of cholera in London (Snow, 1855). Generally, natural experimental studies are defined as observational studies in which particular interventions have been implemented but are not under the control of researchers (Leatherdale, 2019). For example, outcomes of interest can be compared between populations that are newly exposed or unexposed to policies or environmental changes (i.e., experiment and control groups, respectively), and/or changes before and after the changes go into effect can be compared within a population (i.e., pre-post observations).

The difference-in-differences (DiD) model is used frequently in natural experiments. This model permits comparisons of differences in outcomes from before to after an intervention and between groups by controlling for biases from unobserved variables that remain fixed over time (Dimick and Ryan, 2014). In recent years, the DiD model has been used widely in public health and environmental–behavioral studies to estimate differences in an outcome for two or more populations over a specific period.

The number of natural experimental studies that assessed the effects of changes in the built environment on physical activity has increased during the last five years (Kärmeniemi et al., 2018). Several natural experiment studies showed that exposure to new greenways was associated with increases in overall and transportation-related physical activities (Marquet et al., 2017; Smith et al., 2017; Xie et al., 2021). Some evidence suggests that perceptions of esthetics and safety are major determinants of physical activity (Giles-Corti et al., 2013; Humpel et al., 2004; Panter et al., 2014), and that access to large, attractive public parks is associated with higher levels of walking (Christian et al., 2017; Sugiyama et al., 2013). In a study conducted in Australia, researchers identified an association of local recreational walking with objectively measured access to a medium- or large-sized park (Christian et al., 2017). Another study confirmed that positive perceptions of the presence of and proximity to green spaces and the total and largest areas of green space contribute significantly to a higher likelihood of walking (Sugiyama et al., 2013). Researchers also observed a relationship between the quality of streetscape greenery and "green" activity, but not with total physical activity (de Vries et al., 2013).

2.4. Contribution of the current study

Most natural experimental studies support the link between access to urban green spaces and increased physical activity and health outcomes during normal periods (i.e., the period before the COVID-19 pandemic). However, little is known about the effect of urban green spaces on physical activity during the global COVID-19 pandemic. Several studies have offered some tentative findings. A recent study in Norway used average mobile tracking data from the same day over a 3-year period and found that outdoor recreational activity increased by 291 % during lockdown (Venter et al., 2020). Furthermore, the propensity of visiting green spaces increases with the number of weekly new COVID-19 cases in four high-density Asian cities (Lu et al., 2021). Urban green spaces may have accrued health benefits for urban residents during the pandemic via five pathways (Lu et al., 2021): 1) Urban green spaces are suitable settings for people to conduct physical activity, which improves the physical health (Maas et al., 2008; Richardson et al., 2013); 2) People have prolonged electronic device use during the pandemic, which leads to negative mental health. Visiting green spaces provide necessary breaks from electronic device use (Jiang et al., 2018). 3) People have elevated stress and anxiety during the pandemic, especially when confined to indoor settings. Exposure to green space may help to reduce stress and negative moods (Kaplan, 1995). 4) People may be exposed to negative interpersonal factors and/or environmental factors at home, e.g., domestic violence, noise, crowding, while visiting urban green space may reduce such exposure (Douglas et al., 2020). 5) People may have fewer social interactions during the pandemic. Visiting urban parks and other open green space and seeing others may increase a sense of social cohesion and social belonging (Fone et al., 2014). Such findings suggest the importance of urban green space as a resilience infrastructure during times of crisis. However, these longitudinal studies did not implement a rigorous natural experiment design and lacked clearly defined experimental and control groups.

In this study, we compared the change in physical activity from before to during the COVID-19 pandemic between two groups of residents in Hong Kong, a high-density metropolitan area. One group of residents lived in greener neighborhoods (treatment group), while the other lived in less green neighborhoods (control group). By examining the changes in physical activity in these two groups, we determined that exposure to urban greenery may mitigate the decline in physical activity caused by the pandemic and related social distancing measures.

Our study is the first to obtain rigorous evidence supporting the association between urban greenery and physical activity during the COVID-19 pandemic in a high-density urban context. The following three aspects of this study are significant. 1) In terms of the methodological contribution, we used a natural experimental research design to discover more rigorous evidence between urban greenery and changes in physical activity, in contrast to previous cross-sectional studies. 2) In terms of the theoretical contribution, our study can elucidate the association between greenery and physical activity during a pandemic in a high-density urban area from a time-varying perspective. 3) In terms of the planning implications, our findings will support a reconsideration of the role of green spaces in cities and encourage the creation of resilient cities by urban planners and designers in the future.

Based on the existing research evidence, we hypothesized that urban residents who lived in greener neighborhoods would be less likely to reduce their physical activity levels during the pandemic than those who lived in less green neighborhoods.

3. Study design

This study was conducted in Hong Kong, a high-density city with a gross population density of 6777 residents/km^2. On January 25, 2020, the Hong Kong government declared the COVID-19 outbreak as an "Emergency" and announced the temporary closure of all indoor sports facilities, outdoor land sport facilities, and aquatic facilities. Though these facilities resumed service in mid-March transitorily (11–22 March), in view of the worsening situation of COVID-19, the government announced to close these facilities again on March 23. It is worth noting that Hong Kong did not implement a strict "lockdown" policy so far. Though these facilities were closed, green spaces and outdoor jogging tracks remained open as well. This change in the public policy provided the set-up for a natural experiment in which we may be able to collect longitudinal pre–post physical activity data on a cohort of urban-dwelling residents of neighborhoods with different levels of greenery who were subject to the imposed changes. The baseline data were self-reported during January 6–10, 2020 (T_1), and the follow-up data were self-reported during May 2–5, 2020 (T_2). Only participants included in both data reports were retained in the analysis. Accordingly, the data of 661 residents were analyzed. Of them, 332 lived in a neighborhood with higher greenery (normalized difference vegetation index, or NDVI $>$ 0.292, more details in the section below), and 329 lived in a neighborhood with lower greenery (NDVI $<$ 0.199).

3.1. Study areas and participants

Hong Kong is a high-density city; only 25 % of the land area has been developed, while the remaining 75 % has been left in a relatively natural state. Thus, the vegetation cover varies considerably between the developed urban and natural areas. The tertiary planning unit (TPU), which is the smallest planning and census tract in Hong Kong, was used as the analysis unit in our study. Only TPUs in urban built-up areas were kept as potential candidate areas, while those in natural areas were removed from our sampling area. We calculated the average greenery level of each urban TPU and classified the TPUs into quintiles according to the average greenery level. We defined the two highest quintiles as the high greenery group and the two lowest quintiles as the low greenery group. Eleven TPUs were selected randomly from both the high and low greenery groups, and they were distributed in the three major regions: Hong Kong Island, the Kowloon Peninsula, and the New Territories.

The overall greenery level of each TPU was measured using the NDVI, which was extracted from LANDSAT 5 Thematic Mapper satellite images available in the Global Visualization Viewer from the United States Geological Service (USGS). By capturing vegetation density at a spatial resolution of 30 m, the NDVI can assess the gross urban greenness of a whole area from a multispectral imagery dataset based on the contrast between two bands: the chlorophyll pigment absorption of plants in the red band and high reflectivity in the near-infrared (NIR) band.

The NDVI was calculated using the following equation:

$$NDVI = (NIR - Red)/(NIR + Red)$$

The NDVI values range between -1.0 and 1.0, with higher values representing higher levels of vegetation. Fig. 1 depicts the NDVI values at the TPU level in the urban areas of Hong Kong. The average NDVI value of eleven selected high greenery TPUs is 0.34 (SD = 0.04), while the average NDVI value of eleven selected low greenery TPUs is 0.11 (SD = 0.08). Fig. 2 illustrated the street view for high and low greenery neighborhoods.

3.2. Physical activity data

Trained interviewers visited public open spaces in selected TPUs to recruit participants using a convenience sampling method. Approximately 30–35 participants were interviewed in each TPU, and this process was not restricted by the age, gender, or ethnicity of the potential recruits.

The survey was completed via face-to-face interviews conducted by trained interviewers during the baseline period (T_1, January 6–10, 2020, before the pandemic in Hong Kong). During the interviews, the participants were asked the following three questions adopted from the International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003): 1) During the past 7 days, how much time did you spend engaging in leisure-time physical activity in your neighborhood? It included the physical activity for leisure and recreational purpose, which is conducted outside their home and in the nearby neighborhood, such as jogging, square dancing, and walking. 2) During the past 7 days, how much time did you spend visiting country parks for leisure and recreational purpose? 3) During the past 7 days, how much time did you spend engaging in leisure-time physical activity at home, e.g., yoga, rope skipping, and workout? The same three questions were posed to the same groups of participants during the follow-up period (T_2, May 2–5, 2020, during the pandemic). We used the individual physical activity data at the baseline (T_1) and follow-up (T_2) as the outcomes.

3.3. Covariates

The survey also collected individual-level data as potential

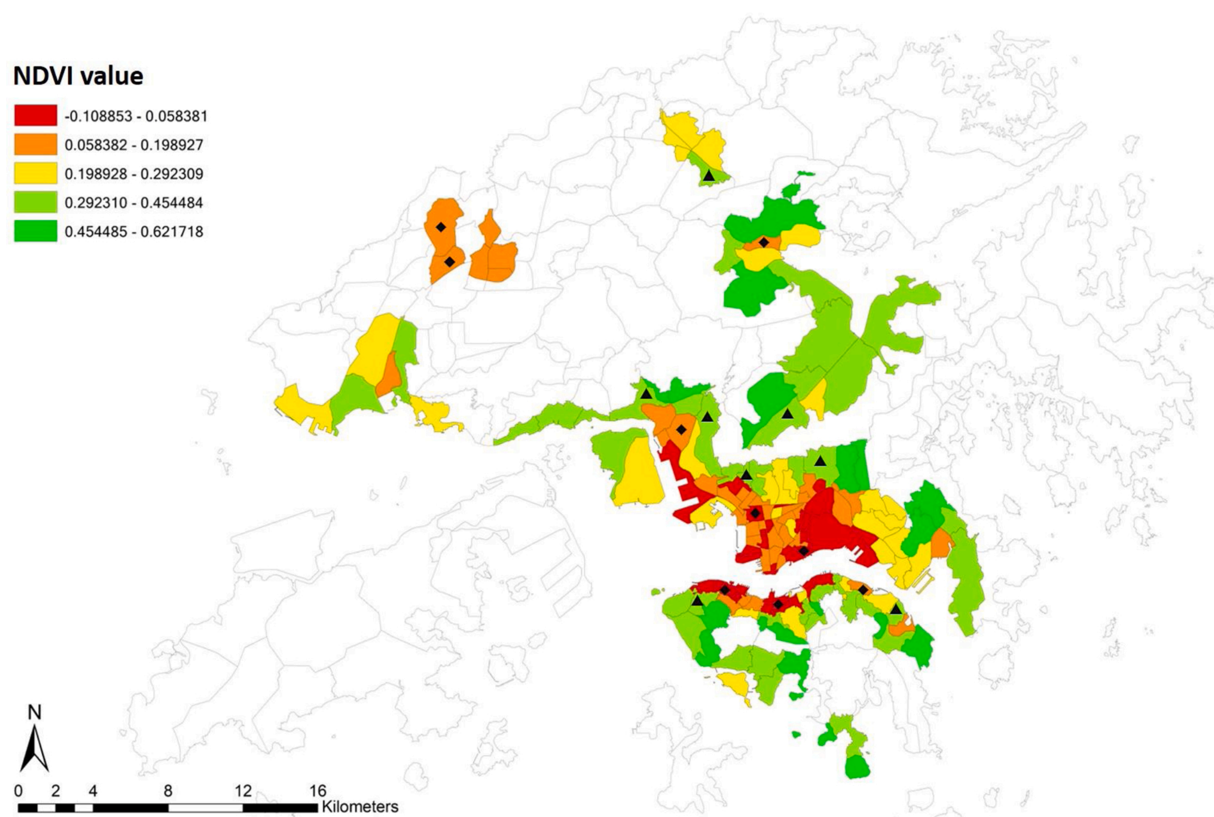

Fig. 1. The distribution of the normalized difference vegetation index (NDVI) in this survey of Hong Kong (urban built-up areas only). "▲" represents a high NDVI neighborhood (treatment group), while "◆" represents a low NDVI neighborhood (control group).

Fig. 2. Street view of low greenery neighborhood (left) and high greenery neighborhood (right).

covariates for the analysis, including the age (years), gender (male/female), education level (in four bands), and family monthly income (Hong Kong dollars in five bands). The education level was categorized as primary school and under, middle school, high school, or post-secondary. The household monthly income was categorized as HKD < 10,000, 10,000–20,000, 20,000–30,000, 30,000–50,000, or >50,000. Age was also converted to a four-band variable (<18, 18–44, 45–64, >65 years). We also added some neighborhood-level built environment factors, which may affect the changes of physical activities, into the analysis model. These factors include population density, the number of indoor sports and recreational facilities, street connectivity, and land use mix (McCormack and Shiell, 2011). The variance inflation factor (VIF) test was used to assess the multicollinearity between neighborhood greenery and other independent variables. The result shows that all the VIF values were smaller than 4, indicating that multicollinearity was not an issue in our model.

Variable	VIF
NDVI	2.45
Street connectivity	3.24
Population density	2.38
Number of Indoor recreation facilities	2.29
Land use mix	2.95

3.4. Statistical analyses

We used the DiD model to compare the change in physical activity from before to during the pandemic between people living in high and low greenery neighborhoods. We assume that no difference in the change in physical activity should be observed when comparing the two groups of participants. Therefore, if any differences are observed between the high and low greenery neighborhoods, they can be attributed largely to the effect of urban greenery. In other words, if urban greenery has no impact on physical activity, there should be no significant differences in the change in physical activity between the two groups from before to during the pandemic. The model used to estimate the difference in physical activity at T_1 and T_2 for people in both groups was as follows:

$$Impactofurbangreenry = \left(PA_{highgreenery \cdot T2} - PA_{highgreenery \cdot T1}\right) - \left(PA_{lowgreenery \cdot T2} - PA_{lowgreenery \cdot T1}\right)$$

where *PA* is the outcome of physical activity in the control group (low greenery neighborhood) vs. the treatment group (high greenery neighborhood) at a particular time period (T_1 or T_2).

To obtain standard errors and significance levels for the DiD estimate, a parametric model was used (Singer et al., 2003):

$$Y_{it} = \beta_0 + \beta_1 Greenery + \beta_2 Time + \beta_3 Greenery * Time + \beta_4 * Covariates + \varepsilon_{it}$$

where Y_{it} is the physical activity outcome observed for participant *i* at time period *t*, *Greenery* is the indicator of participant *i* in the treatment group (vs. control group), and *Time* represents the time period (T_1 vs. T_2).The β_0 parameter is the coefficient for baseline average, β_1 is the coefficient for greenery difference between two groups, β_2 is the time trend, and the β_3 is a DiD estimator that accounts for the difference in the changes over time between the two groups.

4. Results

4.1. Descriptive statistics

Table 1 shows the descriptive statistics of demographic characteristics in the treatment group (high greenery neighborhoods) and control group (low greenery neighborhoods). Although slight differences were observed in the compositions of individual factors between the control and treatment groups, these would not influence the effects of the DiD estimators. Briefly, there were slightly fewer females than male participants (49.1 % and 46.2 % female participants in the treatment and control groups, respectively), and the age structure of the participants in the control group was more similar to that of the overall Hong Kong population.

Table 2 summarizes the four physical activity outcomes in the treatment (high greenery neighborhood) and control groups (low greenery neighborhood) before (T_1) and during (T_2) the COVID-19 outbreak. For all participants, the duration of physical activity conducted in the neighborhood and at home and the total duration of physical activity decreased during the outbreak relative to before the outbreak. However, the duration of physical activity conducted in country parks increased. A similar pattern was observed for people

Table 1
Characteristics of participants in high and low greenery neighborhoods.

Characteristics	Participants in high greenery areas Count (%)	Participants in low greenery areas Count (%)	All participants Count (%)
Age Group (years)			
<18	87 (26.2)	51 (15.5)	138 (20.9)
18–44	142 (42.8)	148 (45.0)	290 (43.9)
45–64	56 (16.9)	78 (23.7)	134 (20.3)
>65	47 (14.1)	52 (15.8)	99 (15.0)
Female	163 (49.1)	152 (46.2)	315 (47.7)
Education			
Primary school or under	87 (26.2)	88 (26.7)	165 (25.0)
Middle school	58 (17.5)	49 (14.9)	107 (16.2)
High school	78 (23.5)	102 (33.1)	180 (27.2)
Post-secondary	106 (31.9)	93 (28.3)	199 (30.1)
Household monthly income (HK$)			
<10000	58 (17.4)	68 (20.7)	126 (19.1)
10000–20000	53 (16.0)	66 (20.1)	119 (18.0)
20000–30000	88 (26.5)	108 (32.8)	196 (29.7)
30000–50000	87 (26.2)	76 (23.1)	163 (24.7)
>50000	43 (12.9)	14 (4.3)	57 (8.6)
Sample size	332	329	661

Table 2
Descriptive statistics of leisure-time physical activity outcomes, and mean and standard deviation were reported.

Leisure-time physical activity outcomes	Participants in high greenery neighborhoods(N = 332)		Participants in low greenery neighborhoods (N = 329)		All participants (N = 661)	
	T_1	T_2	T_1	T_2	T_1	T_2
leisure-time physical activity conducted in neighborhood (min)	159.83 (106.82)	143.98 (122.44)	236.93 (277.48)	183.16 (144.60)	198.21 (181.46)	163.48 (135.26)
leisure-time physical activity conducted in country parks (min)	59.71 (111.12)	76.07 (124.88)	55.90 (100.83)	52.61 (101.42)	57.81 (106.06)	64.40 (114.33)
leisure-time physical activity conducted at home (min)	51.73 (83.55)	50.99 (85.59)	61.78 (89.96)	40.00 (54.95)	56.73 (86.88)	45.52 (72.15)
Total leisure-time physical activity (min)	271.27 (221.72)	271.04 (270.51)	354.61 (274.60)	275.77 (194.28)	312.75 (252.72)	273.40 (235.50)

living in high greenery neighborhoods. Nevertheless, for people living in low greenery neighborhoods, all physical activity outcomes decreased during the outbreak relative to before the outbreak. Fig. 3 illustrated the change in the duration of four domains of leisure-time physical activity from before to during the pandemic for people living in high or low greenery neighborhoods, and four domains are leisure-time physical activity conducted in neighborhood, at home, in country park and total.

4.2. Difference-in-differences estimate

Table 3 depicts the model estimations for DiD regressions that examine whether the difference in physical activity varied according to the neighborhood greenery level during the COVID-19 pandemic. After adjusting for individual and neighborhood covariates, we observed a significant positive effect of urban greenery on the changes in three leisure-time physical activity domains. Compared with those living in low greenery neighborhoods, participants living in high greenery neighborhoods reported lesser decreases in the durations of leisure-time physical activity conducted in neighborhoods, at home and the total leisure-time physical activity. Among the three domains, the most important difference can be found in the duration of physical activity conducted in neighborhood (DiD = 37.914). The difference in the duration of physical activity conducted in neighborhood between high and low greenery neighborhoods (159.83 min vs. 236.93 min respectively) was nearly 80 min in T_1. But the difference nearly halved in T_2 (143.98 min vs.183.16 min respectively). In other words, the difference among the two groups generated a 37.914 DiD in the leisure-time of physical activity conducted in neighborhood. Additionally, none of the neighborhood covariates and individual covariates was associated with the change of physical activity.

5. Discussion

5.1. Major findings

Although the positive effect of urban greenery on physical activity is widely supported, the effect of urban greenery on changes in leisure-time physical activity in response to the COVID-19 pandemic remains unclear. In this study, we used a natural experimental study and DiD model to address this question. Accordingly, this is one of the first studies to provide rigorous evidence of a link between the level of urban greenery and changes in leisure-time physical activity in a densely populated Asian city during the COVID-19 pandemic. After controlling for potential confounding variables, our results indicate that urban greenery played a significant role in shaping the observed changes in leisure-time physical activity. We also observed decreases in most physical activity outcomes except those related to country park visits or hiking. More specifically, we identified four major findings, as detailed below.

First, in terms of the change in leisure-time physical activity duration from before to during the COVID-19 outbreak ($\triangle = T_2 - T_1$), the reduced participation in physical activity among urban-dwelling

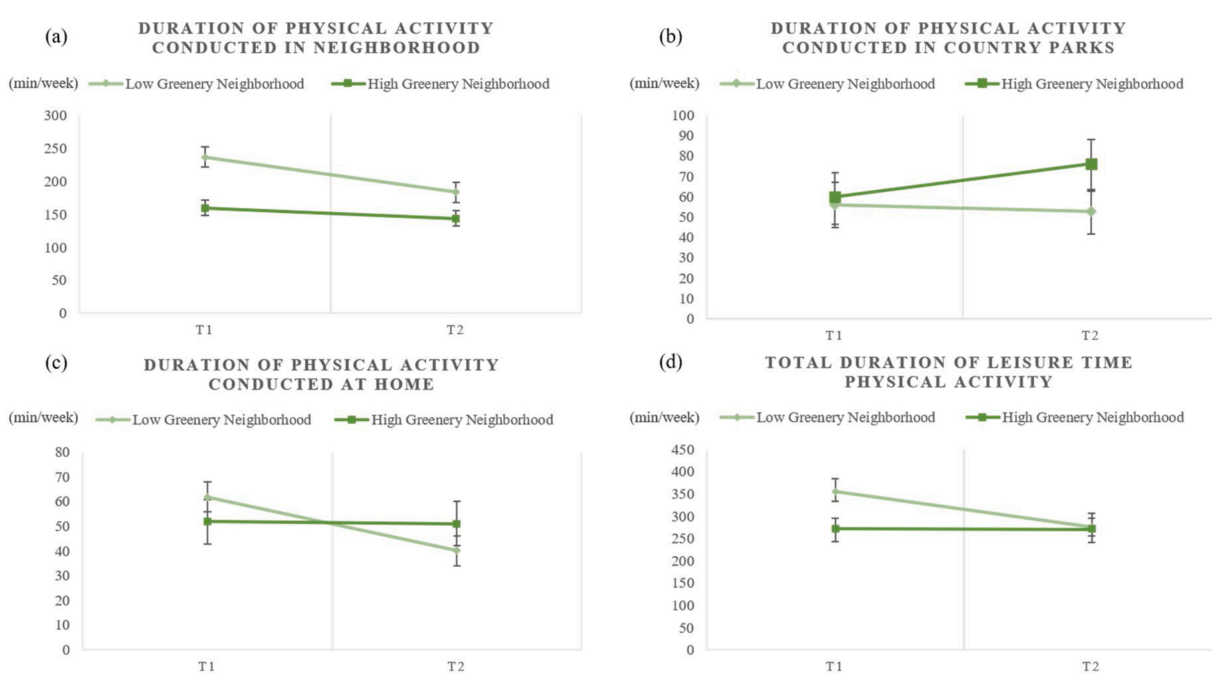

Fig. 3. Changes in the durations of four domains of leisure-time physical activity from before to during the COVID-19 pandemic. T_1, baseline; T_2, follow-up.

Table 3
Difference-in-differences (DiD) estimates of the effect of urban greenery on leisure-time physical activity.

	Duration of leisure-time physical activity conducted in neighborhood		Duration of leisure-time physical activity conducted in country parks		Duration of leisure-time physical activity conducted at home		Total duration of leisure-time physical activity	
	value	p	value	p	value	p	value	p
DiD estimator	37.914	0.025*	19.644	0.101	21.040	0.016*	78.598	0.003**
Neighborhood Covariate								
Population density	0.001	0.333	0.001	0.625	0.001	0.727	0.001	0.467
Recreation facilities	1.493	0.430	0.147	0.288	−0.015	0.886	1.626	0.536
Street connectivity	0.302	0.289	0.216	0.074	0.058	0.284	0.576	0.137
Land use mix	−160.131	0.509	7.183	0.713	−82.336	0.584	−235.284	0.422
Individual covariate								
Gender	6.603	0.436	−2.643	0.661	−5.680	0.197	−1.720	0.896
Age group	7.200	0.112	−2.849	0.376	0.135	0.954	4.487	0.525
Family income	2.780	0.486	−4.868	0.078	−4.485	0.270	−6.645	0.272
Education level	6.102	0.125	13.847	0.769	3.863	0.062	23.452	0.784

Note: ** $p < 0.01$; * $p < 0.05$.

residents in both groups is unsurprising. For all participants, the total duration of leisure-time physical activity decreased from 312.75–273.40 min per week, while the average duration of physical activity conducted in the neighborhood decreased from 198.21–163.48 min. Although the government and public health experts advised people to maintain physical activity at home, the average duration of this type of activity still decreased by 11 min.

Second, we observed a significant positive effect of urban greenery on the changes in the overall leisure-time physical activity and physical activity conducted in the neighborhood and at home. People who lived in a high greenery neighborhood reported a lesser reduction in the overall duration of physical activity participation ($\triangle = -0.23$ min, -0.08 %) than those who lived in a low greenery neighborhood ($\triangle = -78.84$ min, -22.23 %). In terms of physical activity in the neighborhood, participants in high greenery neighborhoods reported a decrease of 15.85 min over time, whereas those in low greenery neighborhoods reported a larger decrease of 53.77 min. A similar pattern was observed for the duration of physical activity conducted at home.

One major reason may explain the greater decrease in physical activity in low greenery neighborhoods. Residents in Hong Kong often rely on public parks to conduct leisure-time physical activity in neighborhood (Chow et al., 2016). During the pandemic, the Hong Kong government also suggested residents to engage physical activity in open green spaces or at home to reduce virus infection risk while still maintain adequate physical activity. Although there is no lockdown in Hong Kong, people living in low greenery neighborhoods may avoid such community parks due to the fear, the crowdedness, and potential virus infection risk in such community parks. On the other hand, people in high greenery neighborhoods have more open green spaces per person. The perceived crowdedness and risk of virus infection in parks and other greenspaces was much smaller. Hence, they may continue to use such parks and other open green spaces, e.g., tree-lined streets, cycling lanes, or greenways. In other words, the disparity in the attitudes towards park use between the two groups may lead to a different reduction in leisure-time physical activity conducted in neighborhood.

The results of previous studies support the beneficial effects of urban greenery, particularly in terms of encouraging urban-dwelling residents to participate in physical activity during normal periods (Astell-Burt et al., 2014; Klompmaker et al., 2018; Lu, 2019; Schipperijn et al., 2017). Our findings contribute to the existing literature and suggest that urban greenery may also mitigate the reduced participation in total physical activity and specific domains of physical activity during a pandemic.

Third, we observed a lower total duration of physical activity among people who lived in high greenery neighborhoods than among those who lived in low greenery neighborhoods. In other words, people in low greenery neighborhoods are more physically active than those in higher greenery neighborhoods. This may be due to two reasons. First, low greenery neighborhoods in Hong Kong generally have a high population density (see Fig. 4). Several empirical studies established a positive association between density and physical activity (Ewing and Cervero, 2010; McCormack and Shiell, 2011). For example, people living in high-density areas are more likely to engage in walking as a means of transportation to their destinations. Second, residential self-selection bias may lead to this disparity. A previous study suggested that households with higher incomes in Hong Kong often choose to live close to urban centers, whereas low-income households tend to live far away from urban centers (Lu, 2018). Affluent people are more likely to have positive attitudes toward healthy activities and tend to engage in more physical activity (Parks et al., 2003; Wilson et al., 2004).

The findings from our study agree with those of two studies that highlighted the surge of green space usage during the pandemic (Lu et al., 2021; Venter et al., 2020). Previous studies also supported a significant association between a closer distance to urban nature or more green exposure and participation in physical activity, including walking, cycling, and other exercises (Astell-Burt et al., 2014; Klompmaker et al., 2018; Schipperijn et al., 2017). By using a natural experiment, our study adds to the body of literature by specifically analyzing a certain level of causal interference by urban greenery.

Fourth, our study determined that the duration of physical activity conducted in country parks increased during the COVID-19 pandemic, especially among participants living in greener neighborhoods. Again, this may be due to two reasons. First, indoor sports facilities were closed and could not provide space for urban-dwelling residents to engage in physical activity; consequently, the residents visited country parks and public beaches, which remained open. Second, country parks and mountains are less crowded than urban built-up areas, which may have encouraged the public to visit these sites rather than walking or performing other physical activity in their neighborhoods. From a psychological perspective, the attention restoration theory holds that exposure to a natural environment can alleviate mental fatigue (Kaplan, 1995). Country parks far from dense urban areas not only provide space for physical activity but may also reduce the anxiety and stress caused by the virus outbreak. By comparison, participants living in low greenery neighborhoods are further away from country parks than those living in high greenery neighborhoods. Hence, participants living in low greenery neighborhoods visited country parks less often due to the long transportation and potential infection risk during transportation.

5.2. Policy implications

Scholars have appealed to the public to maintain regular physical activity, based on the current situation of the COVID-19 pandemic and the effects of exercise in terms of limiting the risks to human health and well-being (Sallis et al., 2020). The findings from our study demonstrate the positive contribution of urban greenery in mitigating the decrease in

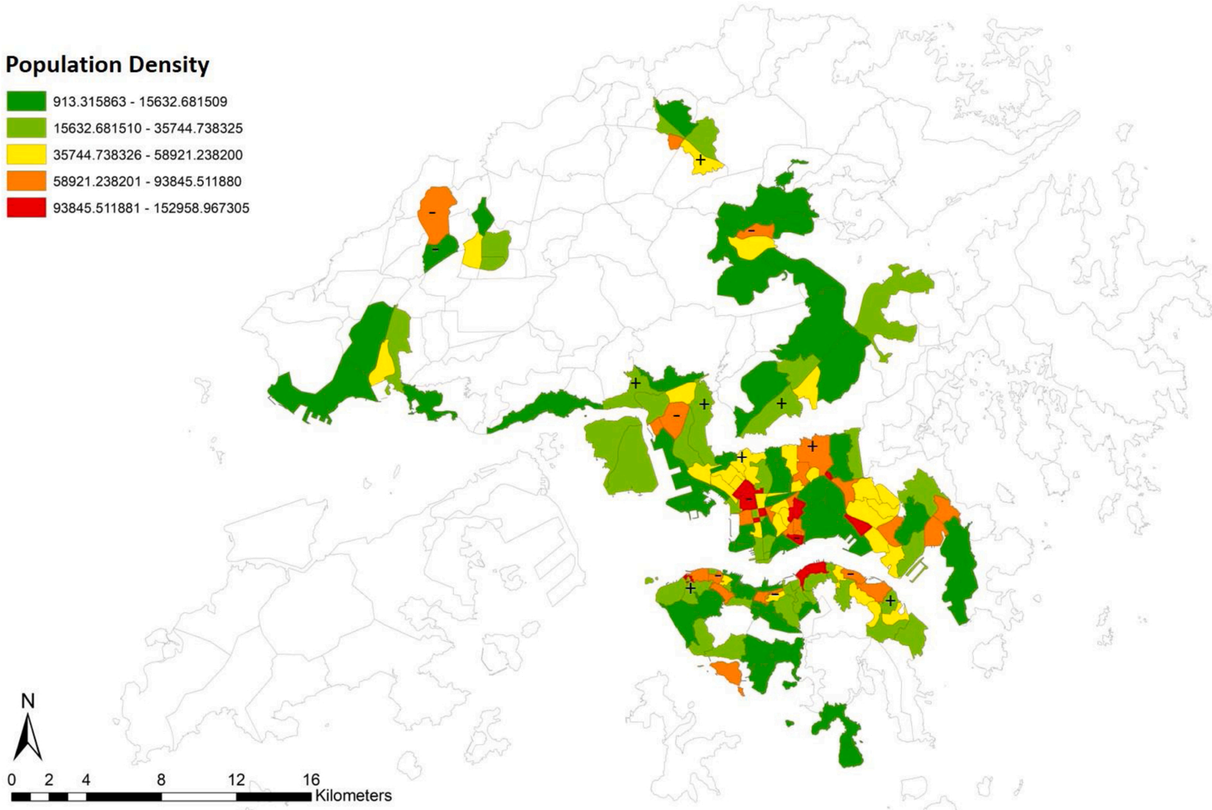

Fig. 4. The distribution of population density in Hong Kong (urban areas only) in this survey. "+" represents the treatment group [high normalized difference vegetation index (NDVI) neighborhood], while "-" represents the control group (low NDVI neighborhood).

physical activity among Hong Kong residents during the COVID-19 pandemic. Our findings provide new evidence to support the development of informed policies related to pandemic control.

In addition, areas of natural greenery outside of urban built-up areas, including country parks and hiking trails, provide a refuge where urban-dwelling residents can meet their physical activity and mental health needs during the pandemic. As the COVID-19 pandemic may last long, governments should balance their guidelines between preventing virus transmission and promoting physical activity. The key point of preventing virus transmission is reducing gathering and risk of cross infection. Therefore, outdoor individual physical activity, for example, leisure walking, jogging, should be allowed in pandemic non-crisis period with clear hygiene guidelines. Even though the indoor recreational facilities were closed, outdoor green spaces should remain open for residents to engage in outdoor activity and meet their daily needs. Another feasible strategy is to establish a booking system to control the number of visitors in these green spaces. Urban planners and designers should reconsider the contributions of urban green spaces to address public health needs during normal and crisis periods. A higher greenery neighborhood may increase the willingness to engage in physical activity during the pandemic, so it is important for each neighborhood to access greenspace easily, equally, and sufficiently. An accessible greenery network, such as pocket parks and roof gardens, was recommended to add in existing low greenery communities to serve residents better. Urban planners should also consider the capacity of greenspace in future design, which may bring evidence for the government to decide how many parks should be closed or opened during the crisis periods.

5.3. Strengths and limitations

One strength of the current study is the natural experimental research design; compared with a cross-sectional study, this design yielded more rigorous evidence supporting the association between the urban greenery level and physical activity during the pandemic. Additionally, we observed the change in physical activity from before to during the COVID-19 pandemic. People who lived in greener neighborhoods were less likely to become physically inactive during the ongoing pandemic. Our study is one of the first to investigate the effect of urban greenery on the change in physical activity caused by the pandemic in a highly dense Asian city. Our findings will inform future studies on urban greenery planning and design and support the creation of resilient and healthy cities during this pandemic and beyond.

However, our study also has limitations. First, we only observed physical activity levels at two time points, and therefore, we did not have sufficient data with which to estimate level and slope parameters that require multiple observations. Second, the physical activity data were self-reported by the participants, which may have introduced recall bias and social desirability bias. The ongoing nature of the COVID-19 pandemic may enable the continuous collection of physical activity data using automatic records from apps and devices (e.g., iPhone Health, WeChat Steps) in future studies. Third, as we mentioned above, the neighborhood population density may also influence the difference in physical activity reduction. Though we focused on physical activity for leisure and recreational purpose rather than physical activity related to transportation and work, a neighborhood with high density might make residents feel crowded and decrease the propensity to engage leisure physical activity in neighborhood. Therefore, the current findings should be interpreted with caution, even though we controlled population density in our analysis. Future studies need to disentangle which built environment factors shape physical activities and more importantly, and to understand the potential mechanism.

6. Conclusion

This natural experimental study is one of the first to rigorously establish the relationship between urban greenery and changes in leisure-time physical activity in a highly dense city during the COVID-19 pandemic. Using two-wave longitudinal panel data, we confirmed an association between changes in leisure-time physical activity and the level of urban greenery. Our findings highlight that exposure to urban greenery mitigates the decline in physical activity caused by pandemic restrictions. A lesser decrease in the leisure-time physical activity level during the pandemic was observed among people who lived in greener neighborhoods than among those in less green neighborhoods. In addition, the total duration of physical activity in country parks increased for all participants, suggesting that urban green areas may provide urban-dwelling residents with a suitable venue to conduct physical activity and reduce stress during the ongoing pandemic. The COVID-19 pandemic and governmental prevention policies have created a natural or quasi-natural experiment research opportunity for public health and urban management studies, and our findings might provide evidence to inform future policy development.

Author statement

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Declaration of Competing Interest

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

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