Environmental Science and Ecotechnology 21 (2024) 100436

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Original Research

Confounding associations between green space and outdoor artificial light at night: Systematic investigations and implications for urban health

Yang Liu [a, b], Mei-Po Kwan [a, b, c, *], Jianying Wang [b], Jiannan Cai [b]

[a] Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China
[b] Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Hong Kong, China
[c] Institute of Future Cities, The Chinese University of Hong Kong, Hong Kong, China

ARTICLE INFO

Article history:
Received 5 January 2024
Received in revised form
5 June 2024
Accepted 6 June 2024

Keywords:
Green space
Outdoor ALAN
Co-exposure
Confounding
Mobility
Spatial non-stationarity

ABSTRACT

Excessive urbanization leads to considerable nature deficiency and abundant artificial infrastructure in urban areas, which triggered intensive discussions on people's exposure to green space and outdoor artificial light at night (ALAN). Recent academic progress highlights that people's exposure to green space and outdoor ALAN may be confounders of each other but lacks systematic investigations. This study investigates the associations between people's exposure to green space and outdoor ALAN by adopting the three most used research paradigms: population-level residence-based, individual-level residence-based, and individual-level mobility-oriented paradigms. We employed the green space and outdoor ALAN data of 291 Tertiary Planning Units in Hong Kong for population-level analysis. We also used data from 940 participants in six representative communities for individual-level analyses. Hong Kong green space and outdoor ALAN were derived from high-resolution remote sensing data. The total exposures were derived using the spatiotemporally weighted approaches. Our results confirm that the negative associations between people's exposure to green space and outdoor ALAN are universal across different research paradigms, spatially non-stationary, and consistent among different socio-demographic groups. We also observed that mobility-oriented measures may lead to stronger negative associations than residence-based measures by mitigating the contextual errors of residence-based measures. Our results highlight the potential confounding associations between people's exposure to green space and outdoor ALAN, and we strongly recommend relevant studies to consider both of them in modeling people's health outcomes, especially for those health outcomes impacted by the co-exposure to them.

1. Introduction

The global trend of urbanization is gradually embracing the increasing population in urban environments. Currently, about half of the global population resides in urban areas, and the proportion is projected to be two-thirds in 2050, according to the United Nations [1]. Urbanization replaces natural environments with urban artificial environments, manifesting as deficient nature and abundant artificial infrastructures. This has led to intensive discussions of the impacts of urban environments on human health. Urban green space and outdoor artificial light at night (ALAN) are two essential urban environmental factors that have attracted increasing attention in recent years [2,3]. Their impacts on urban residents' health outcomes and well-being involve complicated pathways [4,5]. Furthermore, their effects may lead to many health outcomes that need the consideration of co-exposure to both of them, such as people's cardiopulmonary health [6,7], activity space for physical exercises [3,8], sleep quality [9,10], air pollution [11,12], and perception of neighborhood crime/safety [13,14].

A stronger argument for considering the co-exposure to green space and outdoor ALAN is their potential confounding association [4,5]. Since there is spatial and exclusive competition between nature and artificial infrastructures in urban areas, a place with abundant outdoor ALAN is highly possible to have sparse green

* Corresponding author. Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China.
E-mail address: mpkwan@cuhk.edu.hk (M.-P. Kwan).

https://doi.org/10.1016/j.ese.2024.100436

space, such as the downtown areas of a city (Fig. 1). In contrast, a place with abundant green space is highly likely to have inadequate artificial infrastructures like street illumination, such as the suburban areas. Meanwhile, it is not common to see a place with both sparse green space and scarce outdoor ALAN in urban areas except in areas under temporary construction. It seems unreasonable to assume that there are many places with both dense green space and abundant outdoor ALAN in urban areas (Fig. 1). This spatial exclusiveness between urban green space and outdoor ALAN may lead to a strong negative association between people's exposure to green space and outdoor ALAN (Fig. 1). Failing to incorporate people's co-exposure to both green space and outdoor ALAN may lead to erroneous conclusions (i.e., wrongly assigning the negative effects of outdoor ALAN as the positive health effects of green space, and vice versa). The negative association between the environmental settings of urban space and outdoor ALAN is first confirmed by Stanhope et al. in Australian cities [15]. Later, Yi et al. analyzed the modifying effects of urban green space on the association between outdoor ALAN and metabolic syndrome [16].

However, environmental settings do not necessarily equal environmental exposure, which weakens the current evidence of the confounding association between people's exposure to green space and outdoor ALAN. Pertinent exposure definitions are still needed to investigate this potential confounding association systematically. Advanced geographic information system (GIS) techniques enable more pertinent definitions of exposure measures through multiple research paradigms [17,18], including population-level residence-based, individual-level residence-based, and individual-level mobility-oriented paradigms. The population-level residence-based research paradigm discretizes space as different analytical units (e.g., the administrative units). It derives the environmental settings in each unit as exposure levels for the population living within that unit [19–21]. Correspondingly, the disparities between units manifest the disparities in exposure level. A stronger emphasis on the socio-demographic disparities of the population within each unit encourages individual-level research, where the attributes are collected from individuals, and the socio-demographic attributes are employed to more precisely estimate the effect size of the impact on a health outcome [22]. Regarding individual-level research, the residence-based paradigm derives the environmental settings at people's home locations as their long-term and primary exposure [23,24], while the mobility-oriented paradigm further incorporates the complete activity spaces (both within and outside home locations) to mitigate the contextual errors in exposure measures [25]. Different research paradigms retain different assumptions of exposure measures and are suitable for different research questions. For example,

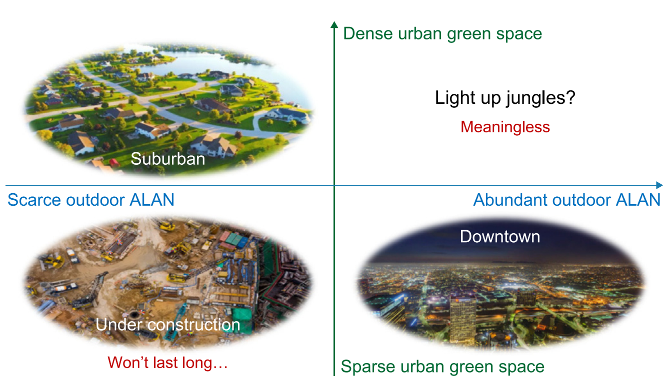

Fig. 1. An illustration of the abundance of urban green space and outdoor ALAN in different city places.

population-level paradigms will be adequate for the decision-making of allocating public resources to promote social equity and environmental justice [19], especially for large spatial scopes on the state or country level. When evaluating environmental factors' health impact, it is necessary to discuss the association at the individual level and incorporate fine-grained individual-level socio-demographic attributes and behavioral characteristics [25].

A systematic investigation and confirmation of the potential confounding association between people's exposure to urban green space and outdoor ALAN need evidence from all three research paradigms. Meanwhile, the environmental settings of green space and outdoor ALAN may vary in different geographic contexts, manifested as spatial non-stationarity [26], and the disparities in exposure levels and the magnitudes of confounding associations may also be different between different geographic contexts. A comprehensive investigation of the confounding association also needs confirmation in different geographic contexts. This study uses the cross-sectional survey data collected in Hong Kong to support our systematic investigation of the potential confounding association between people's exposure to urban green space and outdoor ALAN. Our research objectives are (1) to confirm the negative associations between people's exposure to urban green space and outdoor ALAN across the three research paradigms and (2) to investigate how geographic contexts, socio-demography, and human mobility may impact such negative associations. In the following sections, we first introduce the study area and our data collection. The exposure measure methods are detailed in Section 4. The results and discussions are highlighted in Sections 5 and 6, respectively. Finally, we draw the main conclusions in Section 7.

2. Study area

Hong Kong is one of the world's most urbanized and densely populated cities, and it has excellent environmental settings to support our discussion. Hong Kong had a population of about 7.5 million in diverse socio-demographic groups by the middle of 2023, and all residents are urbanized [27]. About 75% of Hong Kong's land is covered by vegetation, and the green coverage ranges from 14.45% to 44.24% in the downtown areas [28]. Hong Kong also has one of the brightest nightscapes in the world, with a huge variation from totally dark places in the deep core of the natural parks to excessively bright places like the Victoria Harbour (due to the display of bright and colorful lights from the numerous skyscrapers lining the waterfront).

We chose six representative communities in Hong Kong to conduct our survey (Fig. 2), including Sham Shui Po (SSP), Tin Shui Wai (TSW), Sha Tin (ST), Central and Western (CW), Kwun Tong (KTO), and Kwai Tsing (KTS). These six representative communities have similar population sizes and areal sizes but represent diverse geographic contexts. SSP and CW are two old towns that were developed at an early age in Hong Kong. They have comparatively narrow and crowded road networks, low buildings, and scarce open spaces [29]. In contrast, TSW, ST, and KTS are new towns that were developed in recent years, and they are designed with much taller buildings, well-planned road networks, and more open spaces [29]. KTO was an old town that had recently been renovated. The abundance of green space and outdoor ALAN are significantly different, and these representative communities can support our discussion of the spatial non-stationarity in the confounding association between participants' co-exposure to green space and outdoor ALAN.

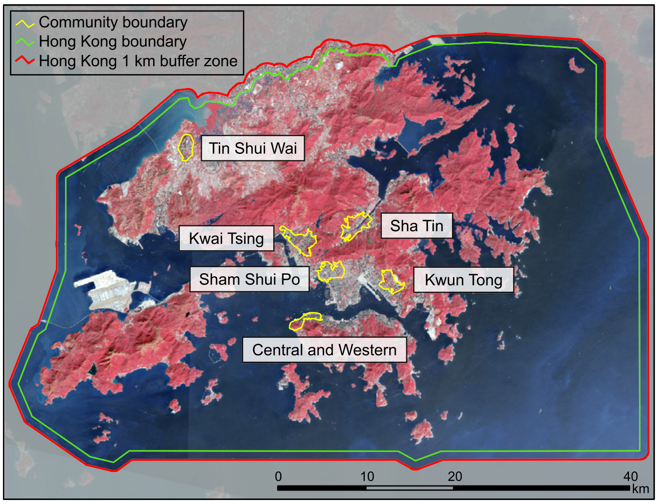

Fig. 2. Study area and the six representative communities.

3. Data collection

3.1. Remote sensing data and the delineation of green space and nightscape

The green space inventory and nightscape of Hong Kong are delineated from fine-grained remote sensing imagery. To conform with the most general pathways of how green space may impact human health, this paper defined all the places covered by vegetation as green space [4]. The green space inventory in Hong Kong was derived from PlanetScope multispectral imagery. The data were collected from Planet Labs, Inc. (https://www.planet.com/explorer/) at no cost using an Education and Research (ER) license [30]. The images have a spatial resolution of 3 m and four spectral bands, including blue, green, red, and near-infrared bands. The images were captured by multiple twin satellites between 8:00 a.m. and 11:00 a.m. on January 29, 2021, which are cloud-free and cover the entire Hong Kong. Original images were orthorectified and georeferenced to the UTM Zone 49 N coordinate system with reference to the WGS84 ellipsoid. After rigorous radiometric calibration and atmospheric correction, a binary classification method was employed to identify green and non-green spaces [25]. The classification used the normalized difference vegetation index (NDVI) and thresholding to separate green and non-green space on the pixel level. About 300 samples were used to train the threshold, and another 1000 samples were used to validate the classification results. The identification of green space has a producer accuracy of 93.3%, a user accuracy of 95.5%, and a Kappa index of agreement (KIA) of 0.858, indicating the quality of green space inventory is adequate to support our derivation of people's exposure to green space. The date of the green space inventory is slightly before our survey period. However, since Hong Kong is a well-developed city in the subtropical climate zone [31], the green spaces in Hong Kong are temporally stationary and ever-green [32]. The slight temporal mismatch will not significantly affect our exposure measure. Please refer to our recent publication for more details of our green space data [25].

The nightscape of Hong Kong was derived from SDGSAT-1 Glimmery Imagery. One image frame was collected from the International Research Center of Big Data for Sustainable Development Goals (http://www.sdgsat.ac.cn/). The panchromatic image has a spatial resolution of 10 m [33]. The image was captured at 9:45 p.m. on July 12, 2022, which is also cloud-free and fully covers Hong Kong. The original image was also orthorectified and georeferenced to UTM Zone 49 N coordinate system based on the WGS84 ellipsoid, and the original digital number (DN) values on the image were calibrated as top-of-atmosphere (TOA) luminosity [34]. The luminosity was in the unit of $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$ and was converted to $nW \cdot cm^{-2} \cdot sr^{-1}$ for convenient numbers. The date of Hong Kong nightscape data matches our survey period well. Please refer to our recent publication for more details of our outdoor ALAN data [35]. Note that the spatial resolutions of green space inventory and nightscape are different. However, our previous methodological studies have confirmed that these data effectively derive causally relevant exposures to model people's health outcomes [25,35].

3.2. Socio-demographic attributes and activity-travel trajectories of participants

The data collected from the participants contain confidential private information, and the project was reviewed and approved by the *Survey and Behavioral Research Ethics (SBRE) Committee* of the Chinese University of Hong Kong (Reference No. SBRE-19-123 approved on January 8, 2020, and Reference No. SBRE(R)-21-005 approved on November 1, 2021). Written informed consent was obtained from all subjects involved in the study before data were collected.

Participants in the six representative communities were screened and recruited through stratified sampling. The socio-demographic dimensions for the stratification include age, gender, monthly household income level, marital status, and education level [29]. Each recruited participant was asked to record and submit data through an integrated individual environmental exposure assessment system (IEEAS) consecutively for seven days, including five work days and two non-work days [36]. One Global Positioning System (GPS) equipped smartphone was distributed to each participant to record the coordinates of the participant's real-time locations (in longitudes and latitudes) at a temporal resolution of 1 s, and participants were requested to carry the smartphone with them for both at-home and out-of-home indoor/outdoor activities at every moment. A stay point detection algorithm was employed to remove drifting points in the GPS trajectories through a clustering and outlier detection approach [37–39], and the original GPS trajectories were resampled to a temporal resolution of 1 min to minimize the uncertainties in positioning. The filtered and resampled GPS trajectories were used to retrospectively delineate the actual activity-travel trajectories of the participants. Meanwhile, participants' home locations, socio-demographic attributes, and health statuses were collected from questionnaires through face-to-face interviews.

The surveys were conducted from March 2021 to April 2023. We recruited 1022 participants from the six representative communities, but a small portion were excluded. A participant was excluded if any of his/her essential socio-demographic attributes were missing, the self-reported home location contained errors, or if the completeness of his/her GPS trajectory was lower than 95% of all the GPS trajectories (less than 98% of completeness). The data screening yielded a sample set of 940 participants that have correct home locations, valid socio-demographic attributes, and complete GPS trajectories. About 74% of the participants are employed and need commuting, indicating that considerable mobility was included in the analysis. About 72% of the participants have a nighttime activity space larger than 0.1 km^2 on weekdays and 52% on weekend days [40]. These fine-grained individual-level data can support individual-level investigations of the confounding associations in the co-exposure to green space and outdoor ALAN.

3.3. Other supplementary data

To facilitate the population-level residence-based measure of people's co-exposure to green space and outdoor ALAN, we also collected the Hong Kong boundary and the boundaries of Tertiary Planning Units (TPUs) of Hong Kong [41]. The dataset is provided by the Hong Kong Planning Department (https://data.gov.hk/en-data/dataset/hk-pland-pland1-boundaries-of-tpu-sb-vc).

4. Methods

4.1. Measures of co-exposure to green space and outdoor ALAN

The co-exposures to green space and outdoor ALAN were measured using three research paradigms. The population-level residence-based measure of green space exposure is defined as the coverage ratio of green space in each Hong Kong TPU, and the population-level residence-based measure of outdoor ALAN exposure is defined as the average luminosity in each Hong Kong TPU.

The individual-level residence-based measure of co-exposure to green space and outdoor ALAN is defined as the environmental settings in the buffer zone around the participants' home locations. The green space exposure in this research paradigm is defined as the coverage ratio of green space in the 300-m buffer zone around a participant's home location. Similarly, the outdoor ALAN exposure in this research paradigm is defined as the average luminosity within the 50-m buffer zone around a participant's home location. These buffer zone sizes are determined as 300 m for green space exposure and 50 m for outdoor ALAN exposure since relevant studies indicate that the contextual units delineated by such buffer sizes can facilitate the measurement of causally relevant exposures and mitigate contextual errors [25,35,40].

We further employed participants' activity-travel trajectories as their activity spaces. We used the spatiotemporally weighted approach to estimate participants' co-exposure to green space and outdoor ALAN in the individual-level mobility-oriented research paradigm [25,35,40,42]. At each visited location along each participant's activity-travel trajectory, we defined a participant's momentary exposure to green space as the green space coverage ratio within the 300-m buffer zone around this visited location, while a participant's momentary exposure to outdoor ALAN is defined as the average luminosity within the 50-m buffer zone around this visited location. The momentary exposure to either green space or outdoor ALAN is considered the spatial weight (WS) along a participant's activity-travel trajectory. We also derived the temporal weight (WT) of each visited location as the duration of stay divided by the total survey period D:

$$WT_i = \frac{t_{i+1} - t_i}{D} \tag{1}$$

where t_i is the timestamp of this visited location and t_{i+1} is the timestamp of the next visited location along the GPS trajectory at the 1-min temporal resolution. Finally, total exposure is defined as the summation of paired spatial and temporal weights along a participant's activity trajectory:

$$E = \sum WS_i WT_i \tag{2}$$

where E is the total exposure to either green space or outdoor ALAN, WS_i is the spatial weight of the i-th visited location, and WT_i is the temporal weight of the i-th visited location. A participant's total exposure to green space uses the momentary exposure to green space as WS_i, while a participant's total exposure to outdoor ALAN uses the momentary exposure to outdoor ALAN as WS_i. Note that people's exposure to outdoor ALAN should be confined to nighttime by definition. We defined the nighttime as the phase of a day after sunset and before sunrise since the light matters [40]. An R package was employed to facilitate the calculation of sunrise time and sunset time (https://CRAN.R-project.org/package=suncalc, accessed on January 10, 2023). The momentary exposure to outdoor ALAN outside nighttime was reassigned as 0.

4.2. Statistical analysis

The primary goal of this study is to confirm the potential confounding association between people's exposure to green space and outdoor ALAN. We employed linear regression to test the negative associations between participants' exposure to green space and outdoor ALAN in Hong Kong, and we used the estimated effect sizes and corresponding p-values as indicators to support our discussion. Our tests were conducted on three levels. On the first level (i.e., the population level), the coverage ratio of green space in each TPU was employed as the independent variable, and the average luminosity in each TPU was employed as the dependent variable for the linear regression.

On the second level (i.e., the individual level), participants' exposure to green space was employed as the independent variable, and participants' exposure to outdoor ALAN was employed as the dependent variable for the linear regression. The linear regression models were analyzed using residence-based or mobility-oriented measures for each community, respectively, since residence-based and mobility-oriented measures represent different research paradigms and each community represents a different geographic context. Twelve independent models were built on the second level. On the last level, to further articulate the potential disparities between different socio-demographic groups, each model on the second level further included a group of dummy variables to adjust the effect sizes of the negative associations. Specifically, the effect sizes of the negative associations were adjusted by age, gender, income level, marital status, and education level [23,25]. Twelve independent models were also built on the third level.

In total, 25 independent models were analyzed in this study. Note that the distribution of outdoor ALAN in Hong Kong is extremely positively skewed. To meet the assumption of linear regression, a logarithmic transformation was applied to the outdoor ALAN exposure measures on all three levels. The logarithmic transformation mitigates the skewness of the distribution of the outdoor ALAN exposure and converts it into a normal distribution [43].

5. Results

5.1. The delineation of Hong Kong green space and outdoor ALAN and the sampling results

We have successfully delineated the green space inventory and outdoor ALAN settings in Hong Kong and in the six representative communities (Table 1). These six representative communities' green space coverage ratio ranges from 13.6% to 41.4%, while the nighttime average luminosity ranges from 186.20 to 325.32 $nW \cdot cm^{-2} \cdot sr^{-1}$. After data screening, our field survey successfully collected data from 940 participants in the six representative communities. The socio-demographic profile of the participants in each community is summarized in Table 2. Note that we have more female participants than male participants in each community, and we did not recruit participants from other genders due to the potentially low participation rate from individuals with non-binary genders in Hong Kong. The proportions for other socio-

Table 1
The geographic contextual settings of the six representative communities in Hong Kong.

Name	Area	Total population	Town type	Green space [a]	Outdoor ALAN [b]	Sample size
Sham Shui Po	5.35 km^2	~300k	Old	13.6%	325.32	104
Tin Shui Wai	4.32 km^2	~300k	New	15.5%	210.78	104
Sha Tin	5.64 km^2	~315k	New	41.4%	186.20	289
Central and Western	2.83 km^2	~175k	Old	27.0%	246.33	89
Kwun Tong	3.93 km^2	~446k	Renovated	33.1%	214.85	182
Kwai Tsing	5.84 km^2	~441k	New	24.0%	322.11	172

[a] Green space coverage ratios are derived from PlanetScope multispectral imagery at the spatial resolution of 3 m, unitless.
[b] Average outdoor luminosity values are derived from SDGSAT-1 Glimmer imagery at the spatial resolution of 10 m, unit in $nW \cdot cm^{-2} \cdot sr^{-1}$.

Table 2
The socio-demographic profiles and self-reported overall health status in the six representative communities in Hong Kong.

Variable		Sham Shui Po	Tin Shui Wai	Sha Tin	Central and Western	Kwun Tong	Kwai Tsing
Gender	Male	44 (42.3%)	48 (46.2%)	92 (31.8%)	27 (30.3%)	55 (30.2%)	47 (27.3%)
	Female	60 (57.7%)	56 (53.8%)	197 (68.2%)	62 (69.7%)	127 (69.8%)	125 (72.7%)
Age	18–24	16 (15.4%)	21 (20.2%)	27 (9.4%)	13 (14.6%)	20 (11.0%)	36 (20.9%)
	25–44	52 (50.0%)	51 (49.0%)	174 (60.2%)	50 (56.2%)	123 (67.6%)	96 (55.8%)
	45–64	36 (34.6%)	32 (30.8%)	88 (30.4%)	26 (29.2%)	39 (21.4%)	40 (23.3%)
Monthly household income [a]	Low	47 (45.2%)	27 (26.0%)	72 (24.9%)	14 (15.7%)	35 (19.2%)	50 (29.1%)
	Middle	32 (30.8%)	48 (46.2%)	115 (39.8%)	32 (36.0%)	73 (40.1%)	69 (40.1%)
	High	25 (24.0%)	29 (27.8%)	102 (35.3%)	43 (48.3%)	74 (40.7%)	53 (30.8%)
Education level [b]	Low	37 (35.6%)	36 (34.6%)	60 (20.8%)	11 (12.4%)	30 (16.5%)	44 (25.6%)
	Middle	55 (52.9%)	56 (53.8%)	146 (50.5%)	49 (55.0%)	118 (64.8%)	106 (61.6%)
	High	12 (11.5%)	12 (11.5%)	83 (28.7%)	29 (32.6%)	34 (18.7%)	22 (12.8%)
Marital status [c]	Single	53 (51.0%)	58 (55.8%)	146 (50.5%)	60 (67.4%)	107 (58.8%)	107 (62.2%)
	Married	40 (38.5%)	35 (33.7%)	120 (41.5%)	25 (28.1%)	63 (34.6%)	53 (30.8%)
	Others	11 (10.6%)	11 (10.6%)	23 (8.0%)	4 (4.5%)	12 (6.6%)	12 (7.0%)
Overall health status	Good	91 (87.5%)	93 (89.4%)	245 (84.8%)	83 (93.3%)	151 (83.0%)	130 (75.6%)
	Bad	13 (12.5%)	11 (10.6%)	44 (15.2%)	6 (6.7%)	31 (17.0%)	42 (24.4%)
Total		104 (100.0%)	104 (100.0%)	289 (100.0%)	89 (100.0%)	182 (100.0%)	172 (100.0%)

[a] Monthly household income: The low-income group has an income of less than 20,000 Hong Kong dollars (HKD), the middle-income group has an income of HKD 20,000–39,999, and the high-income group has an income of HKD 40,000 or above.
[b] Education level: The low group graduated from middle school or lower, the middle group has a bachelor's degree or certification, and the high group has a master's degree or higher.
[c] Other marital statuses include those divorced and widowed.

demographic groups (e.g., age and income groups) are good approximations of the populations in the selected communities.

5.2. Population-level confirmation of negative associations

We successfully estimated about 20 million momentary exposures or total exposures to both green space and outdoor ALAN for our 940 participants. We used these estimated co-exposures to confirm the negative associations between participants' exposure to green space and outdoor ALAN across the three commonly used research paradigms.

We first confirmed the negative association between people's exposure to green space and outdoor ALAN on the population level (Fig. 3). Note that outdoor ALAN settings are measured using a physical scalar variable (i.e., luminosity) while the green space settings are measured using a proportion (i.e., coverage ratio). The different measuring methods indicate that they may not be linearly associated with each other well. Meanwhile, the distribution of outdoor ALAN is extremely positively skewed, and it agrees well with the power law (Fig. 3a) [44]. A logarithmic transformation of luminosity is thus necessary to retain a linear relationship between outdoor ALAN settings and green space settings (Fig. 3b) [43].

We observed a linear and negative association between the logarithmically transformed luminosity (outdoor ALAN settings) and green space coverage ratio (green space settings), and the R^2 and p-value indicate that the association is strong and significant. Our observation is consistent with the observation of Stanhope et al. in Australia [15]. We further mitigated the skewness issue of outdoor ALAN distribution and observed a much stronger association than Stanhope et al. However, environmental settings in population-level studies may not necessarily represent the causally relevant exposures. We thus need to confirm the

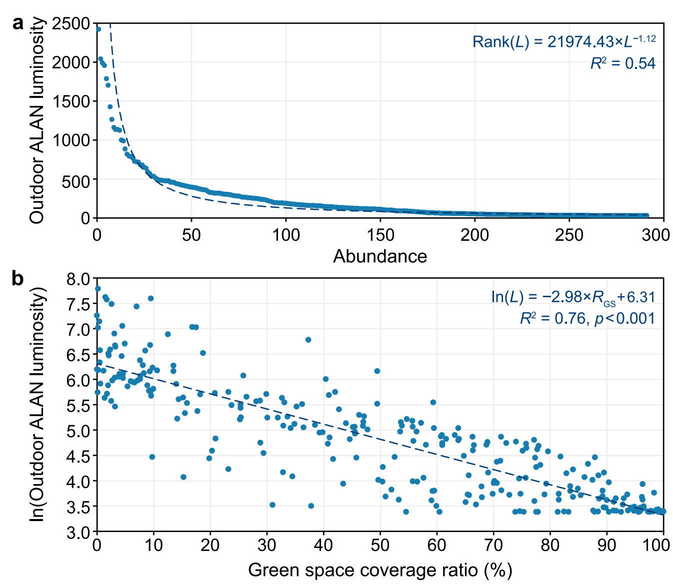

Fig. 3. The negative association on the population level. **a**, The distribution of Hong Kong TPU outdoor ALAN settings, unit in $nW \cdot cm^{-2} \cdot sr^{-1}$; **b**, The negative association between the environmental settings of outdoor ALAN and green space in Hong Kong TPUs.

associations further on the individual level.

5.3. Individual-level confirmation of negative associations

On the second level of our statistical analysis, the co-exposures to green space and outdoor ALAN were measured for each participant in the six representative communities. Descriptive analyses and the one-way ANOVA tests indicate the six representative communities have different environmental settings, and participants' co-exposures to green space and outdoor ALAN are correspondingly on significantly different levels (Fig. 4 and Table 3). These results highlight that our dataset is strong enough to discuss the spatial non-stationarity issue regarding the negative association between people's co-exposure to green space and outdoor ALAN [26].

We then tested the negative associations between participants' exposure to green space and outdoor ALAN on the individual level using residence-based or mobility-oriented measures (Fig. 5). All estimated effect sizes are negative, indicating negative associations in the co-exposure. Most of the estimated effect sizes significantly differ from 0 at the 0.05 level except for the one in TSW using the residence-based measures. Past studies have indicated that residence-based exposure measures may contain influential contextual errors, while a shift to mobility-oriented measures may mitigate this issue [25]. The insignificant association between green space exposure and outdoor ALAN exposure in TSW may be due to the influential contextual errors in the residence-based measures, and our mobility-oriented measures in TSW can considerably mitigate the contextual errors and manifest a significant negative association.

5.4. Disparities induced by geographic contexts, socio-demography, and human mobility

On the third level of our statistical analysis, we further incorporated the socio-demographic attributes of participants in each model in Section 5.3 to test the negative associations between participants' exposure to green space and outdoor ALAN on the individual level. We plotted all the estimated effect sizes (with 95% confidence intervals) for a convenient comparison (Fig. 6). Note that non-overlapping confidence intervals indicate significant differences at the 0.05 level.

We highlight multiple important disparities here, as illustrated in Fig. 6. First, the environmental settings of the population-level study may exaggerate the magnitude of negative association in the co-exposure to green space and outdoor ALAN. For example, the estimated association using TPU is about −3, indicating that the luminosity may be 1000 times stronger from the places with almost

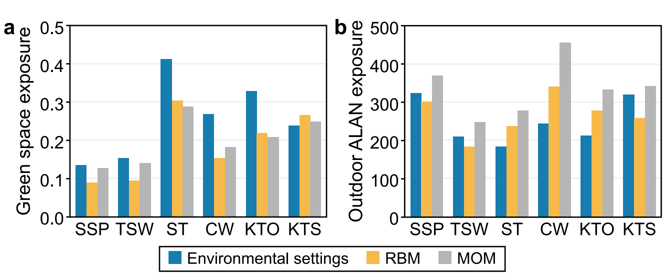

Fig. 4. The average magnitudes of exposures to green space and outdoor ALAN in the six representative communities using different research paradigms. **a**, Green space exposure (unitless); **b**, outdoor ALAN exposure (unit in $nW \cdot cm^{-2} \cdot sr^{-1}$). RBM: residence-based measure, MOM: mobility-oriented measure. Environmental settings refer to each community's green space abundance (coverage ratio) and average outdoor ALAN luminosity.

Table 3
One-way ANOVA tests of differences between exposure measures in different communities.

Measure	MS_b	MS_w	F	p-value
RBM-green space	1.242	0.024	52.359	<0.001
MOM-green space	0.642	0.013	48.030	<0.001
RBM-outdoor ALAN	3.151×10^5	3.003×10^4	10.495	<0.001
MOM-outdoor ALAN	6.132×10^5	3.893×10^4	15.749	<0.001

MS_b: mean squares between groups (communities); MS_w: mean squares within groups (communities). RBM: residence-based measure, MOM: mobility-oriented measure.

no green space cover (e.g., the Victoria Harbour) to the places with full green space cover (e.g., core forests in the Lion Rock Country Park). In contrast, the average estimated association on the individual level is about −1.6, indicating the luminosity may be 40 times stronger from the least green visited places to the greenest visited places. Meanwhile, the longer error bars on the individual-level analyses also indicate more uncertainties induced by human behaviors, and environmental settings in administrative units do not necessarily represent the true and causally relevant exposure for a single person. We also found that the negative associations are spatially non-stationary [26]. For example, the estimated negative associations in CW may be significantly stronger than those in KTO using the mobility-oriented measures.

Socio-demography does not affect the estimated negative associations. In all cases of our analysis, adjusting the effects from socio-demography does not lead to significantly different negative associations. In all the models, only a few socio-demographic groups report significant coefficients in specific cases (Table 4). Female groups may have contradictory modifying effects on the negative associations in different geographic contexts and using different research paradigms. Education levels may be positively associated with outdoor ALAN exposure in some geographic contexts and may adjust the negative associations in the co-exposure to green space and outdoor ALAN. The negative associations in the co-exposure to green space and outdoor ALAN may not be specific for other socio-demographic groups, at least not universally.

Mobility is another strong influencer in the negative associations. Mobility-oriented measures may considerably mitigate the contextual errors in residence-based measures [25,45]. Consequentially, we may observe insignificant associations using residence-based measures but significant associations using mobility-oriented measures, for example, in TSW. By mitigating the contextual errors, we may also observe much stronger negative associations using mobility-oriented measures than residence-based ones. For example, we observed stronger negative associations from mobility-oriented measures than residence-based measures in SSP, ST, CW, and KTO. However, the disparities are not significantly different from 0 at the 0.05 level. Finally, activity spaces in the mobility-oriented measures are much larger than the residential spaces in the residence-based measures, which may alleviate the disparities between local and regional measures. For example, we observed significant disparities between the negative associations using TPU and residence-based measures in TSW and CW, but the disparities were not significant when we switched to mobility-oriented measures in TSW and CW.

6. Discussions

6.1. Confounding associations in different research paradigms

In this study, we discussed the potential confounding

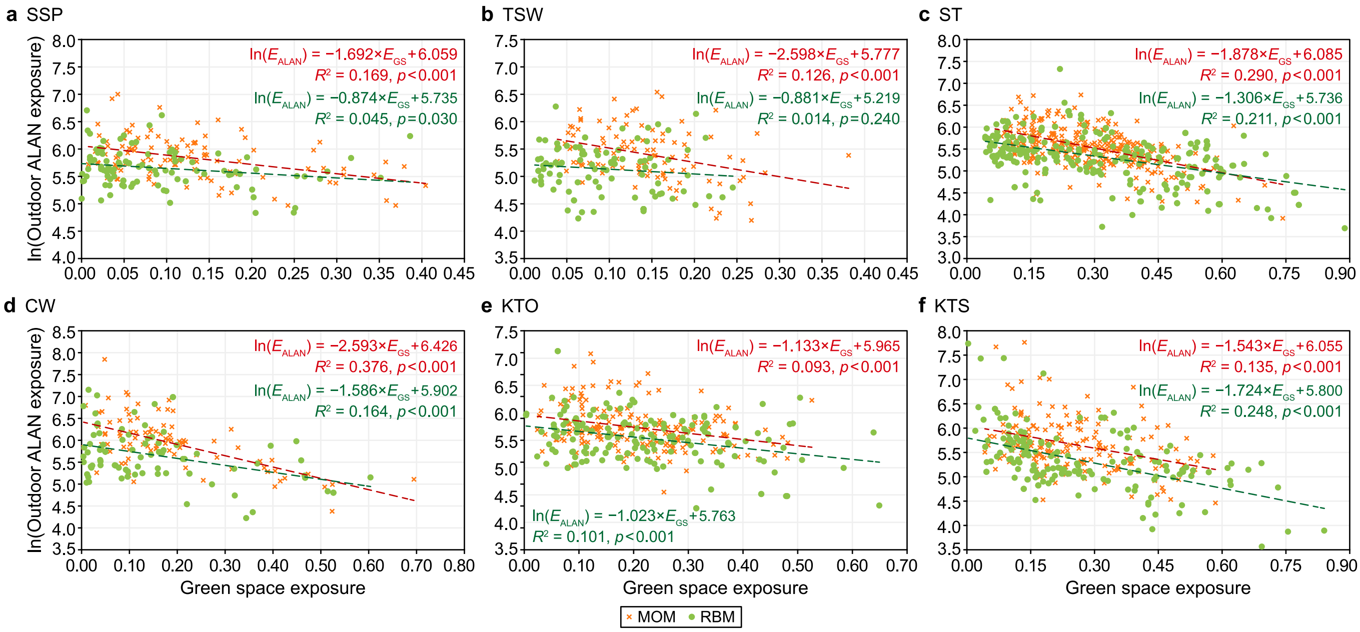

Fig. 5. The negative associations on the individual level. **a**, SSP; **b**, TSW; **c**, ST; **d**, CW; **e**, KTO; **f**, KTS. RBM: residence-based measure; MOM: mobility-oriented measure.

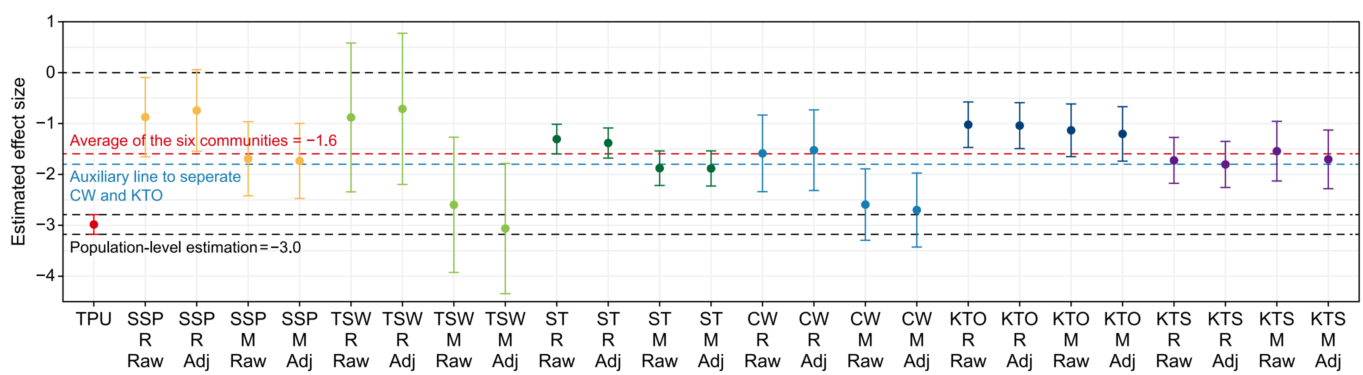

Fig. 6. The effect sizes of all the negative associations discussed in this study. R: residence-based measure; M: mobility-oriented measure. Raw: estimation without adjusting the effects of socio-demography; Adj: estimation after adjusting the effects of socio-demography, including age, gender, income level, marital status, and education level. The variance inflation factor (VIF) of all variables in our linear regression models ranges from 1.034 to 3.302, indicating that multicollinearity is not an issue in our regression analysis. Blue dashed line: an auxiliary line that conveniently illustrates that the 95% confidence intervals of CW and KTO using mobility-oriented measures are not overlapping with each other; red dashed line: the average effect size of the confounding associations of the six representative communities; black dashed lines: the upper and lower limits of the 95% confidence interval on the population-level.

Table 4
The reported socio-demographic groups have significant effect sizes in the linear regression. Report only significant coefficients at the 0.05 level and higher. Only five coefficients are reported from 12 models and 132 estimated coefficients.

Paradigm	Community	Socio-demographic factor	Socio-demographic group	Effect size	Standard Error	*p*-value
RBM	KTS	Gender	Female	0.250	0.090	0.006
RBM	KTS	Education level	Low	−0.265	0.132	0.046
MOM	CW	Gender	Female	−0.237	0.107	0.029
MOM	KTS	Education level	Low	−0.256	0.124	0.041
MOM	TSW	Education level	High	0.583	0.173	0.001

associations between people's exposure to green space and outdoor ALAN by confirming the negative associations in the co-exposure across different research paradigms. We observed the negative associations in all cases, and most cases indicated that the negative associations were significantly different from 0. Our results indicate that people's exposure to green space and outdoor ALAN may not be random between one and the other. In contrast, due to the specific environmental settings in urban areas, a person's high-level exposure to green space may well indicate his or her low-level exposure to outdoor ALAN and vice versa.

These negative associations are universal in space and for different socio-demographic groups but are complex. We observed that the negative associations between people's exposures to green space and outdoor ALAN are spatially non-stationary and with potentially significant changes in magnitude from place to place. Using mobility-oriented measures, we also observed stronger negative associations between exposure to green space and outdoor ALAN by mitigating contextual errors.

6.2. Implications of this study

Since the negative associations between people's exposure to green space and outdoor ALAN are universal in urban areas, the confounding effects of one on the other in the environmental and public health study need attention. Because a high-level exposure to outdoor ALAN may well indicate a low-level exposure to green space and vice versa, a study considering only one factor may wrongly assign the opposite effects of the other factors. This issue of spurious association may be specifically essential for health studies that should have considered the co-exposure to both green space and outdoor ALAN but currently considered only one of them (e.g., people's cardiopulmonary health, activity space for physical exercises, sleep quality, air pollution, and perception of neighborhood crime/safety). As a result, we would like to suggest that scholars simultaneously include both green space exposure and outdoor ALAN exposure in the relevant environmental and public health studies, especially for the health outcomes that are affected by co-exposure to green space and outdoor ALAN. Previous studies considering only green space or outdoor ALAN may need to investigate the confounding associations and re-examine their conclusions.

However, the confounding association between the exposure to green space and outdoor ALAN is specific to health outcomes. A health outcome without parallel pathways through both green space and outdoor ALAN may not need to consider the confounding associations. For example, concerning the falling risk of older adults during the night or the risk of traffic accidents at nighttime, outdoor ALAN may be a relevant factor [46], but green space is not. Consequentially, we suggest that scholars carefully consider the potential pathways and pathology that should incorporate both green space and outdoor ALAN for co-exposure studies.

6.3. Limitations of this study

In this study, we systematically investigated the potential confounding associations between people's exposure to green space and outdoor ALAN using a large sample set, comprehensive measuring approaches across different research paradigms, and multiple potentially influential factors like geographic contexts, socio-demography, and human mobility. However, our study still faces some limitations. First, Hong Kong is in a subtropic climate zone with ever-green vegetation, and our data collection is cross-sectional. We are not able to investigate the temporal stationarity of the potential confounding associations between people's exposure to green space and outdoor ALAN. On the other hand, Hong Kong can excellently support our discussion since Hong Kong has the most pertinent geographic settings. Hong Kong is one of the most urbanized cities in this world, but it still has an abundant green space inventory. The negative associations may also need systematic investigations in other less developed cities and other geographic contexts, especially when spatial non-stationarity is an influential methodological issue.

7. Conclusions

People's exposure to green space and outdoor ALAN may confound each other in environmental and public health studies that consider them factors in many health outcomes. However, this issue has long been neglected and lacks systematic investigation. This study systematically investigated the confounding associations between people's co-exposure to green space and outdoor ALAN in Hong Kong across the three most used research paradigms: population-level residence-based, individual-level residence-based, and individual-level mobility-oriented. The environmental settings of green space and outdoor ALAN in Hong Kong were derived from remote sensing data with high spatial resolutions. The activity-travel trajectories and socio-demographic attributes were collected through the IEEAS. Our results indicate that the negative and potential confounding associations are universal and significant across different research paradigms. The magnitude of the negative associations is spatially non-stationary, consistent in different socio-demographic groups, and stronger negative associations can be observed by considering human mobility. Our results comprehensively and systematically confirm the potential confounding associations in the co-exposure to green space and outdoor ALAN. Neglecting the confounding effects of one factor may lead to wrongly assigning opposite effects of the other factor to the health outcomes and then erroneous conclusions. Consequentially, we suggest that scholars pay attention to the confounding associations in the co-exposure to green space and outdoor ALAN and include the co-exposure in the analysis and conclusion.

Data availability

The dataset contains confidential private information that cannot be deidentified, and thus cannot be shared.

Ethics approval

The study was approved by the *Survey and Behavioral Research Ethics (SBRE) Committee* of the Chinese University of Hong Kong (Reference No. SBRE-19-123 approved on January 8, 2020, and Reference No. SBRE(R)-21-005 approved on November 1, 2021).

CRediT authorship contribution statement

Yang Liu: Writing - Review & Editing, Writing - Original Draft, Visualization, Validation, Methodology, Formal Analysis, Conceptualization. **Mei-Po Kwan:** Writing - Review & Editing, Project Administration, Methodology, Funding Acquisition, Conceptualization. **Jianying Wang:** Writing - Review & Editing, Formal Analysis. **Jiannan Cai:** 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.

Acknowledgements

This research was supported by grants from the Hong Kong Research Grants Council (General Research Fund Grant no. 14605920, 14611621, 14606922; Collaborative Research Fund Grant no. C4023-20GF; Research Matching Grants RMG 8601219, 8601242) and a grant from the Research Committee on Research Sustainability of Major Research Grants Council Funding Schemes (3133235) of the Chinese University of Hong Kong. The funders had no role in study design, data collection and analysis, publication decision, or manuscript preparation. We also would like to thank Lingwei Zheng and Liuyi Song for their diligent help in data preprocessing.

References

[1] U. N. UN, 68% of the world population projected to live in urban areas by 2050, says UN. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. (Accessed 12 February 2023).
[2] J.R. Wolch, J. Byrne, J.P. Newell, Urban green space, public health, and environmental justice: the challenge of making cities 'just green enough, Landsc. Urban Plann. 125 (2014) 234–244.
[3] M. Bożejko, I. Tarski, M. Małodobra-Mazur, Outdoor artificial light at night and human health: a review of epidemiological studies, Environ. Res. 218 (2023) 115049.
[4] Y. Liu, M.-P. Kwan, M.S. Wong, C. Yu, Current methods for evaluating People's exposure to green space: a scoping review, Soc. Sci. Med. (2023) 116303.
[5] Y. Liu, C. Yu, K. Wang, M.-P. Kwan, L.A. Tse, Linking artificial light at night with human health via a multi-component framework: a systematic evidence map, Environments 10 (3) (2023) 39.
[6] S. Sun, et al., Outdoor light at night and risk of coronary heart disease among older adults: a prospective cohort study, Eur. Heart J. 42 (8) (2021) 822–830.
[7] X.-X. Liu, et al., Green space and cardiovascular disease: a systematic review with meta-analysis, Environ. Pollut. 301 (2022) 118990.
[8] E.A. Richardson, J. Pearce, R. Mitchell, S. Kingham, Role of physical activity in the relationship between urban green space and health, Publ. Health 127 (4) (2013) 318–324.
[9] D. Paksarian, et al., Association of outdoor artificial light at night with mental disorders and sleep patterns among US adolescents, JAMA Psychiatr. 77 (12) (2020) 1266–1275.
[10] L. Yang, et al., Neighbourhood green space, perceived stress and sleep quality in an urban population, Urban For. Urban Green. 54 (2020) 126763.
[11] A. Diener, P. Mudu, How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective-with implications for urban planning, Sci. Total Environ. 796 (2021) 148605.
[12] M. Kocifaj, J.C. Barentine, Air pollution mitigation can reduce the brightness of the night sky in and near cities, Sci. Rep. 11 (1) (2021) 14622.
[13] A. Lis, M. Zienowicz, D. Kukowska, K. Zalewska, P. Iwankowski, V. Shestak, How to light up the night? The impact of city park lighting on visitors' sense of safety and preferences, Urban For. Urban Green. 89 (2023) 128124.
[14] J. Maas, P. Spreeuwenberg, M. Van Winsum-Westra, R.A. Verheij, S. Vries, P.P. Groenewegen, Is green space in the living environment associated with people's feelings of social safety? Environ. Plann. 41 (7) (2009) 1763–1777.
[15] J. Stanhope, C. Liddicoat, P. Weinstein, Outdoor artificial light at night: a forgotten factor in green space and health research, Environ. Res. 197 (2021) 111012.
[16] W. Yi, et al., Association of outdoor artificial light at night with metabolic syndrome and the modifying effect of tree and grass cover, Ecotoxicol. Environ. Saf. 264 (2023) 115452.
[17] M.P. Kwan, GIS methods in time-geographic research: geocomputation and geovisualization of human activity patterns, Geogr. Ann. B Hum. Geogr. 86 (4) (2004) 267–280.
[18] M.-P. Kwan, Interactive geovisualization of activity-travel patterns using three-dimensional geographical information systems: a methodological exploration with a large data set, Transport. Res. C Emerg. Technol. 8 (1–6) (2000) 185–203.
[19] D. Liu, M.-P. Kwan, Z. Kan, Analysis of urban green space accessibility and distribution inequity in the City of Chicago, Urban For. Urban Green. 59 (2021) 127029.
[20] J. Zhao, et al., Temporal trend of green space coverage in China and its relationship with urbanization over the last two decades, Sci. Total Environ. 442 (2013) 455–465.
[21] R.A. Al-Naggar, S. Anil, Artificial light at night and cancer: global study, Asian Pac. J. Cancer Prev. APJCP: Asian Pac. J. Cancer Prev. APJCP 17 (10) (2016) 4661.
[22] C.J. Gronlund, V.J. Berrocal, J.L. White-Newsome, K.C. Conlon, M.S. O'Neill, Vulnerability to extreme heat by socio-demographic characteristics and area green space among the elderly in Michigan, 1990–2007, Environ. Res. 136 (2015) 449–461.
[23] J.G. Su, P. Dadvand, M.J. Nieuwenhuijsen, X. Bartoll, M. Jerrett, Associations of green space metrics with health and behavior outcomes at different buffer sizes and remote sensing sensor resolutions, Environ. Int. 126 (2019) 162–170.
[24] K. Hu, et al., Association between outdoor artificial light at night and sleep duration among older adults in China: a cross-sectional study, Environ. Res. 212 (2022) 113343.
[25] Y. Liu, M.-P. Kwan, C. Yu, The uncertain geographic context problem (UGCoP) in measuring people's exposure to green space using the integrated 3S approach, Urban For. Urban Green. 85 (2023) 127972.
[26] M.-P. Kwan, The stationarity bias in research on the environmental determinants of health, Health Place 70 (2021) 102609.
[27] C. a. S. Department. "Mid-year population for 2023 [August 15 2023]." The Government of the Hong Kong Special Administrative Region.. https://www.censtatd.gov.hk/en/press_release_detail.html?id=5265 (accessed December 29, 2023).
[28] Y. Tian, C.Y. Jim, Y. Tao, T. Shi, Landscape ecological assessment of green space fragmentation in Hong Kong, Urban For. Urban Green. 10 (2) (2011) 79–86.
[29] Y. Liu, M.-P. Kwan, Z. Kan, Inconsistent association between perceived air quality and self-reported respiratory symptoms: a pilot study and implications for environmental health studies, Int. J. Environ. Res. Publ. Health 20 (2) (2023) 1491.
[30] P. Team, Planet Application Program Interface: in Space for Life on Earth, vol. 2017, 2017, p. 40. San Francisco, CA.
[31] K.K.-L. Lau, S.C. Chung, C. Ren, Outdoor thermal comfort in different urban settings of sub-tropical high-density cities: an approach of adopting local climate zone (LCZ) classification, Build. Environ. 154 (2019) 227–238.
[32] X. Feng, Z. Zeng, M. He, A 20-year vegetation cover change and its response to climate factors in the Guangdong-Hong Kong-Macao Greater Bay Area under the background of climate change, Frontiers in Ecology and Evolution 10 (2023) 1080734.
[33] H. Guo, et al., SDGSAT-1: the world's first scientific satellite for sustainable development goals, Sci. Bull. 68 (1) (2023) 34–38.
[34] Z. Cui, et al., Vicarious radiometric calibration of the multispectral imager onboard SDGSAT-1 over the dunhuang calibration site, China, Rem. Sens. 15 (10) (2023) 2578.
[35] Y. Liu, M.-P. Kwan, Mobility-oriented measurements of people's exposure to outdoor artificial light at night (ALAN) and the uncertain geographic context problem (UGCoP), PLoS One 19 (4) (2024) e0298869.
[36] J. Wang, L. Kou, M.-P. Kwan, R.M. Shakespeare, K. Lee, Y.M. Park, An integrated individual environmental exposure assessment system for real-time mobile sensing in environmental health studies, Sensors 21 (12) (2021) 4039.
[37] H. Martin, Y. Hong, N. Wiedemann, D. Bucher, M. Raubal, Trackintel: an open-source Python library for human mobility analysis, Comput. Environ. Urban Syst. 101 (2023) 101938.
[38] Q. Li, Y. Zheng, X. Xie, Y. Chen, W. Liu, W.-Y. Ma, Mining user similarity based on location history, in: Proceedings of the 16th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems, 2008, pp. 1–10.
[39] S. Jiang, J. Ferreira, M.C. Gonzalez, Activity-based human mobility patterns inferred from mobile phone data: a case study of Singapore, IEEE Transactions on Big Data 3 (2) (2017) 208–219.
[40] Y. Liu, M.-P. Kwan, C. Yu, How mobility and temporal contexts may affect environmental exposure measurements: using outdoor artificial light at night (ALAN) and urban green space as examples, Ann. Assoc. Am. Geogr. (2024) 1–20, https://doi.org/10.1080/24694452.2024.2319067.
[41] L. Xu, C. Ren, C. Yuan, J.E. Nichol, W.B. Goggins, An ecological study of the association between area-level green space and adult mortality in Hong Kong, Climate 5 (3) (2017) 55.
[42] J. Wang, M.-P. Kwan, G. Xiu, X. Peng, Y. Liu, Investigating the neighborhood effect averaging problem (NEAP) in greenspace exposure: a study in Beijing, Landsc. Urban Plann. 243 (2024) 104970.
[43] K. Benoit, Linear regression models with logarithmic transformations, London School of Economics 22 (1) (2011) 23–36. London.
[44] A. Clauset, C.R. Shalizi, M.E. Newman, Power-law distributions in empirical data, SIAM Rev. 51 (4) (2009) 661–703.
[45] M.-P. Kwan, The uncertain geographic context problem, Ann. Assoc. Am. Geogr. 102 (5) (2012) 958–968.
[46] P.R. Boyce, The benefits of light at night, Build. Environ. 151 (2019) 356–367.