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Unveiling environmental inequalities in high-density Asian city: City-scaled comparative analysis of green space coverage within 10-minute walk from private, public, and rural housing

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HIGHLIGHTS

- Green space coverages near home and along residents' 10-minute walk were examined.
- Disparities were found in pedestrian-centric, mixed-residential settings of high-density city.
- Private housing in low-income, high-density urban core had the least green space coverage.
- Public housing had medium and consistent green space coverage across the city.

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ABSTRACT

While increasing studies acknowledge the potential of green spaces to alleviate urban environmental problems in high-density cities, there is growing attention to the socio-spatial inequalities in green space allocation. Few studies have assessed these inequalities by considering the green space coverage along citizens' walking trips from their homes within the context of pedestrian-centric and mixed-residential developments in high-density cities. Therefore, this study (1) evaluated green space coverage near home and within residents' 10-minute walk from each residential building in Hong Kong, (2) estimated the population living in green space-deprived environments, and (3) explored their relationships with socioeconomic and built-environment characteristics. Results revealed that private housing residents living in lower-income and higher-density areas in the urban core were the most prone to low green space coverage. In contrast, public housing consistently offered medium levels of green space coverages regardless of community income and urban form. Additionally, high-density new town development demonstrated the potential for equitable green space allocation across different housing types. As cities increasingly embrace high-density development and promote active transportation, this study provides valuable insights for implementing housing and greening initiatives that foster healthy living environments in high-density cities.

1. Introduction

Today, 4.4 billion people live in cities, and this figure is expected to double by 2050 (World Bank, 2023). However, unsustainable practices such as urban sprawl and car-centric development have significantly contributed to global greenhouse gas emissions and environmental degradation (Mahtta et al., 2019). In response, increasing scholars and policymakers have advocated for compact development strategies that integrate high-density housing, mixed-use planning, efficient public transport, and pedestrian-friendly design to promote urban sustainability (Burton, 2000; Jabareen, 2006). Nonetheless, concerns have been raised regarding potential conflicts between compact development, urban livability and public health (Ng, 2009; Tan & Rinaldi, 2019). For instance, urban canyons in densely populated areas may suffer from poor ventilation, leading to the accumulation of heat and pollutants, thereby increasing the risk of respiratory and heat-related

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illnesses among residents (Hua et al., 2021; Lai et al., 2013). Furthermore, rising land values can adversely affect housing affordability, resulting in smaller living and public spaces for residents (Burton, 2000).

To address these challenges and enhance urban livability, many have promoted the incorporation of green spaces within residents' living environments (W. Y. Chen & Jim, 2008). These green spaces can encompass various vegetated areas in cities, including natural landscapes such as countryside, nature reserves, as well as *peri*-urban and urban landscapes like parks, roadside trees, and sports fields (Chong et al., 2013; Kloek et al., 2013). They provide essential ecosystem services in urban settings, such as filtering air pollutants (Diener & Mudu, 2021), lowering urban temperature (Venter et al., 2020), and providing a more pleasant environment for physical activities, active travel (Vich et al., 2019), and social interactions (Arnberger & Eder, 2012).

Despite the variegated benefits of green spaces in urban settings, there is growing attention to the socio-spatial inequalities in green space allocation. First, many have documented the inverse relationships between urban density and green space availability, as green spaces around the dense urban core were usually fewer (Tian et al., 2012), less exposed (Song et al., 2021), and less accessible (Y. Chen et al., 2020) for residents than in the urban periphery. Second, studies also found that wealthier people typically have better access and exposure to a greener environment than disadvantaged populations (Dai, 2011; Li et al., 2015). Some positioned green space as an agent of gentrification in cities, which increases property prices and creates enclaves of environmental privilege that displace lower-income dwellers (Anguelovski et al., 2018; Gould & Lewis, 2016; Hubbard & Brooks, 2021). Moreover, some found that private housing provides gated green spaces for residents, while some public housing may lack accessible public green spaces for residents (Kronenberg et al., 2020; Xiao et al., 2016).

When conducting these assessments to understand green space disparities in cities, most studies focused specifically on amenity green spaces (e.g., parks and gardens) (Zhang et al., 2023), only a few accounted for citizens' incidental experiences with green spaces (e.g., roadside greenery) using some mobility samples (Liu et al., 2023; Yang et al., 2023). Still, few studies have assessed green space disparities based on citizens' walking trips from their homes within the context of pedestrian-centric and mixed-use developments in high-density cities. Such exploration can provide (1) meaningful implications on where to improve street greening in high-density cities, and (2) a comprehensive understanding of existing environmental inequalities surrounding green space allocation. Therefore, this study used Hong Kong as a case study to evaluate disparities of green space across citizens' homes and nearby pedestrian paths and explore such disparities by housing types (private, public, rural housing), urban form (urban core, new towns, suburbs and rural areas), urban density and community wealth.

Hong Kong is the best fit for this study for multiple reasons. First, the city features a pedestrian-centric design that enables most residents to walk within five to ten minutes to nearby public transit stations or complete walk-only trips (Transport Department, 2014, 2023). Second, Hong Kong's housing development is highly mixed between the public and private sectors, with nearly half of the city's population living in public housing (Housing Bureau, 2022b). It allows us to evaluate if the living environment around public housing contains sufficient green space for economically disadvantaged populations. Comparing the green space allocation around private and rural housing can also examine if it favors the housing market or particular groups of residents. Third, the prevalence of high-rise apartments (40–70 stories) can reflect whether high-density, high-rise residential developments can provide adequate green space coverage than low-density, low-rise housing. As more policymakers and scholars advocate for high-density development and active travel for urban sustainability, this study provides useful implications for future city planning to equitably allocate green space in high-density urban environments.

2. Study area

Hong Kong (1,117 km^2) is located on the southeast coast of China and is home to approximately 7.3 million residents (Planning Department, 2022). Due to its hilly terrain, human activities are confined to just 25.4 % of the territory, making Hong Kong one of the most densely populated cities in the world (Fig. 1) (Yeh & Li, 2000; Planning Department, 2022). Currently, 30.6 % and 15.4 % of the population live in public rental housing and subsidized-sale public housing, whereas 54 % live in private and rural housing, including private housing blocks, villas, rural villages, etc. (Housing Bureau, 2022b).

More than 4.6 million citizens currently reside in Major Housing Estates (MHEs), i.e., large public or private residential buildings that accommodate at least 3,000 residents or 1,000 domestic households (C&SD, 2022). Most public housing estates are generally among MHEs since they are typically built under large housing projects. All rural housing is a standalone small temporary structure (squatters) or a village house constructed within recognized rural villages (Planning Department, 2023).

All housing types can be found across various urban forms (i.e., urban core, new towns, suburbs and rural areas). The urban core (i.e., Kowloon and northern Hong Kong Island) has the longest development history and contains the Central Business District (Development Bureau, & Planning Department, 2016). The new towns are developed by the government across the New Territories primarily under rapid population growth (GovHK, 2021). The suburbs and rural areas (e.g., typically at the outer edge of the territory) are proximate to country parks and natural landscapes (Tang et al., 2007). Despite the dominance of high-rise high-density residential development in the urban core, few squatter villages remain (Planning Department, 2023). New town developments also retained clusters of other rural villages situated at the fringe of new towns. Furthermore, Hong Kong's public housing schemes cover suburbs and rural areas, which were constructed initially to provide in-site resettlement for the rural villagers affected by the redevelopment projects (Hong Kong Housing Society, 2023).

3. Data and methodology

The research workflow is illustrated in Fig. 2, and the data used are outlined in Table 1.

3.1. Extraction of green spaces

All green spaces in Hong Kong were derived from the cloud-free Sentinel-2 satellite imageries, as commonly used in previous studies (Ling et al., 2024; Sit et al., 2024). The images were first preprocessed using the Sen2Cor v2.10.1 (Table 1). Sen2Cor is a processor provided by the image distributor, European Space Agency (ESA), to atmospherically and topographically correct images and provide additional Scene Classification Map (ESA, n.d.). The preprocessed image contains red, blue, green, and near-inferred bands at 10 m spatial resolution. We used the red and near-inferred bands to derive the Normalized Difference Vegetation Index, widely used for estimating vegetation density. We then sampled the land covers of water, vegetation, and others (41,641 pixels) and trained a random forest model using 80 % of the samples. We applied the model to the five bands to conduct a supervised land cover classification. The classification is satisfactory, demonstrating a high agreement with the validation samples (kappa statistic = 0.985).

3.2. Identification and classification of residential buildings

We first distinguished rural and non-rural residential housing for each building using the Land Utilization map (Table 1). We manually removed non-residential structures (e.g., car parks in residential areas) by referencing building names and Google Maps. In total, 157,512 residential buildings were identified. Public housing was classified by

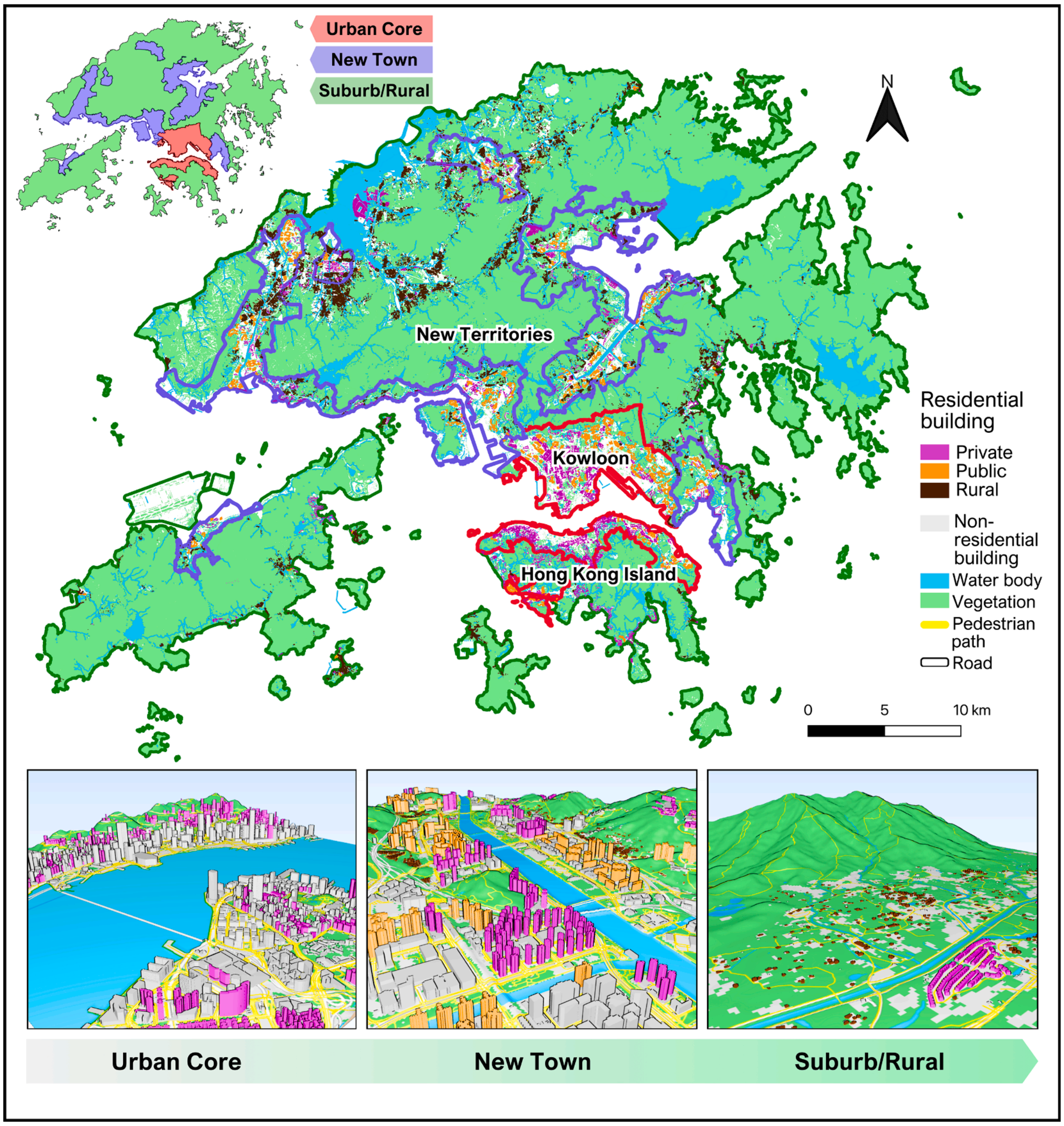

Fig. 1. Spatial distribution of green space, residential building, housing type, and urban forms in Hong Kong. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

matching building names to the public housing inventories. All other buildings were then classified as private housing.

3.3. Population disaggregation

Since the building-level population data are unavailable, we disaggregated the population from census tract (District Council Constituency Area) to each building using the volumetric method (Lwin & Murayama, 2009; Ng et al., 2024) in (1):

$$P_b = \left(\frac{C_j}{\sum_{k=1}^{n} V_k}\right) V_b, where V = A \times H \quad (1)$$

where P_b is the residential population of building b, C_j is the population living in domestic housing at each District Council Constituency Area (DCCA) j, V_k is the building volume of all residential buildings in j, and V_b is the respective building volume. The building volume for each building was calculated by multiplying the building area A by building height H provided in the building data (Table 1).

3.4. Urban form classification

We adopted the boundary of the new towns defined by the 2021 population census (Table 1). We then followed Loo & Chow (2008) and Ng & Koh (2023) to delineate the urban core areas using the Large Subunit Group (LSG) census tract (finest scale with sufficient data). As census boundaries changed over time, we validated the classification by zooming in on each census tract in Google Earth and examining the built environment of the area. The remaining areas are classified as suburbs and rural areas.

3.5. Measurement of green space coverage

We defined green space coverage as the percentage of green space in a defined area, which this study delineated at two scales: Home Vicinity (2) and Neighborhood Vicinity (3):

$$C_H = \frac{\sum_1^n G_{i \in H}}{\sum_1^h L_{i \in H}} \quad (2)$$

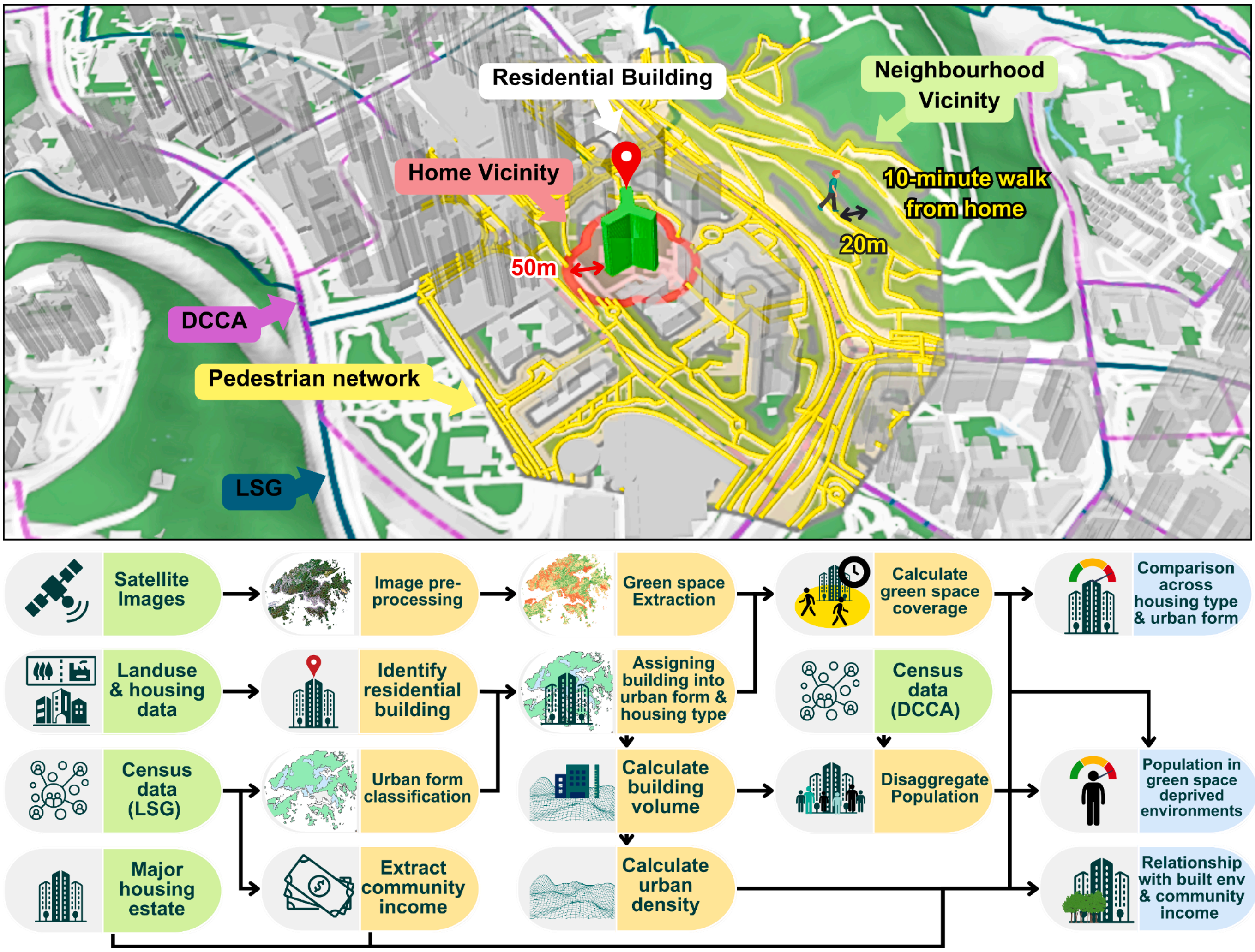

Fig. 2. Graphical diagram of the methodology used in this study.

$$C_N = \frac{\sum_1^n G_{i \in N} - \sum_1^n G_{i \in H \wedge N}}{\sum_1^h L_{i \in N} - \sum_1^h L_{i \in H \wedge N}} \tag{3}$$

For home vicinity H, we summated all green space pixels G_i within 50 m from each residential building, divided it with all land pixels L in the home vicinity, and transformed it into percentage. It aims to capture any greenery within respective housing estates or around the building that residents will be directly exposed to when they go in and out of their homes. Besides, the average block size in Hong Kong is 111 m (SD=36) (Zhao et al., 2021). Therefore, using a 50 m buffer from each building polygon should be able to capture the surrounding environment around each residential building.

For neighborhood vicinity N, we defined it as a 20 m buffer of all pedestrian paths within a 10-minute walk from the residential building excluding any overlapping pixels from the home vicinity. We used the “osmextract” R package to extract the pedestrian network from Open Street Map (OSM) and created a 10-minute walk catchment by using the “opentripplanner” R package (Gilardi & Lovelace, 2023; Morgan et al., 2019). Buffering from pedestrian paths, with a radius ranging from 10 m to 100 m, is commonly used to capture the contextual influence on health and behaviors. These buffer sizes are able to delineate the vicinities of the pedestrian environment, and are more compatible with the common size of the urban parcels (Yi et al., 2019). In Hong Kong, the width of walkways commonly ranges from 1 to 7 m (Zacharias, 2021). In addition, the recommended minimum width of the carriageway ranges from 6.75 to 14.6 m, depending on the function and land use (Planning Department, 2024). For instance, the minimum total width of a 3-lane primary distributor road (10 m) with a high-volume walkway (residential land use) on both sides (11 m) is 21 m. Therefore, buffering 20 m from pedestrian paths would fit the urban contexts of Hong Kong. Moreover, we removed land and vegetated areas overlapping the building towers to ensure that the estimated coverage can better account for the varied streets’ width and the urban canyon.

Note that any vegetation pixels located within the residential building’s home and neighborhood vicinities are included regardless of their difference in urban forms. For instance, a residential building is located at the edge of the urban core, but residents may also walk along the trails of nearby hillsides in suburbs and rural areas within 10 min.

3.6. Analysis

We first used descriptive statistics to explore the green space coverage at home and neighborhood vicinities from each residential building and compare the coverage between housing types and urban forms. To enhance visibility of city-scale spatial variation and minimize spatial bias associated with areal census boundaries, we produced a hexagonal map of the city, aggregating building-level green space coverage at 500 m resolution.

Next, we estimated the resident population with different levels of green space coverage in their living environments. We then grouped residential buildings into “Low,” “Mid,” and “High” by the first and third quantiles of green space coverage and calculated the share of buildings

Table 1
Sources of the spatial data will be used in this study.

Data	Dataset	Date	Data type	Source
Built-environment				
Green space	Sentinel 2 satellite imageries	6th Sep 2022	Raster; 10 m resolution	European Space Agency Copernicus Open Access Hub
Building	Digital Topographic Map iB1000	2023	Vector	Provided by the Lands Department through CSDI[a]
Pedestrian network	Open street map	2022	Vector	Open street map
Land utilization	Land utilization map	2022	Raster; 10 m resolution	Planning Department's website https://www.pland.gov.hk/pland_en/info_serv/open_data/landu/
Socioeconomic				
Census statistics	2021 Population Census Statistics (By District Council Constituency Area)	2021	Vector	Provided by the Census and Statistics Department through CSDI[a]
Small-area census statistics	2021 Population Census Statistics (By Large Subunit Group)	2023	Vector	Provided by the Census and Statistics Department through CSDI[a]
New Towns	Boundaries of New Towns (for 2021 Population Census)	2021	Vector	Provided by the Census and Statistics Department through CSDI[a]
Major housing estates	2021 Population Census Statistics (By Major Housing Estates)	2021	Vector	The 2021 Population Census website https://www.census2021.gov.hk/en/district_profiles.html
Public housing inventories	Location and Profile of Public Housing Estates	2023	JSON and text	Hong Kong Housing Authority through DATA.GOV.HK and Hong Kong Housing Society https://www.hkhs.com/en/housing-archive-index/scheme/All/district/All

Notes:
[a] Hong Kong Common Spatial Data Infrastructure.

by different combinations of home-neighborhood green space coverage.

Then, we further compared the green space coverage of residential buildings by their scale of development (MHE vs. non-MHE), urban density, and median monthly domestic household income.

$$D_H = \frac{\sum_{m=1}^{n} V_m}{A_H} \tag{4}$$

$$D_N = \frac{\sum_{m=1}^{n} V_m}{A_E} \tag{5}$$

For urban density D (4-5), we defined it as the ratio between the total volume of building structures V_m (including non-residential buildings) and total land area of the given area A. For the neighborhood vicinity, the total building volume is divided by the area of the entire 10-minute walking catchment A_E instead of a 20 m buffer around pedestrian paths to capture the surrounding buildings in the neighborhood.

We grouped buildings into "Low", "Mid", and "High" levels of urban density and community income by the first and third quantiles of the distribution. We then built two multinomial logistic regression models for home and neighborhood vicinities using all independent variables mentioned above. The models aim to estimate the odds of residential buildings falling into Low, Mid, and High groups of green space coverage in response to the independent variables. Zoom-in case studies were conducted at the end to explain the findings at the community level.

4. Results

4.1. How did green space coverage near home and along residents' 10-minute walk differ between housing types and urban forms?

Across the city, green space coverage at home and neighborhood vicinities generally increased from the urban core, new towns, to suburbs and rural areas, with spatial disparities observed in each urban form (Fig. 3a).

In the urban core, private housing had the least median coverage in home and neighborhood vicinities (2.86 % vs. 21.60 %) than public (31.27 % vs. 41.74 %) and rural housing (46.77 % vs. 48.13%) (Fig. 3b), it reflected a noticeably uneven distribution between housing type. However, the outliers of private housing imply some residents could enjoy some of the greenest living environments (3rd quartile to Maximum – Home: 16.67 % to 100 %, Neighborhood: 32.27 % to 94.98 %).

In new towns, differences across housing types were reduced. Although private housing had the least median coverage at home vicinity (27.54 %), their neighborhood vicinities (50.81 %) were slightly higher than public housing (44.80 %). Generally, green space coverage near home and along residents' 10-minute walking was better in new towns than in the urban core, but disparities were apparent among private and rural housing.

In suburbs and rural areas, green space coverage was generally higher than in urban core and new towns. Nonetheless, they were largely dispersed, especially among private and rural housing. It suggested that living in private and rural housing in suburbs and rural areas may not always guarantee higher coverage than living in the urban core and new towns. Contrastingly, a narrower interquartile range (i.e., the difference between 1st and 3rd quartile) of public housing may suggest a more consistent coverage of green space for residents.

4.2. What was the estimated resident population that lived in green space-deprived environments?

This study estimated that about 0.61 million or 8.32 % of residents had no green space coverage in their home vicinities, while around 0.12 million or 1.65 % of residents had more than 80 %. For neighborhood vicinities, around 0.94 million (12.89 %) of residents had $\leq$ 20 % of coverage, in contrast to the 0.14 million (1.90 %) of residents who had $\geq$ 80 %.

The most green space-deprived environments were mostly private housing in the urban core (0 % near home: 26.23 %/ ~0.48 million; $\leq$20 % in the neighborhood: 34.06 %/ ~0.62 million) (Fig. 4a). About 1.37 million/75 % of private housing residents in the urban core were living with $\leq$ 25 % of coverage near home and $\leq$ 40 % in their neighborhood vicinity, which was more concerning than ~ 1.10 million/ 75 % of public (Home: $\leq$48 %, Neighborhood: $\leq$52 %) and ~ 3,000/ 75 % of rural housing residents (Home: $\leq$60 %, Neighborhood: $\leq$79 %).

In new towns, while the coverage for ~ 1.05 million/ 75 % of private

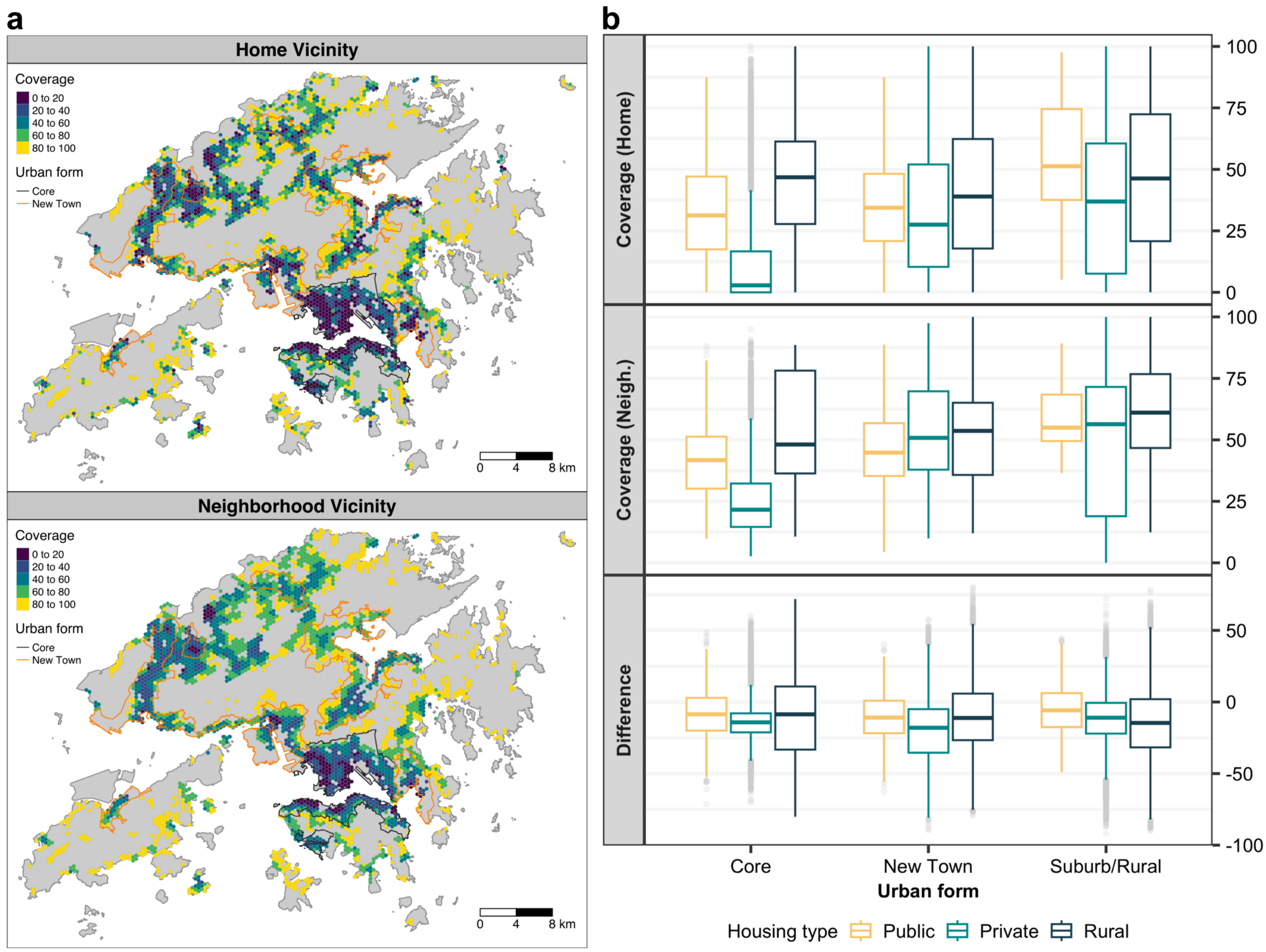

Fig. 3. **(a)** Spatial patterns of green space coverage at the home vicinity and neighborhood vicinity of all residential buildings, and **(b)** box plots of green space coverage at the home vicinity, neighborhood vicinity, and the home-neighborhood difference by urban form and housing type. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

housing residents (Home: ≤40 %, Neighborhood: ≤51 %) was generally higher than the urban core, they were lower than ~ 1.44 million/ 75 % of the public (Home: ≤49 %, Neighborhood: ≤58 %) and ~ 0.14 million/ 75 % of rural housings (Home: ≤58 %, Neighborhood: ≤64 %) in new towns. The total resident population was lower in the suburbs and rural areas than in the urban core and new towns (~7.08 % of the total population); still, not all residents were secured with high green space coverage. About 2.99 % (5.39 %) and 4.21 % (1.47 %) of private and rural housing residents had no green space coverage in the home (neighborhood) vicinities. Contrastingly, no public housing residents in suburbs and rural areas were living in these green space-deprived environments at both home and neighborhood vicinities.

In the urban core, the most common home-neighborhood combination of green space coverage for private housing was Low-Low (64.78 %), contrasting to the Mid-Mid (51.18 %) and Mid-High (31.48 %) for public and rural housing, respectively. In New Town, Mid-Mid was the most common combination for all housing types (Private: 33.58 %; Public: 55.00 %; Rural: 36.77 %), as all other combinations comprised less than 20 %. In suburb and rural areas, although Mid-Mid was also the most common combination (Private: 27.74 %, Public: 57.05 %, Rural: 32.35 %), other combinations also occupied noticeable shares, including 24.37 % of private housing in Low-Low, 19.23 % of public housing in High-Mid, and 22.45 % of rural housing in High-High, underscoring the high disparities across housing types.

4.3. How were built environment and socioeconomic characteristics associated with green space coverage?

We explored how green space coverage varies with developmental scale (MHE vs non-MHE) and urban density in home and neighborhood vicinities. We only compared private and public housing because rural housing is homogeneously low-dense, and none were major housing estates.

In the urban core, private MHEs had a higher median green coverage than private non-MHEs (Home: 9.96 % vs. 2.47 %; Neighborhood: 25.46 % vs. 21.43 %) (Fig. 5a). However, the median coverages for public MHE and non-MHE were similar (Home: 30.36 % vs 31.58 %; Neighborhood: 41.87 % vs. 41.66 %), and both had higher coverages than private housing. In new towns, private MHEs had higher median coverage than private non-MHEs for home vicinity but lower median coverage for neighborhood vicinity. In contrast, public MHEs performed better than public non-MHEs for both home and neighborhood vicinities. Interestingly, in suburbs and rural areas, private MHEs had some of the lowest median coverage across the city (Home: 2.94 %, Neighborhood: 12.97 %), contrasting to private non-MHEs, which were distinctly greener (Home: 48.78 %, Neighborhood: 65.60 %).

As evident in the urban core and new towns, the higher the urban density, the lower the green coverage (Fig. 5b-c). Across the city, private housing in the high-density environment had the lowest median

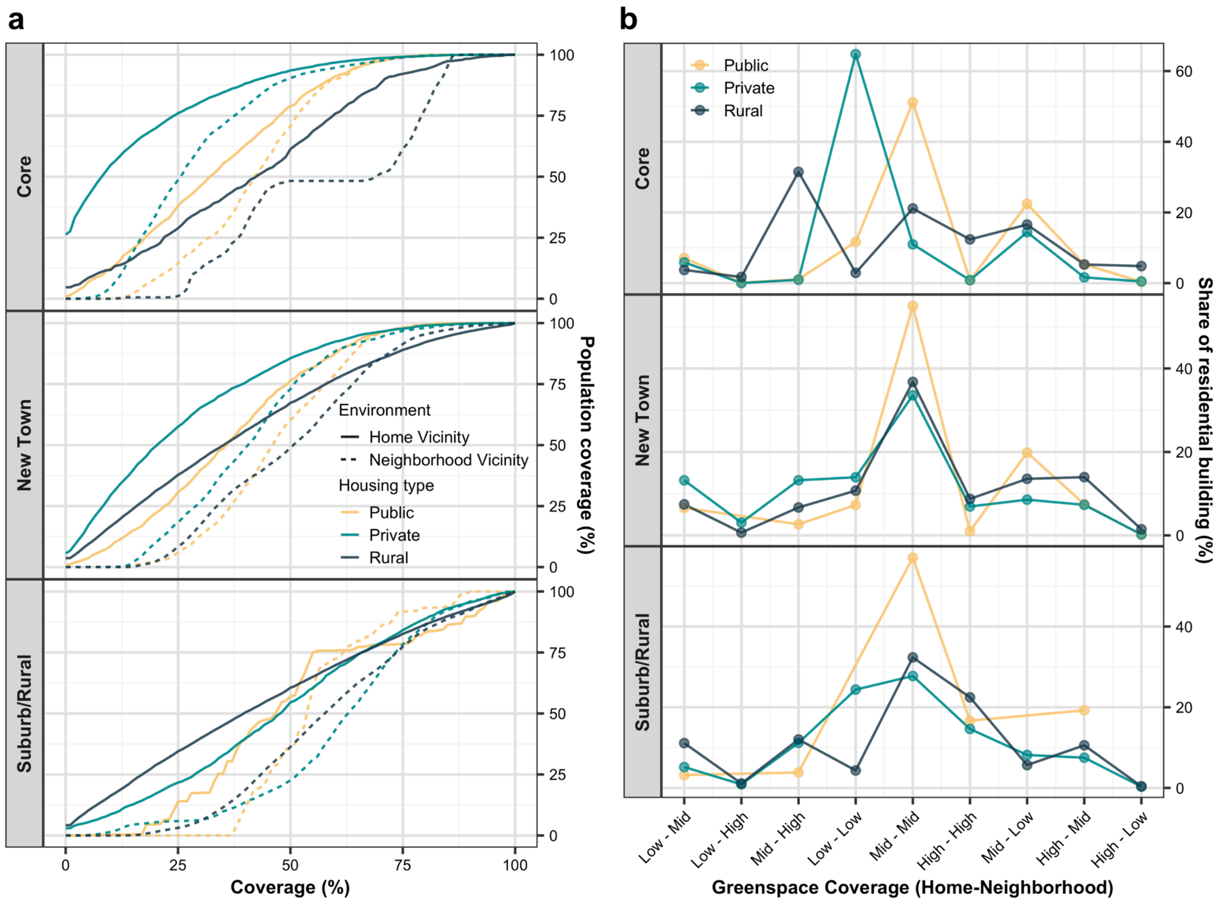

Fig. 4. **(a)** Resident population coverage by green space coverage in their living environments and **(b)** share of buildings by different combinations of home-neighborhood green space coverage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

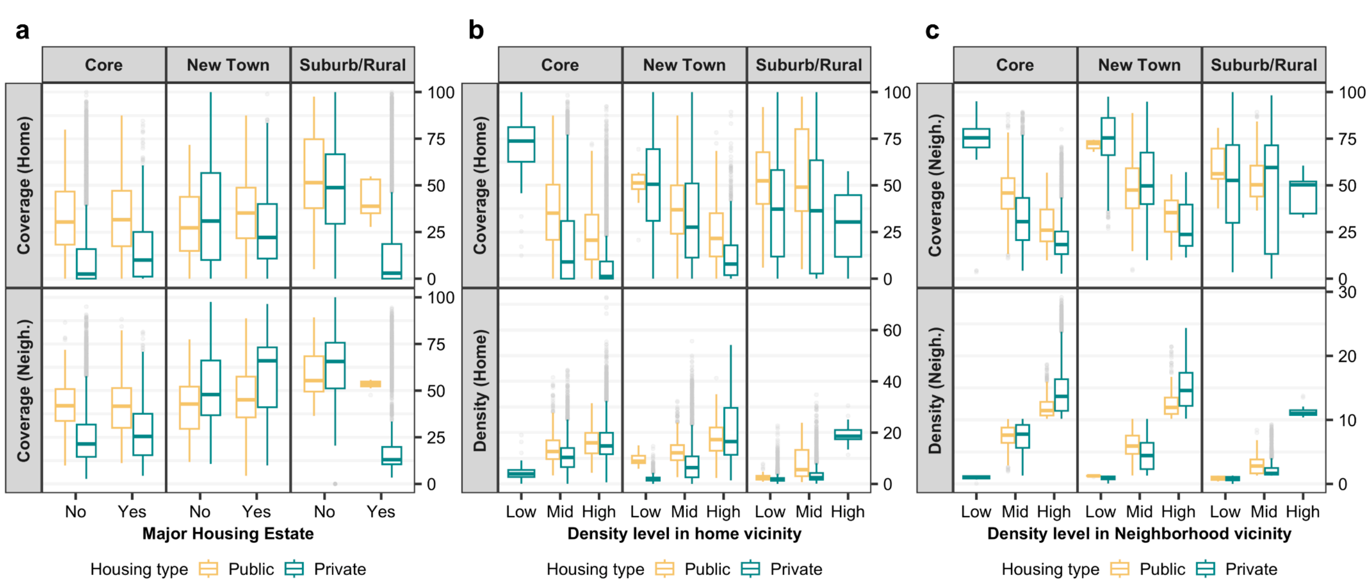

Fig. 5. Boxplots of green space coverage stratified by **(a)** major housing estate (MHE), **(b)** urban density in the home vicinity, and **(c)** urban density in the neighborhood vicinity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coverage in home and neighborhood vicinities (1.20 % vs 18.24 %). Contrastingly, private housing in the urban core also contained the highest median coverage, which was concentrated in low urban density areas (Home: 73.75 %, Neighborhood: 75.46 %).

However, urban density is not the sole determinant for green space coverage, as public housing generally had denser home vicinities than private housing in new towns and urban cores, but they also offered higher median coverage (Fig. 5b). In suburbs and rural areas, private housing shared a dispersedly distributed coverage regardless of urban density, while public housing had slightly better coverage in lower density.

We compared across all housing types for the relationship between community income and green space coverage (Fig. 6). In the urban core, a positive relationship was observed for private housing, as high-income areas had much higher median coverage (19.83 % and 35.23 %) than the low (0 % and 14.66 %) and middle-income (1.96 % and 21.87 %) areas for home and neighborhood vicinities. This relationship was consistent with private housing in new towns, though they had generally higher coverage than in the urban core. Interestingly, in suburbs and rural areas, the higher the income of the area, the lower and more dispersed the green space coverage of private housing. It may be due to the various forms of luxurious private housing, contrasting between secluded mansions located in hillsides with an abundance of green space, and large suburban villa sites that are built with intricate private driveways and limited green space within the estate. However, public housing across the city had a mostly consistent median coverage regardless of community income, while rural housing in new towns, suburbs and rural areas had the lowest median coverage in middle-income areas and the highest in high-income areas.

We conducted multinomial logistic regressions to further examine the relationship between green space coverage and the built environment and socioeconomic variables (Table 2-3). Living in a high-density environment had higher odds of having low green coverages for both home and neighborhood vicinities (AOR: 3.19 and 1.62, $p < 0.001$), and living in a MHE had higher odds of having low green space coverage (AOR – Home: 5.72, $p < 0.001$, Neighborhood: 10.71, $p < 0.001$) than living in a non-MHE.

Compared to private housing, public housing had lower odds of low green space coverage (AOR – Home: 0.02, $p < 0.001$, Neighborhood: 0.02, $p < 0.001$). Living in new towns (AOR – Home: 0.32, $p < 0.001$, Neighborhood: 0.22, $p < 0.001$), suburbs and rural areas (AOR – Home: 0.36, $p < 0.001$, Neighborhood: 0.11, $p < 0.001$) also had lower odds of having low green space coverage than the urban core. In the urban core, residing in low-income areas had higher odds of having low coverage (AOR – Home: 3.59, $p < 0.001$, Neighborhood: 3.14, $p < 0.001$), while living in high-income areas (AOR – Home: 1.98, $p < 0.001$) had higher odds of having high coverage. Contrastingly, for new towns (AOR – Home: 0.30, $p < 0.001$, Neighborhood: 0.15, $p < 0.001$), suburbs and rural areas (AOR – Home: 0.25, $p < 0.001$, Neighborhood: 0.23, $p < 0.001$), living in low-income areas had lower odds of having low green space coverage. Besides, living in high-income areas in suburbs and rural areas had higher odds of having both low (AOR – Home: 4.21, $p < 0.001$, Neighborhood: 5.12, $p < 0.001$) and high green space coverage (AOR – Home: 1.42, $p < 0.001$, Neighborhood: 4.45, $p < 0.001$). These reflected the high variations of influence among urban forms, housing types, levels of urban density, and income on green space coverage.

4.4. Case studies

Few case studies were provided to illustrate our findings (Figs. 7-9). In the middle to high-income areas such as North Point (Fig. 7a), green space was sparsely distributed within private housing, contrasting to public housing with apparent green space coverage in vicinities. Few private housing had high coverage as they were situated on natural

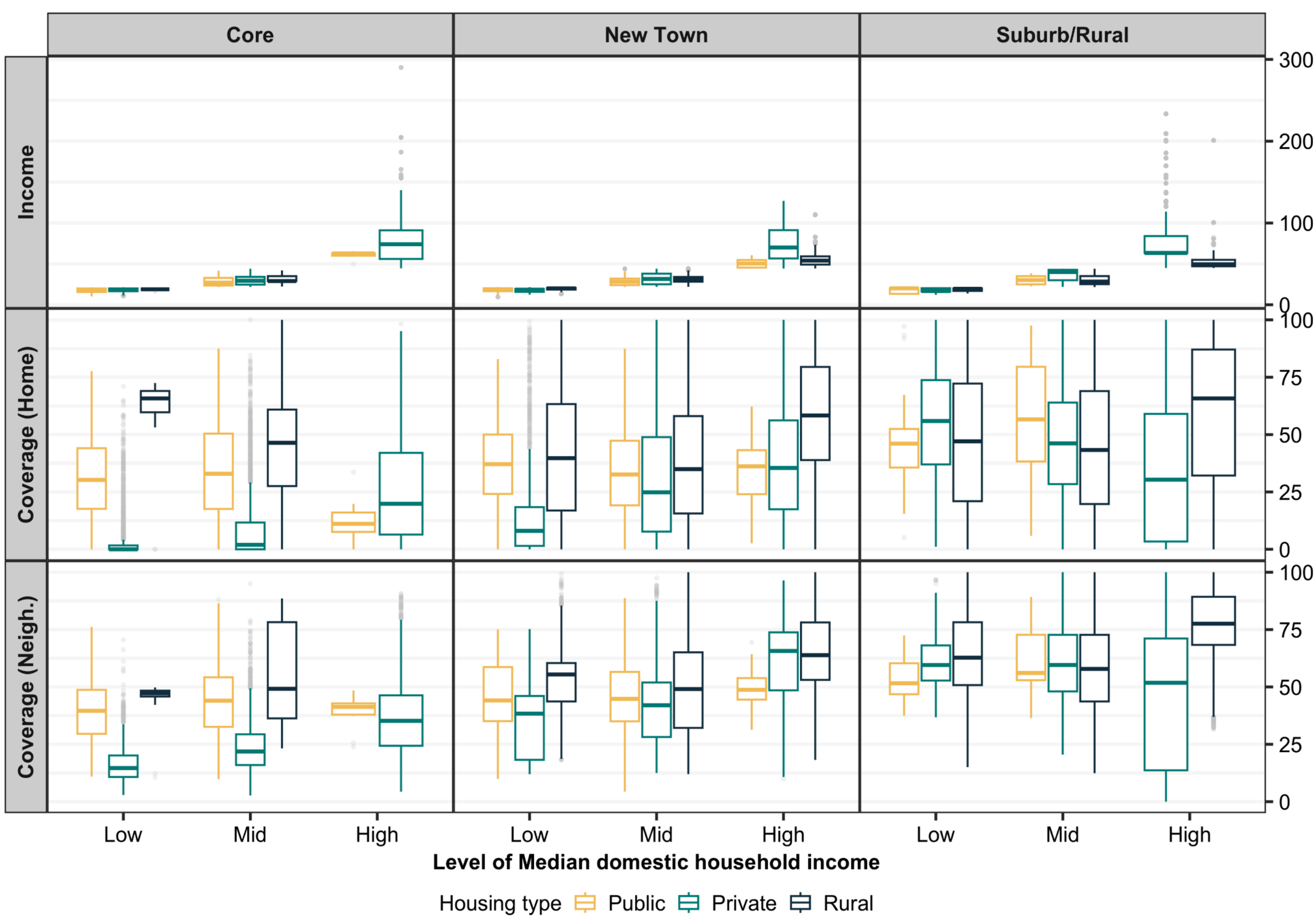

Fig. 6. Green space coverage stratified by median monthly domestic household income (in HKD thousand). (Note: One census tract has no income record, therefore we omitted its 34 residential buildings in the analysis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Multinomial logistic regression of green space coverage at home vicinity.

	Low[a]		High[a]	
Variables	AOR[b]	SE[c]	AOR[b]	SE[c]
(Intercept)	0.823***	0.032	0.170***	0.067
Housing Type				
Private	(Reference)		(Reference)	
Public	0.016***	0.067	2.543***	0.078
Rural	1.172***	0.024	0.809***	0.025
Income[d]				
Mid	(Reference)		(Reference)	
Low	3.592***	0.050	0.708*	0.169
High	0.231***	0.042	1.984***	0.083
Urban Form				
Core	(Reference)		(Reference)	
New Town	0.322***	0.035	1.375***	0.067
Suburb/Rural	0.361***	0.035	1.373***	0.066
Urban Density in the Home Vicinity				
Mid	(Reference)		(Reference)	
Low	0.222***	0.034	8.014***	0.016
High	3.192***	0.019	0.444***	0.031
Major Housing Estate				
No	(Reference)		(Reference)	
Yes	5.723***	0.031	0.330***	0.044
Income * Urban Form				
Low * New Town	0.298***	0.058	1.917***	0.172
High * New Town	1.029	0.056	1.030	0.088
Low * Suburb/Rural	0.249***	0.057	1.912***	0.170
High * Suburb/Rural	4.213***	0.049	1.424***	0.086

[a] *Reference group = Mid.*
[b] *AOR=Adjusted Odds Ratio; *p < 0.05; **p < 0.01; ***p < 0.001.*
[c] *SE=Standard Error.*
[d] *Monthly Median Domestic Household Income.*

Table 3
Multinomial logistic regression of green space coverage at neighborhood vicinity.

	Low[a]		High[a]	
Variables	AOR[b]	SE[c]	AOR[b]	SE[c]
(Intercept)	2.933***	0.037	0.914	0.073
Housing Type				
Private	(Reference)		(Reference)	
Public	0.018***	0.063	0.985	0.109
Rural	0.818***	0.025	0.753***	0.024
Income[d]				
Mid	(Reference)		(Reference)	
Low	3.139***	0.058	0.105***	0.456
High	0.204***	0.044	1.002	0.096
Urban Form				
Core	(Reference)		(Reference)	
New Town	0.215***	0.038	0.405***	0.073
Suburb/Rural	0.112***	0.041	0.217***	0.072
Urban Density in the Neighborhood Vicinity				
Mid	(Reference)		(Reference)	
Low	0.151***	0.043	8.333***	0.017
High	1.622***	0.021	0.109***	0.042
Major Housing Estate				
No	(Reference)		(Reference)	
Yes	10.708***	0.036	0.885**	0.038
Income * Urban Form				
Low * New Town	0.145***	0.065	1.379	0.460
High * New Town	0.333***	0.063	2.875***	0.100
Low * Suburb/Rural	0.230***	0.067	12.551***	0.456
High * Suburb/Rural	5.124***	0.054	4.448***	0.098

[a] *Reference group = Mid.*
[b] *AOR=Adjusted Odds Ratio; *p < 0.05; **p < 0.01; ***p < 0.001.*
[c] *SE=Standard Error.*
[d] *Monthly Median Domestic Household Income.*

hillsides (e.g., Braemar Hill), where urban density was relatively low and community income was high. Although both private and public housing can be found in lower-income areas such as Sham Shui Po (Fig. 7b), private housing residents had little to no green space around their homes and within their 10-minute walk, whereas public housing residents had contrastingly higher coverages. Some private housing in high-income areas could benefit from the green space along the pedestrian paths of public housing, thus increasing their coverage along residents' 10-minute walk. Extensive private MHE can be found in high-income areas like Heng Fa Chuen (Fig. 7c). Despite the open spaces between buildings and extensive green spaces next to the estate, sparse coverage was observed directly near buildings and along a 10-minute walk from most buildings, thus resulting in overall low coverage in the residential environment.

Green spaces in new towns were more commonly found within the urban fabric than in the urban core, and housing types and community income were more heterogeneous within the area (Fig. 8). Private housing located in high-income areas (e.g., Hang Hau and Tai Po) were usually less dense, whereas private housing in low-income areas (e.g., Sheung Shui and Tai Po) were more compactly built with limited open space. Although fewer green spaces were covered at home vicinities of most private housing than nearby public and rural housing, all residents shared an improved coverage of green space along their 10-minute walk due to the connected green spaces around most pedestrian paths.

Despite the common perception of extensive green space coverage in suburbs and rural areas, disparities are apparent in our case studies. In low-density and high-income areas like Discovery Bay (Fig. 9a), private housing was covered with green space near home and along residents' 10-minute walk. However, some low-density private housing in high-income areas of Stanley (Fig. 9b) still had low green space coverage near home, contrasting to other private housing nearby with more greeneries. Interestingly, public housing situated next to the high-income private housing areas had nearly full coverage of green space near home and along pedestrian paths. Moreover, in low to middle-income areas such as San Wai Tsuen (Fig. 9c), uneven distribution of green space at home vicinities was identified for rural housing residents, as some had limited green space coverage near home, while others were located near surrounding natural landscapes. Nonetheless, along the 10-minute walk from rural housing across the site, there was extensive coverage of green space along pedestrian paths.

5. Discussions

This study pondered the opportunities and challenges of equitable green space allocation in high-density cities by comparing green space coverage near home and along 10-minute walking across different housing types and urban forms. We estimated the population living with various green space coverage and explored its associations with socio-economic and built environment variables.

5.1. Public housing can secure economically disadvantaged populations with medium level of green space coverage

Our findings revealed that public housing in Hong Kong could secure economically disadvantaged populations with consistently green near-

Fig. 7. Case studies of **(a)** North Point, **(b)** Sham Shui Po, **(c)** Heng Fa Chun in the urban core. The base map (Aerial Photograph) is accessed through the API provided by the Lands Department.

home and walking environments, even in the high-density urban core. Public housing is observed to have more open space between buildings for green coverage despite sharing similar urban density at home and neighborhood vicinities as private housing. It demonstrated that urban density is not the sole determinant of the availability of green space, as distinct differences in green space coverage can still be found between public and private housing within the same group of urban density. Since the 2000s, the development of public housing has progressively evolved toward environmentally conscious and people-oriented principles. At least 20 % of each estate has to be filled with greenery in various forms, including green slopes, gardens, carpark greening, and greenways (Deng et al., 2016; Housing Authority, 2010). Consistent greening and landscaping improvement programs have also been carried out by the Authority, along with regular vegetation inspections, to ensure residents have high green space coverage (Housing Authority, 2023). The site selection for public housing is also often situated closer to natural landscapes, thus enabling a generally higher coverage than private housing. Public housing in Hong Kong demonstrates the potential for government housing initiatives to secure equitable green space coverage for economically disadvantaged populations in high-density cities.

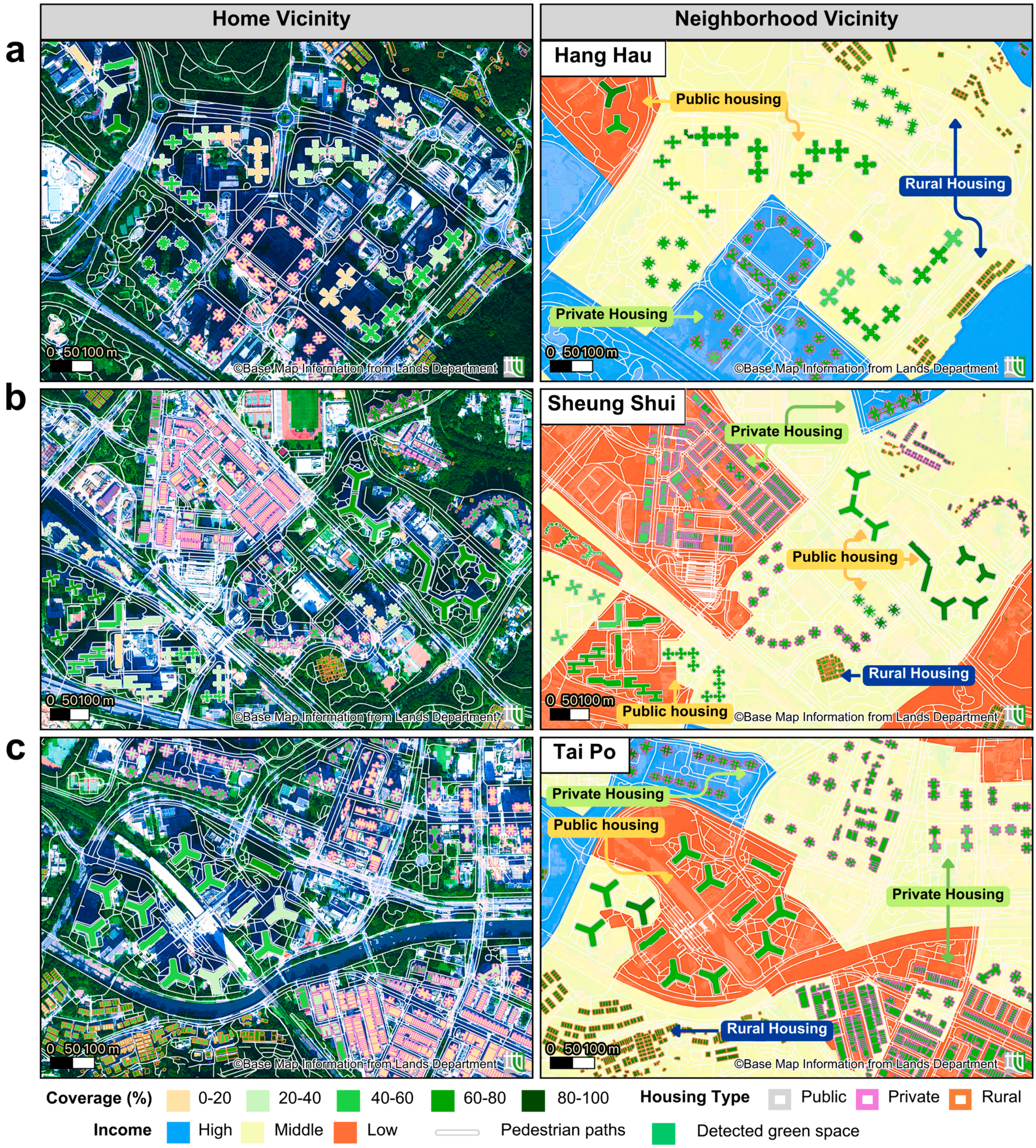

Fig. 8. Case studies of **(a)** Hang Hau, **(b)** Sheung Shui, **(c)** Tai Po in New Towns. The base map (Aerial Photograph) is accessed through the API provided by the Lands Department.

5.2. The unattended population among private housing in the compact city

Though some economically disadvantaged populations could be secured with consistent green space coverage through public housing schemes, environmental inequalities are particularly evident among private housing in Hong Kong. On the one hand, numerous private housing residents who live in low-income and high-density areas of the urban core had scarce green space near home and along their 10-minute walk. On the other hand, residents living in high-income and low-dense urban periphery share some of the highest green coverage. It aligns with the findings of research emphasizing that greener living environments may be more attainable for higher-income residents (Chen et al., 2020; Li et al., 2015, 2021).

Low-income and high-density areas of the urban core are mainly the oldest urbanized areas, which prioritized high-density developments, narrow pavements, and the exclusion of green spaces to cater to rapid population growth since the post-war period (Jim, 2000). The cramped living environments present numerous challenges to reintroducing green spaces, including limited plantable spaces and stressful growing environments above and underground (Jim, 1998, 2013). Today, these unattended residents still endure deficiency in green space under overcrowded living environments. Without green space near home and along their daily walking environments, it amplifies environmental nuisances

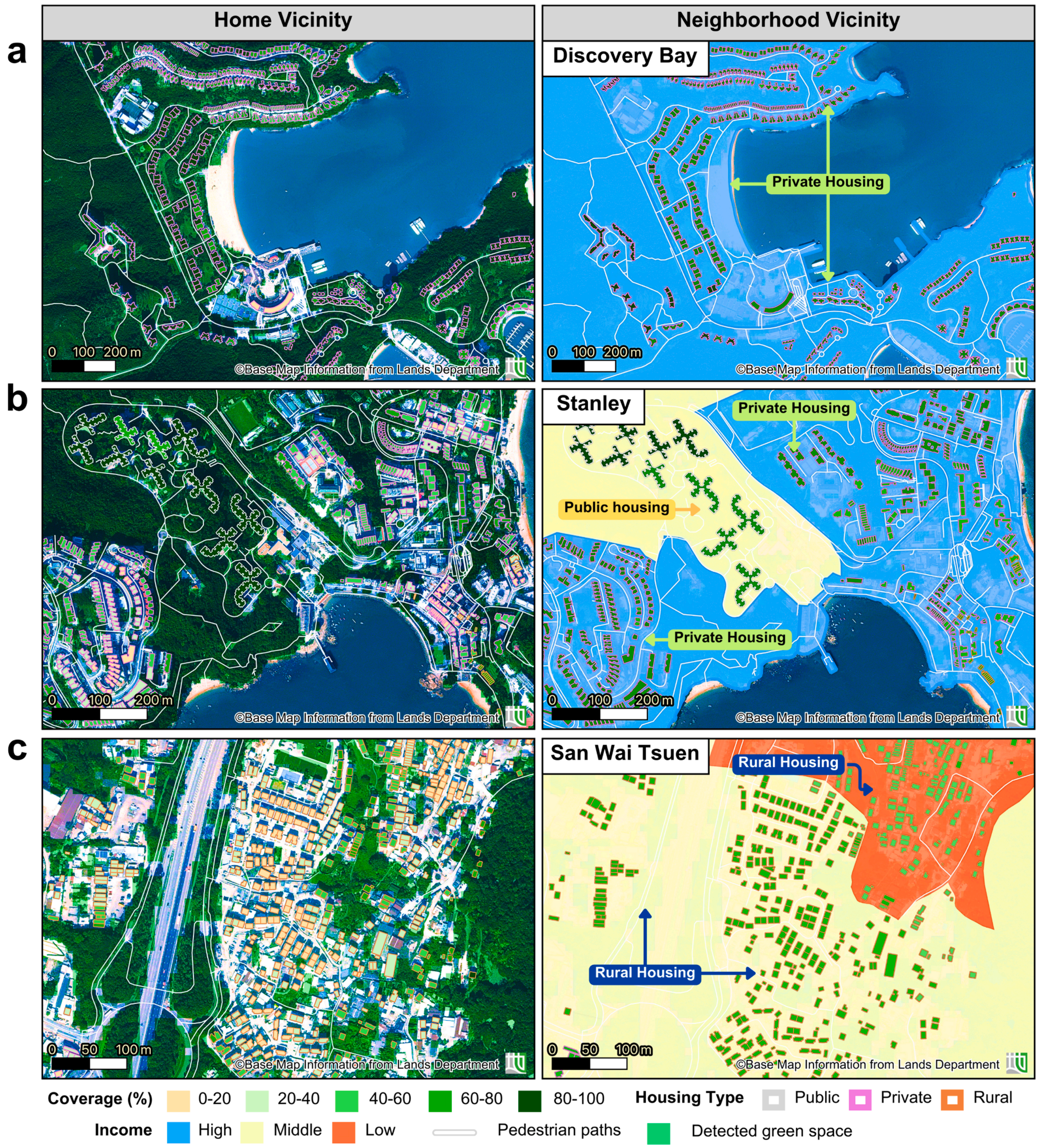

Fig. 9. Case studies of **(a)** Discovery Bay, **(b)** Stanley, **(c)** San Wai Tsuen in suburb and rural areas. The base map (Aerial Photograph) is accessed through the API provided by the Lands Department.

threatening residents' health and well-being, including heavy traffic noise, air and noise pollution, poor air ventilation, and urban heat island effects (Jim & Chen, 2006, 2009). Though public housing provides more green space coverage for vulnerable populations, residents who cannot afford public subsidized sales flats have to endure long waiting times (around six years) for limited vacancies of public rental housing (Housing Bureau, 2022a). Residents have limited choices but to be fatigued by the negative impacts of living in these older neighborhoods before being offered a better living environment.

Greening actions should be prioritized in these areas of the urban core. Although urban renewal projects and new housing developments have been gradually carried out, the potential green gentrification and displacement of the vulnerable population by profit-driven greening should be cautioned (Connolly & Anguelovski, 2021; Curran & Hamilton, 2012). We encourage community-centric urban greening initiatives to be incorporated. Government and community organizations can promote community-led gardening or small-scale urban farming on building podiums that utilize the elevated spaces. These greening initiatives should also be accompanied by increased provision of public housing to secure vulnerable populations with equitable green space.

5.3. New towns balance high-density development and green space provision

Although the urban core presents challenges in allocating equitable green space (Haaland & Konijnendijk, 2015; Madureira & Monteiro, 2021), our findings revealed that low-dense and low-rise development in suburbs and rural areas may not necessarily guarantee all residents with higher green space coverage. Except for a few public housing units in suburbs and rural areas, the distribution of coverage among private and rural housing was dispersed, with some having even less coverage than the high-density urban core and new towns. Despite lower pressure on land development, the utilization of space around residential buildings (e.g., extensive pavement with no street trees, clustered arrangement of buildings within the same village or estate) may also contribute to the low green space coverage near home and along residents' 10-minute walk.

Our studies showed that a balance between high-rise high-density development and equitable allocation of green space could potentially be achieved through government-led new town developments. Our case studies illustrated that in new towns, although green space coverage around residents' home vicinity varies across housing types, green spaces can be equitably shared among residents' 10-minute walk, as green spaces are connected and extensively covered along pedestrian paths of new towns. Moreover, we found that the majority of buildings across housing types shared a medium home-neighborhood combination of green space coverage, contrasting to other urban forms, which contained an uneven distribution of green space across housing types.

Previous studies have also found that new urban areas may provide a greener living environment for residents than the traditional urban core (Song et al., 2020). In Hong Kong, all new towns were initiated after rapid urban development in the urban core. At the planning stage, the government embraced more green spaces in the urban fabric and preserved natural landscapes surrounding the urban areas (Planning Department, 2016a). Notably, new towns in Hong Kong are also under high-density, high-rise development, which has accommodated as many residents as the urban core (Planning Department, 2016b). A more equitable allocation of green space may be contributed by a heterogeneous mixture of public housing developments for lower-income residents, as well as newer private housing, which attracts middle- to higher-income residents (GovHK, 2021; Hills & Yeh, 1983). Moving forward, the high-rise, high-density, and mixed development in new towns in Hong Kong may provide useful planning and urban greening insights for other high-density cities to accommodate more population while securing citizens with equitable green space coverages at home and neighborhood vicinities.

6. Limitations and future directions

Given the scale of our study, we limit green spaces to those that can be derived by satellite, thus potentially neglecting vertical, sheltered, and small-patched greenery. Future studies could further investigate environmental inequalities of green space provision by adding eye-level observations and time-series analysis for higher robustness and accuracy of the results. Detailed morphological data such as pedestrian width and block size could also be incorporated to accurately delineate the home and neighborhood vicinities across different urban forms. Besides, this study only focused on green space coverage near residential buildings and along residents' 10-minute walk from home, which may not comprehensively represent residents' daily mobility. Beyond residents' near-home walking environment, the variation of green space coverage around workspaces, schools, transit stations, and other land uses where citizens visit also contributes to their health and well-being. Future studies could incorporate mobility data and citizen surveys to explore the spatial–temporal disparities of green space coverage around citizens' daily activities.

Due to the unavailability of public open data on household income and housing prices by individual buildings, the current assessment can only leverage community income for analysis. Future studies can explore the possibility of obtaining building-level household income and housing price data for a more accurate analysis of income disparities associated with green space provision. For population estimation, the differences in proportion between building volume and resident population by housing types, variations in household size per unit, and occupancy rate by building may contribute to the uncertainty of population estimation. While this approach is the most suitable given the limited data, future studies may consider collecting samples of the building-level resident population and household data to apply machine learning algorithms for accurate estimation.

7. Conclusions

This study provides useful implications for future city planning by exploring opportunities and challenges for high-density cities to equitably allocate green space proximate to residents' homes and along their 10-minute walk. Our study revealed that government interventions, including public housing schemes, may potentially secure economically disadvantaged populations with green living environments. The connected green space within the urban fabric of new towns also demonstrated potential for high-density, high-rise, and mixed residential development to balance an equitably green coverage for residents. However, prioritized actions for urban greening and housing policies should be focused on private housing residents who live in the lower-income and higher-density areas in the urban core, as they endure the most green space-deprived and overcrowded living environments.

CRediT authorship contribution statement

Ka Ying Sit: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wendy Y. Chen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Ka Yiu Ng:** Writing – review & editing, Software, Methodology, Data curation, Conceptualization. **Keumseok Koh:** Writing – review & editing, Supervision. **Hongsheng Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

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