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Research Paper

Relative importance of quantitative and qualitative aspects of urban green spaces in promoting health

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HIGHLIGHTS

- Study examined relationships between multiple urban green spaces (UGS) provision indicators and two health outcomes.
- There was no significant relationship between objective and subjective UGS indictors.
- Canopy cover, perceived usage quality, and visual greenness showed positive relationships with mental health.
- No indicators of UGS provision had significant relationship with general health.
- Implications of the findings and recommendations for greenery planning were discussed.

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ABSTRACT

The health benefits of urban green spaces (UGS) are important considerations in the design of urban environments. Researchers have analysed how the quantity of UGS impacts health outcomes, but less work has quantified the relative health benefits of different components of UGS provision. We examined the associations of different indicators of UGS provision with self-reported mental and general health based on a national representative household survey (n = 1000) in Singapore. We quantified three quantitative attributes of UGS (vegetation cover, canopy cover, park area) using Geographic Information System (GIS) data and measured visual greenness using the Green View Index (GVI) based on Google Street View panoramic images. We measured the subjective attributes of UGS, namely, usage quality and quantity of UGS within a 400 m circular buffer zone of residences using the survey. Among all the UGS indicators at the 400 m scale, only canopy cover and perceived usage quality were significantly associated with positive mental health, whereas none of the UGS indicators were related to general health. For visual greenness at different distance scales, there was a significant relationship between the indicator calculated by the sum of GVI at a 100 m scale and mental health. Canopy cover at a 400 m scale had a stronger correlation with mental health than perceived usage quality of nearby UGS and visual greenness at a 100 m scale. The findings highlight the importance of measuring both objective and subjective attributes of UGS provision and provide useful information for urban greening.

1. Introduction

Over the past three decades, a large number of studies worldwide point to an emerging consensus that urban green spaces (UGS) can improve the health of urban dwellers (Kaplan & Kaplan, 1989; Bratman et al., 2019; Lai et al., 2019; Zhang et al., 2020). Many studies showed that the amount of UGS within neighbourhoods or regions can have positive associations with self-reported health (Maas et al., 2006; van den Berg et al., 2010; Zhang & Tan, 2019). However, there are inconsistencies in UGS-health studies, as although the majority of studies show positive UGS-health relationships, the strength of relations differs substantially among studies (Zhang et al., 2017). There are several possible reasons for this, such as the study scale used for analysis (Labib, Lindley & Huck, 2020), the socio-economic-cultural context of the study area (Ruijsbroek et al., 2017), and the choice of metrics used to assess greenery (Lachowycz & Jones, 2013; Markevych et al., 2017).

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The metrics that are used to measure UGS cover the spectrum of indicators from quantitative to qualitative aspects of UGS. Quantitative indicators are generally focused on measuring the amount of UGS provided (Jonker et al., 2014), whereas qualitative indicators focus on the characteristics underpinning the performance of UGS related to ecosystem services (Dennis et al., 2020). The indicators can also be differentiated as objective indicators, which are measurable variables irrespective of individual experiences, or subjective indicators, which are based on individual perception and experiences, such as self-reported measures of UGS availability and quality (Dzhambov et al., 2018; Bai et al., 2013).

The choice of metrics used, can in turn, be associated with the putative mechanisms that lead to health improvement. There are three main mechanisms underlying UGS-health relationships: (1) environmental benefits provided by UGS, such as temperature mitigation, air quality improvement, and in dry climates, humidification of the atmosphere (James et al., 2015); (2) short-term physiological and psychological effects caused by the natural elements in UGS, such as improved vitality and attention restoration (Kuo, 2015); and (3) healthy behaviors encouraged by UGS, such as physical activities and social interactions (Dadvand et al., 2016).

These mechanisms can occur during direct and indirect engagement with greenery. One type of engagement is visual. There is increasing evidence that the indirect use of UGS by viewing greenery, whether a view of outdoor vegetation or indoor plants, or even a window view of distant scenery, can provide health benefits (Chang et al., 2020; Lottrup, Grahn & Stigsdotter, 2013; Grinde & Patil, 2009; Velarde, Fry & Tveit, 2007). Such health benefits have been widely applied in our daily lives, for example, through horticultural therapy. For instance, plants in the work place can reduce stress and promote work performance (Chang & Chen, 2005; Al Horr et al., 2016) or a hospital window view with greenery can help recovery from surgery (Ulrich, 1984). In addition to being direct or indirect, engagement can be passive or active (Pretty, 2004). Studies have shown that passing by green spaces whilst involved in other activities (e.g., encountering roadside greenery enroute to a destination) and intentional use of green spaces (e.g., physical activities and social interactions) can both be beneficial to health (Pretty, Peacock, Sellens, & Griffin, 2005).

Hence, metrics of UGS can be defined from the perspective of the mechanisms through which UGS can influence health. As the most widely studied metric, we defined quantity of UGS as "the amount of UGS that actually exist". This indicator forms the physical foundation for greenery to deliver health benefits and it normally involves both direct and indirect engagements, and is relevant to all the three mechanisms involved leading to health. Visual greenness, defined as "the amount of greenery seen from the residents' perspective", is another quantitative metric that is associated with the first two mechanisms leading to health benefits.

In contrast to UGS quantity, another aspect of UGS increasingly recognized for its effect on health is UGS quality (Feng & Astell-Burt, 2019, 2017; van den Berg et al., 2015). The assessment of UGS quality is challenging, however, as "quality" is mainly a subjective assessment depending individual preferences (Brindley et al., 2019; Lindholst et al., 2015). There is no universally accepted definition of quality and how it can be measured (Knobel, Dadvand & Maneja-Zaragoza, 2019). Researchers have proposed several slightly different definitions, such as "attractiveness" (Giles-Corti et al., 2005) or "users want to visit again and again" (Fors et al., 2015). The complexities and intricacies of defining UGS quality could be reasons why there are only a limited number of empirical studies examining the effects of UGS quality on health (Knobel, Dadvand & Maneja-Zaragoza, 2019). To focus on direct engagement, we defined UGS usage quality as "the quality of UGS that influences usage experience and intention to directly use UGS". This indicator is mainly related to the third mechanism described above.

In reviewing studies conducted in the past decade (see Appendix 1 in Supplementary Materials), we found that about 50% of studies investigated the role of only UGS quantity in promoting health, 38.5% examined both quantity and quality, and 15.4% measured quantity, quality and accessibility. Only a few studies measured both objective and subjective attributes of UGS. Finally, only three studies compared the contributions of different UGS metrics to different health outcomes. Among them, one study presented a program protocol that applied both UGS quantity and quality and various short-term and long-term health outcomes to produce a robust evidence base (Nieuwenhuijsen et al., 2014). Two other studies, Jonker et al. (2014) and van Dillen et al. (2012), found different strengths of UGS-health associations for different UGS and health indicators. Both studies observed stronger UGS quality and health associations than the relationships with UGS quantity for certain metrics used to measure UGS and health, but no significant association was also found between quality of green areas and mental health status (van Dillen et al., 2012).

We thus suggest that the dependence of reported health outcomes on the metrics used remains a largely unexplored area, and focus our study to address this knowledge gap. In addition to enhancing our knowledge on the mechanisms leading to health improvement, we also believe that the improved knowledge on metrics of UGS has important practical significance to the planning and design of UGS for health. Our review above suggests that there is currently a lack of generalizable metrics that can be confidently used to design landscapes for health. For instance, is the amount of UGS, type of green spaces, UGS quality, or accessibility to people more effective in promoting health? This uncertainty makes it difficult to maximise health benefits from urban greening. To understand the relative roles of different UGS attributes in promoting different aspects of health, there is a need to first compare multiple attributes of UGS provision within combined studies.

In this context, the goal was to compare quantitative and qualitative aspects of UGS provision, measured by objective indictors and subjective perceptions, and assess their correlation with self-reported mental and general health. The underlying hypothesis was that different UGS provision indicators have different associations with different health outcomes. To evaluate our hypothesis, we analysed the associations between each UGS provision indicator and health outcomes and investigated the relative importance of each feature providing health benefits.

2. Methodology

2.1. Study area and household survey

Singapore is a city state located at 1.18 degrees north latitude and 103.51 degrees east longitude. The total land area is 724.2 km^2, and the population density is 7866 persons per square km (Department of Statistics, Singapore, 2019). Singapore has a rainy climate, with small annual and daily temperature differences. As a compact garden city, Singapore has strongly emphasized greening, but the impacts on health remain unclear. Whilst the aesthetic, economic, and ecological benefits of UGS in Singapore are well studied (Tan & Hamid, 2014), their potential health benefits have received little systematic assessment. In such a high-density city, UGS inevitably competes with other types of land uses. Therefore, greening for health benefits needs to be more deliberate, attaching importance to different aspects of UGS and not focusing on simply providing more green spaces.

A research project called "The Assessment of Dose-Response Relationships between Urban Green Spaces and Self-Reported Health" conducted a nationally representative household questionnaire survey between June and December in 2017 (approval number A-16-383E by Institutional Review Board of National University of Singapore) based on a sample size of 1000. On the basis of the conceptual framework described in a previous study (Zhang et al., 2017), the survey questionnaire was developed to collect data on self-reported health, perceived UGS provision, UGS exposure, moderators, and mediators (see Appendix 2 in Supplementary Materials). The sampling frame and the survey process were introduced in an earlier study (Zhang & Tan, 2019).

Singapore citizen or Permanent Resident aged 21 years old and above, and has stayed a minimum one-year in the selected household address was screened as eligible respondent. The sampling frame obtained from the national Department of Statistics ensured that the sample was representative of all households in Singapore. Standard methods used to identify replacement for households which did not respond to the survey ensured that all the pre-selected locations in the sampling frame had completed surveys.

2.2. Self-reported health

The study used two scales previously applied in the Singapore National Health Survey to assess two aspects of self-reported health: mental health and general health.

2.2.1. Mental health

Self-reported mental health was measured using the 12-item General Health Questionnaire (GHQ-12) assessing general feelings of psychological distress. The GHQ-12 has been widely used in the field of UGS-health relationships (Alcock et al., 2015; Astell-Burt et al., 2014; van den Berg et al., 2010; Tsurumi et al., 2018), and it is a valid and reliable measure of mental health for the Singaporean population (Lim et al., 2005; Satghare et al., 2016). The GHQ-12 focuses on the ability to carry out normal functions (e.g., feeling useful, able to concentrate) and the presence of distressing mental phenomena (e.g., lost sleep, feeling worthless) over the past six weeks. For each question, the response indicating a positive health outcome (e.g., better than usual, same as usual) is coded as 0 and a negative outcome (e.g., less than usual, much less than usual) is coded as 1. Scores across the 12 items were summed together and then a total score of 3 is used as the cut-off value to determine poor mental health (total score: 3–12) and good mental health (total score: 0–2) (Satghare et al., 2016). We coded good mental health as 1 and poor mental health as 0. Internal consistency analysis was further performed for these 12 items.

2.2.2. General health

The study used a single General Self-Rated Health (GSRH) question for respondents to rate their general health on the date of survey. The question from the GSRH provides five options to indicate both physical and psychological well-being: "very good", "good", "moderate", "bad", and "very bad". The GSRH question has been found to be a good predictor of mortality (DeSalvo et al., 2006). For our data analysis, we reversed the score; thus, higher values indicated better general health. Following Weimann et al. (2015), Reid et al.(2017), Maas et al. (2006), and Lim, Ma, Heng, Bhalla, and Chew (2007), we further dichotomized general health responses into "good general health" ("good", "very good") and "poor general health" ("moderate", "bad", "very bad").

2.3. UGS provision

2.3.1. UGS quantity

The study empirically measured the quantities of three different forms of UGS: vegetation cover, canopy cover, and park area. We obtained the island-wide map of vegetation cover and canopy cover from an earlier study (Hamid & Tan, 2017), which used supervised classification to generate these spatial data based on 2-meter-resolution WorldView-2 satellite images acquired in 2015. The polygon distribution of park area, including both parks and nature reserves, was obtained in 2017 from Singapore Land Authority (https://www.sla.gov.sg/geospatial-development-and-services/onemap). Vegetation cover refers to the land covered with any type of vegetation, including trees, shrubs, and grasses; canopy cover refers to the land covered by tree canopies; parks refer to green open spaces designed for a wide range of recreational activities and consisting of both vegetated areas and built structures. The assessment of UGS quantity was based on the proportion of green spaces within a given spatial scale. Given that, in Singapore, five minutes is the maximum travel time that frequent users are willing to spend to visit a neighborhood park (Ling, 2012), we generated circular buffers with a 400 m (equivalent to five-minute walking distance) radius around respondents' residences (geocoded point generated from residence's postcode) to determine the amount of nearby UGS. In the larger research project, more spatial scales were generated to delineate UGS quantity; details appeared in an earlier paper (Zhang & Tan, 2019).

In addition to measuring UGS quantity using Geographic Information System (GIS) analysis, we solicited residents' subjective evaluation of nearby UGS quantity in a questionnaire survey. Respondents were asked to rate their perception of the quantity of the green spaces located within a five-minute walking distance of their residence (equivalent to a 400 m circular buffer) using a five-point Likert scale ("very insufficient", "insufficient", "neutral", "sufficient", "very sufficient").

Although very few studies have linked the visual greenness of UGS with human health, some have measured visual greenness, and we adapted their methods for this study (e.g., Li et al., 2015; Yang et al., 2009; Yao et al., 2012). Based on the Green View Index (GVI) proposed by Yang et al. (2009), we measured the visual greenness as the ratio of greenery pixels to the total pixels of an image.

The data for visual greenness were derived from previous work using Google Street View (GSV) images downloaded on 28 April 2016 in Singapore (Richards & Edwards, 2017; Ye et al., 2019; Richards & Wang, 2020). GVIs were quantified at regularly-spaced visual points along the road network, with GSV images and detailed street networks of Singapore collected through Google API and Open Street Map (OSM), respectively. Subsequent image processing and extraction of visible street greenery within the images were performed in R 2.3 (R Core Team, 2015). To achieve a comprehensive representation of greenery across the Singapore streetscape, a GSV panoramic street image was analysed every 50 m. Overall, 98,863 sample sites were generated along the OSM street network, a cumulative street length of 4,791,966 m. To assign a GVI to each respondent, we extracted the visual points located within a certain distance. We applied ten different circular scales (radii: 50 m, 100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, 1000 m) to test the scale-dependence of visual greenness. We calculated both the sum and the average of the GVI values of the visual points to represent the overall visual greenness of green spaces at a certain scale surrounding each respondent.

2.3.2. UGS quality

To obtain an overall understanding of how UGS usage quality has been measured, we reviewed usage quality measures and indicators used in previous studies (see Appendix 3 in Supplementary Materials). Although objective indicators can give a detailed description of the characteristics of green space, the measuring process is time-consuming because of the need for field observation or desktop audits; in addition, observers require training. Furthermore, a single application of the audit tool can detect the quality of only one green space. It is used predominantly to assess large green spaces, such as parks larger than 1 ha (Gidlow, Ellis & Bostock, 2012). For example, some studies have chosen a certain number of large green spaces within each neighbourhood to measure quality and used the average value to represent the overall quality of green spaces in the neighbourhood (de Vries et al., 2013; van Dillen et al., 2012). The veracity of the result is equivocal because of the lack of detailed information about the unselected green spaces. Perceived attributes more effectively capture the overall quality of all the green spaces within a certain scale in a feasible way.

Following Jonker et al. (2014), we used one question in the household survey questionnaire to assess the perceived usage quality of nearby UGS (within a circular buffer around the residence with a radius of 400 m). Respondents were asked, "How would you rate the overall quality of nearby green spaces surrounding your residence?" They were asked to rate this on a five-item Likert scale ("very bad", "bad", "neutral", "good", "very good"). Respondents were told the quality of green spaces referred to the attributes of green space affecting user

Table 1
Factors of UGS usage quality included in the questionnaire.

Perspectives	Factors	Questions: If the green spaces…, I will use green spaces more
Manmade infrastructures	Size	are larger in size
	Facilities	have more facilities for physical activities
	Amenities (passive)	have more amenities for passive social interaction (e.g., sit down for chatting)
	Amenities (active)	have more amenities for active social interaction (e.g., community activities, gardening)
	Activities	have more human activities/more visitors
	Convenience	have more amenities for convenience (e.g., toilets and drinking water points, etc.)
Precondition for usage	Accessibility	have higher accessibility (e.g., shorter distance, shorter travel time from your residence)
	Safety	are safer
	Cleanliness	are cleaner
Environmental setting	Plant diversity	have more types of plants
	Animal diversity	have more types of animals
	Water	have more water features
	Greenery	have a higher amount of greenery
	Shade/breeze	are more comfortable (e.g., have enough shade, have breeze)
Supplementary elements	Contemplation	have more place for contemplation/relaxation
	Aesthetics	are more attractive/aesthetically pleasing
	Maintenance	are better maintained (facilities and landscape are in good condition, e.g., the presence of irrigation)

experience, including facilities, amenities, water features, maintenance, cleanliness, safety, etc.

To develop a better understanding of the components shaping perceptions of UGS usage quality, we asked respondents' opinions about the relative importance of each usage quality factor in encouraging UGS use. The factors chosen to assess usage quality have varied in previous studies. After analysing the questions asked by standardized audit tools, we identified four main perspectives (see Appendix 4 in Supplementary Materials). The first is existing manmade infrastructures for physical activities, recreation, and communication, such as sporting facilities, benches, picnic tables, and walking paths. The second is the environmental setting, such as plant and birdlife, shade, and water features (Humpel, Owen, & Leslie, 2002). The third points to the preconditions affecting whether people will visit this green space, including accessibility, safety, the presence of lighting, surrounding constructions, and cleanliness (Giles-Corti et al., 2005; Herzele & Wiedeman, 2003). The fourth category includes the supplementary elements for improving people's use experience, such as maintenance, signs, and overall appearance.

Based on the factors extracted from existing audit tools and local context in Singapore, we included 17 factors in the household survey questionnaire (Table 1). For each factor, respondents were asked to indicate the degree of their agreement or disagreement about its ability to encourage use of UGS ("disagree strongly", "disagree", "neutral", "agree", and "agree strongly", coded as 1, 2, 3, 4, and 5 respectively). Respondents were then asked to rank the top (up to) five indicators of UGS quality, specifically, the more important factors that would encourage them to use UGS (number "1–5" was used to indicate its relative importance, the larger the number, the lower the importance). To represent the most important quality factors, we ranked the top five usage quality factors based on six different assessment methods: the average value of respondents' agreement (average agreement), the percentage of respondents who indicated the importance as "1" (first order), "2" (second order), "3" (third order), "4" (fourth order), and "5" (fifth order). Based on the combination of these six measurements, the factors that featured identified as the most important factors.

To summarize, this study measured different aspects of UGS

Table 2
Summary of UGS provision variables.

Different aspects of UGS provision	Variables	Objective or subjective attribute
UGS quantity	Vegetation cover at different buffer widths	Objective
	Canopy cover at different buffer widths	
	Park area at different buffer widths	
	Visual greenness at different buffer widths	
	Perceived quantity of nearby UGS	Subjective
UGS quality	Perceived usage quality of nearby UGS	

provision, including six measures. The variables for each aspect of UGS provision, including whether the variable is an objective or subjective UGS attribute, are shown in Table 2.

Table 3
Demographic and socio-economic characteristics of respondents.

Factors	n (% of total sample)	Factors	n (% of total sample)
Gender		**Housing type**	
Men	442 (45.2%)	HDB 1–2 room flat	61 (6.2%)
Women	535 (54.8%)	HDB 3 room flat	187 (19.1%)
Age		HDB 4 room flat	325 (33.3%)
21–24	49 (5.0%)	HDB 5 room or executive flat	218 (22.3%)
25–34	123 (12.6%)	Private condominium/ apartment	123 (12.6%)
35–44	190 (19.4%)	Private housing (landed property)	63 (6.4%)
45–54	183 (18.7%)	**Employment status**	
55–64	194 (19.9%)	Full-time	376 (38.5%)
65–74	157 (16.1%)	Part-time	106 (10.8%)
75–84	72 (7.4%)	Self-employed	65 (6.7%)
85 & over	9 (0.9%)	Retired	168 (17.2%)
Ethnicity		Student/NSF	25 (2.6%)
Chinese	702 (71.9%)	Homemaker/Unemployed	237 (24.3%)
Malay	152 (15.6%)	**House ownership**	
Indian	91 (9.3%)	Owned	896 (91.7%)
Others	32 (3.3%)	Rental	81 (8.3%)
Marital status		**Highest Education level**	
Single	185 (18.9%)	Below Secondary	224 (22.9%)
Married	701 (71.8%)	Secondary	280 (28.7%)
Widowed	51 (5.2%)	Post-Secondary (Non-Tertiary)	87 (8.9%)
Divorced/ Separated	40 (4.1%)	Diploma & Professional Qualification	170 (17.4%)
		University & above	216 (22.1%)
Individual income		**Household income**	
No income	396 (40.5%)	No income	56 (5.7%)
1000 or less	99 (10.1%)	1000 or less	57 (5.8%)
1001–2000	104 (10.6%)	1001–2000	77 (7.9%)
2001–3000	91 (9.3%)	2001–3000	96 (9.8%)
3001–4000	75 (7.7%)	3001–4000	63 (6.4%)
4001–5000	53 (5.4%)	4001–5000	66 (6.8%)
5001–6000	42 (4.3%)	5001–6000	59 (6.0%)
6001–7000	17 (1.7%)	6001–7000	46 (4.7%)
7001–8000	15 (1.5%)	7001–8000	26 (2.7%)
8001–9000	11 (1.1%)	8001–9000	29 (3.0%)
9001–10000	3 (0.3%)	9001–10000	28 (2.9%)
10001–11000	6 (0.6%)	10001–11000	38 (3.9%)
11001–12000	3 (0.3%)	11001–12000	16 (1.6%)
Above 12,000	17 (1.7%)	Above 12,000	74 (7.6%)
Missing data	45 (4.6%)	Missing data	246 (25.2%)

HDB: Public housing in Singapore managed by the Housing and Development Board; NSF: National Servicemen Full-time; Missing data: Respondents reported don't know the income level or refused to answer the question.

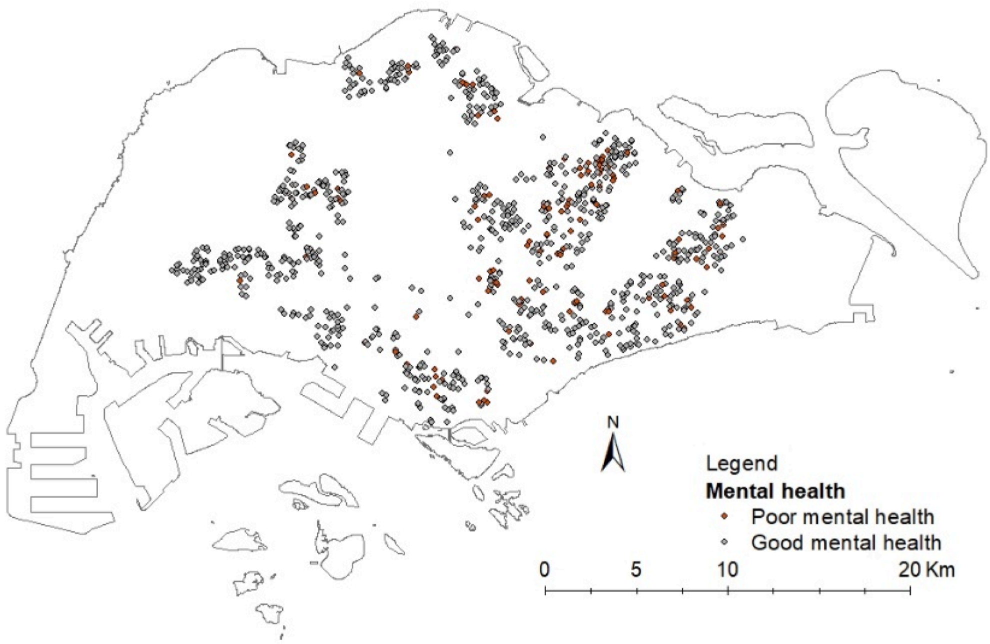

Fig. 1. Spatial distribution of mental health outcome.

2.4. Confounding factors

The survey questionnaire asked respondents for demographic and socio-economic details, including gender, age, ethnicity, marital status, education level, employment status, individual and household income. It included behavioral factors such as levels of cigarette smoking and alcohol drinking, and levels of physical activity, travel-related activity, and sedentary behavior. We also collected information on body mass index (BMI), level of health problems, level of community involvement, and nature relatedness. Detailed information can be found in Zhang and Tan (2019). The inclusion of these factors allowed us to screen for confounding factors in our statistical analyses.

2.5. Statistical analyses

A total of 977 respondents were included in the statistical analyses due to the lack of GIS data information regarding UGS quantity for 23 respondents. We began by using descriptive analysis to understand the characteristics of UGS provision. We then used bivariate correlation analysis, hypothetical test, and variable selection techniques (stepwise) to check whether a variable is a confounder. Confounders identified in previous local studies (Chong et al., 2012; Lim et al., 2007) were also considered. The screening results were then included in the statistical regression models for adjustment. Afterwards, we developed binary logistic regression models for each indicator and each health outcome,

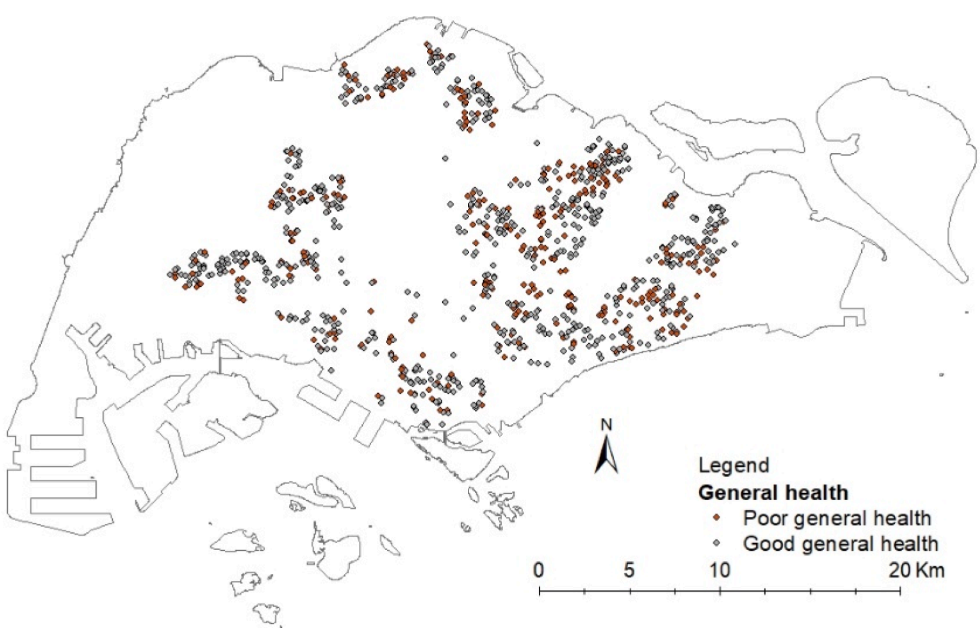

Fig. 2. Spatial distribution of general health outcome.

Table 4
Quantity of nearby UGS.

UGS quantity withina 400m buffer	Descriptive statistics (%) Range	Minimum	Maximum	Mean	SE	SD
Vegetation cover	70.11	4.53	74.64	28.02	0.32	10.14
Canopy cover	71.17	1.79	72.96	19.63	0.33	10.37
Park area	48.02	0.00	48.02	3.35	0.20	6.27

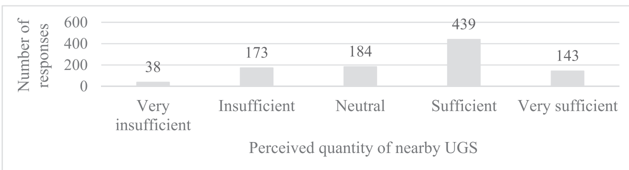

Fig. 3. Responses for perceived quantity of nearby UGS.

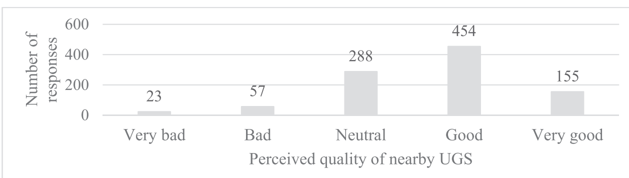

Fig. 4. Responses for perceived quality of nearby UGS.

controlling for confounding factors. For each model, odds ratios (ORs), p-value, standard errors and 95% confidence intervals (CIs) were calculated to show the associations of each UGS metric with health outcomes. Finally, we calculated standardized coefficients to compare the importance of each of the strongest UGS variables relative to socioeconomic covariates. We also calculated the standardized coefficients to compare the relative importance of each of the UGS provision variables. All the statistical analyses were performed in IBM SPSS Statistics 24 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Study population and results of health responses

The respondents' main characteristics and the spatial distributions of health outcomes are presented in Table 3, Fig. 1, and Fig. 2. For the total sample, 45.2% of the respondents were male and 54.8% were female. The percentage for Chinese, Malay, Indian, and other ethnicities were 71.9%, 15.6%, 9.3%, and 3.3% respectively. Of all participants, 12.2% reported poor mental health and 30.1% reported poor general health. For further information, see Appendix 5 in Supplementary Materials. The 12 items in the mental health measure showed a high degree of internal consistency (Cronbach's alpha = 0.87). The correlation between mental health and general health was weak (Spearman's coefficient = 0.247, $p < 0.01$), indicating that these two measures represented distinct aspects of health.

Table 5
Visual greenness at different scales.

	Buffer radius (m)	Range	Minimum	Maximum	Mean	SE	SD
Visual greenness calculated by the sum of GVI values of the visual points	Buffer radius (m)	Range	Minimum	Maximum	Mean	SE	SD
	50	7.10	0.00	7.10	0.99	0.04	1.10
	100	19.66	0.00	19.66	4.82	0.10	3.24
	200	58.35	0.00	58.35	20.31	0.30	9.38
	300	104.30	1.51	105.81	45.67	0.56	17.65
	400	163.89	6.10	169.99	80.52	0.88	27.50
	500	247.67	15.61	263.28	124.86	1.26	39.34
	600	308.08	28.23	336.31	177.92	1.69	52.88
	700	386.74	42.85	429.59	239.75	2.18	67.98
	800	478.15	66.49	544.64	309.98	2.67	83.49
	1000	753.89	97.58	851.47	473.42	3.92	122.46
Visual greenness calculated by the average of GVI values of the visual points	Buffer radius (m)	Range	Minimum	Maximum	Mean	SE	SD
	50	1.49	0.00	1.49	0.37	0.01	0.34
	100	1.70	0.00	1.70	0.56	0.01	0.22
	200	0.93	0.00	0.93	0.59	0.00	0.10
	300	0.63	0.22	0.84	0.59	0.00	0.08
	400	0.52	0.31	0.83	0.59	0.00	0.07
	500	0.47	0.32	0.78	0.59	0.00	0.06
	600	0.42	0.32	0.74	0.59	0.00	0.06
	700	0.43	0.36	0.79	0.59	0.00	0.05
	800	0.35	0.43	0.78	0.59	0.00	0.05
	1000	0.31	0.45	0.76	0.59	0.00	0.05

Table 6
Bivariate correlations between different UGS provision indicators within a 400 m buffer.

Variables within a 400 m circular buffer	Vegetation cover	Canopy cover	Park area	Perceived quantity	Perceived usage quality	Visual greenness (sum)	Visual greenness (average)
Vegetation cover	1.000						
Canopy cover	0.618**	1.000					
Park area	0.163**	0.247**	1.000				
Perceived quantity	0.089**	0.042	0.094**	1.000			
Perceived usage quality	0.023	−0.012	0.058	0.496**	1.000		
Visual greenness (sum)	0.102**	0.083**	0.065*	−0.055	−0.016	1.000	
Visual greenness (average)	0.318**	0.346**	0.143**	0.077*	0.044	0.214**	1.000

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

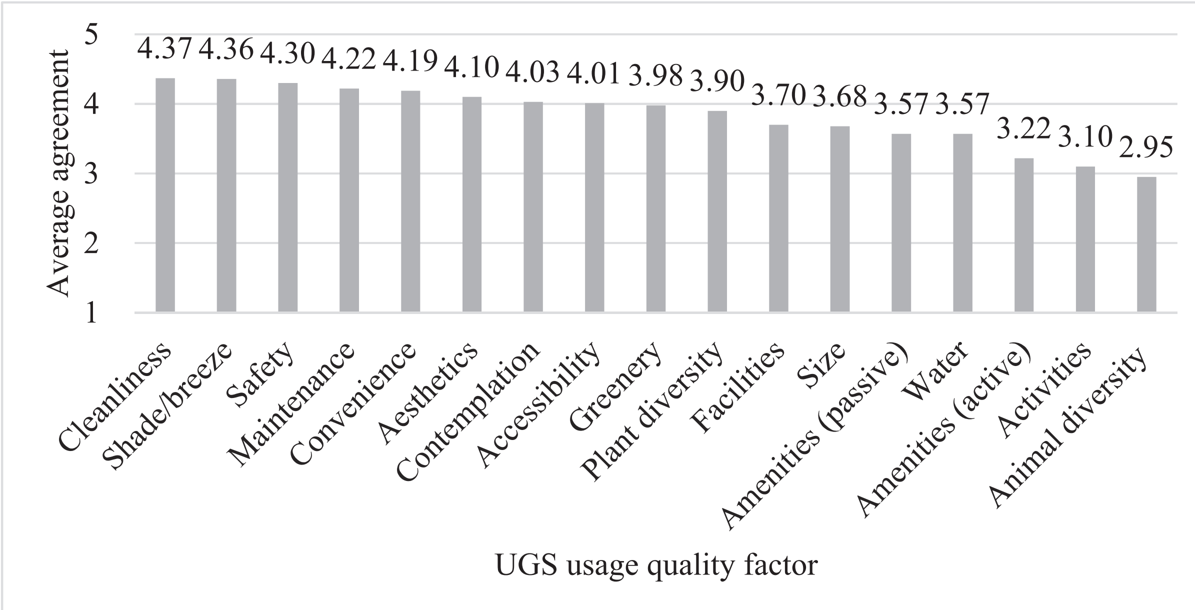

Fig. 5. Average agreement on the ability of UGS usage quality factors to encourage UGS use.

Table 7
Summary of important UGS usage quality factors.

Assessment items	Top 5 UGS usage quality factors
Average agreement	Cleanliness, shade/breeze, safety, maintenance, and convenience
First order	Accessibility, shade/breeze, cleanliness, facilities, convenience
Second order	Cleanliness, shade/breeze, convenience, safety, maintenance
Third order	Cleanliness, shade/breeze, maintenance, safety, convenience
Fourth order	Shade/breeze, maintenance, safety, convenience, cleanliness
Fifth order	Convenience, shade/breeze, cleanliness, maintenance
Combination	Accessibility, shade/breeze, cleanliness, facilities, convenience, safety, maintenance

3.2. Results of UGS provision

The descriptive characteristics of the various attributes of UGS provision are presented in Table 4, Fig. 3, Fig. 4, and Table 5 (More details are provided in Appendix 6 in Supplementary Materials). On average, there were more vegetation cover than canopy cover and park area within the 400 m scale. Among all the respondents, 44.9% of them reported sufficient quantity of nearby greenery and 14.6% reported very sufficient quantity. For perceived UGS quality, 46.5% of respondents reported good quality and 15.9% reported very good quality. Overall, there were more respondents making positive responses for UGS usage quality than quantity. For visual greenness at each scale, there were large differences among the residences for the indicator calculated by the sum of GVI values while small variances for that calculated by the average of GVI values.

We used bivariate correlation analysis to examine the correlations between the UGS provision indicators within a 400 m radius buffer zone encircling each respondent's residence (Table 6). The very low coefficient values suggest none of the objective UGS indicators were related to perceived UGS attributes. We found weak correlations between visual greenness and the other three objective indicators of UGS quantity, and moderate correlations between the two perceived UGS attributes. To explore the factors that might influence perception, we examined the correlations between perceived attributes and demographic variables, including age, gender, ethnicity, highest educational level, employment status, marital status, individual and household income levels, nature relatedness, and length of residence. Of these, only age had a positive albeit weak association with perceived quantity (Spearman's coefficient $= 0.258$, $p < 0.01$) and perceived quality (Spearman's coefficient $=$ 0.240, $p < 0.01$).

We calculated the average value of respondents' agreement on the

Table 8
Associations of UGS provision indicators within a 400 m circular buffer with mental and general health.

UGS provision indicators within a 400 m circular buffer	Variables	Adjusted models for mental health[1]				Adjusted models for general health[2]			
		Odds Ratio	p value	95% C.I. for Odds Ratio		Odds Ratio	p value	95% C.I. for Odds Ratio	
				Lower	Upper			Lower	Upper
Quantity	Vegetation cover	1.017	0.107	0.997	1.039	0.997	0.719	0.983	1.012
	Canopy cover	1.035**	0.004	1.012	1.060	1.004	0.569	0.990	1.019
	Park area	1.041	0.072	1.000	1.093	1.024	0.073	0.999	1.052
	Perceived quantity	1.037	0.709	0.855	1.254	0.958	0.542	0.832	1.100
	Visual greenness(sum)	1.005	0.220	0.997	1.013	1.002	0.467	0.997	1.008
	Visual greenness (average)	4.054	0.372	0.187	87.813	1.820	0.592	0.204	16.341
Quality	Perceived usage quality	1.366**	0.006	1.094	1.706	1.074	0.396	0.910	1.266

1. Adjusted for health problems, community involvement, house ownership, BMI, gender, indoor physical activity, adjusted household income, smoking, residential status, number of children, age, ethnicity.
2. Adjusted for health problems, number of children, community involvement, BMI, ethnicity, smoking, indoor physical activities, age, travel time, gender.
*. $p \leq 0.05$, **. $p \leq 0.01$, ***. $p \leq 0.001$

Table 9
Associations of visual greenness at different circular scales with mental and general health.

Visual greenness(sum) atdifferent scales (radius size: m)	Adjusted models for mental health[1]				Adjusted models for general health[2]			
	Odds Ratio	p value	95% C.I. for Odds Ratio		Odds Ratio	p value	95% C.I. for Odds Ratio	
			Lower	Upper			Lower	Upper
50	1.095	0.369	0.904	1.343	1.064	0.380	0.928	1.224
100	1.075*	0.041	1.004	1.153	1.014	0.571	0.968	1.062
200	1.021	0.070	0.999	1.046	1.002	0.795	0.987	1.018
300	1.010	0.124	0.998	1.022	1.004	0.381	0.995	1.012
400	1.005	0.220	0.997	1.013	1.002	0.467	0.997	1.008
500	1.002	0.449	0.997	1.007	1.002	0.292	0.998	1.006
600	1.000	0.863	0.996	1.004	1.001	0.517	0.998	1.004
700	1.000	0.956	0.997	1.003	1.000	0.859	0.998	1.002
800	1.000	0.958	0.997	1.002	1.000	0.946	0.998	1.002
1000	1.000	0.902	0.998	1.002	1.000	0.593	0.998	1.001
Visual greenness(average) at different scales (radius size: m)	Adjusted models for mental health[1]				Adjusted models for general health[2]			
	Odds Ratio	p value	95% C.I. for Odds Ratio		Odds Ratio	p value	95% C.I. for Odds Ratio	
			Lower	Upper			Lower	Upper
50	1.590	0.154	0.841	3.006	1.241	0.340	0.797	1.933
100	0.973	0.958	0.353	2.685	0.849	0.646	0.421	1.709
200	2.835	0.310	0.380	21.171	1.213	0.793	0.287	5.126
300	7.004	0.150	0.496	98.984	1.675	0.590	0.256	10.948
400	4.054	0.372	0.187	87.813	1.820	0.592	0.204	16.341
500	1.301	0.878	0.045	37.303	1.169	0.899	0.105	13.029
600	1.254	0.903	0.033	46.963	1.420	0.791	0.106	19.070
700	1.187	0.931	0.025	56.587	0.990	0.994	0.060	16.309
800	1.150	0.946	0.019	68.194	1.037	0.981	0.053	20.433
1000	0.586	0.813	0.007	49.056	0.620	0.774	0.024	16.158

1. Adjusted for health problems, community involvement, house ownership, BMI, gender, indoor physical activity, adjusted household income, smoking, residential status, number of children, age, ethnicity.
2. Adjusted for health problems, number of children, community involvement, BMI, ethnicity, smoking, indoor physical activities, age, travel time, gender.
*. $p \leq 0.05$

ability of UGS usage quality factors to encourage UGS use (Fig. 5). Cleanliness, shade/breeze, safety, maintenance, and convenience were the most widely acknowledged factors. However, a smaller number of respondents agreed with the capacity of both passive and active amenities, water features, activities, and animal diversity, to encourage UGS use.

The top five usage quality factors are summarized in Table 7. As the table shows, several factors overlapped; accessibility, shade/breeze, cleanliness, facilities, convenience, safety, and maintenance were the most important factors in respondents' perception of UGS usage quality.

3.3. *Associations between UGS provision indicators and health indicators*

We examined the relationships between each indicator of UGS provision within a 400 m buffer zone surrounding respondents' residences and the two health indictors (mental and general health) using binary logistic regression (see Table 8). For UGS quantity, only canopy cover was significantly associated with mental health at a confidence level of 95% (OR = 1.035, 95% CI: 1.012–1.060, $p < 0.01$). If the canopy cover were increased one percent, the odds of having good mental health would increase 3.5%. When we calculated the standardized coefficient for each variable in the model (see Appendix 7 in Supplementary

Table 10
Associations of canopy cover, visual greenness, and usage quality with mental health.

Variables	B	SE	df	Odds Ratio	95% C.I. for Odds Ratio		Standardized coefficient
					Lower	Upper	
Canopy cover_400 m	0.033**	0.012	1	1.034	1.010	1.058	0.347
Visual greenness_100 m (sum)	0.069	0.036	1	1.072	0.999	1.150	0.224
Perceived usage quality	0.319**	0.115	1	1.375	1.099	1.722	0.284
Health problem	−0.732***	0.123	1	0.481	0.378	0.612	−0.587
Community involvement	0.276**	0.105	1	1.318	1.072	1.621	0.284
House ownership (owned)	0.669*	0.336	1	1.953	1.011	3.771	0.185
BMI	0.046	0.025	1	1.047	0.997	1.100	0.211
Gender (male)	0.881***	0.261	1	2.413	1.446	4.028	0.439
Indoor physical activities	0.015*	0.007	1	1.015	1.002	1.028	0.287
Adjusted household income	0.102**	0.035	1	1.108	1.034	1.186	0.378
Smoking	−0.231*	0.090	1	0.794	0.665	0.948	−0.295
Residential status (citizen)	0.607	0.364	1	1.834	0.898	3.746	0.181
Number of children	0.150	0.097	1	1.162	0.961	1.404	0.192
Age	0.042	0.086	1	1.043	0.881	1.235	0.070
Ethnicity			3				
Ethnicity (Indian)	−0.106	0.402	1	0.900	0.409	1.979	−0.031
Ethnicity (Malay)	0.503	0.386	1	1.653	0.775	3.526	0.182
Ethnicity (Others)	−0.825	0.497	1	0.438	0.166	1.160	−0.147
Constant	−3.624***	1.005	1	0.027			2.405

Dependent variable: mental health (0 = poor mental health, 1 = good mental health); Reference category for house ownership: rental; Reference category for gender: female; Reference category for residential status: Permanent resident, Reference category for ethnicity: Chinese.
***. $p \leq 0.001$, **. $p \leq 0.01$, *. $p \leq 0.05$.

Materials), we found having more canopy cover within a 400 m buffer zone showed stronger associations with mental health compared to community involvement, smoking habit, indoor physical activities, BMI, number of children, house ownership, residential status, ethnicity, and age, but weaker relationships compared to household income, gender (being male), and health problems. However, we found no significant associations between UGS quantity and general health. Neither of the visual greenness indicators within a 400 m circular buffer zone was related to either health measure.

Turning to the perceived UGS indicators, we found a positive relationship between perceived usage quality and mental health. The odds ratio of perceived usage quality was 1.366 (95% CI: 1.094–1.706, $p < 0.01$). If the perceived usage quality were increased one level, the odds of having good mental health would increase 36.6%. When we compared the standardized coefficients for each variable in the model (see Appendix 7 in Supplementary Materials), we discovered perceived usage quality showed stronger relationships with mental health compared to smoking habit, BMI, number of children, house ownership, residential status, ethnicity, and age, but weaker relationships compared to indoor physical activities, community involvement, household income, gender (being male), and health problems. Perceived quantity and perceived usage quality were unrelated to general health.

We built binary logistic models for both visual greenness indicators at each circular buffer zone and each of the health outcomes separately. Results showed that none of these indicators had a significant relationship with general health, and only the visual greenness calculated by the sum of GVI at the scale of 100 m was significantly associated with mental health (OR = 1.075, 95% CI: 1.004–1.153, $p < 0.05$) (see Table 9). If visual greenness within a 100 m buffer were increased one level, the odds of having good mental health would increase 7.5%. When we calculated the standardized coefficient for each variable in the model (see Appendix 7 in Supplementary Materials), we found visual greenness had a stronger correlation with mental health than BMI, house ownership, number of children, residential status, ethnicity, and age, but a weaker correlation than smoking habit, indoor physical activities, community involvement, household income, gender (being male), and health problems. Interestingly, as shown in Appendix 8 in Supplementary Materials, none of the three UGS quantity indicators within a 100 m circular buffer was significantly correlated with mental or general health.

3.4. Comparison of UGS provision indicators

Based on the above results, we added the quantity of canopy cover within a 400 m circular buffer, the visual greenness (sum) of UGS within a 100 m circular buffer, and perceived usage quality of UGS at a 400 m circular buffer into the regression model, simultaneously adjusting the corresponding confounding factors. We then calculated the standardized coefficients. As shown in Table 10, canopy cover and perceived usage quality remained significantly related to mental health, but visual greenness calculated by the sum of GVI did not. Canopy cover of nearby UGS (standardized coefficient: 0.347) showed a higher correlation with mental health than perceived usage quality (standardized coefficient: 0.284) or visual greenness (standardized coefficient: 0.224).

4. Discussion

4.1. Relationship among indicators of UGS provision

The objective indicators of UGS quantity (vegetation cover, canopy cover, parks) and visual greenness showed no or very weak relationships with respondents' perceptions of UGS provision (perceived quantity and perceived usage quality), indicating that the subjective perception of UGS are different from those assessed by objective indicators. This implies that objective and subjective indicators capture different aspects of UGS provision. We thus suggest both measurements should be included to collectively characterize UGS provision. The lack of agreement between objective and subjective attributes has also been reported in previous studies (Kothencz & Blaschke, 2017; Gebel, Bauman & Owen, 2009; Leslie et al., 2010; Parra et al., 2010; Wen, Hawkley & Cacioppo, 2006). For example, a study in Australia observed little agreement between NDVI (normalized difference vegetation index) and perceived measures of greenness (Leslie et al., 2010).

Findings of moderate and positive correlations between the two perceived UGS provision indicators (perceived UGS quantity and usage quality at 400 m scale) suggest the study's respondents tended to evaluate different aspects of UGS provision in the same direction. In this study, except for age, none of the demographic or socio-economic factors was an influencing factor for these perceived UGS provision indicators. Our older respondents tended to be more satisfied with their surrounding UGS. Arguably, people are less demanding and more prone to accept the status quo as they age (Cao, Heng & Fung, 2019).

Our finding of a weak correlation between visual greenness and objective UGS quantity indicators is not surprising: visual greenness is a three-dimensional measure while UGS quantity is a traditional two-dimensional measure based on a top-down view. Our finding confirmed that people's daily visual experience of UGS does not mirror the quantity of UGS measured by overhead view maps (Yang et al., 2009; Larkin & Hystad, 2019; Lu et al., 2019).

4.2. Comparison of quantitative and qualitative aspects of UGS provision

Of the two perceived UGS attributes, only usage quality was related to mental health. Perceived usage quality had stronger associations with mental health than vegetation cover, park quantity, and visual greenness at 400 m scale. However, at this scale, canopy cover showed the strongest association with mental health. Overall, we were not able to draw a conclusion on the relative role of quantitative and qualitative aspects of UGS in promoting health. In previous studies, relationships between UGS and mental health were generally stronger for qualitative aspects than for quantitative aspects (Feng & Astell-Burt, 2018; Francis et al., 2012; Fuller et al., 2007; de Vries et al., 2013) whereas UGS quantity was also found to be more important than quality (Larson, Jennings & Cloutier, 2016).

The findings from our study are consistent with some of the previous studies investigating the associations between UGS and mental health measured by GHQ-12. A study in Spain observed positive associations between surrounding greenness at 300 m scale and mental health (Triguero-Mas et al., 2015). Another study in Spain found higher vegetation cover was associated with better mental health for scales of 50, 100, 250 and 500 m (Su et al., 2019). However, a study in Bulgaria did not detect significant associations of vegetation cover and canopy cover at 500 m scale with GHQ-12 in youth, although indirect effects on mental health were found (Dzhambov et al., 2018).

In univariate models with one single UGS indicator controlling for confounders, only visual greenness calculated by the sum of GVI at a 100 m scale was significantly associated with mental health, with a confidence level of 0.05. We found no relationships between mental health and the visual greenness (sum) of distant UGS or the visual greenness measured by the average of GVI. However, the number of GSV data points might be different in the buffers around different respondents, so the visual greenness calculated by the sum of GVI may be influenced by the layout of street networks. Respondents living in an area with longer total street length within a 100 m buffer may have better mental health, even though the average GVI is low. The total visual greenness of each data point allocated for every 50 m on the streets within a 100 m buffer played a more critical role in promoting mental health than the average of visibility within the complete 100 m buffer, suggesting that a more targeted planting strategy is feasible. Therefore, it may not be necessary to allocate trees evenly to every street, and resources can be concentrated on greening certain targeted streets using the same tree planting budget. Another finding was that visual greenness at closer proximity was more important than visual greenness further away. This may be because individuals' most frequent visual contact with greenery is within the immediate vicinity of their residence. Interestingly, at the adjacent spatial scale (a 100 m buffer zone surrounding residence), we found visual greenness measured by the sum of GVI played a more important role in promoting mental health than UGS quantity. A previous study found visual greenness was an important factor affecting people's impression of greenery; a threshold value of 30% of visual greenness triggered a rich impression (Aoki, 1991). Another study discovered a range of 24–34% of tree cover density measured by images led to the greatest stress reduction in males (Jiang et al., 2014). A careful spatial arrangement of vegetation and vertical structure of greenery would increase the greenness residents see in their daily lives and promote their mental health.

Unexpectedly, for UGS located within a 400 m buffer, none of the UGS provision indicators showed significant associations with general health. This corresponds to a study in New York which showed that tree cover was unrelated to general health at a small scale (300 m) (Reid et al., 2017). Reid et al (2017), however, observed significant benefits at a more distant scale (1000 m). Previous studies (Dadvand et al., 2016; Tsai et al., 2020) suggest that general health benefits are related to the mechanisms of physical activities and social support, which are closely linked to the positive usage of UGS. A larger amount of UGS or UGS with higher quality does not necessarily lead to higher level of UGS usage. Our survey also collected data on UGS exposure; we found UGS exposure within a 400 m buffer (total time spent in UGS within a 400 m buffer) was unrelated to any of the UGS provision indicators except for a weak relationship with perceived usage quality (Spearman's coefficient = 0.217, $p < 0.01$). Such gaps between UGS provision and UGS exposure may prevent the observation of significant UGS-general health relationships. It is also possible that the general health value of green spaces was dwarfed by other important risk factors, such as dietary habits (Richardson et al., 2013). However, our findings are inconsistent with some of the previous studies. For instance, a study in California found that 10% increase in tree canopy cover at 250 m-radius scale led to 2.9% of improvement of general health (Ulmer et al., 2016). A U.S. national cohort study also found contradicting results showing that canopy cover was associated with general health at both proximate (250 m) and distant (1250 m) scales (Tsai et al., 2020). These mixed findings might be ascribed to the large diversity of data resources used in different studies and varied climate zones of study areas (Tsai et al., 2020).

4.3. Comparison of objective and subjective attributes of UGS provision

This study demonstrated that canopy cover plays a more important role in promoting mental health than perceived quantity, while perceived usage quality is more important to mental health than objective quantity and visual greenness. Consequently, we cannot conclude whether the perceived attributes or objective indicators are better predictors of health. Other studies have also had contradictory findings. A study in Perth (Francis et al., 2012) showed that the objective tangible attributes of green space quality, such as water features, birdlife, and walking paths, had stronger relationships with mental health than the perceived quality. Conversely, a study in Bogotá (Parra et al., 2010) discovered that the perception of green space quality was more related to health than objective indicators. These mixed findings indicate the need to measure both objective and subjective attributes of UGS provision. This will allow us to assess the relative contributions of objective attributes and subjective perceptions. Each measure has distinctive advantages. The objective indicators are useful for planners and policy-makers to develop concrete design guidelines, whilst the perception-based indicators are more proximal predictors of people's behaviours (e.g., use of UGS) and self-reported health, as perception is related to cognitive processes (Leslie et al., 2010).

A qualitative study involving sit-down and walk-along interviews plus field surveys on greenery could investigate the mismatch between objective and perceived UGS attributes. For example, we need to understand why our respondents misperceived the real situation of UGS provision. Examining the characteristics of those who overrated the UGS quantity, as well as those who underestimated it, would shed light on the individual factors shaping perception.

4.4. Limitations

This research measured UGS provision based on a series of spatial ranges around respondents' residences. It is possible that some respondents spent most of their time in work places farther away from their residences. Furthermore, the window views and corridor views in different residences might vary in different locations and on different floors. Studies have reported that providing UGS in the work environment and having greenery visible from a window also yield health benefits (Gilchrist et al., 2015; Grinde & Patil, 2009; Kaplan, 2001). Therefore, our findings might be inaccurate due to these confounders. Additionally, although this research measured the visual greenness of UGS, people's contact with nature is not limited to visual exposure but includes other sensory experiences (van den Berg et al., 2017). We did not address how other senses, such as smell and hearing, influence health. Moreover, GSV images capture only the greenery on streets and exclude the visual contact with other off-street greenery.

Many qualitative aspects of visual greenness, such as the composition of trees, shrubs, and grasses, openness, and the fascination value, were overlooked in this measurement. It would be more accurate to include specific qualitative assessments in the measurement of visual greenness. For example, the visual aesthetic of green spaces and visual landscape preferences can be incorporated into the measurement of visual greenness (Dramstad et al., 2006; Du et al., 2016; Yao et al., 2012). Visual greenness can be also evaluated based on the presence and intensity of such features as coherence, disturbance, imageability, complexity, and naturalness (Tveit, Ode & Fry, 2006).

This study only investigated the circular buffers and mainly focused on the 400 m-radius buffers. Network buffers and more buffer distances can be further explored as a supplement for the existing evidence. Our earlier study has tested a series of circular, network, and nested buffers and revealed the dependence of UGS-mental health relationships on different buffers (Zhang & Tan, 2019). Moreover, the self-reported indicators, including both UGS provision and health outcomes, measured in this study may evoke self-reporting response bias (Rosenman, Tennekoon & Hill, 2011).

Another limitation is on the study design. The cross-sectional approach applied in this research cannot completely rule out the possibility that some respondents with stronger motivation to maintain healthy lifestyle may have chosen to live in greener neighbourhoods, leading to self-selection bias that have been reported in other studies (Gascon et al., 2018). However, given that the sampling was a randomized sample representing the overall population, self-selection bias would be included as part of the random error and addressed in the statistical tests. In addition, as indicated in a study conducted in Hong Kong, residents living in public housing has relatively little freedom to select housing locations, and hence the self-selectionbias can be reduced significantly for public housing respondents (Zang et al., 2019). Although the administration of public housing system is not identical to Hong Kong, 80% of Singaporeans living in public housing for which allocation of a property is done through computerized balloting (https://www.hdb.gov.sg/about-us/news-and-publications/publications/hdbspeaks/balloting-process-for-buildtoorder-bto-flats). Thus, residents do not have a complete choice on exact location of unit. In addition, 81% of total samples were public housing residents in this study. Self-selection could thus be partially mitigated through these factors. Future studies can examine this issue further and also consider application of mediation analysis to provide stronger support for the causal link between UGS provision and health outcomes. Moreover, longitudinal studies can be conducted to corroborate the findings.

4.5. Implications

The main findings from this study provide important insights for formulating recommendations on urban greening for the sake of better health outcomes. In general, planting more trees better promotes mental health than simply increasing the amount of vegetation cover. At the adjacent scale, the visual greenness of a 100 m circular buffer surrounding a residence should be the target. Planting more trees with dense leaves near residential buildings and on adjacent roads is one way to create an environment with more visible greenery. A vertical greenery system can be introduced into residential buildings as well. Singapore has paid little attention to the visual characteristics of UGS. We suggest local governments should develop guidelines to increase the amount of visible greenery and thus tap into the restorative quality of greenery. Corridor greening in residential buildings is one possible strategy, as residents travel the corridors on a daily basis.

Increasing the vegetation cover to reach a certain level should no longer be the only objective of health promotion. Instead, we should shift from purely quantitative to embrace qualitative aspects of UGS as well. Thus, in Singapore, a city-state with scarce land resources, urban greening efforts should be shifted from the quantitative to the qualitative aspects of UGS. There are multiple ways to increase quality; our discovery of the relative importance of several UGS usage quality factors gives some hints in this direction.

5. Conclusion

This study is unique in its use of different measures to compare the roles of quantitative and qualitative aspects of UGS provision in the promotion of general health and mental health. It revealed general patterns of how different UGS indicators are associated with health. Not all indicators showed significant associations with health outcomes, and different indicators showed different strengths of the UGS-health relationship. Interestingly, we found that at a 400 m buffer, canopy cover and perceived usage quality were important UGS indicators for improved mental health; however, at a 100 m circular buffer, visual greenness measured by the sum of GVI should be the targeted UGS attribute. Unexpectedly, general health was uncorrelated with any of the UGS indicators measured in this study. The findings indicate how the choice of metrics can influence the strength of the relationships found between UGS and health. At the same time, they suggest the significance of UGS in promoting mental health.

Based on the findings, we have formulated three main urban greening recommendations to promote residents' satisfaction with UGS: plant more street trees at an adjacent scale, especially within a 400 m circular buffer zone around residential areas; advocate vertical greening and corridor greening in residential buildings; design green spaces as accessible, safe, clean, and well-maintained environments with enough shade, breeze, and adequate facilities for physical activities as well as enough amenities for convenience.

Future research could integrate both objective and perception-based indicators into the assessment of UGS quantity and quality to develop generalizations about the role of each attribute of UGS provision in promoting health. We recommend that the specific aspects of UGS provision measured should depend on the hypotheses and mechanisms being tested. More nuanced UGS provision indicators need to be developed by combing quantitative and qualitative understanding and by leveraging advanced techniques and technologies.

CRediT authorship contribution statement

Liqing Zhang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Data curation, Visualization, Project administration, Funding acquisition. **Puay Yok Tan:** Conceptualization, Methodology, Resources, Investigation, Supervision, Writing, Project administration, Funding acquisition. **Daniel Richards:** Software, Validation, Formal analysis, Data curation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104131.

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