2021

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Urban Forestry & Urban Greening 64 (2021) 127267

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Tree species composition, growing space and management in Hong Kong's commercial sky gardens

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ARTICLE INFO

Handling Editor: Cynnamon Dobbs

Keywords:
Green roof
Sky garden
Tree composition
Tree planting space
Urban tree management
Urban tree health

ABSTRACT

Sky gardens, a type of above-ground urban green space, have been increasingly welcomed and installed in cities. However, few studies have assessed tree planting, management and health in high-rise greenery. This study investigated tree species composition, planting space design and management, and their relationships with tree health in sky gardens in 15 commercial sky gardens with 480 trees in Hong Kong. We assessed the differences between old and new sites regarding tree species, height, crown diameter, and health. We also evaluated selected planting and management factors, including planter type, distance to neighbor trees, root-growth obstacles, canopy barriers, canopy overlap and topping history. Tree species selection in commercial sky gardens was substantially different from public and private residential green spaces. Older sky gardens had more palm trees by species and tree counts. Newer gardens had increased adoption of broadleaf and conifer species with high ornamental value and compact form but fewer native tree species and lower species diversity. The widely planted *Ficus spp*. had created long-term management issues. Trees were often densely planted, particularly in newer sky gardens. The common practice of topping indicates poor species selection and mismanagement. Planter types with insufficient growing space had dampened tree health. Our findings reveal the trend of tree species adoption, narrower planting spaces and wider adoption of the sunken planter. Improvements in species selection, growing space design and management practices could promote healthy, stable and safe trees in sky gardens with contributions to biodiversity and other ecosystem services.

1. Introduction

Elevated landscapes have received increasing attention in cities. They offer an alternative solution to inadequate plantable space at ground level in dense cities (Fernandez-Cañero et al., 2013). The green roof, referring to a vegetated space at either the elevated level or rooftop of a building, is now a trend in many developed countries (Vijayaraghavan, 2016). The green roof system can be broadly divided into two types, intensive and extensive. The simple extensive green roof has grasses or herbs with some small shrubs supported by a thin substrate layer. The intensive green roof, or sky garden, has higher plant height, density, biomass and diversity, including trees and shrubs. It has a more elaborate landscape design with a deeper substrate and higher water holding capacity (Shafique et al., 2018). Sky gardens require more labor, irrigation and maintenance, and a higher load-bearing capacity of the building structure (Bianchini and Hewage, 2012). A sky garden can perform multiple ecosystem services, including air pollution control (Yang et al., 2008), thermal comfort provision (Lee and Jim, 2019), and passive recreation and amenity space (Williams et al., 2010).

Studies on plant communities in extensive green roofs are widely available (e.g. Köhler, 2006; Thuring and Dunnett, 2014; Tran et al., 2019), but few are available for sky gardens. Some sky-garden studies have focused on the diversity of insects (MacIvor and Lundholm, 2011) and performance of benefits such as air pollutant abatement (Yang et al., 2008), temperature reduction (Darkwa et al., 2013; Lee and Jim, 2019) and rainwater retention (Speak et al., 2013). Trees are often excluded in studies of intensive green roofs (Madre et al., 2014). Tree health should be accorded a high priority because of potential danger to people and property if they are improperly chosen, established and maintained. To minimize risk, it is important to maintain tree health and structural condition.

Compared to trees at ground level, trees in sky gardens are subject to extreme conditions like higher wind loading pressure (Hui, 2011) and strong direct sunlight exposure (Architectural Services Department,

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https://doi.org/10.1016/j.ufug.2021.127267
Received 2 December 2020; Received in revised form 17 July 2021; Accepted 26 July 2021
Available online 29 July 2021

2007). These natural factors highlight the importance of proper species selection, practical design of the planting environment, and suitable management practices to ensure that the trees can withstand harsh environments and remain stable and safe. Healthy trees with robust structures can provide amenity value to the sky gardens and reduce long-term management costs. They require less pruning and maintenance in the long run and maximize the green-space benefits (Nowak et al., 2004). Such well-planned green space can enhance the urban-forest stock and urban biodiversity (Wang et al., 2017). Understanding this specific green-space type can improve the species selection strategy to promote biodiversity (Alvey, 2006).

The lack of understanding of tree installation and management practices of sky gardens and their effects on tree health may weaken the contributions of this rapidly expanding green-space type. Like many cities worldwide, sky gardens are becoming more common in densely developed urban Hong Kong for both private residential and commercial buildings.

Using Hong Kong's commercial sky gardens with trees as a case study, we investigated their tree community and design and management issues which have received scarce research attention. In particular, some local greening-industry practitioners have complained about densely-planted trees in sky gardens, resulting in poor tree performance and difficulties in management. We therefore investigated the planting density and management practices via-a-vis the growing space. Our study focused on the planting and management practices that are more specifically an issue to the sky gardens compared with the ground level urban green space. Some other planting conditions like root flare visibility, staking condition, soil quality and mulching may also impact the tree health. However, they are beyond the scope of our study.

We also explored the temporal differences in sky garden characteristics before and after the release of a key professional guideline on trees by the Hong Kong Government in 2007, the "Tree Preservation and Tree Removal Application for Building Development in Private Projects" (Lands Department of Hong Kong SAR Government, 2007; hereinafter the "Tree Practice Note"). This document requires compensation for removed trees in private lots by planting trees at a 1:1 ratio by aggregated DBH and tree count. This stringent and rigid stipulation also demands planting in situ, thus forcing private developers to plant too many trees in the cramped space.

Our study of commercial sky gardens in Hong Kong aimed at four objectives:

(1) To evaluate species composition, growing space, design and management of landscape trees;
(2) To compare the differences in tree species composition and growing space design and management between old and new sites;
(3) To investigate the impact of growing space design and management on tree health;
(4) To provide recommendations to improve growing space design and management of sky gardens.

2. Study areas and methods

2.1. Study areas

Hong Kong is located to the south of China's Guangdong Province, on the east side of the Pearl River estuary. The built-up areas are concentrated in the 25 % of the territory's total land area of 1,111 km^2 (Planning Department, 2019). It has a mean annual temperature of 23.6 °C and a mean annual rainfall of 2,398 mm. Around 80 % of the rain falls between May and September, typical of the humid subtropical monsoon climate. Tropical typhoons frequently strike between May and November (Hong Kong Observatory, 2019), bringing tree damage and toppling.

Our target sites were the public accessible sky gardens on commercial buildings. We studied an almost equal number of old and new sky gardens to assess the temporal difference on species composition and planting space. Table 1 presents the basic information of 15 surveyed sky gardens. Sites completed in or before 2007 are labeled as old sites and those after new sites. This division marks the release of the Tree Practice Note in 2007 (Lands Department, 2007).

Following the local government standard (Development Bureau, 2020), plants with at least 95 mm trunk diameter at breast height (DBH) at 1.3 m above the ground level were considered as trees in our study. We classified them into palm trees (to include palm-like *Ravenala madagascariensis* of the Strelitziaceae) and woody trees (all non-palm tree species). Hereinafter, the term "tree" refers to both palm trees and woody trees. For plants with multiple stems, the aggregate DBH was calculated by the square root of the sum of all the squared stem DBH (Treeplotter, 2020). We collected the field data in April 2019 before the typhoon season in Hong Kong to minimize wind effects on the tree survey data.

We assessed the performance of individual trees, including topping history and health status. Basic information of the individual trees, including species name, tree height and crown diameters in both east-west and north-south directions, was recorded. Planting site conditions covered growing space type, distance to neighbor trees, crown and root-growth obstacles, and degree of canopy overlap. We divided the growing space into three types, namely tree pit, raised planter and sunken planter.

A tree pit refers to a growing space with an underground soil volume for root growth and without hard edges installed above the ground level. A planter is wrapped around by raised hard edges. A raised planter has hard edges taller than 40 cm, and a sunken planter has edges shorter than 40 cm which includes the at-grade one (see planter cross-sections and images in Fig. 1).

The distance to neighbor trees was measured as the stem to stem distance at 1.3 m height of a sampled tree to its nearest tree. Crown barrier referred to artificial obstacles within 2 m of the crown edge. Root-growth obstacle referred to obstacles to root growth situated within the crown projection area. Canopy overlap was defined as no overlap, partial overlap ($\leq$1/3 of canopy area overlap with the canopy of neighbor tree), or large overlap (>1/3 of canopy area overlap with the canopy of neighbor tree). The lopping of large (high-order) branches indicated topping. Tree health was rated as excellent, good, average and poor according to crown and foliage conditions. For example, sparse foliage, abnormally small leaves, and yellowing leaves were indicators of deteriorated health. We used a four-point scale to judge tree health: (a) *excellent* for no defects, (b) *good* for minor defects such as slight dieback, (c) *average* for major defects such as moderate dieback or with less than 50 % foliage compared to a normal tree, and (d) *poor* for unlikely recovery of tree health such as extensive wilting or dieback.

2.2. Data and statistical analysis

We employed IBM SPSS 26 to conduct statistical tests (SPSS Inc., Chicago, IL) and R version 4.0.1 (http://www.r-project.org). We computed the key species diversity indexes for the sites:

(a) Shannon index, H' = −Σpi ln(pi), where pi = number of individuals of a species divided by the number of total individuals, and
(b) Pielou's evenness index, J' = H'/ln(S), where S = total number of species.

We applied statistical tests to evaluate or compare sites or trees:

(a) Chi-squared test or Fisher's exact test to compare the differences between tree types and site history.
(b) Mann-Whitney *U* test to compare the size parameter of trees by tree growth form type and site history.

Table 1
Basic site information and site code of the 15 sky gardens selected in this study. O = Old sites and N = New sites, referring to building project completed in or before 2007 and after 2007, respectively.

Location (Level of floor)	Site area (m^2)	Altitude (m a.s.l.)		Elevation of sky garden (m) *	Tree count	Tree density (no./100 m^2)	Year of completion	Site Code
		Ground level of building	Sky garden					
ELEMENTS (3/F)	35,158	7	26	19	29	0.1	2007	O1
HSBC Centre (above UG/F)	2,919	6	13	7	22	0.8	1999	O2
ifc mall (5/F)	8,961	3	27	24	37	0.4	2003	O3
New Town Plaza (7/F)	3,073	6	38	32	87	2.8	1985	O4
Taikoo Place (above lobby floor)	442	5	20	15	6	1.4	2003	O5
Tin Shui Shopping Centre (2/F)	7,536	5	13	8	30	0.4	1992	O6
Tuen Mun Town Plaza (4/F)	3,230	5	28	23	32	1.0	1988	O7
Domain Mall (4/F)	8,254	17	37	20	14	0.2	2012	N1
Exchange Tower (3/F)	968	6	11	5	11	1.1	2008	N2
Kerry Hotel Hong Kong (2/F)	4,594	2	6	4	92	2.0	2017	N3
Lee Tung Avenue (5/F)	1,219	10	28	18	48	3.9	2015	N4
Maritime Square Two (4/F)	6,105	10	33	23	61	1.0	2017	N5
The Forest (3/F)	226	7	16	9	6	2.7	2017	N6
The Hennessy (2/F)	391	6	18	12	2	0.5	2008	N7
The One (16/F)	2,044	7	118	111	3	0.1	2010	N8

*Note**: Elevation of sky garden is measured from the ground level of its building.

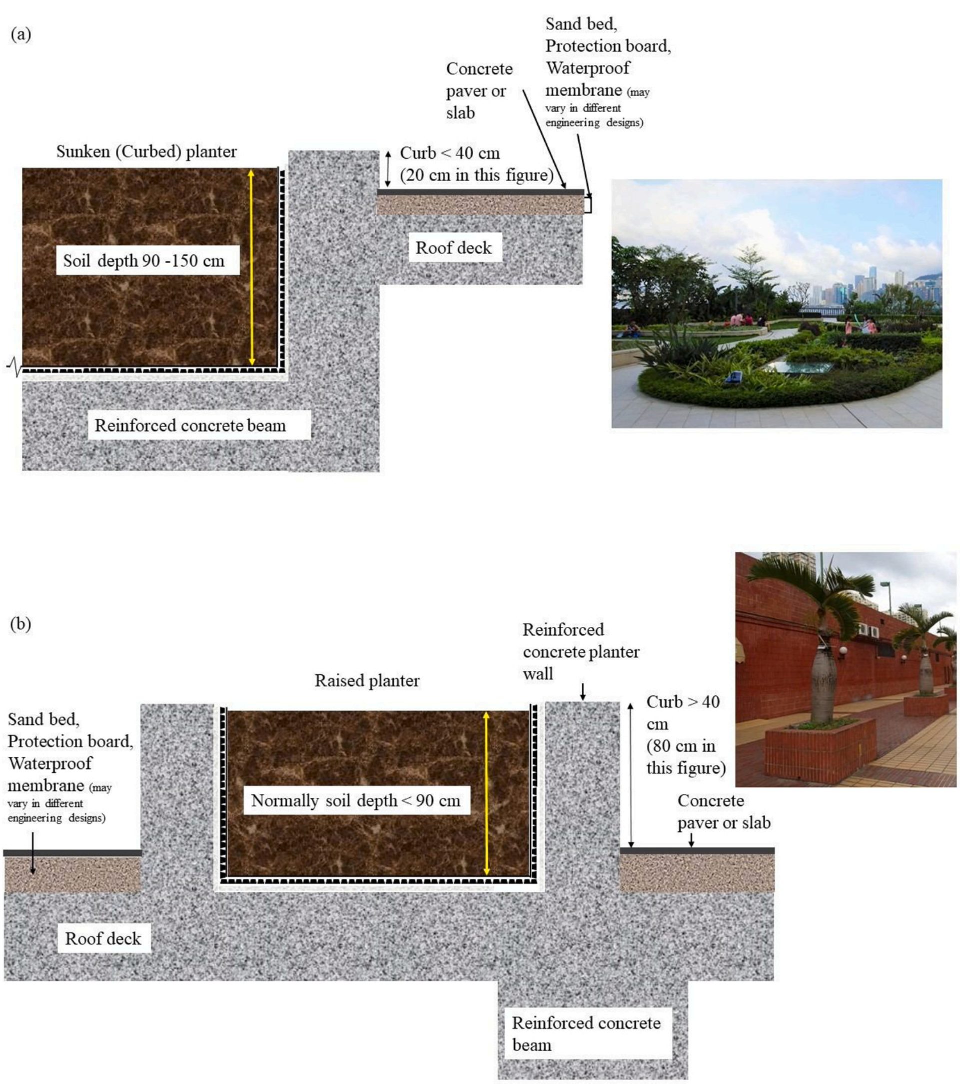


Fig. 1. Cross section of (a) sunken and (b) raised planter (Inset photos show their appearance).

(c) Wilcoxon Rank-sum test to evaluate the impacts of different factors on tree health indicated by tree rating. As only three trees were rated as poor health, they were grouped under the average category in our analysis.
(d) Multiple correspondence analysis (MCA) to explore the relationships between different growing-space designs and management factors and tree health. MCA is a multivariate analysis technique for categorical data, an analog of the principal component analysis for continuous data (Abdi and Valentin, 2007).

3. Results

3.1. Tree community in sky gardens

We counted 480 trees representing 38 species in the 15 studied sites. We found nearly two-thirds of the species (24) in one particularly diverse site. Floristic composition varied greatly even for sites within the same age group. Some 14.4 % of trees were native to Hong Kong in all sites. Old sites had significantly more native trees (18.9 %) than new sites (9.7 %) (Chi-squared test: $p = 0.004$).

Table 2 shows the ten most abundant species in the sky gardens compared to the ten most abundant species in Public Housing Estates (PHE) (Zhang and Jim, 2014a) and Domestic Gardens (DG) (Zhang and Jim, 2014b) in Hong Kong. Tree species in old sky gardens had more species in common with PHE and DG than the new ones. The abundant species in common included three palms and one woody species, *Ficus benjamina*, which was also the only high-abundance species in both old and new sites. Four of the ten most abundant species in old sites were palm species, and only one palm-like species, *Ravenala madagascariensis,* was abundant in new sites. *R. madagascariensis* and *Phoenixdactylifera* were the only palm species commonly found in new sites. In contrast, in old sites, 8 out of the 10 abundant species were palms. In terms of distribution, *Ficus benjamin*a was found in one-third of the sites (i.e. 5), followed by *Livistona chinensis*, *Elaeocarpus hainanensis* and *Plumeria rubra* 'Acutifolia', which were observed in four sites. *E. hainanensis* was found in new sites only, and the palm *L. chinensis* in old sites only.

Table 3 shows the tree community diversity and structure of the 15 sites. Three new sites had only one species, possibly due to the small number of trees. Species diversity (H') for most sites was 1–2, with three of them (O3, O5 and N1) below 1. As a whole, H' reaches 3 across all sites. Species evenness (J') of different sites were generally above 0.79, except O6 (0.65) and N3 (0.48). H' and J' across all old sites were higher than new sites. For growth form, around 40 % were palms and 60 % were woody trees. New sites had a smaller proportion of palms (Chi-squared test: $p = 0.039$).

Table 2
Growth form (GF), origin (O), abundance (A), relative abundance (RA), frequency (F) of the 10 abundant species at all sites, old sites and new sites. The remarks indicate species that matched the top 10 species in Public Housing Estates (PHE) (Zhang and Jim, 2014a), and Domestic Gardens (DG) (Zhang and Jim, 2014b) in Hong Kong. P = Palm tree; W = Woody tree; E = Exotic species; N = Native species.

Species	GF	O	A	RA(%)	F	Remarks
All sites						
Ravenala madagascariensis	P	E	77	16.0	3	
Livistona chinensis	P	E	49	10.2	4	PHE
Tabebuia rosea	W	E	37	7.7	1	
Elaeocarpus hainanensis	W	E	34	7.1	4	
Ficus benjamina	W	E	30	6.3	5	PHE
Ficus religiosa	W	E	19	4.0	1	
Ficus altissima	W	N	18	3.8	1	
Archontophoenix alexandrae	P	E	17	3.5	2	DG
Cinnamomum camphora	W	N	16	3.3	2	
Hibiscus tiliaceus	W	N	15	3.1	2	
Plumeria rubra 'Acutifolia'	W	E	15	3.1	4	
		Total	327	68.1		
Old sites						
Livistona chinensis	P	E	49	20.2	4	PHE
Tabebuia rosea	W	E	37	15.2	1	
Ficus religiosa	W	E	19	7.8	1	
Ficus altissima	W	N	18	7.4	1	
Archontophoenix alexandrae	P	E	17	7.0	2	DG
Cinnamomum camphora	W	N	11	4.5	1	
Phoenix dactylifera	P	E	10	4.1	1	
Dypsis lutescens	P	E	9	3.7	1	PHE, DG
Ficus benjamina 'Variegata'	W	E	9	3.7	1	
Ficus benjamina	W	E	6	2.5	2	PHE
Hibiscus tiliaceus	W	N	6	2.5	1	
		Total	191	78.6		
New sites						
Ravenala madagascariensis	P	E	72	30.4	2	
Elaeocarpus hainanensis	W	E	34	14.3	4	
Ficus benjamina	W	E	24	10.1	3	PHE
Callistemon viminalis	W	E	13	5.5	1	
Lagerstroemia speciosa	W	E	12	5.1	1	
Senna surattensis	W	E	11	4.6	1	
Plumeria rubra 'Acutifolia'	W	E	10	4.2	3	
Hibiscus tiliaceus	W	N	9	3.8	1	
Cinnamomum burmannii	W	N	7	3.0	2	
Schefflera actinophylla	W	E	7	3.0	1	
		Total	199	84.0		

3.2. Growing space design and tree management in sky gardens

In the studied sites, the tree count per site ranged from 2 to 92, and the tree density 0.1–3.9 per 100 m^2. Table 4 lists the tree growing-space design and management in old and new sites, respectively. Significant differences existed between old and new sites at the overall level (treating sites of the same age category as a single plot), though not at the mean values, for all types of growing spaces. Tree pits existed only in old sites, and sunken planters were more common in new than old sites. For palms, old sites had a larger distance to a neighbor than new sites. Woody trees at old sites had a relatively high proportion planted <1 m to another; a lower proportion of trees was situated at <3 m to neighbors. Trees with large canopy overlap were more common in new sites for both palms and woody trees.

Root-growth obstacles and crown barriers were more common in

Table 3
Number of species, species diversity (H'), species evenness (J') and percentage of palm species and woody tree species in the 15 studied sites.

Site	Species no.	Diversity index		Growth form	
		H'	J'	Palm (%)	Woody tree (%)
Old sites					
O1	4	1.33	0.96	48.3	51.7
O2	3	1.00	0.91	77.3	22.7
O3	2	0.69	1.00	0.0	100.0
O4	6	1.51	0.84	27.6	72.4
O5	3	0.87	0.79	0.0	100.0
O6	6	1.17	0.65	73.3	26.6
O7	7	1.79	0.92	75.0	25.0
Mean	**4.4**	**1.19**	**0.87**	**43.1**	**56.9**
Overall	**23**	**2.70**	**0.86**	**41.6**	**58.4**
New sites					
N1	3	0.88	0.80	57.1	42.9
N2	6	1.60	0.89	0.0	100
N3	7	1.05	0.48	69.6	30.4
N4	9	1.81	0.93	8.3	91.7
N5	7	1.54	0.79	0.0	100.0
N6	1	0.00	–	0.0	100.0
N7	1	0.00	–	0.0	100.0
N8	1	0.00	–	100.0	0
Mean	**4.4**	**0.86**	**0.78**	**22.5**	**77.5**
Overall	**25**	**2.42**	**0.79**	**33.3**	**66.7**
All sites	**38**	**3.03**	**0.88**	**37.5**	**62.5**

Table 4
Growing space design and management of palms and woody trees at old and new sites. Significant values (p) between old and new sites by Fisher's exact test at overall level are listed.

	Palm				Woody tree			
	Old	New	Old	New	Old	New	Old	New
Planter type	Mean		Overall		Mean		Overall	
Sunken planter	45.8 ± 50.9	53.6 ± 49.8	45.5	89.5	48.7 ± 43.8	70.8 ± 37.2	26.8	73.3
Raised Planter	39.9 ± 44.4	46.4 ± 49.8	44.6	10.5	43.7 ± 43.0	29.2 ± 37.2	59.2	26.7
Tree pit	14.3 ± 31.9	0	9.9	0	7.6 ± 19.3	0	14.1	0
			$p = 0.000$				$p = 0.000$	
Distance to neighbor trees	Mean		Overall		Mean		Overall	
d≤1	33.8 ± 35.4	32.8 ± 56.8	36.6	82.9	24.2 ± 36.3	21.5 ± 25.4	35.9	21.7
1<d≤3	34.0 ± 37.4	33.3 ± 57.7	34.7	10.5	36.0 ± 28.9	22.8 ± 23.2	16.9	41.6
3<d≤5	18.6 ± 41.5	33.3 ± 57.7	12.9	5.3	30.1 ± 35.5	26.2 ± 37.9	35.9	25.5
d>5	13.6 ± 14.2	0.5 ± 0.9	15.8	1.3	9.7 ± 9.9	29.5 ± 40.1	11.3	11.2
			$p = 0.000$				$p = 0.000$	
Barrier	Mean		Overall		Mean		Overall	
No	81.7 ± 9.8	45.3 ± 50.7	81.2	35.5	43.2 ± 24.9	43.4 ± 41.0	57	47.2
Crown	14.1 ± 8.8	33.9 ± 57.3	13.9	11.8	37.3 ± 22.5	12.5 ± 21.9	33.8	11.8
Root	2.5 ± 5.6	2.6 ± 4.5	3.0	6.6	0	7.7 ± 14.3	0	13.7
Root and crown	1.7 ± 3.7	18.2 ± 31.6	2.0	46.1	20.4	36.4 ± 45.3	29.0	27.3
			$p = 0.000$				$p = 0.000$	
Canopy overlap	Mean		Overall		Mean		Overall	
Large	24.1 ± 39.5	36.5 ± 52.7	24.8	82.9	7.5 ± 14.9	8.4 ± 13.6	4.9	9.9
Partial	32.9 ± 32.4	63.5 ± 52.7	36.6	17.1	54.5 ± 28.3	31.6 ± 0.2	64.8	47.2
No	43.0 ± 33.8	0	38.6	0	38.0 ± 34.3	59.9 ± 36.7	30.3	42.9
			$p = 0.000$				$p = 0.000$	
Topping	Mean		Overall		Mean		Overall	
Presence	0	0	0	0	44.6 ± 40.8	30.9 ± 32.9	42.3	15.5
							$p = 0.000$	

new sites than old ones, particularly for palms. In new sites, crown barriers were less common, but root-growth obstacles were more common. Topping was not applied to palms. Woody trees were more commonly topped in old sites than new ones.

The old and new sites differed significantly in tree height, crown spread, and C/H ratio (Table 5). Shorter palms with smaller crown widths had been planted in new sites. In contrast, woody trees in new sites had relatively narrower crowns than old sites. No significant difference in height was found between palms and woody trees in old sites (Mann-Whitney U test: $p = 0.105$), and in C/H ratio between palms and woody trees in new sites (Mann-Whitney U test: $p = 0.472$). The remaining size parameters showed significant differences between palms and woody trees (Mann-Whitney U test: all at $p = 0.00$). In both old and new sites, tree height on average was below 5 m for both palms and woody trees, and crown width was below 4 m for woody trees and below 2.2 m for palms.

Table 5
Height (H) and crown (C) dimensions of palms and woody trees at old and new sites. Significant value (p) between old and new sites by Mann-Whitney U test at overall level are listed.

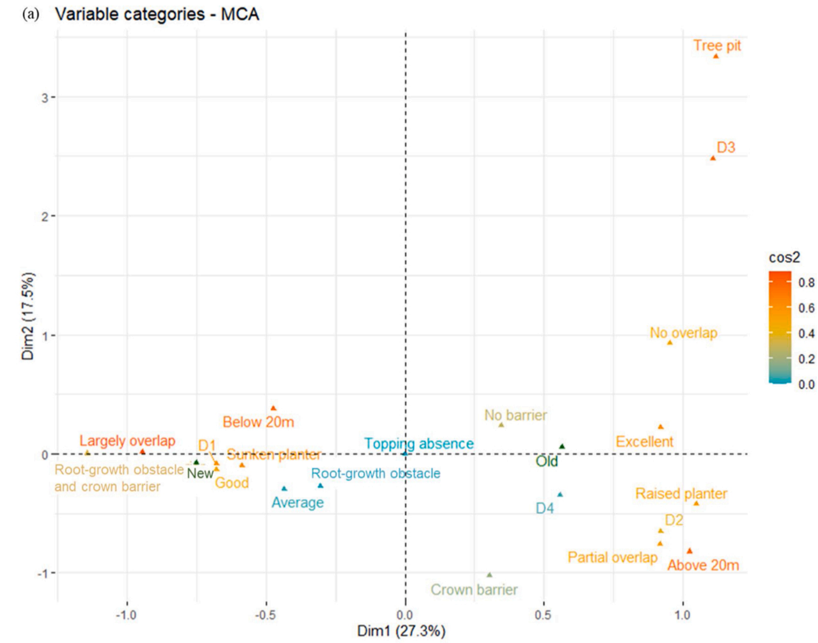
	Palm		Woody tree	
	Old	New	Old	New
Height (m)	4.77 ± 2.85 $p = 0.000$	2.57 ± 1.26	4.91 ± 1.63 $p = 0.000$	4.06 ± 1.20
Crown (m)	2.20 ± 0.92 $p = 0.000$	1.68 ± 1.09	3.92 ± 2.14 $p = 0.000$	2.55 ± 1.05
C/H	0.56 ± 0.24 $p = 0.019$	0.64 ± 0.17	0.77 ± 0.26 $p = 0.000$	0.63 ± 0.23

3.3. Relationship between planting and management conditions and tree health

Table 6 displays the health of palms and woody trees under different growing spaces and management. The two MCA plots (Figs. 2 and 3) visualized the correlations of different factors with tree health. For palms (Fig. 2), the first axis accounted for 27.3 % of the variance and the second axis 17.5 %. For woody trees (Fig. 3), the first axis accounted for

Table 6
Average health ratings (Excellent tree health = 3, Good tree health = 2, Average or poor tree health = 1) of palms and woody trees with different planting and management conditions. Different letters denote significant differences by Wilcoxon rank sum test.

	Average health rating	
	Palm	Woody tree
Planter type		
Sunken planter	2.1b	2.2a
Raised planter	2.7a	2.0b
Tree pit	3.0a	1.5c
Distance to neighbor trees		
d≤1	2.1b	2.0
1<d≤3	2.7a	2.1
3<d≤5	3.0a	2.1
d>5	2.1b	2.1
Barrier		
No	2.5a	2.2
Crown	2.2ab	2.0
Root	2.0b	1.8
Root and Crown	2.0b	1.9
Canopy overlap		
Large	1.9b	1.7c
Partial	2.8a	2.0b
No	2.7a	2.2a
Topping		
No	–	2.1
Yes	–	2.0
Elevation		
Below 20m	2.2b	2.0
Above 20m	2.6a	2.1



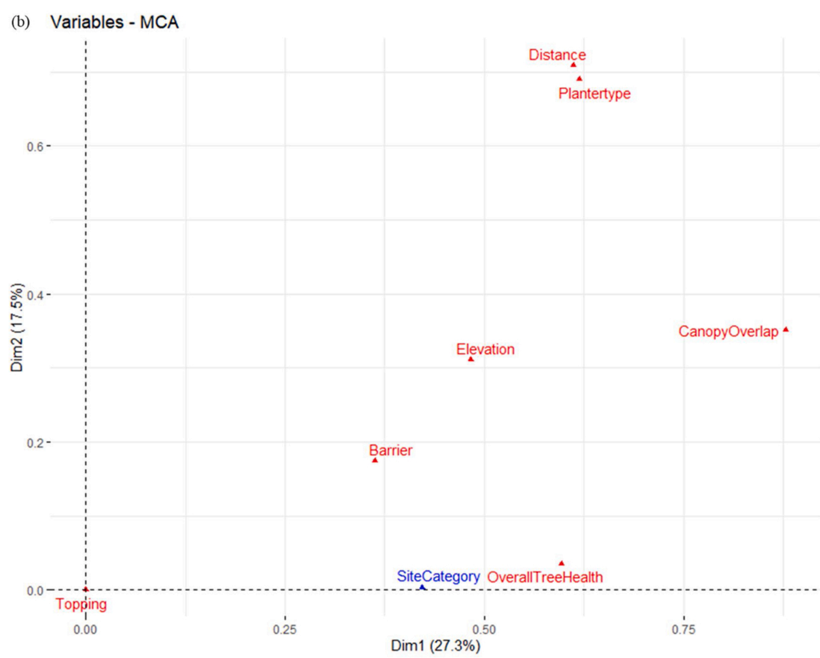


Fig. 2. (a) MCA biplot of variable categories on the first two dimensions, and (b) correlation between variables and first two dimensions of palms. cos2: representation of the variable on the principal component. A higher cos2 indicates a higher degree of representation of the variable on the principal component. Site category (old and new) is set as supplementary quantitative variable and has no influence on the dimensions.

16.8 % of the variance and the second 12.1 %. Correlations varied between tree growth forms.

The two growth forms showed the opposite health performance concerning growing space. Palms in raised planters and tree pits were generally healthier. Woody trees in sunken planters had better health. Palms and woody trees with a large distance to neighbor trees (D4: > 5 m) were associated with excellent health. Meanwhile, trees with a small distance to neighbor trees (D1: ≤ 1 m) were unlikely to have excellent health. The absence of root-growth obstacles was linked with better tree health for palms. No significant relationship between the absence of root-growth obstacles and woody tree health was found. However, it appeared from the MCA plot that the presence of barriers, particularly root-growth obstacles, was related to a lower tree health rating.

Considerable canopy overlap was correlated to average health for both palms and woody trees, whereas no canopy overlap was a factor associated with excellent health. The health of topped woody trees and non-topped ones was not significantly different. The significant relationship between site elevation and tree health could only be observed for palms. Palms growing in sites with an elevation above 20 m were healthier than their counterparts.

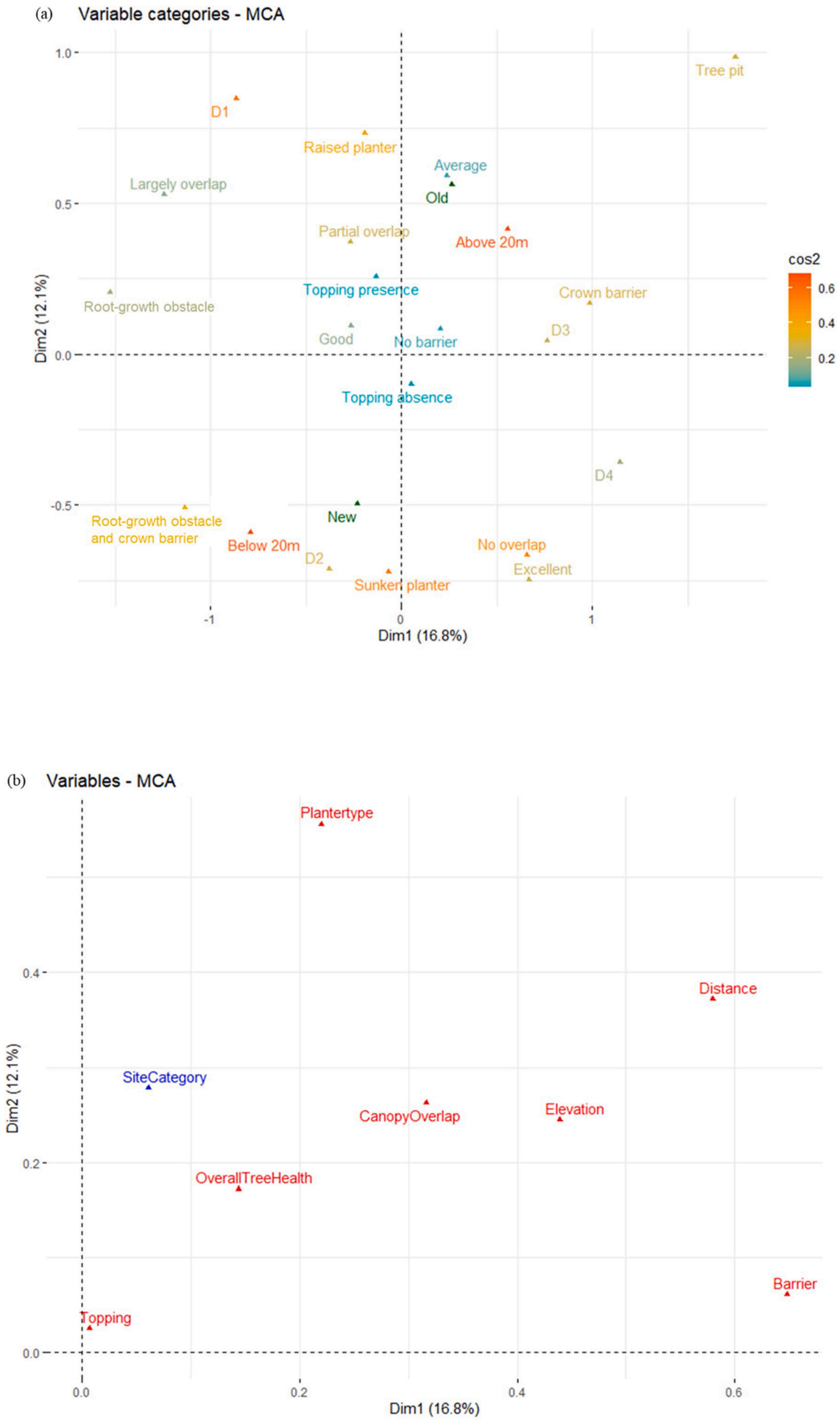


Fig. 3. (a) MCA biplot of variable categories on the first two dimensions and (b) correlation between variables and first two dimensions of woody trees. cos2: representation of the variable on the principal component. A higher cos2 indicates a higher degree of representation of the variable on the principal component. Site category (old and new) is set as supplementary quantitative variable and has no influence on the dimensions.

4. Discussion

4.1. Species adoption in sky gardens

Sky gardens on commercial buildings were low in diversity if we considered alpha diversity (within a sky garden) but quite high in beta diversity (between sky gardens). This result matched a previous study showing that commercial land had high species diversity across different locations (Bourne and Conway, 2014). The differential tree preference of multiple private developers or landscape architects, operating as disparate units, accounted for the aggregate floristic diversity (Zeunert, 2017). In contrast, tree species selection in public sites is subject to a prescribed species list to bring inter-site floristic convergence. The shift in species preference through time in the private sector contributed to the cumulative increase in species diversity. Our findings have verified this phenomenon in Hong Kong's sky gardens.

Compared to typical ground-level urban green spaces, a unique feature of sky gardens is that all trees were planted rather than inherited from the pre-urbanization natural vegetation. Some trees may exist before site formation and development in PHE and domestic gardens.

The commercial sky gardens were designed under different and independent development regimes, thus explaining the differentiation in the abundant species cohort compared with PHE (Zhang and Jim, 2014a) and domestic gardens (Zhang and Jim, 2014b). The rooftop sites also offer a different initial state in terms of constraints and opportunities for tree planting.

Another inherent factor is related to the unique safety concern for tree planting on building podiums and roofs. With trees usually located at more than 10 m above the ground level, tree failure at this height may generate projectiles to fall to the street level, creating severe hazards. Thus, the choice of trees suitable to sky gardens is constrained to species with smaller final dimensions and a lower probability of trunk or branch snapping in strong wind. Planting at the edge of sky gardens is particularly prone to this hazard.

Similar to private domestic gardens in Hong Kong, privately-owned commercial sky gardens have adopted few native species. Lacking native species was also common in urban landscapes, including commercial (Bourne and Conway, 2014), private residential gardens (van Heezik et al., 2012) or urban centers (Morgenroth et al., 2016) in other cities. Despite recent promotion by the local authority in green spaces to increase urban biodiversity (Environment Bureau, 2016), it is perhaps perplexing that even fewer native species were planted in new sky gardens. The departure from public landscaping policies indicates that the private sector operates in a different landscape fashion regime.

While the native species are not always a better choice than the exotic ones (Sjöman et al., 2016), planting native trees in urban green spaces has been widely regarded as a sound and beneficial decision from an ecological viewpoint (Berthon et al., 2021). The tree species list currently provided by the local tree management office for roof planting included merely three natives out of a surprisingly short list of 18 suggested species (Development Bureau, 2016). It indicates a need for more horticultural research to identify more suitable native and exotic species for sky gardens to diversify the species composition, particularly native ones underused and neglected in the past. Government proactive actions, preferably in conjunction with the landscape industry, to compile a comprehensive list of recommended native and exotic species could better foster their supply in the market (Conway and Vander Vecht, 2015).

Comparing with old sites, the new ones showed a clear shift of species preference. The reduced use of palms indicates a desirable trend due to their lower environmental and ecological value than woody trees (Nagendra and Gopal, 2011). Recently, woody tree species with small final size and neat-tidy form are getting more popular, such as broadleaf *Elaeocarpus hainanensis* and conifer *Podocarpus macrophyllus*. In addition, more flowering ornamental species have been planted in recent years. Although two flowering trees, *Tabebuia rosea* and *Hibiscus tiliaceus,* are found in old sites, their small DBH indicated recent additions or replacemets. This adoption trend reflects the increasing demand for species with high aesthetic value in sky gardens.

Promoting biodiversity in sky gardens is particularly important in cities with a densely-packed and high-rise development mode like Hong Kong. Private gardens could be managed to enhance collective urban biodiversity (Goddard et al., 2010). However, the influence of the local tree management authority on privately-owned green space is limited (Kirkpatrick et al., 2012). The specific environment of sky gardens may limit the use of some species, but using a broader species palette could realize the sites' full potentials contribute to the total biodiversity of the city.

Another notable finding is the frequent use of *Ficus spp*., particularly the exotic *F. benjamina*. *Ficus spp.* are commonly planted in other green spaces like parks and roadsides. Some members of the genus have a long cultivation history in Hong Kong due to their tolerance to harsh environmental conditions, high ecological value, magnificent tree form and provision of excellent shading (Zhang and Jim, 2014a). However, planting them in sky gardens can pose a risk generated by the extensive root system, fast-growing rate and large final dimensions. Frequent pruning and a high degree of maintenance effort are required to keep them small, particularly in restricted root-growth space. Fig. 4 shows several *Ficus microcarpa* planted in a narrow raised planter in one of our study sites, which was not a rare phenomenon. Restricted root growth could induce the formation of girdling roots and compromise anchorage. Also, limited soil volume would suppress the availability of nutrients and water. As a result, such trees will be susceptible to dampened growth, leaning or uprooting in strong wind. In addition, *Ficus* roots are very opportunistic, as they can penetrate cracks in weathered hardscapes and intertwine with buried structures and utilities. Once they are established, removing them can be difficult and costly.

Another growth problem can be illustrated by Fig. 5, showing a group of *Ficus* trees planted at the periphery of the sky garden and situated too close to the adjoining walls and other building structures. The large crown of *Ficus spp.* is prone to extend beyond the podium or roof edge and induce a grave safety concern. Regular and often heavy pruning is necessary to contain the tree size to abate the hazard. Therefore, *Ficus* or other species with similar properties should be adopted with great caution in sky gardens. Their success in other green spaces in Hong Kong may not be translated to planting sites on elevated landscapes.

4.2. Limited growing space in sky gardens

Many subaerial and subterranean constraints to urban tree growth (Jim, 2017) are present if not exaggerated in the sky garden ambience. The proximity between trees, large canopy overlap, and crown and root-growth obstacles collectively indicate restricted growing space in new sites. These limitations on aboveground and belowground growing space contribute to poor tree health (Development Bureau, 2012). The root-growth obstacles on tree growth has been widely evaluated (Grabosky and Gilman, 2004; Sanders et al., 2013; Sanders and Grabosky, 2014). However, how planting distance and crown constraint correlate with tree health has received limited attention.

On our sky gardens, the percentage of trees with neighbor trees within 1 m is quite high. Landscape designers often plant trees closely together to achieve an immediate visual impact and high canopy coverage. The demand for the 1:1 compensatory planting by the local Tree Practice Note may also have triggered dense planting in cramped space. Sparse tree spacing is associated with lower soil surface temperature and higher soil moisture, favoring a better tree survival rate (Chen et al., 2017). This association could be explained by the close tree spacing leading to competition for available soil moisture.

We did not find a significant correlation between tree planting distance and tree health. However, continued growth of closely planted trees can induce a high degree of canopy overlap, a factor associated with tree-health decline or structural problems like leaning (Fig. 6).

Fig. 4. *Ficus microcarpa* planted in a narrow raised planter.

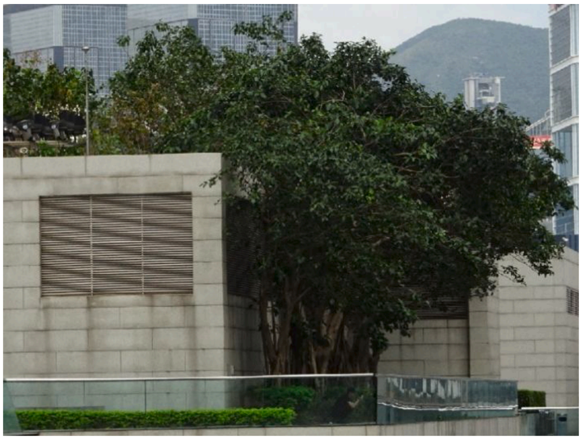


Fig. 5. *Ficus altissima* planting at the peripheral locations of the sky garden, resulting in a barrier to crown growth.

Fig. 6. Dense planting of trees in small raised planters, as a result of limited distance to neighbor trees at <1 m; leaning of some trees can be observed.

Small planting distance is the main contributor to canopy overlap, thus frequent pruning is needed in the long term to avoid excessive overlap. The high management cost incurred by the frequent pruning has not been duly recognized by landscape designers or communicated to clients at the design stage of sky gardens. A balance between aesthetic function and actual space requirement of trees could be achieved to ensure healthy and sustainable greening.

On the other hand, trees installed with a wider planting distance do not necessarily show better growth. In our study, most solitary open-grown trees were trapped in small planters with restricted soil. Moreover, many trees encountered crown barriers that may depress tree health. Designers should carefully consider the final tree size of the species to ensure sufficient aboveground growing space in the long term (Hui et al., 2020). Both canopy overlap and crown barriers could shade trees and reduce light availability.

Closely planted trees have to compete for light by growing too tall with a thin trunk, resulting in a potentially hazardous height:DBH ratio (Blood et al., 2016). The slender but tall trees will be vulnerable to wind damage (MacFarlane and Kane, 2017), which is particularly undesirable for sky gardens. Fig. 7 is an example of the common conflict between tree crown and adjacent wall structure, resulting in tree defects of heavy pruning, leaning and asymmetrical crown.

4.3. *Topping as a common practice*

Topping is a rather common practice in sky gardens, as observed

Fig. 7. Trees planted in close proximity to the adjacent wall, resulting in confined and asymmetrical crown development.

during our site surveys and data analysis. A higher percentage of topping in old sites is expected as many trees have reached an undesirably large size vis-à-vis physical confinements after growing for some years. However, the heights of most trees in our study sites are generally quite subdued even in old sites, and the height difference between old and new sites is very small. The high incidence of tree topping and associated drastic crown reduction reflects that sky-garden managers have been quite determined and diligent to keep the trees small to minimize the failure risk.

Although the topped and non-topped trees displayed no difference in health at the time of our study, problems such as fungal decay and sluggish recovery may aggravate in due course. Many studies have verified that tree topping could in time adversely influence tree structure and lower stress tolerance. The resulting increase in management cost, in the long run, can exceed the cost-saving of drastic and expedient low-cost tree size control (Campanella et al., 2009; Fini et al., 2015). A Hong Kong government guideline follows the international best practice to forbid topping (Development Bureau, 2010). Unfortunately, administrative advice without statutory backup and enforcement has been widely ignored in tree management. Even though the scientific knowledge of tree care is well established and widely available, the gap between science and practice has continued to beset the landscape industry (Jim, 2019a) with spillover impacts on sky garden design and management.

Regarding sky gardens, we advocate preventing unnecessary topping or excessive and frequent pruning by adopting a high standard of arboricultural practice. A set of best practices can forestall the need to adopt drastic crown reduction, including species selection, site design, soil provision, planting location, and planting density commensurating with the growth requirements of chosen species. Planting small-sized and slow-growing tree species in adequate soil volume (Jim, 2019b) could considerably lower the need for frequent or excessive pruning to maintain tree form and lessen wind resistance. Size control of trees is undoubtedly critical in sky garden management because of relatively limited soil volume and high wind exposure. Still, proper pruning, marked by a regular but skillful pruning regime of crown reduction and thinning, could be developed to achieve this target.

4.4. *Planter type and tree health*

Although the surface area of planters was not measured in our study, we observed that the sunken planter (curb planter) with a generally larger surface area has greater soil volume to store more moisture. On the contrary, the soil in the raised planter is filled from ground level and often shallower, as shown in Fig. 6. Thus the raised planter commonly has relatively limited soil volume because the soil depth is often less than 90 cm. Our results indicated that the planter type is correlated with tree performance.

Palm growth is facilitated by good drainage and good soil structure with little compaction. The limited root size and spread of palms is relatively less confined and stressed by inadequate soil. Palms generally perform better in raised planters than sunken ones. For palms, sunken planters tended to be associated with small planting distance and crown and root growth obstacles. On the other hand, woody trees performed better in sunken planters as soil volume and moisture retention are more favorable for root growth. This difference could be explained by a comparatively more extensive root system for woody trees than palms. Soil moisture retention is a particularly important issue for trees in sky gardens, as higher sun and wind exposure and more limited soil depth could induce moisture deficit. The findings suggest the importance of using the correct planter type for different tree forms.

4.5. Site elevation and tree health

As sky gardens located at higher elevations may experience harsher environmental conditions and poor tree growth, site elevation was included in our analysis. We cannot find any evidence that a higher site elevation would lead to poorer tree health in our study. On the contrary, we even found that palms growing at sites with lower elevation had poorer health. One reason is that other factors discussed above may have more critical influences on tree health. In any case, the elevation difference of our sky gardens was not large (all sites except one had <32 m elevation), hence its elevation factor would be subdued. Thus, the anticipated harsh environment in sites with higher elevations, including stronger sunlight and wind exposure, may not be experienced in full by the trees. Other environmental factors in the compact city, such as nearby buildings blocking sunlight and wind, would have nullified the impact of elevation. The frequent typhoon strikes in Hong Kong with extremely high wind speed have discouraged green roof installation on tall buildings. Future studies can focus on evaluating the effects of elevation and the associated microclimate variations on tree health.

5. Conclusion

Our study has documented tree communities by species composition and growth form as well as planting space design and management issues in Hong Kong's commercial sky gardens, which have seldom been studied. Differences between old and more recently installed sky gardens in both species adoption and site design are observed. In newer sky gardens, there is reduced use of palm species and increased use of woody tree species to prefer those with neat and tidy forms. There are also fewer native species in the new sites.

Limited growing space, a common problem in Hong Kong commercial sky gardens, has been accentuated in new sites. Aggravating inadequacy in this crucial factor can diminish tree health and create long-term management burdens. It is perhaps surprising if not disappointing that the growth constraints have deterioriated in the more recently installed sky gardens. The problem can be intensified by improper species selection accompanied by improper pruning practice that includes drastic topping and lopping.

Sky gardens can offer valuable green spaces in compact cities to provide ecosystem services and valuable amenities to citizens. They provide a precious alternative to supplement the shortage of green space at the street level. It is important to have sensible designs regarding planting space and suitable species adoption, to ensure long-term sustainability while minimizing the risk of tree failure.

CRediT authorship contribution statement

Caroline M. Y. Law: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Project supervision. **L. C. Hui:** Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing. **C.Y. Jim:** Writing - review & editing. **T. L. Ma:** Data collection.

Declaration of Competing Interest

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

Acknowledgements

We would like to convey sincere gratitude to Ms Yasmin Chir and Mr Terence Lam for their valuable advice. The kind help and comments provided by the editor and anonymous reviewers are gratefully appreciated.

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