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Heritage Trees in Macau: Relationships Among Biomass Structure, Age, and Ecosystem Services

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Abstract. Older trees in good health are expected to provide more ecosystem services and equivalent economic values due to their large size. The relationship of tree dimensions, respective tree height, crown area, diameter at breast height (dbh), and total leaf area vis-a-vis age were studied for 790 heritage trees ≥ 100 years old in Macau; 50 genera and 63 species were represented. Seven out of ten common genera showed no significant increase for all tested parameters except increase of dbh with age. Other factors, such as condition and geometry of growing spaces, controlled the performance of heritage trees, as well as the realization of their biological potential size, with implications on the provision of ecosystem services. The effects of these heritage trees on air-quality improvement and gross carbon sequestration were quantified by the i-Tree Eco model. Overall, 806.8 kg of air pollutants were removed annually, with benefits valued at US $8,091. The heritage trees stored 3,041 t carbon in total and sequestered 842 kg carbon/yr, equivalent to US $601 in annual benefits. The values were much higher than ordinary urban forest trees. Ten common heritage tree genera were ranked by their capacities for air quality improvement, carbon storage, and sequestration. The findings can serve as a decision tool for heritage tree management and conservation and to estimate potential ecosystem services of established trees.

Keywords. Air-Pollutant Removal; Carbon Sequestration; Carbon Storage; Ecosystem Service; Heritage Tree; Monetary Value.

INTRODUCTION

Rapid and intensive urbanization often aggravates environmental degradation. The impacts could be ameliorated by preserving or creating natural elements subsumed under urban green infrastructure. Quantifying and monetizing the benefits can help us to understand and advocate for the multiple ecosystem services of urban vegetation. In recent years, a rising number of studies have quantified the benefits and services of trees in mitigating environmental problems (Roy et al. 2012; Mullaney et al. 2015). They tended to focus on two key environmental functions, namely air-pollution abatement and carbon sequestration.

Trees are effective in capturing air pollutants such as nitrogen oxide (NO_x), sulfur dioxide (SO_2), ozone (O_3), and particulate matters (PM) including $PM_{2.5}$ and PM_{10} to enhance citizen well-being (Nowak et al. 2006; Rao et al. 2014; Vranckx et al. 2015). A modeling study estimated that urban trees in the United States could remove a large amount of air pollutants (711,000 t/yr of NO_2, SO_2, CO, O_3, and PM_{10}). The improved urban air quality was valued at US $3.8 billion/yr (Nowak et al. 2006). Urban trees in the city of Guangzhou, China, could remove 312 tonnes (t) of NO_2, SO_2, and PM, equivalent to US $11,000 value annually (Jim and Chen 2008).

Urban areas are significant emitters of CO_2 with impacts on climate change (Chen and Chen 2012; Fragkias et al. 2013). Trees can effectively serve as a carbon sink by fixing atmospheric carbon dioxide (CO_2) during photosynthesis and storing carbon in biomass (Nowak et al. 2013), thereby reducing net CO_2 emission in a city. The total carbon stock in urban trees of the United States in 2005 was estimated at 643×10^6 t, with 18.9×10^6 t net annual carbon sequestration. The carbon storage and sequestration benefits were valued at US $50.5 billion and US $2.0 billion respectively (Nowak et al. 2013). The urban forests in the city of Shenyang, China, stored 337,000 t of carbon valued at US $13.9 million, with a sequestration rate of 29,000 t/yr valued at US $1.2 million (Liu and Li 2012).

Although trees can provide considerable values as ecosystem services, on a per-tree basis the highly varied benefits increase with tree size. Large and old trees are recognized as keystone components in furnishing landscape value and multiple ecosystem services (Manmoud et al. 2015). The unique ecological, landscape, and amenity services of large and old trees can hardly be substituted by young ones (Le Roux et al. 2014). In New York City, the overall net benefits of urban trees were quantified at US $5 to $9 for a small tree, US $36 to $52 for a medium tree, and US $85 to $113 for a large tree (McPherson et al. 2007). The capacity of trees to remove air pollutants increased with tree canopy cover and total leaf area (Mullaney et al. 2015). Large trees could remove 60 to 70 times more air pollutants than small ones (McPherson et al. 1994). Carbon storage and sequestration also increased with tree size. Large trees had carbon storage rates 1,000 times and carbon sequestration rates 90 times those of small ones (McPherson et al. 1994). Large trees have been identified as key carbon-storage entities in natural forests. Preserving large trees with a trunk diameter at breast height (dbh) > 1.1 m was recommended to improve aboveground biomass balance (Sist et al. 2014). Meanwhile, Albani et al. (2006) argued that mature trees have reduced net annual CO_2 uptake and hence they no longer served as significant recurrent carbon sinks.

Even though large and old trees can provide greater ecosystem services, few trees could persist for a long time in a stressful urban environment (Jim 2004). Shading imposed by high-rise and densely packed buildings, confined physical growth space above- and belowground, impermeable urban surface, air and soil pollution, and frequent modifications of adjacent buildings and roads inflict many acute and chronic challenges on urban trees (Jim 2003; Cekstere and Osvalde 2013; Mullaney et al. 2015). The small cohort of trees that can survive decades or centuries of stresses and remain strong and vigorous are often respected and protected as heritage trees (Jim 2005, 2018). Such exceptional trees may embody remarkable values in culture, history, ecology, landscape, and amenity (Beijing Garden Administration Bureau 1992; Jim and Zhang 2013) to justify special care and conservation.

Unfortunately, continued urban expansion, redevelopment, and densification have often degraded physical and physiological habitat conditions to induce a decline in heritage trees (Le Roux et al. 2014). Recognizing their important ecosystem services denotes a key step towards their conservation and restoration in the changing urban fabric (Howarth and Farber 2002). Because of the uniqueness of heritage trees, studies have quantified their ecosystem services and equivalent monetary values. In Israel, trees older than 100 years provided an annual value between €2.35 to €19.9 million through a contingent valuation study (Becker and Freeman 2009). Quantification of the multiple benefits of old growths can inform policymakers in resource allocation for enhanced care and preservation.

This study aimed at estimating the capability of heritage trees in Macau to remove air pollutants and sequester carbon. As tree size was one of the major parameters in estimating the capacity to provide ecosystem services, tree dimensions of the heritage trees were evaluated against their age. Understanding their potential growth and benefits could provide reliable information to guide decisions on their conservation or restoration in Macau, and the findings can be applied to other Chinese and developing cities. Decision-makers could have scientific, objective data to make judgments on the trade-offs among expenditures in preservation, restoration, and alternative regulatory, policy, or management actions. The results could enhance people's awareness of the realistic values of heritage trees to strengthen their support of relevant official policies.

METHODS

Study Area

The Macau Special Administrative Region (SAR) sits at the west side of the Pearl River estuary at the south coast of China (22°N, 113°E). The humid subtropical climate is dominated by the Asian Monsoon system. Macau has experienced rapid economic growth in recent decades. Its gross domestic product (GDP) increased over seven times in the past 20 years, attaining US $44,800 million in 2016 (The World Bank 2017a). The population of 644,900 in 2016 (Statistics and Census Service 2016) dwelt in a tiny territory of 30.3 km^2. An adverse consequence of rapid economic growth and high population density is extensive environmental degradation. In the 1990s, 40% of daily average SO_2 concentration exceeded the Chinese National Primary Standard (Mok and Tam

1998). The annual mean roadside PM_{10} and $PM_{2.5}$ concentrations reached 60 μg/m^{-3} and 29 μg/m^{-3}, respectively, in 2014 (Meteorological and Geophysical Bureau, personal communication). The PM results were almost triple of the international guideline at an annual mean of PM_{10} at 20 μg/m^{-3} and $PM_{2.5}$ at 10 μg/m^{-3} (World Health Organization 2005). The CO_2 emission was 3.8 t/capita in Macau in 2013 (The World Bank 2015), bringing 2.2 million t/yr of CO_2 emission.

Founded by the Portuguese in 1557, the city has witnessed over five centuries of urban history. Despite its small size and compact development mode, the urban design has adopted the European tree-planting tradition in streets and public parks. The present cityscape has inherited some old trees planted in the early days. Trees aged 100 or more years with special historical and other values were identified as Ancient and Precious Trees (APTs) in 2011 (Department of Gardens and Green Area and South China Botanical Garden 2013). Most of them are roadside trees dominated by *Ficus rumphii,* but the highest diversity and largest tree dimensions are found in parks and gardens (Zhang et al. 2017). In this study, 790 APTs in 63 species were recognized as heritage trees, excluding 3 with special historical value and 2 with incomplete records.

Tree Dimensions

Tree assessment was conducted from July 2011 to April 2012 by the Department of Gardens and Green Areas of the Civic and Municipal Affairs Bureau of the Macau SAR Government and the South China Botanical Garden of the Chinese Academy of Science (Department of Gardens and Green Area and South China Botanical Garden 2013). Tree inventory data included species, location, tree height (m), under-branch height (m), dbh (m), crown W–E and N–S width (m), age (year), and health conditions.

i-Tree Eco Model

To quantify the ecosystem services of air-quality improvement and carbon sequestration of the heritage trees in Macau, the i-Tree Eco v5.0 model was used (www.itreetools.org). The model enlisted field data of tree dimensions and conditions, together with local meteorological and pollution concentration data. This model has been widely adopted to estimate the amount of air-pollutant removal by urban forest, carbon storage, carbon sequestration, and other ecosystem services, with recent implementation examples by Kim et al. (2015), Selmi et al. (2016), Jayasooriya et al. (2017), and Riley et al. (2017).

We assumed the heritage trees to have 100% live crown ratio, i.e., "Total Tree Height" equaled "Height to Live Top"; "Percentage Crown Missing" and "Crown Dieback" were set at zero; and "Height to Crown Base" equaled to the under-branch height. DBH was measured at a height of 1.37 m. We estimated the crown light exposure (CLE) through maps in the book *The Charm of Trees, Ancient and Precious Trees in Macao* (Department of Gardens and Green Area and South China Botanical Garden 2013), supplemented by satellite imagery and Google Street View. Hourly air-pollution concentration (C) was recorded by Automatic Air Quality Monitoring Stations in Macau, and the monitoring data were supplied by the Macao Meteorological and Geophysical Bureau. Concentrations of NO_2, SO_2, O_3, and PM_{10} from 1 June 2011 to 31 May 2012 were extracted to match the tree inventory period. The concentration of $PM_{2.5}$ in 2014 was selected because such data were only recently recorded and released.

Monetary Values of the Ecosystem Services

Nowak et al. (2008) calculated the ecosystem services of urban forests for the United States in 2007; the externality per-tonne monetary values were: NO_2 at US $9,906, SO_2 at US $2,425, CO at US $1,407, O_3 at US $9,906 (same as NO_2), and PM_{10} at US $6,614. With a 19.6% inflation rate based on the Consumer Price Index of Macau in 2007 through 2012 (The World Bank 2017b), the adjusted per-tonne values were: NO_2 at US $11,848, SO_2 at US $2,900, CO at US $5,152, O_3 at US $11,848, and PM_{10} at US $7,910. $PM_{2.5}$ was assumed to be the same as PM_{10}. Carbon value of $23/t with marginal costs of carbon dioxide emissions for 2001 through 2010 was used in the US (Nowak et al. 2008). We adjusted the value as $25/t in 2012 by an 8.8% inflation rate in 2010 through 2012 in Macau.

These monetary values were multiplied with the benefits of air purification, total carbon stored, and sequestrated by the 790 heritage trees in Macau in order to estimate the ecosystem service value.

Statistical Analysis

Spatial distributions of old growths were associated with the tree habitats and land ownerships such as urban gardens and country parks (Zhang et al. 2017). As poorer air quality was usually associated with traffic, the trees were further divided into "street trees" and "non-street trees." We also measured the road widths adjacent to the measured trees. Roads with < 5-m width were classified as "narrow"; 5- to 7-m as "medium"; and > 7-m as "wide." Trees situated on other land uses (such as parks) but adjacent to roads were also identified as "street trees," but trees in pedestrian-only streets were recognized as "non-street trees." The non-street trees were classified into "trees in parks," "trees in built-up area," and "trees at remote area." "Urban Park" referred to relatively large public green sites such as Guia Municipal Park, Camões Garden, Lou Lim Ieoc Garden, Garden of Commander Ho Yin, Montanha Russa Park, and S. Francisco Garden. "Built-up area" was occluded in residential lots, building compounds, religious sites, and other areas influenced by development. "Remote area" included more natural environments such as country parks, slopes, or seashores. The tree community ecology was evaluated by detrended correspondence analysis (DCA) in R with the "vegan" package (Oksanen et al. 2017).

We analyzed the relationships among tree height, crown area, dbh, leaf area (calculated from the i-Tree Eco model), and tree locations by principal component analysis (PCA) in R with the "ggfortify" package (Horikoshi and Tang 2016).

The heritage trees were grouped into genera due to the limited information of the i-Tree Eco database on south China native species. The grouping also helped to tackle the large proportion of uncommon or rare species (≤ 3 trees per species). The relationships of tree dimensions against ages were analyzed by Pearson correlation with SPSS Version 22 (IBM Corp.) for the 10 most common genera.

We ranked the top 10 genera by their ecosystem-service capacity and analyzed their mean values by a nonparametric independent samples Kruskal-Wallis Test, followed by a series of Mann-Whitney tests to identify the pairs that differed significantly from the others. The ecosystem services were compared between street trees and non-street trees, as well as between native and exotic species by an independent samples *t*-test. These analyses were performed by SPSS Version 22 (IBM Corp.). The associations of ecosystem services by different tree families were analyzed by principal component analysis (PCA) in R with the "ggfortify" package (Horikoshi and Tang 2016).

RESULTS AND DISCUSSION

Tree Composition

This study analyzed 790 heritage trees with age ≥ 100 years in Macau. The trees were composed of 289 street trees (36.6%) and 300 native trees (38.0%) (Table 1). Figure 1 indicates tree distribution patterns by six habitat types. Roads with different widths had a similar tree composition, but the narrow roads had more *Ficus* spp. Tree composition at roadsides (all three width classes) was similar to "built-up area," but differed from "remote area" and "urban park." Small land lots surrounded by roads have been a common development mode since the founding of Macau in the 1550s. Trees along such roadsides and in scattered tree pits or in small green pockets within the governmental, institutional, and private residential areas formed a finely divided and mixed land-use pattern. The confined and stressful habitat conditions in these cloistered sites are similar to the circumstances at roadsides, which explained the similarity in tree compositions of the two types of sites. Meanwhile, the "remote area" of the countryside and low-maintenance slopes or seashore favored species with voluntary-growth capability. Thus, such natural or ruderal habitats were characterized by common native genera of *Celtis*, *Pterospermum*, and *Syzygium*. In contrast, common ornamental and mainly exotic species in genera *Albizia*, *Aleurites*, *Bombax*, *Cinnamomum*, *Delonix*, *Litsea*, *Plumeria*, and *Podocarpus* were found in urban parks.

Tree Dimensions and Age

Heritage trees denoted the largest urban trees in Macau, with a mean dbh of 78.2 cm and a mean height of 12.4 m. In aggregate, they covered 68,710.4 m^2 of crown area and provided 354,841.5 m^2 of leaf area. The solitary *Macaranga* sp. had the largest canopy of the heritage tree species in Macau, with a crown area of 283.5 m^2 and a leaf area of 1,247.5 m^2. The dominant *Ficus* spp. covered 39,587 m^2 of crown area (57.6% of total) and provided 204,744 m^2 of leaf area (57.7% of total)(Table 1).

The principal component analysis explored the relationships among tree height, crown area, dbh, leaf area, and age of the 10 most common genera reckoned by the number of trees per genus (Figure 2).

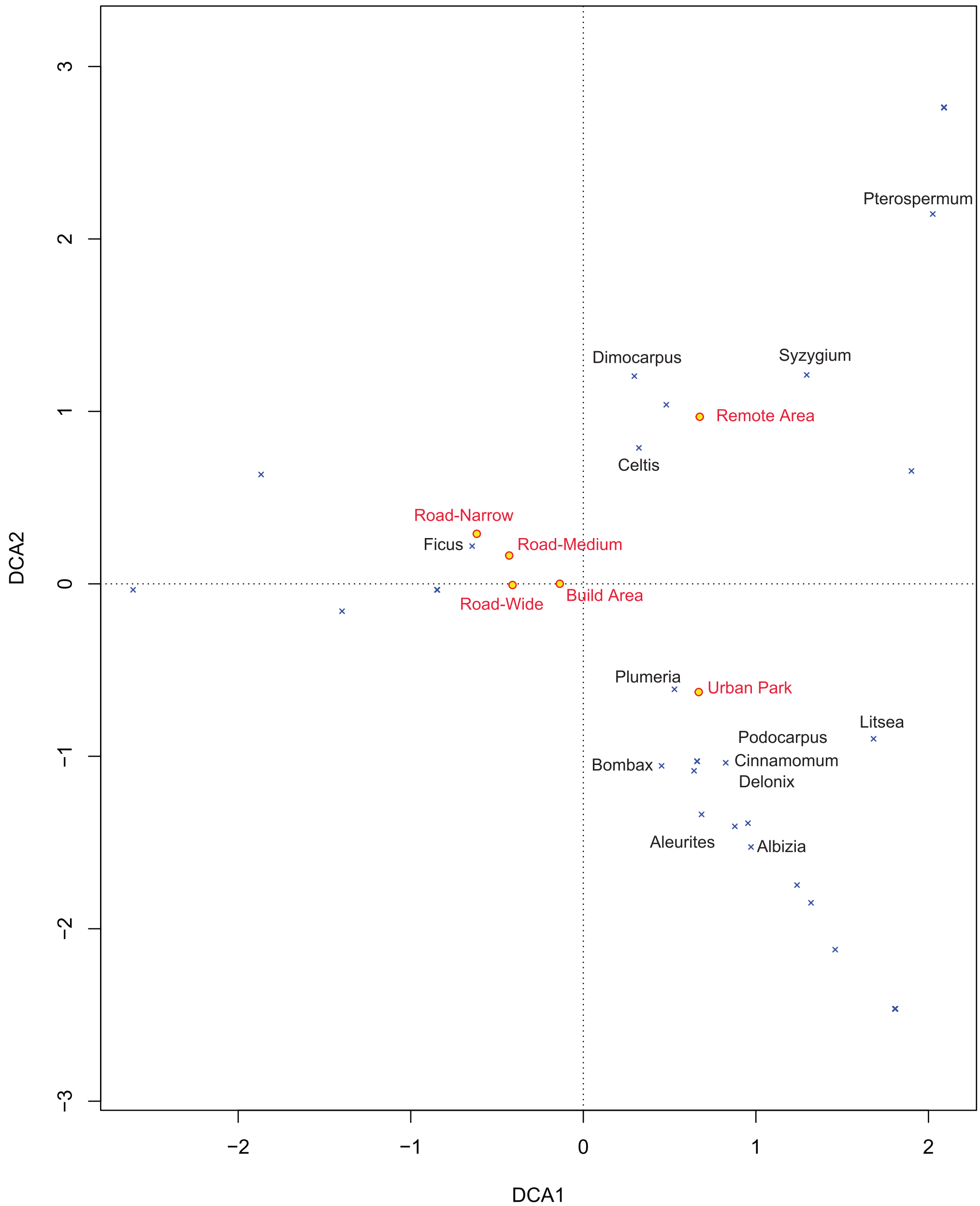


Figure 1. The first two axes of the DCA ordination of six locations of the heritage trees and tree genus composition in Macau. The first and second axes represent 0.28 and 0.23 of the eigenvalues, respectively. The genera with > 10 individuals were listed. Road-Narrow: roads with < 5-m width; Road-Medium: roads with 5- to 7-m width; Road-Wide: roads with > 7-m width.

Table 1. Botanical composition, tree dimensions, and mean age of the 790 heritage trees in Macau grouped by 50 genera.

Genus	Total no. of trees	No. of street trees	No. of non-street trees	No. of native trees	No. of exotic trees	Mean height (m)	Mean crown area (m^2)	Total crown area (m^2)	Mean dbh (cm)	Total leaf area (m^2)	Mean leaf area (m^2)	Mean age
Acacia	2	1	1	2		11.0	49.1	98.1	92.5	675.0	337.5	100
Aglaia	1		1	1		3.2	7.1	7.1	27.0	13.2	13.2	100
Albizia	14	4	10	14		15.1	97.7	1,368.1	89.0	7,377.4	527.0	109
Aleurites	10	2	8	10		12.8	66.2	662.2	89.9	2,797.0	279.7	111
Aporosa	1		1	1		9.2	19.6	19.6	47.0	103.9	103.9	100
Araucaria	1		1		1	20.0	12.6	12.6	80.0	135.7	135.7	100
Artocarpus	6	2	4	3	3	13.0	78.1	468.5	82.8	2,299.9	383.3	120
Averrhoa	4	2	2		4	11.0	86.3	345.0	84.5	1,483.7	370.9	208
Bombax	21	7	14	21		17.7	98.2	2,063.1	99.5	10,675.7	508.4	127
Bridelia	3		3	3		13.3	119.5	358.5	57.5	1,974.6	658.2	113
Canarium	1		1	1		18.5	23.8	23.8	73.0	197.7	197.7	100
Cassia	2		2		2	12.8	66.3	132.6	78.0	765.4	382.7	110
Celtis	10		10	10		13.0	142.8	1,428.3	92.6	8,686.4	868.6	133
Cinnamomum	44	12	32	44		13.9	120.6	5,307.9	107.2	23,290.1	529.3	157
Cleistocalyx	3		3	3		15.5	109.3	328.0	92.0	1714.2	571.4	107
Cordia	1		1	1		17.0	50.3	50.3	90.0	341.8	341.8	220
Delonix	11	2	9		11	14.6	114.5	1,259.1	96.4	5,827.8	529.8	101
Dimocarpus	38	14	24		38	12.0	87.3	3,315.5	65.8	16,767.9	441.3	152
Diospyros	1		1	1		9.0	36.3	36.3	65.0	272.8	272.8	100
Dracontomelon	2		2	2		16.0	158.9	317.7	86.5	1,088.2	544.1	110
Elaeocarpus	3		3	3		9.7	72.9	218.8	79.0	1,133.2	377.7	100
Erythrina	8	7	1		8	14.7	107.6	860.6	111.6	4,773.2	596.7	111
Eucalyptus	1		1		1	13.5	18.1	18.1	140.0	193.2	193.2	110
Ficus	440	231	209	64	376	13.8	90.0	39,587.0	158.8	204,744.0	465.3	108
Hibiscus	1		1	1		7.0	28.3	28.3	58.0	135.6	135.6	100
Ilex	2		2	2		12.5	94.7	189.4	78.5	1,042.4	521.2	100
Lagerstroemia	2		2	2		5.5	17.1	34.1	29.0	148.7	74.3	120
Litchi	2		2	2		13.5	81.7	163.4	63.5	975.8	487.9	100
Litsea	21	1	20	21		14.0	57.0	1,197.1	83.7	6,869.7	327.1	126
Lophostemon	1		1		1	12.0	70.9	70.9	69.0	462.4	462.4	100
Macaranga	1		1	1		13.0	283.5	283.5	100.0	1,247.5	1247.5	100
Machilus	2		2	2		15.0	182.7	365.4	106.0	1,777.6	888.8	155
Mangifera	2		2		2	15.3	88.5	176.9	102.5	941.5	470.7	140
Manikara	1		1	1		10.0	38.5	38.5	64.3	329.0	329.0	100
Michelia	3		3	2	1	15.7	77.6	232.7	83.3	1,580.5	526.8	100
Morus	4		4		4	9.0	65.3	261.2	75.7	1,408.7	352.2	163
Murraya	3		3	3		7.0	20.8	62.4	46.7	319.3	106.4	133
Ormosia	1		1	1		15.0	122.7	122.7	42.5	687.2	687.2	100
Phyllanthus	1		1	1		7.0	28.3	28.3	39.6	179.1	179.1	100
Pinus	3		3		3	15.5	27.8	83.4	79.3	469.9	156.6	110
Plumeria	26		26		26	7.6	28.7	744.9	62.5	4,193.4	161.3	132
Podocarpus	12		12	12		13.0	35.1	421.2	56.1	5118.9	426.6	145
Pterospermum	13		13	11	2	19.1	164.5	2,138.9	108.7	1,0311.5	793.2	141
Rhaphiolepis	4		4	4		6.6	13.7	54.8	17.6	302.9	75.7	100
Sapindus	3		3	3		12.2	64.0	192.1	68.3	1016.0	338.7	117
Sapium	6	1	5	6		12.3	62.3	373.5	62.0	1,770.8	295.1	110
Schefflera	2		2	2		8.9	12.0	23.9	65.0	141.0	70.5	100
Sterculia	7		7	7		11.1	48.2	337.5	62.4	1,634.4	233.5	111
Syzygium	38	2	36	31	7	12.7	70.7	2,685.5	88.8	13,895.7	365.7	156
Ulmus	1	1		1		12.0	113.1	113.1	110.0	550.3	550.3	125
Total	790	289	501	300	490			68,710.4		354,841.5		
Mean						12.4	74.6		78.2		397.9	119.8

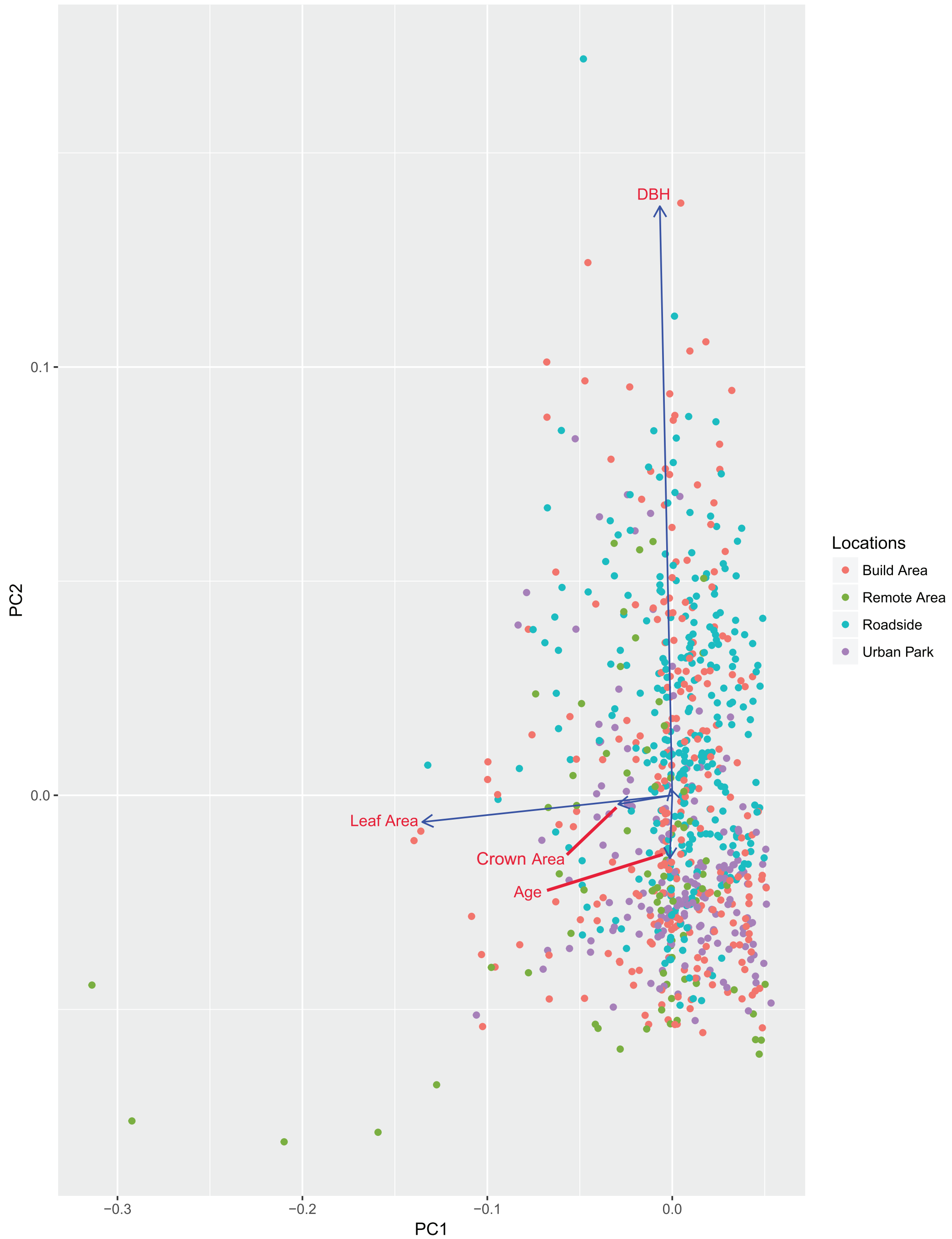


Figure 2. The first two principal components (PCs) for the growth characteristics of 790 heritage trees in Macau. The arrows showed some major correlated ecosystem services to the PCs.

Two principal components (PC1 and PC2) were identified with an eigenvalue larger than 1. PC1, explaining 48% of the variance, was mainly correlated with leaf area, followed by crown area. PC2, explaining 21% of the variance, was positively correlated with dbh but negatively correlated with age. Considering all heritage trees, the associations were weak between tree dimensions and age, and among tree dimension attributes.

The distribution of the heritage trees did not show distinctive clusters with reference to tree habitats, but a few trees from Figure 2 were characterized by older age and larger leaf area with lower PC1 and PC2 factor scores. These trees were located at the remote area where more natural site conditions permitted attainment of maximum potential biological dimensions. Meanwhile, trees at urban parks had a lower PC2 factor–scores value, implying that they were older but with a relatively thinner tree trunk (Figure 2). It could be explained by a divergent genus composition and close planting of trees (Figure 1). Further analysis is needed to understand tree dimension and age among species. Accordingly, the study selected the 10 most common heritage tree genera (≥ 12 trees/genus) to compare their dimensions with age.

For the heritage trees from the 10 most common genera, only *Ficus* had a positive correlation of height, crown area, dbh, and leaf area versus age. *Bombax*, *Dimocarpus*, *Podocarpus*, and *Syzygium* only increased their dbh with age. No tree dimensions of *Albizia*, *Litsea*, and *Plumeria* were significantly correlated with age (Table 2 and Figure 3). Tree dimensions were expected to increase with age and to provide more ecosystem services. However, trees ≥ 100 years old at high-density areas suffered from confined growing space or poor growth conditions, which restricted extension of branches and height. For some old and weak trees, the crown might have experienced retrenchment. Some trees only increased their dbh but not their crown. Better management practice and growth-site protection can allow trees to increase their dimensions and ecosystem services.

Overall Ecosystem Services

Total air purification by heritage trees amounted to 841.7 kg/yr due to combined pollutant removal by absorption and deposition (Table 3). Street trees accounted for 36.0% and natives 38.9% of removal. No significant differences in total pollutant removal were found between street trees and non-street trees or between native and exotic species (independent samples *t*-test, $P > 0.05$).

The total capacity of air-pollutant removal depended on individual pollutants, with NO_2 being the highest. The heritage trees totally intercepted 251.0 kg of NO_2, 237.3 kg of PM_{10}, 237.2 kg of O_3, 78.6 kg of SO_2, and 2.7 kg of $PM_{2.5}$ per year. *Ficus* contributed 61% of total air pollutant removal due to a large number of individuals, followed by 5.6% of *Cinnamomum* and 4.6% of *Dimocarpus*.

Although the dimensions of some trees were limited by age, overall heritage trees still provided efficient and active sites for pollutant deposition or absorption. Although tree age would reduce leaf growth and lower functional efficiency of individual leaves, older trees have a larger total leaf area per tree to raise the aggregate leaf area of the whole cohort (Stephenson et al. 2014). A large aggregate leaf area of heritage trees could compensate partly for their general decline. These trees were found to have a rather high capacity and value in air-cleansing capability. Common species in Florence, Italy, could remove 4.5 g/tree/yr (*Carpinus* spp.) to 362 g/tree/yr (*Pinus* spp.) in total air pollutants (NO_2, SO_2, CO, O_3, and PM_{10})(Paoletti et al. 2011). In nearby Guangzhou city, 1,794,455 urban trees could remove 312 t/yr of

Table 2. Pearson correlations of tree height, crown area, dbh, and leaf area with tree age of the 10 most common genera of the heritage trees.

	Albizia	*Bombax*	*Cinnamomum*	*Dimocarpus*	*Ficus*	*Litsea*	*Plumeria*	*Podocarpus*	*Pterospermum*	*Syzygium*
Height	-0.334	-0.066	0.102	-0.199	0.183**	0.118	-0.225	0.195	0.406	0.279
Crown area	-0.205	0.164	0.346*	-0.081	0.220**	-0.190	0.320	-2.390	0.557*	-0.234
dbh	-0.445	0.697**	0.738**	0.458**	0.252**	0.429	-0.118	0.703*	0.402	0.608
Leaf area	-0.218	0.214	0.190	-0.129	0.219**	0.128	0.152	-0.279	0.609*	-0.200

(*$P < 0.05$, **$P < 0.01$)

SO_2, NO_2, and PM in total (Jim and Chen 2008). Each tree was able to take away 174 g/tree/yr of air pollutants. In this study, the large heritage trees with high leaf surface area could remove considerably more air pollutants at an average of 1.0 kg/tree/yr, equivalent to an aggregate of 806.8 kg/yr by the whole lot of 790 trees.

The generally large size of the heritage trees could store a considerable amount of carbon in biomass. Carbon stock in tissues could be continually enhanced by annual accretion. In this study, the heritage trees removed carbon from the air at a rate of 24.0 t/yr in total (Table 3). The average carbon sequestration was 30.4 kg/tree/yr on average and reached 47.3 kg/tree/yr for *Albizia* spp. The results were significantly higher than the overall 12 to 21 kg/tree/yr in US urban forests (Vaccari et al. 2013); 23 to 33 kg/tree/yr of species with the highest sequestration rate (*Eucalyptus leucoxylon* and *Ficus rubiginosa*) in Perth, Australia (Saunders et al. 2011); and 26 to 34 kg/tree/yr in Florence, Italy (Paoletti et al. 2011). Gross carbon sequestration of the i-Tree Eco model was determined by the differences in carbon storage between year x and year x + 1. The tree biomass in year x + 1 was calculated from year x taken as the base growth rate. The exceptional biomass of heritage trees contributed to the high annual increment. Although most heritage trees in Macau are in good health conditions, many large and old trees are at risk of dieback and decline worldwide. However, even if a heritage tree is retrenched, it could still provide considerable carbon storage and other ecosystem services that are superior to urban trees in general.

A study examined more than 670,000 trees from more than 400 species for the growth rate of old and large trees (Stephenson et al. 2014). The results showed that the growth rate of many species increased with dimensions, indicating that old and large trees did not only act as a large carbon sink, but they were also able to continuously fix a large amount of carbon in comparison with smaller trees. This finding implied a notable potential for heritage trees in Macau to fix carbon despite their old age.

The carbon storage by heritage trees in Macau was 3,040.8 t in total (Table 3), with an average of 3.8 t/tree. Street trees accounted for 43.8% and natives 31.3%. The genus *Ficus*, with particularly bulky trees with a mean dbh of 158.8 cm and a mean height of 13.8 m (Table 1), predominantly accounted for 73.7% of the total carbon storage. The second and third ranks were *Cinnamomum* and *Syzygium*, which contributed merely 5.1% and 3.3%, respectively.

Significant differences in carbon sequestration and carbon storage between the street and non-street trees, and exotic and native species (independent samples *t*-test, $P < 0.05$) were likely due to the dominance of exotic *Ficus rumphii* mainly planted along roadsides.

Macau has a record of 488,364 trees (Commission of Audit of Macao SAR 2010), of which less than 0.2% (790 trees) reached the age of ≥ 100 years. With better tree management and growing environment, more trees could reach larger dimensions in the future to offer more ecosystem services.

Ecosystem Services by Genus

The study selected the 10 most common heritage tree genera (≥ 12 trees/genus) to compare their capacity in providing ecosystem services (Table 4). A Kruskal-Wallis H test showed statistically significant differences in all pollutant removal, carbon sequestration, and carbon storage between genera, with mean values shown in Table 4.

The annual air-pollutant removal on a per-tree basis was the highest in *Podocarpus* for CO (88.6 g/tree/yr); *Ficus* for O_3 (355.2 g/tree/yr); *Podocarpus* for NO_2 (689.8 g/tree/yr); *Ficus* for SO_2 (124.2 g/tree/yr); *Pterospermum* for $PM_{2.5}$ (6.4 g/tree/yr) and PM_{10} (479.8 g/tree/yr). The most capable genera for total pollutant removal were *Pterospermum* and *Podocarpus*, reaching about 1.5 kg/tree/yr (Table 4). Overall, the air purification ability of heritage trees was notably higher than urban trees in general. In comparison, a study in the nearby city of Guangzhou found total pollutant removal of only 174 g/tree/yr (Jim and Chen 2008).

Carbon storage on a per-tree basis of the 10 most common heritage tree genera was the highest for *Ficus* spp. (> 5,000 kg/tree) which differed considerably from other genera except for *Pterospermum* (about 3,800 kg/tree)(Figure 4). *Podocarpus* had the lowest carbon sequestration rate and were significantly different from the remaining nine common genera (Figure 4). Despite a smaller dbh (Table 1) and the least carbon storage in biomass, *Podocarpus* managed to fix 10 kg/tree.

This study compared the capacity of different tree genera in providing environmental benefits. The

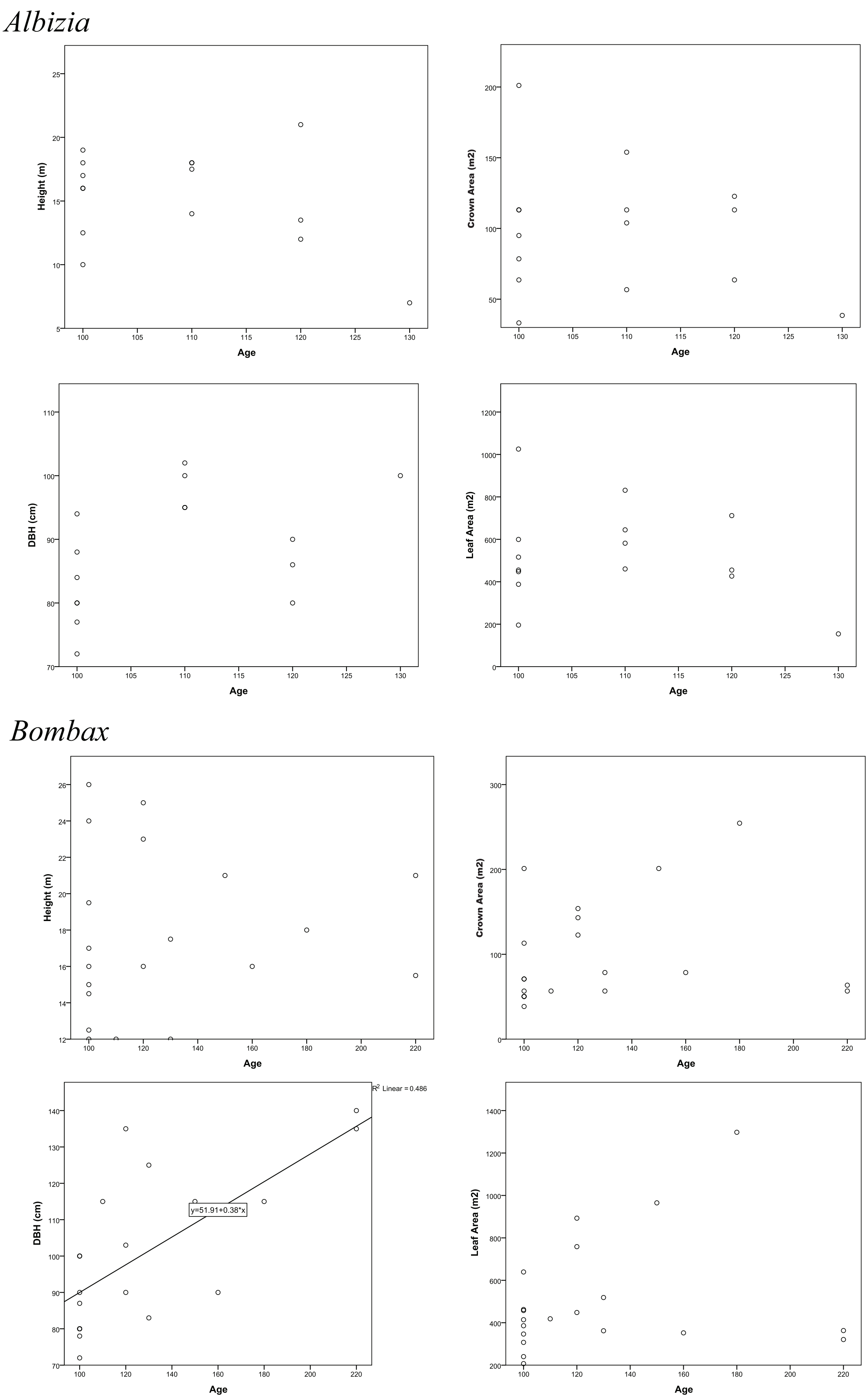
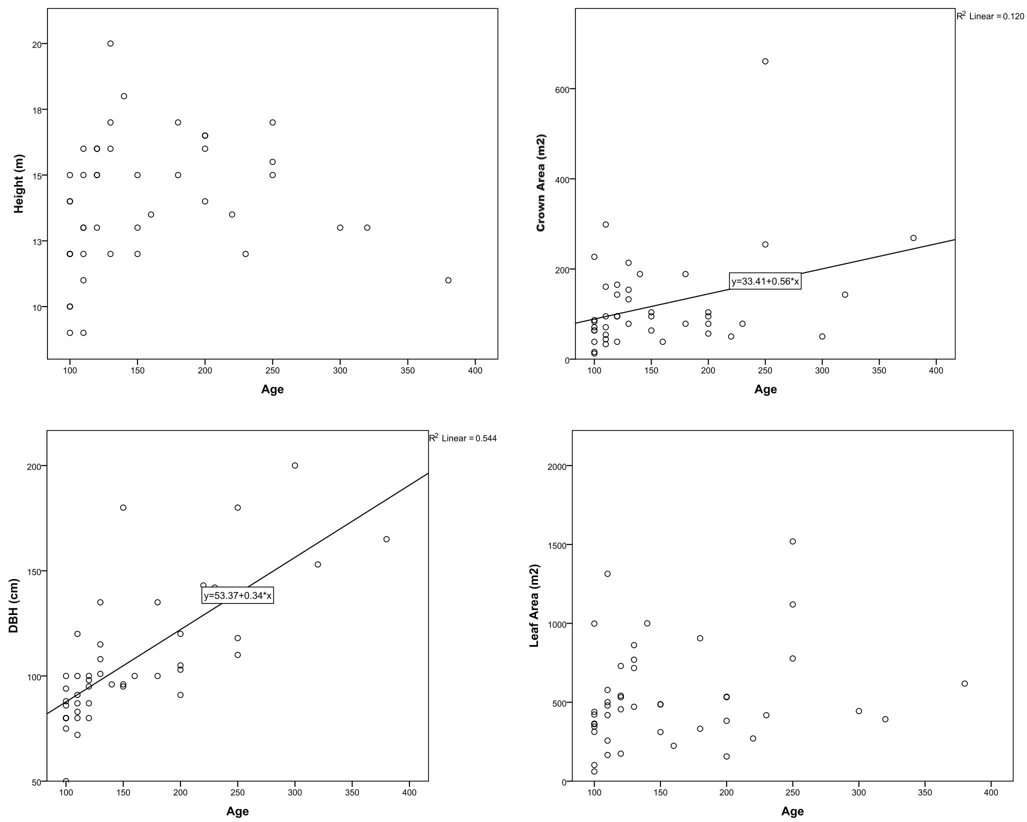
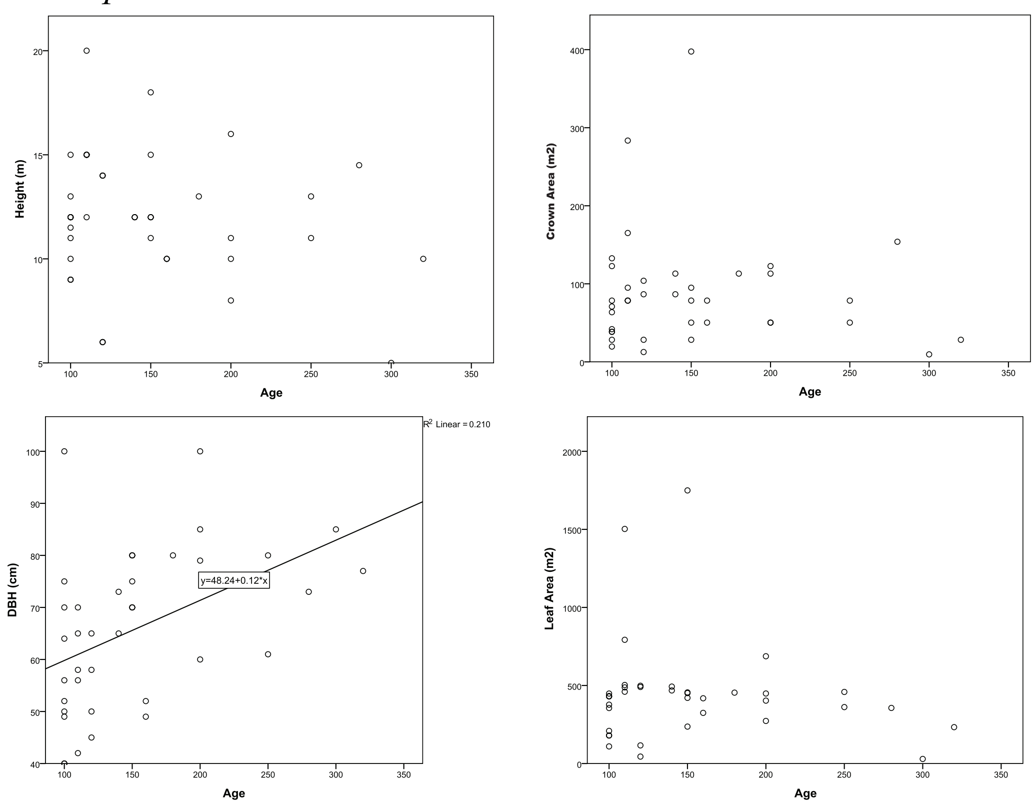


Figure 3. Relationships of tree height, ground area, dbh, and leaf area with tree age of the 10 most common genera of the heritage trees.

Cinnamomum



Dimocarpus



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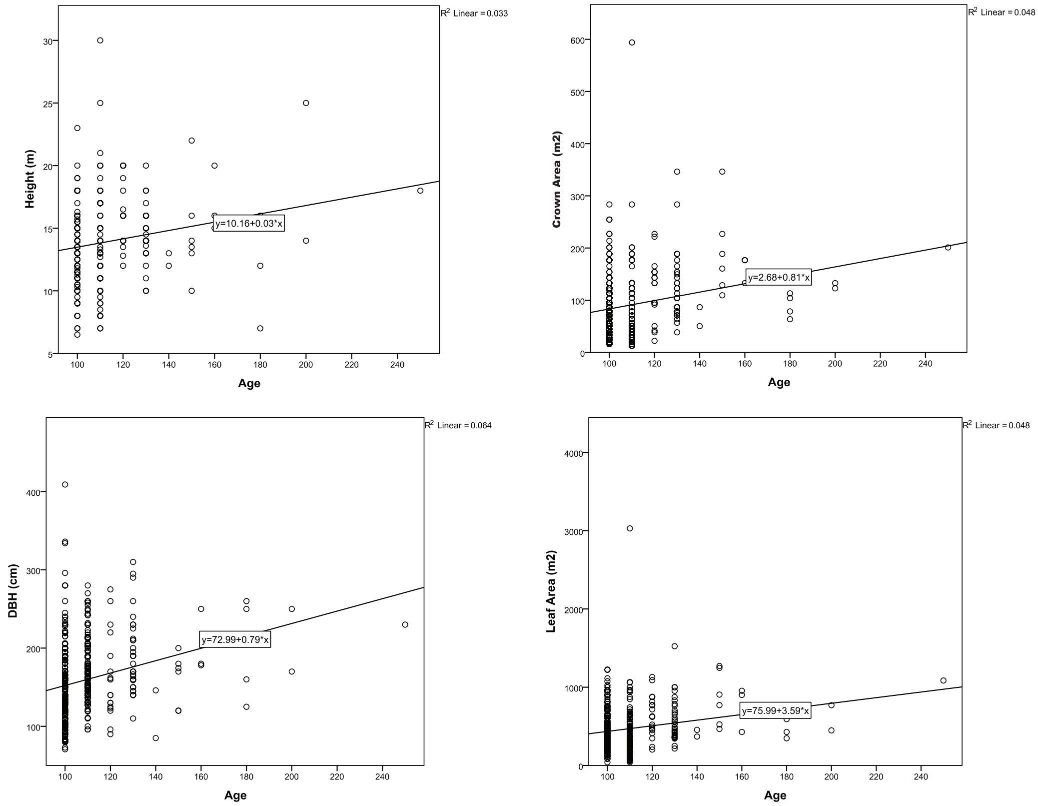
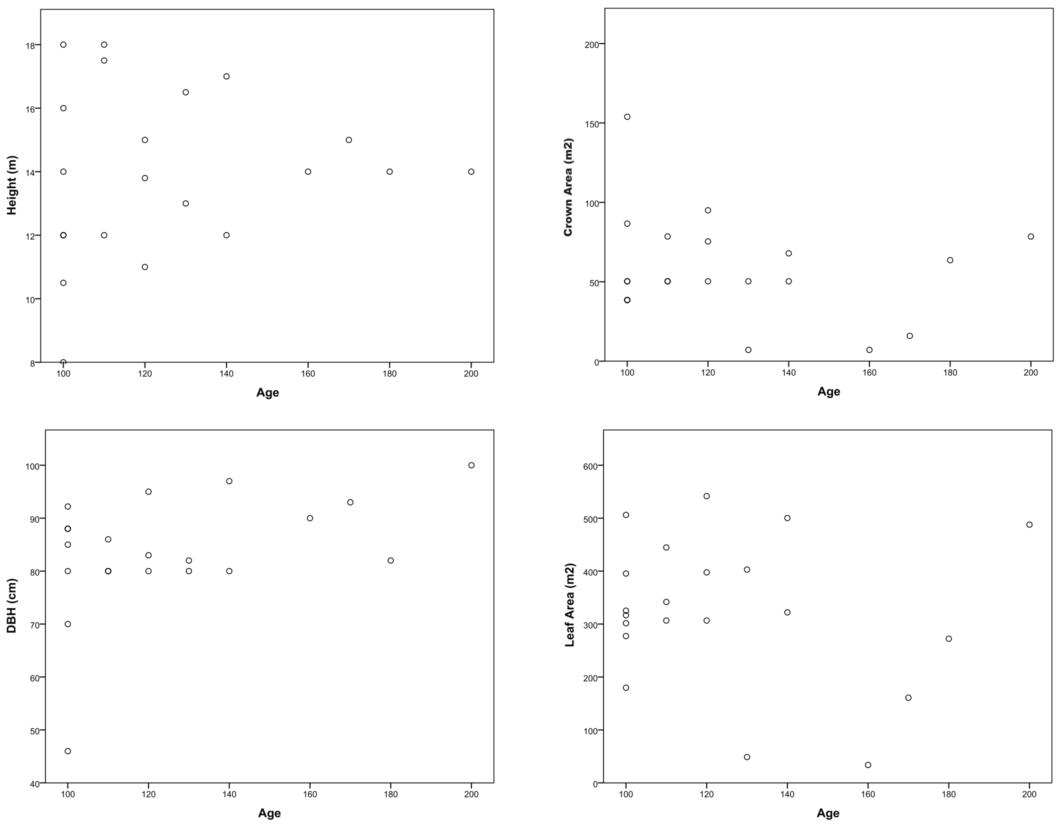
Ficus



Litsea



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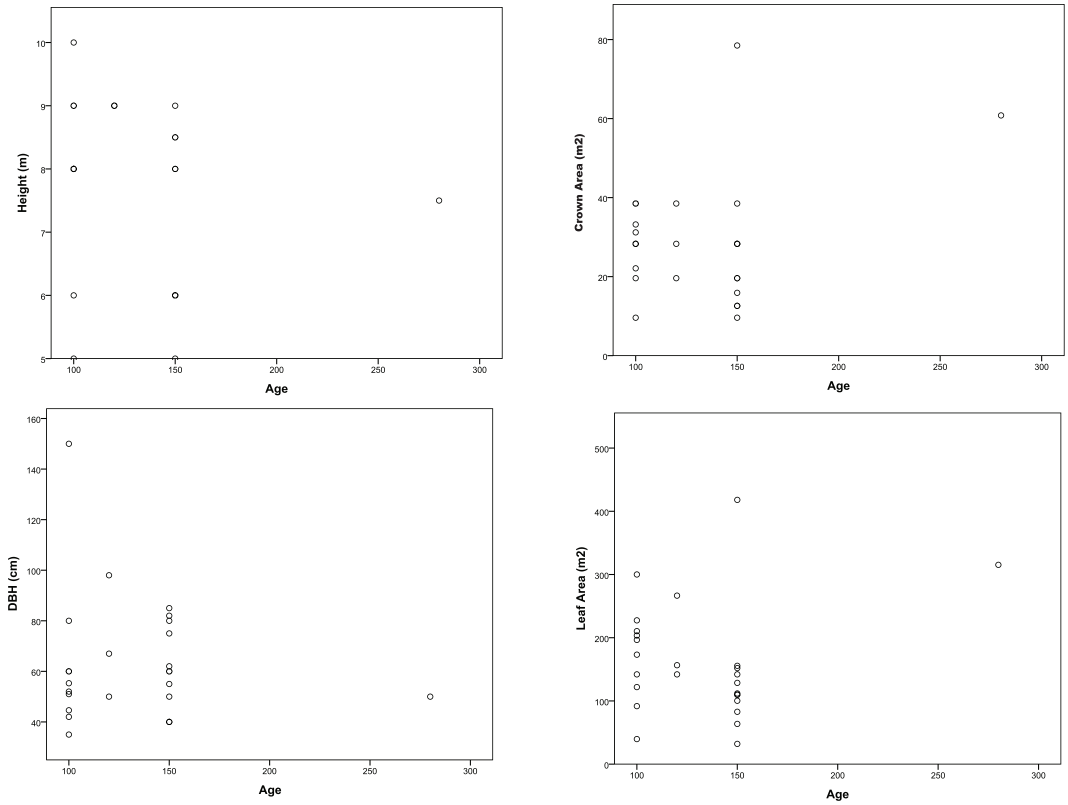
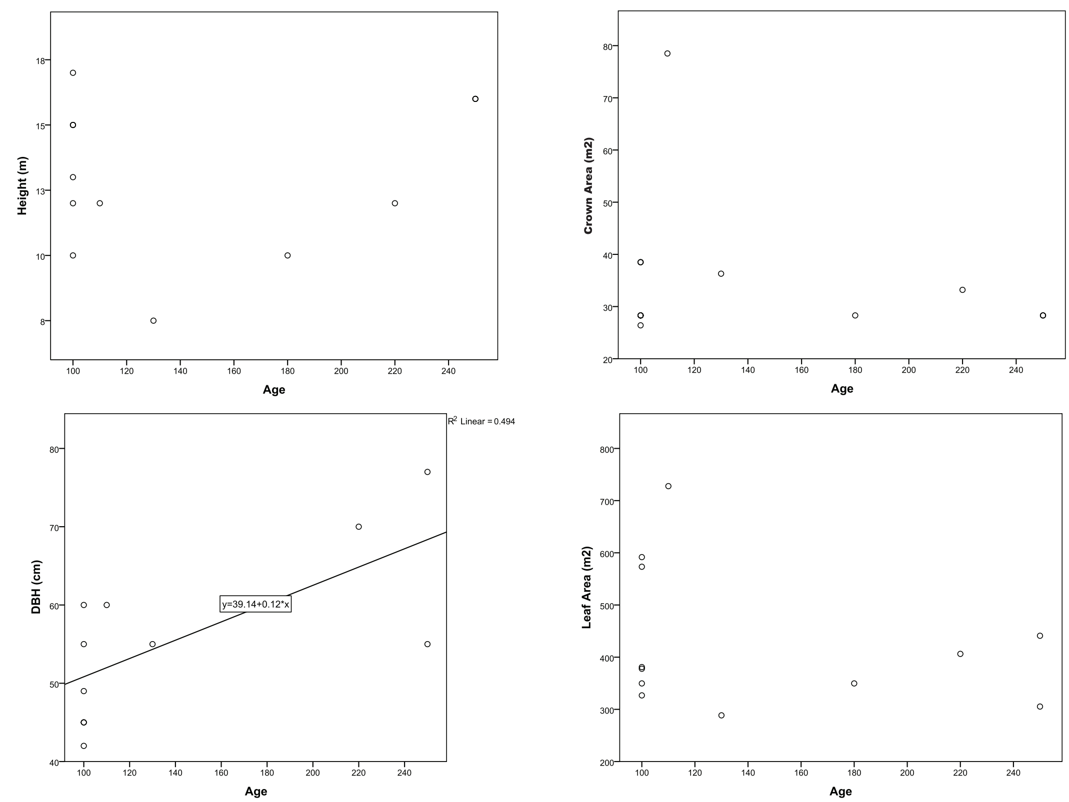
Plumeria



Podocarpus



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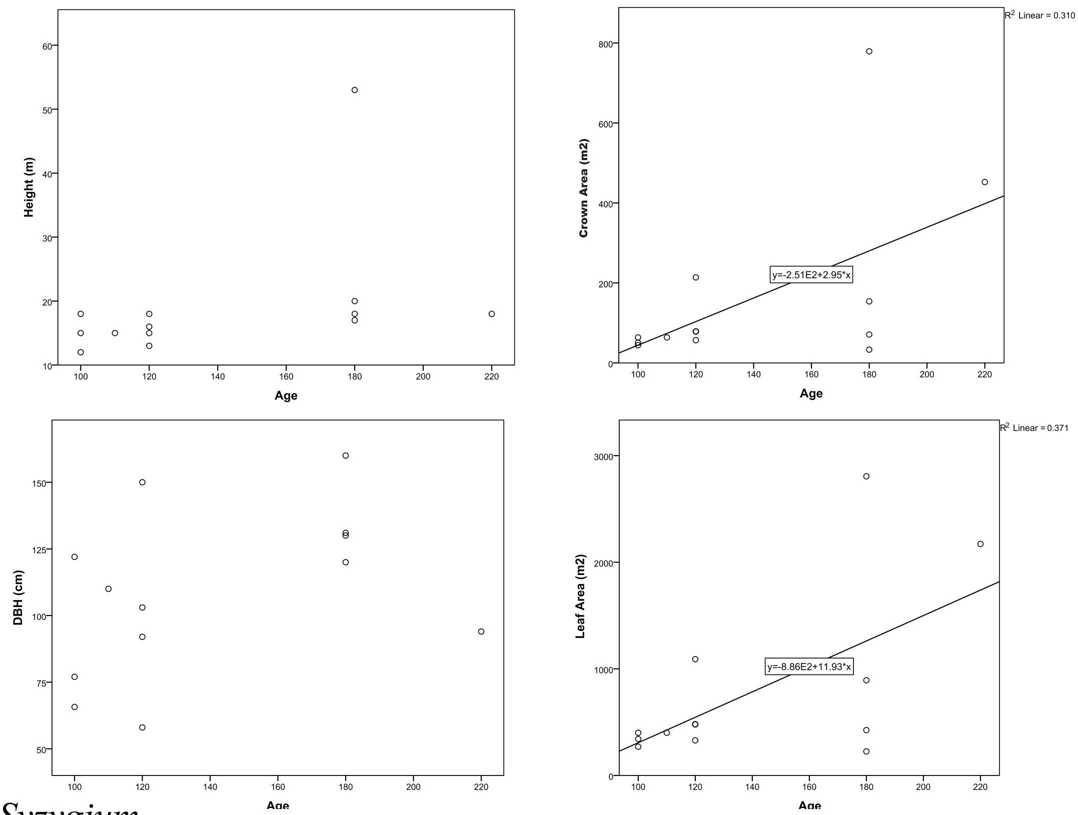
Pterospermum



Syzygium

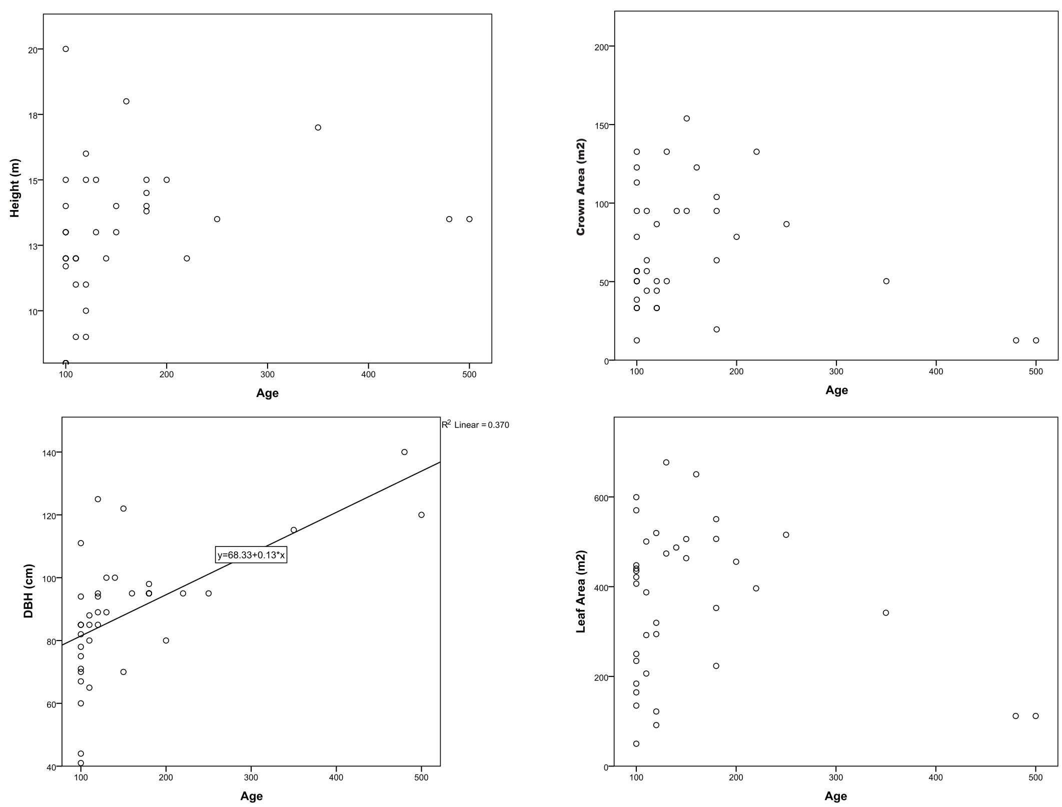


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Table 3. Annual air pollutant removal, gross carbon sequestration, and carbon storage of 790 heritage trees in Macau, 2011 through 2012, computed by genus, tree location, and geographical origin.

	Genus	No. of trees	Air pollutant removal (g/yr)							Gross carbon sequestration (kg/yr)	Carbon storage (kg)
			CO	O_3	NO_2	SO_2	$PM_{2.5}$	PM_{10}	Total		
	Acacia	2	199	2,653	1,600	983	5	438	5,877	79	5,747
	Aglaia	1	1	5	10	1	0	11	29	8	135
	Albizia	14	425	1,617	3,313	318	58	4,339	10,070	663	36,278
	Aleurites	10	278	1,056	2,163	208	24	1,754	5,482	480	26,441
	Aporosa	1	10	39	80	8	1	61	200	17	534
	Araucaria	1	28	107	219	21	1	70	447	16	919
	Artocarpus	6	221	1,654	1,742	523	18	1,471	5,629	211	13,703
	Averrhoa	4	145	1,090	928	404	12	1,129	3,707	180	9,254
	Bombax	21	1,025	4,966	7,301	1,558	83	7,089	22,021	986	69,295
	Bridelia	3	188	1,586	1,488	524	15	1,252	5,052	70	2,977
	Canarium	1	20	75	153	15	1	107	370	33	1,611
	Cassia	2	264	1,002	2,053	197	6	443	3,965	71	3,763
	Celtis	10	670	4,212	4,790	1,360	64	5,531	16,627	333	26,588
	Cinnamomum	44	2,073	10,759	15,285	3,066	189	15,576	46,949	1,751	154,241
	Cleistocalyx	3	163	1,355	1,293	445	13	1,098	4,367	123	8,490
	Cordia	1	34	129	264	25	3	191	646	44	2,638
	Delonix	11	568	3,286	4,456	920	47	3,685	12,962	489	33,445
	Dimocarpus	38	1,656	10,557	10,799	3,705	127	11,853	38,697	1,337	50,363
	Diospyros	1	27	103	211	20	2	150	513	27	1,166
	Dracontomelon	2	108	411	842	81	10	728	2,179	83	4,918
	Elaeocarpus	3	113	428	876	84	9	673	2,182	107	5,693
	Erythrina	8	483	3,353	2,121	1,479	33	3,966	11,435	425	30,878
	Eucalyptus	1	35	135	276	27	1	100	574	18	5,448
	Ficus	440	19,793	156,280	140,949	54,667	1,555	140,142	513,386	11,558	2,241,163
	Hibiscus	1	11	42	86	8	1	82	230	23	880
	Ilex	2	185	703	1,439	138	8	610	3,083	71	3,870
	Lagerstroemia	2	14	181	109	67	1	108	479	17	359
	Litchi	2	94	656	741	202	7	592	2,292	60	2,303
	Litsea	21	681	2,924	5,168	695	53	4,102	13,622	871	47,292
	Lophostemon	1	42	563	340	209	3	303	1,460	30	1,379
	Macaranga	1	124	471	965	93	10	773	2,436	50	3,391
	Machilus	2	162	2,165	1,305	802	14	1,248	5,696	37	6,472
	Mangifera	2	93	356	728	70	8	555	1,810	79	7,123
	Manikara	1	33	124	254	24	2	176	614	27	1,152
	Michelia	3	157	597	1,222	117	12	884	2,988	114	7,043
	Morus	4	130	1,211	1,032	412	11	911	3,706	169	7,022
	Murraya	3	32	121	247	24	3	190	616	52	1,832
	Ormosia	1	63	837	505	310	5	466	2,186	15	454
	Phyllanthus	1	16	218	132	81	1	118	566	13	350
	Pinus	3	60	228	468	45	4	274	1,078	41	2,316
	Plumeria	26	417	1,680	3,110	391	32	2,531	8,162	609	31,255
	Podocarpus	12	1,063	4,042	8,278	795	35	2,609	16,822	117	5,018
	Pterospermum	13	1,023	3,893	7,973	766	84	6,237	19,976	425	49,477
	Rhaphiolepis	4	28	369	222	137	2	206	964	18	246
	Sapindus	3	103	578	521	236	7	794	2,239	99	4,221
	Sapium	6	173	1,006	1,354	283	14	1,117	3,946	153	6,522
	Schefflera	2	14	53	109	11	1	81	269	54	2,351
	Sterculia	7	162	617	1,264	121	13	987	3,165	181	9,054
	Syzygium	38	1,386	6,406	9,613	1,861	107	9,124	28,497	1,529	100,190
	Ulmus	1	83	315	646	62	4	332	1,442	72	3,502
Location	Street tree	289	11,434	94,160	77,555	34,530	888	84,263	302,830	9,653	1,334,392
	Non-street tree	501	23,441	143,053	173,483	44,065	1,832	153,005	538,879	14,383	1,706,371
Origin	Native species	300	16,657	89,907	123,546	26,123	1,322	108,472	366,028	11,406	953,895
	Exotic species	490	18,217	147,306	127,492	52,473	1,398	128,796	475,681	12,630	2,086,869
Total		790	34,875	237,213	251,038	78,596	2,720	237,268	841,709	24,036	3,040,764

Table 4. The associations between the 10 most common genera and annual air pollutant removal indicated by Kruskal-Wallis test and their gross carbon sequestration and carbon storage per tree.

	Air pollutants removal (g/tree/yr)								
Genus	CO	O_3	NO_2	SO_2	$PM_{2.5}$	PM_{10}	Total	Gross carbon sequestration (kg/tree/yr)	Carbon storage (kg/tree)
Albizia	30.4	115.5	236.6	22.7	4.1	309.9	719.3	47.3	2,591.3
Bombax	48.8	236.5	347.7	74.2	3.9	337.6	1,048.6	47.0	3,299.8
Cinnamomum	47.1	244.5	347.4	69.7	4.3	354.0	1,067.0	39.8	3,505.5
Dimocarpus	43.6	277.8	284.2	97.5	3.4	311.9	1,018.3	35.2	1,325.3
Ficus	45.0	355.2	320.3	124.2	3.5	318.5	1,166.8	26.3	5,093.6
Litsea	32.4	139.3	246.1	33.1	2.5	195.3	648.7	41.5	2,252.0
Plumeria	16.1	64.6	119.6	15.1	1.2	97.3	313.9	23.4	1,202.1
Podocarpus	88.6	336.8	689.8	66.2	2.9	217.4	1,401.8	9.8	418.2
Pterospermum	78.7	299.5	613.3	58.9	6.4	479.8	1,536.6	32.7	3,805.9
Syzygium	36.5	168.6	253.0	49.0	2.8	240.1	749.9	40.2	2,636.6
χ^2	341.4	142.4	83.8	134.4	81.1	74.6	141.1	68.4	99.7
df	9	9	9	9	9	9	9	9	9
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

results can be considered by decision-makers as a factor for species selection in establishing an urban forest that can maximize ecosystem services in terms of air-pollutant removal and carbon sequestration. However, it should be reminded that concentrating on a few species for the urban forest as a whole is undesirable due to limitations to biodiversity.

The principal component analysis was used to investigate the relationships among carbon sequestration, carbon storage, and air-quality improvement of the 10 most common genera. Two principal components had an eigenvalue larger than 1. PC1 explained 59% of the variance, mainly correlated with carbon storage. PC2 explained 20% of the variance, mainly correlated with O_3, NO_2, PM_{10}, and SO_2 removal (Figure 5). The trees clustered at relatively high carbon storage and average air-pollutant removal were mostly shouldered by *Ficus* spp. (Figure 5). A *Ficus microcarpa* with 25 × 30 m canopy scored the best performance by carbon storage and air purifying capacity, followed by a *Pterospermum heterophyllum* with 28 × 35 m canopy. Both trees were sited at the remote Ilha Verde. Without growing stresses of the dense urban center, these exceptional heritage trees had realized their potential biological capacity to provide outstanding ecosystem services. *Plumeria* spp., common in urban parks and cemeteries (Zhang et al. 2017), had a lower capacity in carbon storage and air purification. It might not be a suitable species for effective provision of ecosystem services.

This study provided estimation of ecosystem services furnished by heritage trees. Pollutant removal varied among cities due to the amount of tree cover, tree age, size and performance, pollution concentration, length of the in-leaf season, and meteorological variables that affect transpiration and deposition velocities (Nowak et al. 2006). Macau has to accommodate a large human population relative to its tiny land area. With an excessively compact development mode, little land is available for urban greening. For the dispersed air pollutants that are difficult to scrub by artificial means, the meager amount of greenery offers some natural and sustainable abatement. Tree quantity, quality, dimension, and location would jointly regulate the efficacy of air-pollution mitigation. Poor air quality in urban areas impinges on an exceptionally large number of citizen victims. The heritage trees, comprised of the largest and longest-living doyens of the urban tree stock, play a critical role in bestowing ecosystem services and environmental health on the city.

Monetary Values

Together, the studied trees generated US $8,692 monetary benefits per year, in which CO removal was US $180, O_3 was US $2,810, NO_2 was US $2,974, SO_2

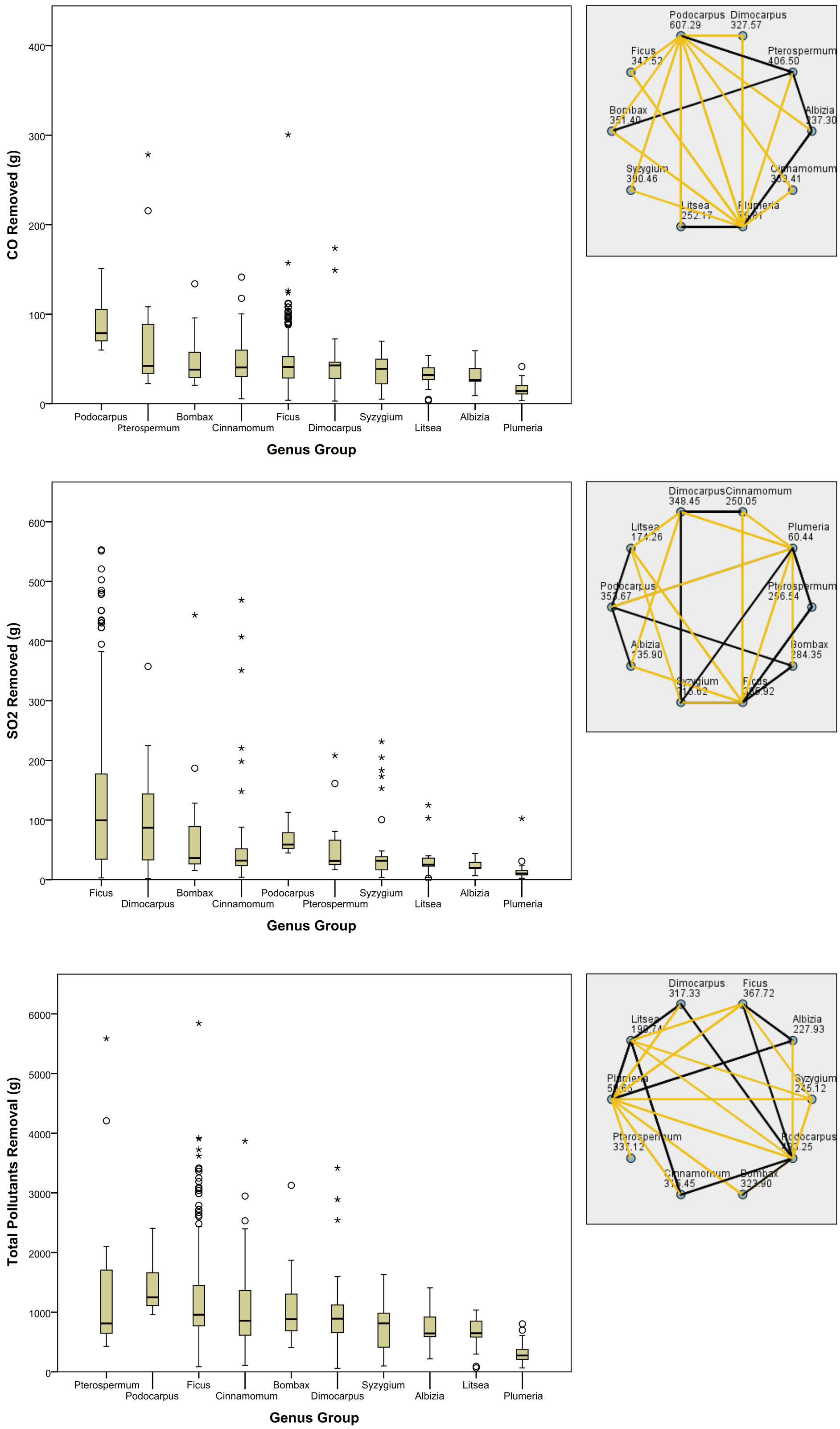
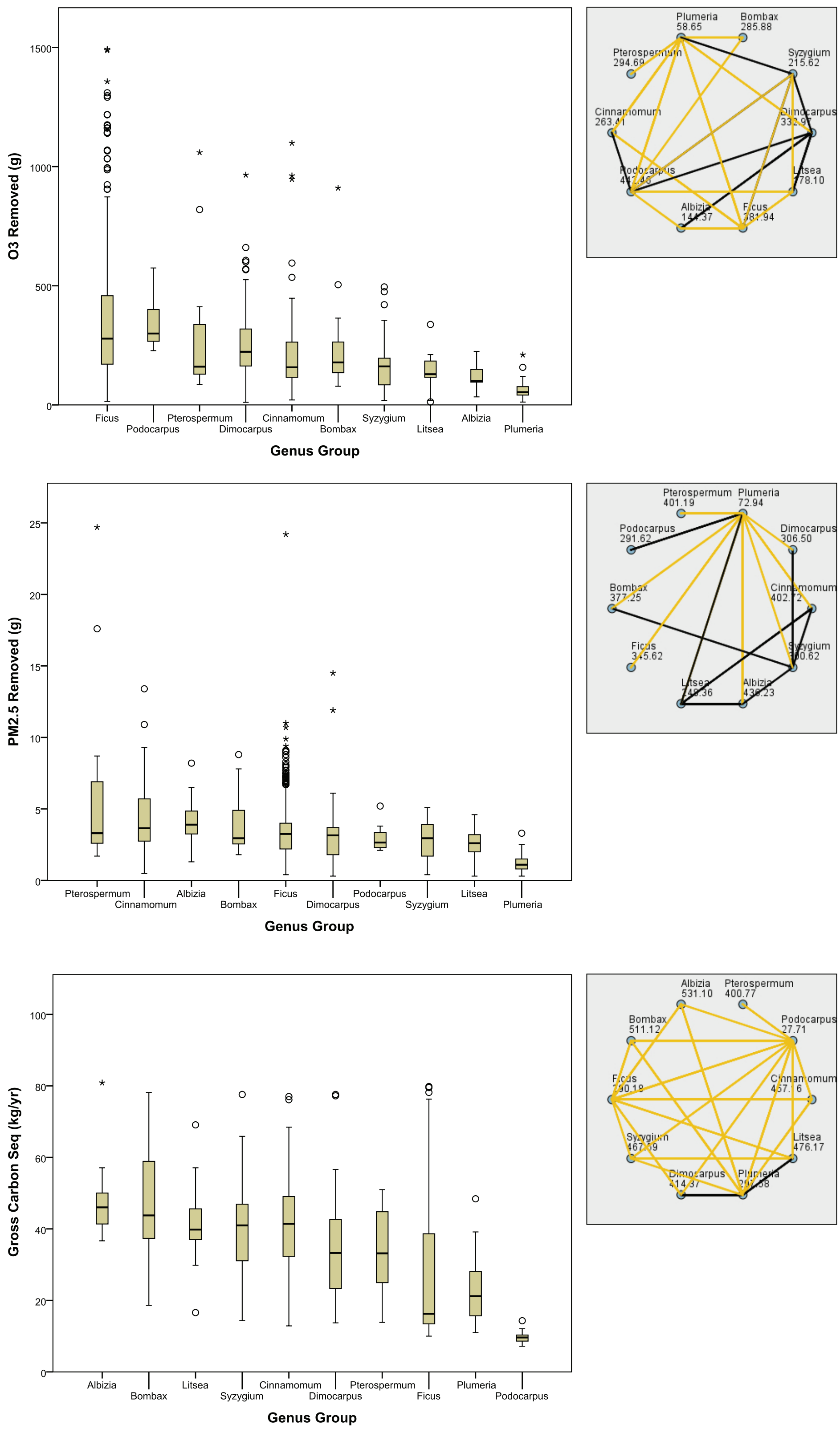


Figure 4. Annual air-pollutant removal, gross carbon sequestration, and carbon storage per tree of the 10 most common genera. Dark line in the boxes: the median; boxes: the 25th and 75th percentile; T-bars: inner fences; points: outliers; asterisks: extreme outliers (cases with values more than three times the height of the boxes). Results of the pairwise comparisons of genus groups are shown at the right of the boxplots. Each node shows the sample average rank of genus group. Yellow lines indicate $P < 0.05$.



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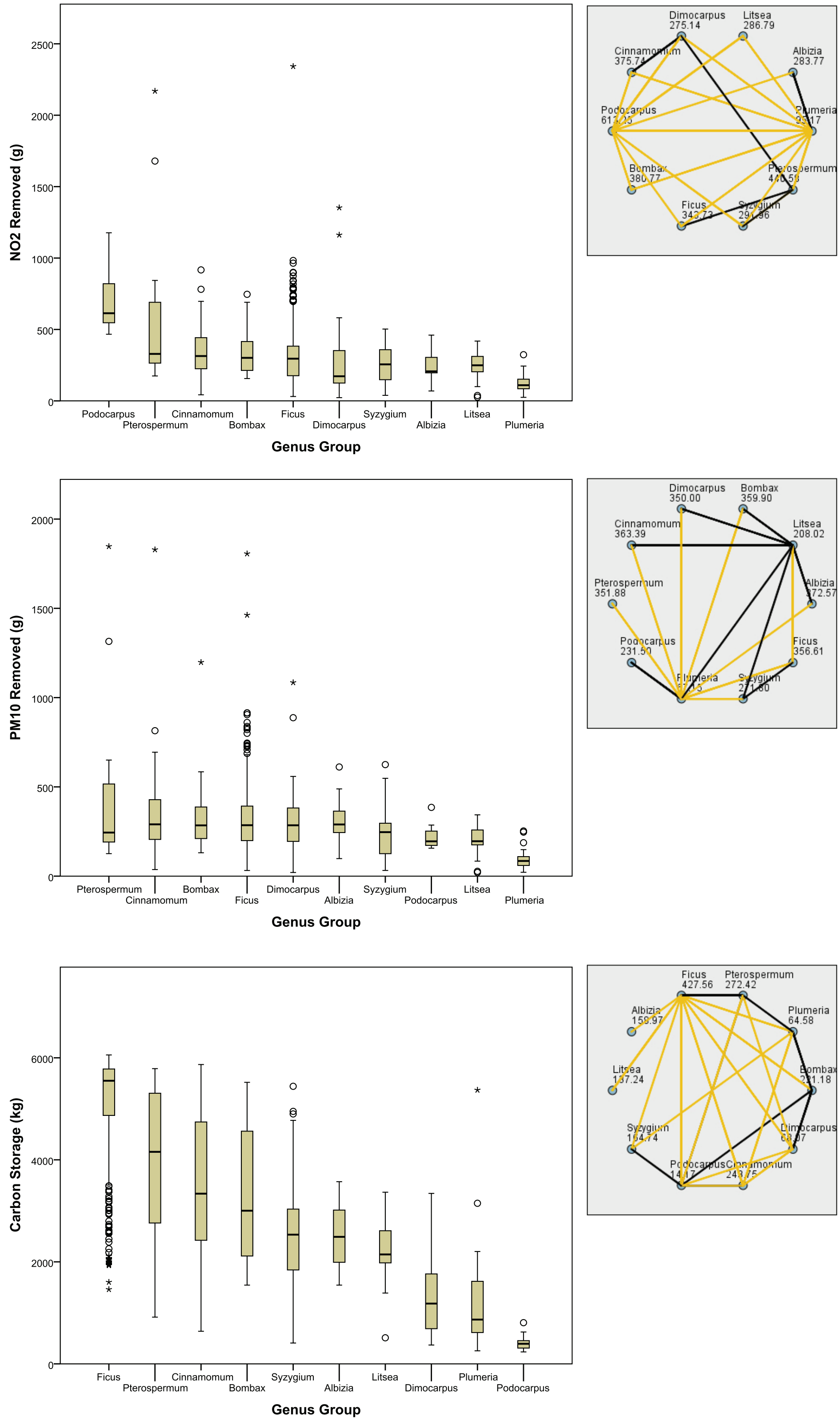

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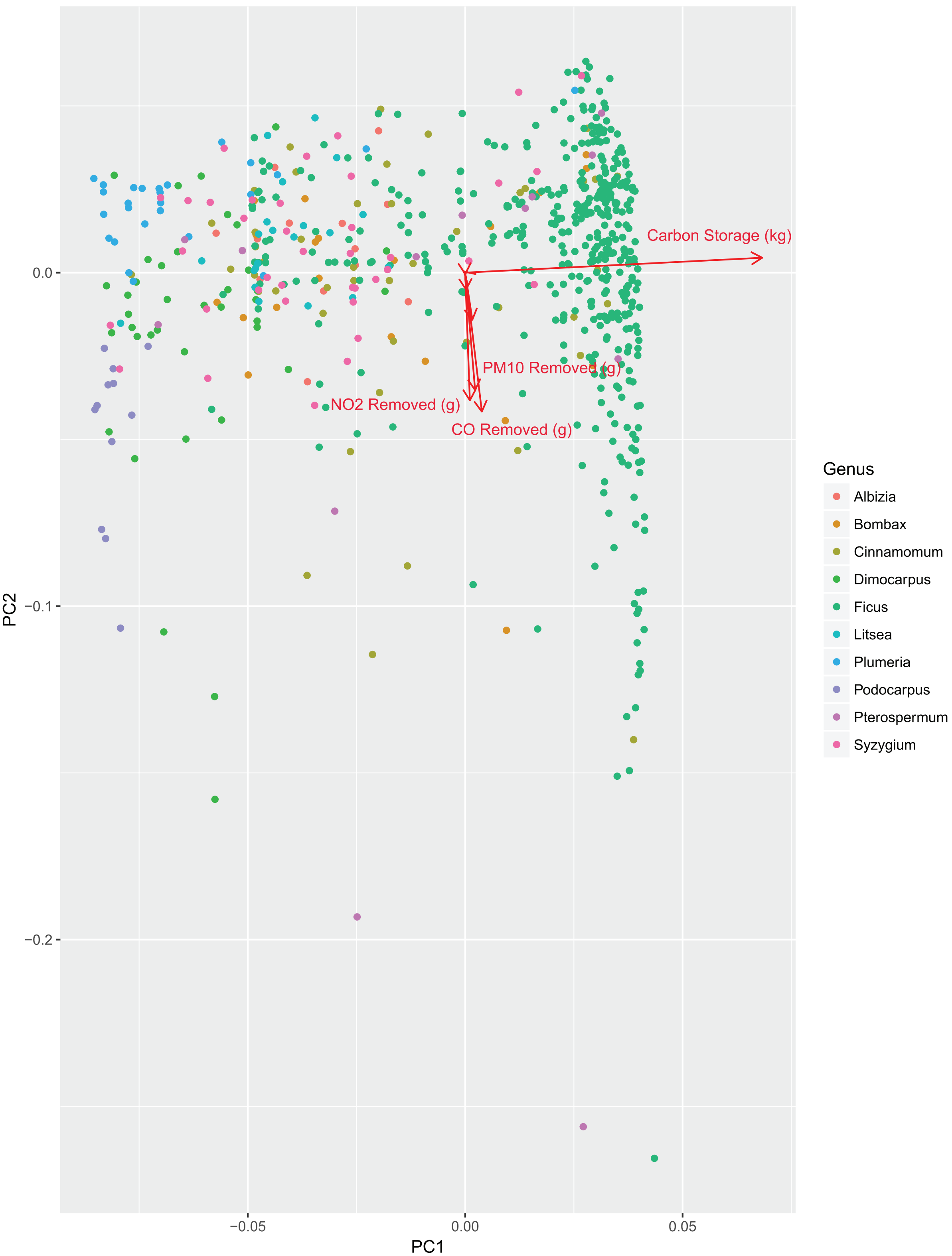

Figure 5. The first two principal components (PCs) for the ecosystem services of the 10 most common genera of the heritage trees in Macau. The arrows show major ecosystem services that are correlated with the PCs.

was US $228, $PM_{2.5}$ was US $22, PM_{10} was US $1,877, and carbon sequestration was US $601. The carbon storage value by all of the heritage trees was US $76,019. The average value provided by heritage trees was US $10.2/tree/yr from air purification, US $0.8/tree/yr from carbon sequestration, and US $96.2/tree/yr from carbon storage. The monetary values were much lower than expected.

Calculation of monetary values depended on the cost of pollutant removal or the market price of carbon emission. Regarding the monetary values of ecosystem services, the relevant information is lacking for Macau and rather inadequate in the literature. Nowak et al. (2008) calculated the values of ecosystem services of urban forests for the United States. Other similar studies have been conducted. For example, in China, the economic benefits of NO_2 reduction were estimated to be CNY 21,383/t, and the benefits of SO_2 reduction were estimated to be CNY 4,757/t in 2010 (Pedersen et al. 2014). Converted by the exchange rate (exchange rate at USD : CNY = 1 : 6.8 in 2010) and adjusted by inflation (8.8% in 2010 through 2012 in Macau), NO_2 reduction had an estimated value of US $3,421/t and SO_2 an estimated value of US $761/t. Based on these values, the heritage trees in Macau only provided one-fourth to one-third of the benefits of NO_2 and SO_2 removal on a monetary basis because of a lower monetary value projection for air-pollutant removal in China, partly due to the considerable discrepancy in price indices between China and western countries.

However, the air purification ability of trees subsidized the cost of air-pollution reduction or created economic benefits to the society such as reduction of health-care costs. The benefits were proportional to the population density. The per-tonne values of NO_2, SO_2, O_3, and $PM_{2.5}$ were calculated by regression equations in conjunction with population density for urban areas in the United States by Hirabayashi (2014). With Macau's high population density, which reached 19,000 people/km^{-2} (Statistics and Census Service 2013), the monetary values were US $10,564/t, US $2,838/t, US $74,008/t, and US $2,821,256/t, respectively, for NO_2, SO_2, O_3, and $PM_{2.5}$. The monetary value of air purification by the heritage trees would be about 3.5 times the calculated values from Nowak et al. (2008). A similar situation was found for the cost of carbon removal. For example, the economic benefits of CO_2 reduction in China were CNY 130/t in 2010 (Pedersen et al. 2014). Meanwhile, the Carbon Pricing of Guangdong Emissions Trading Scheme was only set at US $10/t in 2013 (The World Bank 2014). The differences in the carbon reduction price could be as large as 13 times the current literature. The monetary benefit gained from carbon sequestration and storage of the heritage trees in Macau depended not only on the tree size and carbon sequestrating ability; it also depended on the market's monetary value for CO_2 reduction using technological means.

Different monetary values of the heritage trees could be estimated due to widely divergent costs of abatement for pollutants and carbon, which may differ by 10 times. The benefits of air-pollutant reduction should be unusually large in Macau in comparison with other cities, due to the inordinately high average population density, which is the second highest in the world (The World Bank 2017c). Adverse impacts of air pollution have affected millions of residents in dense urban areas. Reducing pollution concentration can significantly depress the total medical expenses of a community and generate a huge economic value to the society. Trees in urban areas with a large human population can bestow an exceptionally valuable health service on more citizens on a sustainable basis.

This study estimated the value of the removal of five air pollutants and gross carbon sequestration by the heritage trees without addressing additional local and direct ecosystem services of trees, such as micro-climate regulation, noise abatement, rainwater drainage, groundwater recharge, flood prevention, sewage treatment, and recreational and cultural values (Bolund and Hunhammar 1999). Cooling due to urban greening can contribute to potential carbon avoidance from energy saving of buildings, which could be four times larger than the direct carbon sequestration rate of vegetation (Nowak and Crane 2000). The 309 park trees in Toronto, Canada, were estimated to provide US $29,251 in total (US $95/tree/yr)(Millward and Sabir 2011), which contributed 61% of services in relation to local property value, energy savings, and stormwater reduction. Air-quality improvement and CO_2 reduction only accounted for 5% and 1% of total benefits, respectively. The potential values of the heritage trees will be much higher if the monetary value computation can include more ecosystem services. Under such estimation, the heritage trees in Macau would provide up to US $221,905 (US $281/tree) annually.

Further Studies

A tree increases its dimensions with age, and this progressive accretion provides more and better ecosystem services, fostered by good management practices and a suitable growing environment. In this study, not all heritage trees showed a positive relationship between tree dimensions and tree age. Surveys have to be carried out to understand the growth rate of trees at different ages at remote and urban areas. Any established equations would help better modeling of projected future ecosystem service provision. Besides employing the growth factors of old trees to improve carbon sequestration calculation, it can serve as a management tool to estimate changing growth space and associated tree-care requirements.

i-Tree Eco provided a reasonable estimation of ecosystem services contributed by the heritage trees in Macau. However, relationships between trees and environment were complex and they tended to highlight the inherent limitations of the common models. Additional studies could be conducted to enhance the understanding of ecosystem services provided by heritage trees. Firstly, research on crown volume and biomass equations for species in south China will provide a more accurate estimate of their ecosystem services. Secondly, finding out growth factors at different ages will refine the carbon sequestration calculation for trees at various growth stages. Thirdly, the current monetary values of air-pollution abatement are limited to common pollutants, and the values vary greatly among study regions. Investigation of the marginal cost of a wider range of pollutants at regional and local scales could be attempted. Lastly, other hitherto widely neglected potential benefits of heritage trees, including environmental, ecological, social, and cultural benefits, could be evaluated and quantified. These suggested studies could begin with heritage trees and extend to other urban-forest components. The results could provide a comprehensive and objective basis to strengthen decisions and management.

CONCLUSIONS

The increasingly urbanized world population, driving rapid urban sprawl and in situ urban renewal and densification, especially in developing countries, can induce widespread degradation in urban environmental quality. Climate change impacts, urban heat island effects, and air pollution have jointly aggravated the conditions of life in many cities. Stresses on human mental and physical health and other natural components embedded in cities call earnestly for effective solutions. Among different mitigating measures, urban trees and associated urban green infrastructures could contribute notably to nature-based solutions to drive cooling and cleaning in a cost-effective and sustainable manner. Understanding the air-pollution abatement, carbon sequestration capabilities, and the more critical ecosystem services offered by trees can inform tree planning, planting, care, and conservation.

Whereas the environmental benefits of greenery have been widely advocated for and understood, the economic value has received less attention. Conversion of tree benefits to dollar terms can enhance assessment and appreciation of their benefits using a universal and layman language. The monetary value can also strengthen the justifications to deploy public funds in urban greening programs and put the requests on a level playing field in the keen competition for funding with other pressing public expenditure items. Decision makers, managers, and citizens will be better equipped to appreciate the important contributions of trees vis-à-vis other environmental protection and enhancement measures. The long-term monetary values, in particular, can enrich debates and inform judgments in the contests between development and conservation. Using the i-Tree Eco model in the study site has several limitations. A localized database for evaluating values of heritage trees could be developed. It is important to develop planning and conservation policies based on scientific research to justify the costs of management and conservation of heritage trees and urban trees in general.

As the finest exemplars of the urban tree stock in terms of age, size, tree form, aesthetic qualities, genetic composition, growth performance, ecological benefits, biodiversity significance, historical connection, cultural association, and sentimental attachment, heritage trees play a pivotal role in offering truly multivariate if not outstanding services to cities. They are the remnant daughter population of the toughest constitution that has survived the harsh urban selective forces. Some of them have exceptional ability to tolerate environmental stresses and human abuses. Some could attain heritage caliber due to survival in suitable places where they could escape damage or removal by changing land use or urban intensification. Some could be overlooked or ignored and left by default. Others could be given special protection under the aegis of enabling public policies or legislation, often in response to people's quests to preserve them as living landmarks or cultural or religious symbols. In most cities, only a small cohort of urban trees could soldier on for a century or more to reach extraordinary size. Their cumulative sizeable dimensions and relative vigor offer a high capacity for ecosystem services. Their persistence in the urban milieu provides ample hints to optimize tree growth and management in cities. Their numbers may not be large, but their individual and collective environmental contributions, measured mainly by crown size, leaf area, and trunk diameter, can be appreciably higher than ordinary urban trees. An in-depth study of this special cohort can lay a foundation for a comprehensive assessment of the whole urban tree stock. Past studies of heritage trees tended to focus on botanical and ecological domains. Evaluation could be expanded to cover their varied ecosystem services and economic valuation.

Contributions of urban trees have been studied in many cities, but few have focused the scope squarely on the most outstanding tree subset. The results of this study have provided an approximation of air-quality improvement and gross carbon sequestration by heritage trees using the well-established and well-tested i-Tree Eco model. Despite some data inadequacies and estimation uncertainties, some useful results have been generated. They demonstrate convincingly that heritage trees can be effective in removing air pollutants and sequestrating and storing carbon, which can bestow considerable monetary values in the long run. The benefits were several times higher than ordinary urban trees.

A clairvoyant strategy can be distilled from the findings with far-reaching consequences. Keeping more urban trees healthy and vigorous can be extremely worthy of the extra efforts and investments. By extending their life span and sustaining their performance, more individuals can be ushered to the superior heritage tree cohort, thus significantly raising overall services and values of the urban tree population. The findings, therefore, highlight a new dimension in the interpretation of heritage tree benefits in urban areas. Especially for compact cities where planting sites are inadequate, tree management should concentrate on nurturing a meritorious cohort of outstanding elites, rather than providing a multitude of commonplace products.

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Résumé. Il est attendu que les vieux arbres en bonne santé fourniront davantage de services écosystémiques ainsi que leur équivalent en valeurs économiques en raison de leurs grandes dimensions. Le rapport entre les dimensions des arbres, respectivement la hauteur, la superficie du houppier, le diamètre à hauteur de poitrine (DHP) et la surface foliaire totale vis-à-vis de l'âge fut analysé pour 790 arbres monumentaux âgés de 100 ans et plus situés à Macau; 50 genres et 63 espèces furent représentés. Parmi les dix genres les plus courants, sept ne montrèrent aucune augmentation significative pour tous les paramètres analysés à l'exception de l'accroissement en diamètre avec l'âge. D'autres facteurs, dont la condition et la configuration des espaces de croissance, influent sur la performance des arbres monumentaux, tout autant que la réalisation de leur potentiel biologique en termes de dimensions avec des implications pour la production de services écosystémiques. Les impacts de ces arbres monumentaux sur l'amélioration de la qualité de l'air et la séquestration brute du carbone ont été quantifiés par le modèle i-Tree Eco. Au global, 806.8 kg de polluants atmosphériques ont été extirpés annuellement pour des bénéfices évalués à 8,091 US $. Les arbres monumentaux ont emmagasiné au total 3,041 tonnes de carbone et séquestré 842 kg de carbone par année, équivalent à 601 US $ de bénéfices annuels. Ces valeurs furent nettement supérieures à celles des arbres usuels des forêts urbaines. Un classement de dix genres courants d'arbres monumentaux fut établi en fonction de leur capacité pour l'amélioration de l'air, le stockage et la séquestration du carbone. Ces résultats peuvent être utilisées comme un outil décisionnel pour la gestion et la conservation des arbres monumentaux ainsi que pour évaluer les services écosystémiques potentiels d'arbres établis.

Zusammenfassung. Von älteren Bäumen mit guter Gesundheit erwartet man, daß sie wegen ihrer Größe mehr ökonolischen Nutzen und äquivalent auch ökonomische Werte liefern. In Macau wurden die Beziehung von drei Dimensionen, respektive Baumhöhe, Kronenfläche, Brusthöhendurchmesser und totale Blattfläche im Hinblick zum Alter an 790 Naturschutzbäumen ($\geq$ 100 Jahre alt) untersucht, wobei 50 Gattungen und 63 Arten repräsentiert waren. Sieben von zehn häufigen Gattungen zeigten keinen signifikanten Anstieg bei allen getesteten Parametern mit Ausnahme des gestiegenen Brusthöhendurchmessers mit dem Alter. Andere Faktoren, so wie der Zustand und die Geometrie von Pflanzflächen, kontrollierten die Leistung der Naturschutzbäume mehr, wie auch die Realisation von ihrer biologischen potentiellen Größe, mit Implikationen auf deren Ökosystemleistungen. Die Effekte dieser Naturschutzbäume auf die Luftqualitätsverbesserung und die maximale Kohlenstoffbindung wurden mit dem i-Tree Eco Modell quantifiziert. Insgesamt wurden jährlich 806.8 kg von Luftverschmutzern entfernt, was einen Nutzen im Wert von US $8.091 entspricht. Die Naturschutzbäume speicherten 3.041 t Kohlenstoff und verwandelten 842 kg Kohlenstoff/Jahr, das entspricht einem Äquivalent von US $601 Nutzen pro Jahr. Die Werte waren viel höher als bei normalen Stadtbäumen. Zehn Naturschutzbaumgattungen wurden bewertet durch ihrer Kapazitäten für Luftverbesserung, Kohlenstoffspeicherung und Bindung. Die Ergebnisse können als Entscheidungskriterium für die Pflege von Naturschutzbäumen und deren Erhaltung und zur Abschätzung von potentiellen Ökosystemleistungen von etablierten Bäumen dienen.

Resumen. Se espera que los árboles más viejos con buena salud y debido a su gran tamaño proporcionen más servicios del ecosistema y valores económicos equivalentes. La relación de las dimensiones de los árboles: altura, área de la copa, diámetro a la altura del pecho (dap) y área total de la hoja con respecto a la edad se estudiaron para 790 árboles patrimoniales de ≥ 100 años en Macao. Estuvieron representados 50 géneros y 63 especies. Siete de cada diez géneros comunes no mostraron un aumento significativo para todos los parámetros probados, excepto el aumento de dap con la edad. Otros factores, como la condición y la geometría de los espacios de crecimiento, controlaron el rendimiento de los árboles patrimoniales, así como la realización de su potencial biológico, con implicaciones en la provisión de servicios ecosistémicos. El modelo i-Tree Eco cuantificó los efectos de estos árboles patrimoniales en la mejora de la calidad del aire y el secuestro bruto de carbono. En total, se eliminaron 806.8 kg de contaminantes del aire anualmente, con beneficios valorados en US $8,091. Los árboles patrimoniales almacenaron 3,041 t de carbono en total y secuestraron 842 kg de carbono/año, lo que equivale a US $601 en beneficios anuales. Los valores fueron mucho más altos que los árboles forestales urbanos comunes. Diez géneros de árboles de patrimonio común se clasificaron según sus capacidades para mejorar la calidad del aire, el almacenamiento y el secuestro de carbono. Los resultados pueden servir como una herramienta de decisión para el manejo y la conservación de los árboles del patrimonio y para estimar los servicios potenciales del ecosistema de los árboles establecidos.