Aerosol and Air Quality Research, 15: 1291–1299, 2015
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ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2015.02.0110

Tree Species Diversity and Carbon Storage in Air Quality Enhancement Zones in Taiwan

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ABSTRACT

Taiwan had established air quality enhancement zones (AQEZs) by planting trees, aiming to improve air quality and ecological environment. Trees in the AQEZs reduce the amount of carbon dioxide in the atmosphere by storing carbon in their tissues. Species diversity is a critical factor influencing the capacity of trees to capture carbon. In this study, we assessed tree species diversity and estimated the carbon storage of AQEZs of 98 sampling plots located in four regions. The zones examined contained 210 species from 145 genera and 61 families. Study results showed that despite this apparent diversity, at least one species represented more than 10% of the identified trees in the four regions. The overall proportion of non-native species was relatively high at 58%. The greatest individual tree carbon storage was 8.93 metric tons and the mean tree carbon storage was 0.05 tons C/tree. An overall carbon storage of 672.20 tons C in the sampling plots is estimated and carbon storage benefits are expected to increase as these trees mature. The research outcomes can be used for reference for authorities in carbon policy making. Due to the benefits of tree planting, more AQEZs are suggested to build considering the increasingly important global warming issue.

Keywords: Air quality enhancement zone (AQEZ); Forest carbon; Urban forest; Green space.

INTRODUCTION

Climate change has been recognized worldwide as an unprecedented challenge. To continue reducing greenhouse gas emissions and to mitigate global warming, various carbon capture technologies have been proposed to reduce carbon dioxide (CO_2) emissions. CO, can be directly utilized, e.g., via microalgae, or converted to chemicals and energy products (Huang *et al.*, 2014). Regarding utilization, CO_2 can be used as an important carbon source to produce valuable chemicals and fuels (Reich *et al.*, 2014; Yan *et al.*, 2014). For example, CO, can be recycled through the photocatalytic reduction of CO_2 into hydrocarbon fuels (Wang *et al.*, 2014). CO, can also be absorbed by special materials, such as Zr-Fumarate MOF (Ganesh *et al.*, 2014). In Nature, CO, can be stored in sea rocks and trees. Deep saline aquifers are reported to have massive carbon storage capability through saline formation (Soong *et al.*, 2014; Yang *et al.*, 2014). Trees play an essential role in mitigating atmospheric carbon dioxide by sequestering carbon dioxide in growing trees and storing carbon dioxide in plant tissues (Nowak and Crane, 2002).

Forest tree shade and evapotranspiration also reduce increasing air conditioning demand, thereby reducing carbon dioxide emissions from burning fossil fuels for energy production (Akbari, 2002; Nowak and Crane, 2002). With rapid urbanization worldwide, urban forests and green spaces have become an increasingly crucial component of the world's forested ecosystems. Urban forests also entail multiple social, aesthetic, landscape, physical, ecological, and economic benefits. Among these are reducing urban air pollution and improving air quality (Akbari, 2002), controlling rainfall-generated runoff (Xiao and McPherson, 2003), regulating microclimates (McPherson, 1990), decreasing noise pollution (Millward and Sabir, 2010), providing wildlife habitat (Angold *et al.*, 2006; Millward and Sabir, 2010), mitigating the urban heat island effect, and saving electricity (Donovan and Butry, 2009). Urban forests also provide pleasant environments that promote physical and mental health (Ulrich, 1984; Price, 2003) and increase the value of nearby real estate (Tyrvainen and Miettinen, 2000).

Suitable management and maintenance are relatively critical to maximizing the health benefits of urban forests

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and green spaces and their ability to provide multiple benefits, among which are maintaining rich species diversity (Raupp *et al.*, 2006). Species diversity is critical to the sustainable development of urban forests (Clark *et al.*, 1997). Species diversity and forest health are closely related, thus properly managing urban forests requires fully understanding species richness and evenness (Sun, 1992).

From 1911 to 2009 in Taiwan, the mean annual temperature increase was 1.4°C, with a mean warming rate of 0.14°C every 10 years, higher than the global mean warming rate of 0.074°C (Intergovernmental Panel on Climate Change [IPCC], 2007). Taiwan's mean annual sea level increase from 1993 to 2003 was 5.7 mm/yr, with the mean increase rate doubling over the past 50 years, greater than the global mean increase rate of 3.1 mm/yr over the same period (IPCC, 2007). Varied scientific evidence and the current situation demonstrate that Taiwan faces even greater impacts and challenges from climate change than do numerous other countries. In 1995, Taiwan began promoting the establishment of air quality enhancement zones (AQEZs). These zones function as both urban forests and green spaces, and thus can improve air quality and the quality of the living environment, provide ecological and environmental education, and encourage sustainable practices. As of 2012, 527 AQEZs had been established in Taiwan. Forests in AQEZs mitigate the effects of carbon dioxide in the atmosphere. Species diversity is critical to this mitigation and to multiple other benefits of forests.

This study conducted an extensive survey of tree species diversity, growth, and estimated carbon storage at AQEZs in Taiwan. The contributions of this study are twofold. First, tree species diversity was extensively surveyed. Importance value index of plants is calculated in order to manifest the value of each tree species in different regions. Second, carbon storage of the trees was estimated. Timber volume and timber density are carefully examined and required forest biomass expansion coefficients and carbon content conversion coefficients are properly extracted. The amount of the estimated carbon storage can be used as an important index for future studies in carbon capture/storage and for carbon policy making.

MATERIALS AND METHODS

Plot Data

As of 2012, 527 AQEZs had been established island-wide. In this study, Taiwan was divided into northern (25 plots), central (35 plots), southern (28 plots), and eastern (10 plots) regions for sampling, comprising a total of 98 plots and five bicycle paths covering 53.29 ha and 7.42 km, respectively (Fig. 1).

Fig. 1. Survey regions.

Tree Survey Scope and Methods

To understand the status of forest growth in the AQEZs, this study conducted sampling surveys from August 2010 to December 2011 to collect forest-related data in zones in each county. The total area of sampling plots within the AQEZs was surveyed, and species names, numbers of trees, diameters at breast height (DBH), tree heights (Hs), and crown widths (CWs) were recorded. Herbaceous vegetation planted for landscape greening was not recorded.

Tree Species Diversity Survey

10–20–30 Rule Analysis

Barker (1975) first stressed the need to diversify street trees and suggested that the numbers of any single species should not exceed 5% of the total number of trees. To meet this objective of tree species diversity (Burcham, 2009), and had different views of the requirements for forest tree species diversity. Moll (1989) broadened the requirement by suggesting that the number of trees of any one genus should not exceed 10% of the total number of trees and that the number of tree of any one species should not exceed 5% of the total number of trees. Smiley *et al.* (1986) wrote that the total number of trees of a single species should not exceed 10% of the total number of trees. Grey and Deneke (1986) adopted a looser standard, suggesting that trees of a single species should not exceed 10–15% of the total number of trees. Currently, the most commonly used standard in studies of urban forest tree species diversity is the 10–20–30 rule that the number of trees of the same species, genus, and family should not exceed 10%, 20%, and 30%, respectively, of the total number of trees (Santamour, 1990). In addition to species diversity, whether the tree species planted are native or non-native and follow-up management are crucial. Trees planted in urban forests include different non-native species in addition to native species; therefore, although this increases tree species diversity, the impacts on forest health and the environment should also elicit widespread discussion among researchers (Pauleit *et al.*, 2002; Zhao *et al.*, 2010). Therefore, this study also considered whether planted trees were native or non-native species.

Importance Value Index Analysis

Importance value index (IVI) of woody plants, as proposed by Curtis (1959) and his associates at the Wisconsin School of North American Plant Ecology, were calculated to understand the dominance of tree species in the afforested sampling plots. In ecology, three plant community parameters (density, frequency, and dominance) are commonly used to express the degree of dominance of various plant species in a plant community, where frequency is the percentage of inventory points occupied by a given species, which is a measure of species distribution across the site; density is the average number of individuals per unit area (per acre or hectare); dominance is the average dominance of each species within the study area, which is estimated by its total basal area per unit area (ft^2 per acre or m^2 per hectare). However, the same parameters may have different uses among various plant species and communities. In this study, the IVI was represented as the average of relative frequency, relative density, and relative dominance, as described as follows:

$$\text{Importance Value Index (IVI)} = (\text{relative density} + \text{relative dominance} + \text{relative frequency})/3 \tag{1}$$

where
Relative frequency (%) = (frequency of a given plant species/sum of frequencies of all plants in the stand) × 100;
Relative density (%) = (number of individuals of a given plant species/number of individuals of all plant species in the sample plot) × 100;
Relative dominance (%) = (dominance of a given plant species/sum of dominances of all plant species in the sample plot) × 100.

Relative frequency represents the frequency of a given species divided by the sum of the frequencies of all of the species; relative density is the density of a given species divided by the sum of the densities of all of the species; relative dominance is the basal area of a given species divided by the sum of the basal areas of all of the species.

Estimating Tree Carbon Storage

Tree carbon storage can be estimated by converting timber volume and timber density to forest biomass and then using aboveground and underground forest biomass expansion coefficients with carbon content conversion coefficients to estimate carbon sequestration. Individual tree carbon content estimates were based on allometric timber volume regression-transformation models. The following equation was used to estimate aboveground single tree carbon storage from single-tree volume (IPCC, 2006):

$$C_{single\_tree} = V \times BD \times BEF \times (1 + R) \times CF \tag{2}$$

where C_{single_tree} = individual tree carbon storage (tons C), V = individual tree volume (m^3), BD = basic wood density ($tons/m^3$), BEF = biomass expansion factor, R = root:shoot ratio, and CF = forest carbon fraction. The details of these terms are described as follows.

Individual Tree Volume

Individual tree volume (V) was estimated using a form factor method calculation (according to the Taiwan Forestry Bureau [TFB], Forest Products Division's Volume Table for Harvest in Taiwan; TFB, 1997) by multiplying a mean form factor by breast height basal area (BA) and tree height, as in the following equation:

$$V = BA \times H \times f = (DBH/100)^2 \times 0.79 \times H \times 0.45 \tag{3}$$

where V = mean individual tree volume (m^3), BA = tree breast height basal area (m^2), DBH = diameter at breast height (cm), H = tree height (m), and f = mean form factor (0.45).

Basic Wood Density

The basic wood density (BD) is the oven-dry weight to volume ratio of peeled logs. Studies by Lin *et al.* (2002) determined that 24 types of timber products in Taiwan could be categorized as softwood (coniferous) or hardwood (broadleaf), with BDs of 0.31–0.55 kg/m^3 (mean 0.42 kg/m^3) and 0.37–0.77 kg/m^3 (mean 0.56 kg/m^3), respectively. Therefore, in this study, 0.42 kg/m^3 and 0.56 kg/m^3 were used for the BD of softwood and hardwood species, respectively.

Biomass Expansion Factor

The biomass expansion factor (BEF) is biomass expansion factor for conversion of merchantable volume to aboveground tree biomass. The BEFs used by Wang and Liu (2006) for Japanese cedars (*Cryptomeria japonica*) and camphor trees (*Cinnamomum camphora*) of 1.23 and 1.20, respectively, were used in this study for softwood and hardwood species.

Root:Shoot Ratio

The root:shoot ratio (R) is the ratio between belowground and aboveground biomass. Studies show that, among coniferous plantations in Taiwan, the greatest area is afforested with Japanese cedar. Therefore, according to previous studies, the Japanese cedar R of 0.280 (Lin *et al.*, 1999) was used for all softwood species in this study. Studies by Chen and Lu (1988) and Lin *et al.* (2007, 2009) have demonstrated interspecies differences in R among species in broadleaf plantations in Taiwan. Because many broadleaf species were investigated in this study, a mean R of 0.234, based on the above three studies, was used in the analysis of hardwood species.

Carbon Fraction

Carbon fraction (CF) here indicates the carbon fraction of the dry mass. Studies by Lin *et al.* (2002) determined the CF of 24 types of timber products in Taiwan, discovering that the mean CF of coniferous species was 0.4821 and that the mean CF of broadleaf species was 0.4691, values which were used for softwood and hardwood species, respectively, in this study.

RESULTS AND DISCUSSION

Results of Forest Growth Estimation in Sampling Plots

The year of establishment of the AQEZs ranged from 1995 to 2009 and sampling plot areas ranges from 4.8 to 0.002 ha (mean 0.573 ha) (Table 1). Various trees (209 species) were planted in the sampling plots, with the number of species per plot ranging from 1 (bicycle path) to 75 (mean 11 species/sampling plot). The total number of planted trees sampled in the study (all sampling plots) was 13,943. However, the density of planted trees varied greatly

Table 1. Plot areas and number of trees planted.

Plot Parameter	Mean	SD	Min.	Max.
Area (ha/plot)*	0.573	0.728	0.002	4.800
Species of Trees (no./plot)	11	11	1	75
Number of Trees (no./plot)	142	165	5	1,181
Number of Trees per Unit Area (no./ha)*	681	1,245	15	7,000

* Bicycle paths are not included.

among sampling plots, ranging from 15 trees/ha to 7,000 trees/ha, with a mean of 681 trees/ha.

Of the 13,943 trees surveyed in the 98 sampling plots, height (H) ranged from 1.13 to 21.00 m (mean H = 5.76 m). Mean diameter at breast height (DBH) ranged from 0.5 to 190 cm (mean DBH = 15.57 cm). Mean crown width (CW) ranged from 0.1 to 25.5 m (mean CW = 3.95 m).) Individual tree mean tree breast height basal area (BA) was 0.03 m^2 and mean crown cover area (CW^2) was 17.57 m^2. The main factor in relatively large differences in DBH was that, in some sampling plots, some of the original trees on the site (with larger DBHs than newly planted trees) were retained when AQEZs were established. In general, H increases with DBH, and, from a regional perspective, tree growth values (H, DBH, CW, BA, and CW^2) in the southern region were greater than those in the other three regions (Table 2).

Results of Forest Plant Diversity

10–20–30 Rule Results

The 13,943 trees surveyed comprised 210 species, 145 genera, and 61 families. Overall, the most populous species was goldenrain tree (*Koelreuteria henryi*) with 1,106 counted (7.93%). The top 10 species in terms of number of individual trees comprised 50.18% of the total number of trees of all species; the top 50 species comprised 89.31% of the total number of trees, and the remaining 160 species comprised only 10.69% of the total number of trees. From the perspective of number of tree species, forest diversity was relatively high, with the numbers of trees per individual species all less than 10% of the total number of trees. Inter-regional differences were greater, with the most species (130) in the northern region, the fewest (49 species) in the eastern region, and 117 and 124 species in the central and southern regions, respectively. The top 10 tree species in terms of number of individual trees in the eastern region comprised 80.02% of the total number of trees in the region, with the top 10 species in the northern, central, and southern regions comprising 57.85%, 57.88%, and 54.88% of the total number of trees in those regions, respectively.

From a tree-planting perspective, the number of Chinese sweet gum (*Liquidambar formosana*) in the northern region exceeded 10% at 10.52% and in the central region the numbers of Indonesian cinnamon (*Cinnamomum burmannii*) and goldenrain trees exceeded 10%, with 13.11% and 11.36%, respectively. In the southern region, the number of golden shower trees (*Cassia fistula*) exceeded 10% at 10.77%, and in the eastern region the number of big-leaf mahoganies (*Swietenia macrophylla*) and Bengal almonds *(Terminalia catappa)* exceeded 10%, with 25.66% and 16.08%, respectively. These data indicate that the different spatial scales substantially influence the results. Countrywide, no individual species comprised more than 10% of the total number of trees. However, inter-regionally, the differences in proportions of major tree species was substantial, with each region having one or two species with numbers exceeding 10% of the total number of trees. In the eastern region, 25.66% of the total number of trees were big-leaf mahoganies. Among species with individual numbers exceeding 5% of the total number of trees surveyed in one region, non-native species included Chinese banyan (*Ficus microcarpa*), big-leaf mahogany, Madagascar almond (*Terminalia boivinii*), Indonesian cinnamon, golden shower tree, and golden trumpet tree (*Tabebuia chrysantha*); such native species were Camphor tree, goldenrain tree, Chinese sweet gum, Bengal almond, and Javanese bishopwood (*Bischofia javanica*) (Table 3).

Overall, in sampling plots in all regions, the proportion of native species was 41.92%. Inter-regionally, the proportion of native species was 51.26% in the northern region, with the other three regions lower than 50%; the southern region was the lowest at 29.70%.

Overall, of the 145 genera surveyed, none of the number of individual trees of one genus exceeded 20% of the total number of trees, with *Cinnamomum* (Lauraceae) the highest at 11.89%, followed by *Ficus* (Moraceae) and *Terminalia* (Combretaceae) at 8.73% and 8.63%, respectively. Inter-regional differences were greater, with the highest number of genera (98) in the northern region and the lowest number

Table 2. Results of forest growth estimation in sampling plots.

Growth Parameter \Region	Northern	Central	Southern	Eastern	Total
H (m)	5.76 (1.13–19.54)	4.92 (1.38–17.50)	7.11 (1.50–21.00)	5.54 (1.65–18.00)	5.76 (1.13–21.00)
Mean DBH (cm)	15.89 (0.5–158)*	12.03 (0.6–106)	21.35 (1–125)	13.45 (1–190)	15.57 (0.5–190)
CW (m)	3.93 (0.1–21.5)	3.43 (0.3–23.5)	5.01 (0.2–25.5)	3.37 (0.1–16.2)	3.95 (0.1–25.5)
BA (m^2)	0.03 (0.00–1.96)	0.02 (0.00–0.88)	0.06 (0.00–1.23)	0.02 (0.00–2.84)	0.03 (0.00–2.84)
CW^2 (m^2)	17.52 (0.01–363.05)	13.06 (0.07–433.74)	26.66 (0.03–510.70)	12.50 (0.01–206.12)	17.57 (0.01–510.70)

* (Min.–Max.)

Table 3. Number of tree species with individual numbers exceeding 5% of the total number of trees surveyed in sampling plots in different regions.

Species		Region				
		Northern	Central	Southern	Eastern	All
Total Number of Species (N)		130	117	124	49	210
Goldenrain tree (*Koelreuteria henryi*)	%	7.9	11.36	6.31		7.93
Indonesian cinnamon (*Cinnamomum burmannii*)	%		13.11		7.42	6.56
Indonesian cinnamon (*Cinnamomum burmannii*)	%		9.8	5.56		6.18
Big-leaf mahogany (*Swietenia macrophylla*)	%			6.67	25.66	5.37
Camphor tree (*Cinnamomum camphora*)	%	9.65			5.38	5.21
Chinese banyan (*Ficus microcarpa*)	%			5.62		5.1
Chinese sweet gum (*Liquidambar formosana*)	%	10.52				
Golden shower tree (*Cassia fistula*)	%			10.77		
Golden trumpet tree (*Tabebuia chrysantha*)	%			5.41		
Bengal almond *(Terminalia catappa)*	%				16.08	
Javanese bishopwood (*Bischofia javanica*)	%				5.13	

of genera (40) in the eastern region. In sampling plots in the northern region, the proportion of *Ficus* was the highest at 16.55%, followed by *Cinnamomum* at 12.59%. Sampling plots in the central region were most populated by *Cinnamomum* at 16.01%, *Koelreuteria* (Sapindaceae) at 11.36%, and *Terminalia* at 10.38%. Sampling plots in the southern region were most populated by *Cassia* (Fabaceae) at 10.77% and *Ficus* at 9.96%. Sampling plots in the eastern region were most populated by *Swietenia* (Meliaceae) at 25.66%, *Terminalia* at 16.08%, and *Cinnamomum* at 13.05%. Only *Swietenia*, in the eastern region, exceeded 20% (Table 4).

Overall, of the 61 families of trees in the sampling plots, the number of individual trees in no single family exceeded 30% of the total number of trees, with Lauraceae the highest at 12.97%, followed by Fabaceae and Moraceae at 12.87% and 10.23%, respectively. Inter-regional differences were greater, with the greatest number of families (50) in sampling plots in the northern region and the lowest (25) in the eastern region. Sampling plots in the northern region were most populated by trees in the Moraceae and Lauraceae families at 17.40% and 15.55%, respectively. Sampling plots in the central region were most populated by trees in the Lauraceae family at 16.19%, followed by Sapindaceae at 13.62%, Fabaceae at 12.20%, and Combretaceae at 10.38%. Sampling plots in the southern region were most populated by trees in the Fabaceae, Moraceae, and Bignoniaceae families at 21.33%, 10.50%, and 10.05%, respectively. Sampling plots in the eastern region were most populated by trees in Meliaceae family at 26.47%, followed by Combretaceae at 16.08% and Lauraceae at 13.23% (Table 5).

Although the results indicate that spatial scale affects the estimates of forest tree diversity, the overall estimates of diversity for all four regions corresponded with the 10–20–30 rule that the number of trees of any one species should not exceed 10% of the total number of trees of all species, that the number of trees of any one tree genus should not exceed 20% of the total number of trees of all genera, and that the number of trees in any one family should not exceed the total number of trees of all families. If the regions are considered separately, no region satisfied the 10% standard, because each region had one or two species of trees with numbers exceeding 10% of the total number of trees. The eastern region did not satisfy the 20% standard, with trees in the genus *Swietenia* comprising 25.66%; moreover, the overall proportions of non-native species and native species were 58.08% and 41.92%, respectively. In the southern region, only 29.70% of the planted trees were native species, another concern in satisfying forest tree species diversity standards. Among considerations in diversifying forest trees, the adaptability of the forest to its environment is another crucial consideration that cannot be disregarded. Care must be exercised before a new species is introduced into urban forest habitats without adaptive testing (Raupp *et al.*, 2006), because inappropriate species selection will increase forest mortality, decrease the life expectancy of trees, and increase management costs (Raupp *et al.*, 2006). Moreover, excessive use of non-native species may increase the incidence of diseases and pests in native species. Therefore, ongoing monitoring of forest growth is required to understand how non-native tree species affect the local ecosystem and native tree species.

Results of IVI Analysis

After surveying all trees in every sampling plot, the mean IVI of all tree species were derived using both relative dominance and relative coverage results. Thus, the tallest tree species, although not necessarily the most numerous, may have a higher relative dominance and higher IVI because of longer post-planting time. Tree species with a lower relative dominance but a higher relative coverage may similarly have a higher IVI; thus, IVI can reflect the varying preferences of different regions for nursery stock used in greening.

Of the 210 tree species counted, 21 species had an IVI greater than 1 and 10 species had IVI greater than 3. Chinese banyan had the greatest IVI at 11.65, followed by Madagascar almond at 6.59, goldenrain tree at 5.60, and golden shower tree at 5.51, with the IVI of the remaining species, including the native species goldenrain tree, Camphor tree, Indian beech (Pongamia pinnata), and Bengal almond, all lower than 5 (Table 6).

Table 4. Number of tree genera with individual numbers exceeding 5% of the total number of trees surveyed in sampling plots in different regions.

(Family) *Genus*		Region				
		Northern	Central	Southern	Eastern	All
Total Number of Genera (N)		98	88	94	40	145
(Lauraceae) *Cinnamomum*	%	12.59	16.01		13.05	11.89
(Moraceae) *Ficus*	%	16.55		9.96		8.73
(Combretaceae) *Terminalia*	%		10.38	7.03	16.08	8.63
(Sapindaceae) *Koelreuteria*	%	7.9	11.36	6.31		7.93
(Meliaceae) *Swietenia*	%			6.67	25.66	5.39
(Hamamelidaceae) *Distylium*	%				6.25	
(Bignoniaceae) *Tabebuia*	%			6.34	5.94	
(Euphorbiaceae) *Bischofia*	%				5.13	
(Magnoliaceae) *Michelia*	%				5.01	
(Fabaceae) *Cassia*	%			10.77		

Table 5. Number of tree families with individual numbers exceeding 5% of the total number of trees surveyed in sampling plots in different regions.

Family		Region				
		Northern	Central	Southern	Eastern	All
Total Number of Families (N)		50	46	46	25	61
Lauraceae	%	15.55	16.19		13.23	12.97
Fabaceae	%	9.31	12.20	21.33	6.49	12.87
Moraceae	%	17.40	6.72	10.50		10.23
Sapindaceae	%	7.94	13.62	6.52		8.81
Combretaceae	%		10.38	7.03	16.08	8.63
Meliaceae	%			7.33	26.47	7.23
Bignoniaceae	%		5.73	10.05	6.00	5.30
Magnoliaceae	%				6.86	
Hamamelidaceae	%				6.31	
Euphorbiaceae	%	5.39			5.69	
Apocynaceae	%			5.17		
Rosaceae	%	6.51				

Table 6. Results of analysis of importance value index (IVI) of woody plants in the sample plots.

Species	Relative Density	Relative Dominance	Relative Frequency	IVI
Chinese banyan (*Ficus microcarpa*)	5.10	17.71	12.14	11.65
Madagascar almond (*Terminalia boivinii*)	6.18	5.57	8.00	6.59
Goldenrain tree (*Koelreuteria henryi*)	7.79	3.43	5.59	5.60
Camphor tree (*Cinnamomum camphora)*	5.21	5.28	6.05	5.51
Golden shower tree (*Cassia fistula*)	3.79	3.87	7.02	4.89
Blackboard tree (*Alstonia scholaris*)	2.65	7.90	3.88	4.81
Big-leaf mahogany (*Swietenia macrophylla*)	5.37	3.50	2.46	3.78
Indonesian cinnamon (*Cinnamomum burmannii*)	6.56	1.86	2.47	3.63
Indian beech (*Pongamia pinnata*)	3.91	2.06	3.46	3.15
Bengal almond (*Terminalia catappa*)	2.45	2.41	4.40	3.09

Furthermore, the sampling plots of each region varied slightly regarding tree species with IVI exceeding 3. In the northern region, 10 species had IVI exceeding 3, the top three of which were Chinese banyan at 20.4, Camphor tree at 10.20, and goldenrain tree at 6.19. In the central region, nine species had IVI exceeding 3, the top three of which were Madagascar almond at 12.17, goldenrain tree at 9.31, and Indonesian cinnamon at 9.20. In the southern region 10 species had IVI exceeding 3, the top two of which were golden shower tree at 10.91, and Chinese banyan at 10.65. In the eastern region, 10 species had IVI exceeding 3, the top three of which were Bengal almond at 28.01, big-leaf mahogany at 17.70, and Camphor tree at 5.24.

Of the all the surveyed species with IVI exceeding 3, only Camphor tree was planted in all four regions. Chinese banyan, blackboard tree (*Alstonia scholaris*), Madagascar almond, and goldenrain tree were planted in all regions but the eastern region, and the tree species with the highest IVI in the eastern region varied significantly from those in the other regions (Table 7).

Tree Growth and Carbon Storage

The mean individual tree volume (V_{tree}) of the 98 sampling plots was 0.12 m^3, the highest individual tree volume was 22.97 m^3, and the total volume of all trees (V_{total}) was 1728.03 m^3. The highest individual tree carbon storage (C_{tree}) was 8.93 tons C, the mean individual C_{tree} was 0.05 tons C, and the total carbon storage (C_{total}) of all trees in the sampling plots was 672.20 tons C (Table 8). Excluding the five bicycle paths, the trees in the remaining 93 AQEZs had a V_{total} of 1463.84 m^3 and a mean volume (V_{mean}) per unit area of 27.47 m^3/ha. The C_{total} was 565.30 tons, with mean carbon storage (C_{mean}) per unit area in the 93 AQEZs of 10.61 tons C/ha.

The results of this study were somewhat higher than those in a study of Jersey City, NJ (United States) at 5.02 tons C/ha (Nowak and Crane, 2002) but lower than estimates for other urban forests; for example, the estimated carbon storage in some urban forests in China were 30.25–43.70 tons C/ha (Yang *et al.*, 2005; Zhao *et al.*, 2010; Liu and Li, 2012). Nowak and Crane (2002), using field surveys of trees in 10 urban forests in the United States, calculated a national mean carbon sequestration density of 25.1 tons C/ha. The levels of carbon storage in urban forests differ according to the forest stand structure, tree species, tree ages, and planting densities.

This study surveyed 98 sampling plots containing 210 species of trees. The tree species and numbers occurring in the different sampling plots varied greatly, with only one individual of some tree species counted in some sampling plots. Therefore, tree growth and carbon storage analyses were conducted only for those 10 species with IVI exceeding 3. These species comprised 6,852 individuals and represented 49.14 of the total 13,943 individual trees surveyed.

Goldenrain tree (1,106 individuals), Indonesian cinnamon (914 individuals), and Madagascar almond (862 individuals) were the top three species, comprising 20.67 of the total number of individual trees in those 10 species with IVI exceeding 3. Of the 10 species, the mean H was the greatest for blackboard tree, golden shower tree, and Madagascar almond, with mean H of 9.37, 7.66, and 7.51 m, respectively. Camphor tree had the lowest mean H at 3.98 m. The mean DBH exceeded 30 cm for blackboard tree and Chinese banyan, at 31.25 and 30.22 cm, respectively. The mean DBH exceeded 15 cm for Bengal almond, golden shower tree, Camphor tree, and Madagascar almond, and Indonesian cinnamon had the lowest mean DBH at 9.16 cm. The mean CW exceeded 5 m for Chinese banyan, golden shower tree, Bengal almond, and blackboard tree, at 6.12, 5.81, 5.77, and 5.24 m, respectively, and was lowest for Indonesian cinnamon and big-leaf mahogany, at 2.57 and 2.74 m, respectively (Table 4). The mean V_{tree} was greatest for blackboard tree at 0.47 m^3, followed by Chinese banyan at 0.43 m^3; Indonesian cinnamon and goldenrain tree were the lowest at 0.02 and 0.04 m^3, respectively. The highest individual tree volume was for Chinese banyan at 10.611 m^3. The mean individual C_{tree} was the highest for blackboard tree and Chinese banyan at 0.18 and 0.17 tons C, respectively.

Table 7. Trees species with IVI exceeding 3 in sampling plots in different regions.

Species	Northern	Central	Southern	Eastern	All
Chinese banyan (*Ficus microcarpa*)	20.40	6.36	10.65		11.65
Madagascar almond (*Terminalia boivinii*)	4.25	12.17	6.16		6.59
Goldenrain tree (*Koelreuteria henryi*)	6.19	9.31	4.01		5.74
Camphor tree (*Cinnamomum camphora*)	10.20	3.26	3.37	5.24	5.51
Golden shower tree (*Cassia fistula*)		3.01	10.91		4.89
Blackboard tree (*Alstonia scholaris*)	4.32	5.35	6.10		4.81
Big-leaf mahogany (*Swietenia macrophylla*)			4.62	17.70	3.78
Indonesian cinnamon (*Cinnamomum burmannii*)		9.20		4.62	3.63
Indian beech (*Pongamia pinnata*)	3.43	5.25			3.15
Bengal almond (*Terminalia catappa*)				28.01	3.09

Table 8. Analysis of growth and carbon storage of principal tree species in the sampling plots.

Tree Species	N	H (m)		DBH (cm)		CW (m)		V_{tree} (m^3)		C_{tree} (ton)	
		Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.
Chinese banyan (*Ficus microcarpa*)	711	6.42	15	30.22	158	6.12	23.5	0.43	10.16	0.17	3.95
Madagascar almond (*Terminalia boivinii*)	862	7.51	19.54	16.66	52.8	4.85	15	0.13	0.96	0.05	0.37
Goldenrain tree (*Koelreuteria henryi*)	1106	5.03	13.52	11.6	69	3.52	10.4	0.04	1.51	0.02	0.59
Camphor tree (*Cinnamomum camphora*)	726	6.46	14.5	17.85	55.93	4.4	13.7	0.12	1.6	0.05	0.62
Golden shower tree (*Cassia fistula*)	528	7.66	16	18.14	59	5.81	13.5	0.14	1.59	0.05	0.62
Blackboard tree (*Alstonia scholaris*)	370	9.37	18.12	31.25	118	5.24	12.1	0.47	8.92	0.18	3.47
Big-leaf mahogany (*Swietenia macrophylla*)	749	6.17	15	13.75	48.2	2.74	14.3	0.08	0.88	0.03	0.34
Indonesian cinnamon (*Cinnamomum burmannii*)	914	3.98	11.83	9.16	36	2.57	9	0.02	0.48	0.01	0.19
Indian beech (*Pongamia pinnata*)	545	5.09	10.41	13.08	65.44	4.08	10.7	0.04	0.87	0.02	0.34
Bengal almond (*Terminalia catappa*)	341	6.05	10.8	18.25	45.07	5.77	16.2	0.1	0.52	0.04	0.2

The highest individual tree carbon storage was for Chinese banyan at 4.128 tons C (Table 8). Large differences in tree growth were due to different site conditions and planting times.

The results of urban forest and green space cost-benefit analysis indicated that, although annual cost input is high, all the accrued benefits exceed the costs. According to McPherson & Simpson's (2002) findings, every U.S. dollar invested in urban forest management yields US$1.52–1.85 in benefits. Moreover, McPherson *et al.* (2005) found that, although the annual cost per tree in five large U.S. cities was approximately US$13–US$65, the benefits obtained per tree were US$31–US$89; in other words, investing US$1 in urban forest management could yield US$1.37–US$3.09 in benefits. Due to the lengthy growing period for trees, carbon sequestration benefits will increase yearly after planting.

CONCLUSIONS

The results of the surveys showed that tree plantings were extremely diverse, with 210 species, 145 genera, and 61 families among the 13,943 individual trees surveyed. Growth performance and carbon sequestration varied greatly among individual trees, species, and regions. The most abundant single species in the sampling plots was goldenrain tree, with 1,106 individuals (7.93% of the total number of trees). Twenty-one species had IVI exceeding 1 and 10 species had IVI exceeding 3; Chinese banyan had the highest IVI at 11.65. In addition, the spatial scale of analysis affected the estimation results; none of the four regions satisfied the standard that the number of individual trees of any single species not exceed 10% of the total number of trees. The mean individual tree volume was 0.12 m^3, with a total volume of all trees of 1,728.03 m^3. The Mean individual tree carbon storage of 0.05 tons C and the tree carbon storage of all trees in the sampling plots was 672.20 tons C. The results of urban forest and green space cost-benefit analysis indicated that all the accrued benefits exceed the costs. The carbon sequestration benefits will increase yearly owning to the lengthy growing period of trees. Sustainable management can increase carbon storage and increase the multiple benefits of AQEZs. The research outcomes of this study can be used for reference for authorities in carbon policy making. More AQEZs are suggested to build considering the increasingly important global warming issue.

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Received for review, March 14, 2015
Revised, May 18, 2015
Accepted, May 21, 2015