Research paper

Carbon Storage Benefit by Trees of Air Quality Purification Zones in Taiwan's Five Municipalities

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【Summary】

In 1995, the national government in Taiwan began setting up air quality purification zones (AQPZs) by planting trees in order to improve the air quality, increase carbon sequestration, enhance the quality of the living environment, and achieve numerous other environmental benefits. This study investigated tree growth and carbon storage benefits in 28 AQPZs in Taiwan's 5 major municipalities (Taipei, New Taipei City, Taichung, Tainan, and Kaohsiung). Results of the survey showed that 3963 trees of 99 species had been planted in sample plots. Overall, the average tree height was 6.31 m, the average diameter at breast height was 17.77 cm, the average crown width was 4.53 m, the average basal area was 0.040 m^2, the average crown cover area was 21.64 m^2, the average individual tree volume was 0.163 m^3, the total timber volume of all sample plots was 645.336 m^3, the average individual tree carbon storage was 0.063 tons of C, and the total forest carbon storage capacity of all sample plots was 251.036 tons of C. Among the 99 tree species identified in the survey, *Ficus microcarpa*, *Terminalia mantaly*, *Koelreuteria elegans*, and *Cinnamomum camphora* were the most common in the AQPZs of the 5 municipalities. Since this study included survey date from only one time point, information on growth among different years could not be obtained, and the analysis of carbon content results applied only to currently existing carbon storage rather than to interannual variation. Therefore, under the premises of "measureable, reportable, and verifiable," continued monitoring of AQPZs is needed to provide quantification of future national carbon sink benefits.

Key words: urban forest, green space, air quality purification zones, carbon storage.

Wang YC, Lin MY, Ko SH, Lin JC. 2013. Carbon storage benefit by trees of air quality purification zones in Taiwan's five municipalities. Taiwan J For Sci 28(4):159-69.

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Received July 2013, Accepted September 2013. 2013年7月送審 2013年9月通過。

研究報告

台灣五都空氣品質淨化區之林木碳儲存量調查

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摘 要

政府自1995年起開始設置「空氣品質淨化區」藉由植栽綠化以達到改善空氣品質、增加碳吸存、提昇生活環境品質等多重環境效益，本研究調查五都共28個空氣品質淨化區之林木生長與碳儲存效益。調查結果顯示：栽植的林木種類約有99種，總調查株數為3963株，總平均樹高為6.31 m，總平均胸高直徑為17.77 cm，總平均冠幅為4.53 m，總平均胸高斷面積為0.040 m^2，總平均樹冠覆蓋面積為21.64 m^2，總平均林木單株材積為0.163 m^3，所有樣區之總林木材積為645.336 m^3，總平均林木單株碳儲存量為0.063 tons，所有樣區之總林木碳儲存量為251.036 tons。在五都所調查的99種喬木中，其中榕樹、小葉欖仁、台灣欒樹、樟樹在五都空氣品質淨化區栽植較為普遍。由於本研究僅有一次的調查資料，因此無法取得不同年度的生長資料，所分析的碳量結果僅為現有的碳儲存量，而非年變化量。因此在可量測、可報告與可查證前提下，需針對空氣品質淨化區之未來碳吸存效益進行持續性監測，可提供國家針對空氣品質淨化區之林木碳匯效益數量。

關鍵詞：都市林、綠地、空氣品質淨化區、碳儲存。

王義仲、林敏宜、柯澍馨、林俊成。2013。台灣五都空氣品質淨化區之林木碳儲存量調查。台灣林業科學28(4):159-69。

INTRODUCTION

In Taiwan, air pollution control is an important link in the task of environmental protection. Therefore, since 1995, Taiwan's government has promoted establishment of air quality purification zones (AQPZs) to improve air quality, enhance the quality of the living environment, and provide ecological and environmental education and sustainable use of resources, by planting trees. As of 2010, 504 AQPZs have been established in Taiwan, including greening of 20 remediated landfill sites, 107 bare-land sites, 87 waste disposal (dumps) and other contaminated sites, 80 green open space sites, 55 urban bicycle paths, 77 green urban roadways, and 78 environmental protection parks (not including campus dust improvement areas and wooded environmental protection roadways).

AQPZs function as urban forests and green spaces, and where urban forests and green space exist, they simultaneously provide, through tree growth, the sequestration and storage of carbon in plants. Urban forests, through shading and evapotranspiration, can also reduce air conditioning demands in buildings, thereby reducing carbon dioxide emissions caused by the use of fossil fuels for energy production, as well as storing organic carbon in forest soils (McPherson et al. 1999, Jo 2002, Akbari 2002, McPherson and Simpson 2003, Pouyat et al. 2002, 2006, Pataki et al. 2006, McHale et al. 2007).

Much research has focused on quantifying the ecological aspects of urban forest carbon storage and sequestration. Rowntree and Nowak (1991), in US urban forests, extrapolated across the entire US, urban forest carbon storage would thus be 725×10^6 tons of C. Nowak (1994) estimated urban forest carbon sequestration of individual trees; with an average tree diameter of 31~46 cm (with a crown width (CW) of about 50 m^2), individual tree carbon sequestration was 19 kg yr^{-1}. McPherson (1998) estimated the urban forest carbon sequestration for Sacramento, California, at 1.2 tons of C ha^{-1} yr^{-1}. Nowak and Crane (2002), based on field survey data from 10 US urban forests, estimated that US urban forests could sequester 700×10^6 tons of carbon (a US$14.3 billion value) with an annual net carbon sequestration rate of 22.8×10^6 tons of C (a US$460 million value), 2.9 tons of C ha^{-1} yr^{-1} of carbon sequestration, a carbon density of 9.1 kg m^{-2} of tree cover, and an average annual net growth of forest cover of 0.3 kg m^{-2}. Brack (2002) investigated case studies of the value of urban forests in Canberra, Australia, with special reference to pollution mitigation. The study used forest surveys, model estimation, and decision support systems to collect data on these forests. Using decision support system simulation for the 5-yr period of 2008~2012, the combined energy reduction, pollution reduction, and carbon sequestration value of these forests was US$20~67 million.

Major forest carbon management strategies and measures of forestry sectors of every country include increasing reforested and afforested areas, strengthening forest management, and greening urban spaces, so air quality purification zones (AQPZs) have important benefits and play an important role in sequestration of atmospheric carbon dioxide. This study employed forest carbon sequestration estimation methods approved by the United Nations Intergovernmental Panel on Climate Change to investigate forest growth and assess carbon storage in AQPZs in Taiwan's 5 major municipalities (Taipei, New Taipei City, Taichung, Tainan, and Kaohsiung, hereafter referred to as the 5 municipalities).

MATERIAL AND METHODS

AQPZ sampling plots and data

There were 170 AQPZs (with a total area of 240.09 ha and a total length of bicycle paths of 72 km) in the 5 municipalities, and the type of site, location, planting area, planting year, and density of the zones all differed. There were 7 sample plots for each municipality, while considering that Taipei City is surrounded by New Taipei City, and both of them had fewer AQPZs, the survey examined 7 sample plots within the 2 cities, for a total amount of sample plots of 28. As to the main type of sites, 3 or 4 environmental protection parks of sample plots for each municipality were set, while the remaining were chosen from other types of sites (Table 1).

Tree survey approach and items

In this study, forest-related data were collected in AQPZs in the 5 municipalities in order to understand forest growth conditions and the status of the forest resources in the zones, including the area, location, and distribution of the zones, species and numbers of planted trees, forest and planting information (number of trees, diameter at breast height (DBH), tree height (H), and crown cover), and other relevant statistics. AQPZs in each of the 5 municipalities were sampled in order to achieve a comprehensive survey. The species and numbers of all trees planted in the AQPZs sampled were recorded. The DBH and H of each tree were measured with a DBH tape, and crown width (CW) was measured with a tape measure. All trees recorded in the sampled plots are listed in alphabetical order by family, genus, and species (scientific

Table 1. Number of air quality purification zones in 5 municipalities of Taiwan, and quantity sampled

Municipality	Total			Quantity sampled		
	Number	Area (ha)	Bicycle paths (km)	Number	Area (ha)	Bicycle paths (km)
Taipei	7	2.49	1.4	2	1.1	--
New Taipei	9	19.4	6.7	5	4.5	--
Taichung	47	41.2	21.3	7	5	--
Tainan	31	133.4	11.4	7	2	2.4
Kaohsiung	76	43.6	31.2	7	1.4	1.0
Total	170	240.09	72	28	14	2.4

Numbers of bicycle path sampling plots in Tainan and Kaohsiung were 2 and 1, respectively.

name). Other green landscaping herbaceous plants were not recorded. The CW was used to calculate the AQPZ areal coverage. Higher areal coverage of trees in an AQPZ indicated better tree growth, whereas tree coverage lower than the area of an AQPZ indicated that forest growth conditions needed to be improved or that an insufficient number of trees had been planted.

Estimating forest carbon storage

Forest carbon storage can be estimated by converting timber volume and timber density to forest biomass, then aboveground and underground forest biomass expansion coefficients with carbon content conversion coefficients are used to estimate carbon sequestration. Individual tree carbon content estimates were based on allometric timber volume regression-transformation models. Timber volume was first estimated using the DBH, H, and other parameters; then, the basic wood density (BD) was converted to tree trunk biomass. Next, a biomass expansion factor (BEF) was used to estimate the aboveground biomass from the tree trunk biomass, and the underground biomass was further estimated from the root-shoot ratio (R). The forest carbon fraction (CF) was obtained by multiplying an individual trees aboveground carbon content by the aboveground forest biomass. The following equation was used to estimate aboveground single tree carbon storage from single tree volumes (IPCC 2006):

$C_{tree} = V \times BD \times BEF \times (1+R) \times CF$;

where C_{tree} is the average individual tree carbon storage (metric tons), V is the average individual tree volume (m^3), BD is the basic wood density (metric ton m^{-3}), BEF is the biomass expansion factor, R is the root-shoot ratio, and CF is the forest carbon fraction.

Individual tree volume

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

$V = BA \times H \times f = (DBH / 100)^2 \times 0.79 \times H \times 0.45$;

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

Allometric models using the DBH, H, and other parameters were used to estimate tree volume (V). Single tree volume estimates were based on a form factor calculation multiplied by the average BA and H. The formula to calculate the tree DBH and BA was:

$BA = (DBH / 200)\ 2 \times \pi = (DBH / 100)\ 2 \times (\pi/4)$;

where BA is the tree basal area (m^2) and DBH is the diameter at breast height (cm). A Taiwan Forestry Bureau investigation produced a timber volume table (TFB 1997) using the general tree volume formula.

BD

BD is the oven-dried weight to volume ratio of peeled logs. Studies by Lin et al. (2002) determined that 24 kinds of timber products in Taiwan could be divided into softwood (coniferous) and hardwood (broadleaf) categories, among which the BD of softwood ranged 0.31~0.55 kg m^{-3} (with an average of 0.42 kg m^{-3}), and the BD of hardwood ranged 0.37~0.77 kg m^{-3} (with an average of 0.56 kg m^{-3}). Therefore, in this study, 0.42 and 0.56 were respectively used for BDs of softwood and hardwood species.

BEF

The BEFs used by Wang and Liu (2006) for *Cryptomeria japonica* and *Cinnamomum camphora* were respectively used in this study for softwood and hardwood species.

Root-shoot ratio

Studies show that among coniferous plantations in Taiwan, the greatest area is afforested with *C. japonica*. Therefore, based on previous studies (Lin et al. 1999), a root-shoot ratio (R) of 0.28 for *C. japonica* was used for all softwood species in this study. Studies by Chen and Lu (1988) and Lin et al. (2007, 2009) showed that there were interspecific differences in R among species on broadleaf plantations in Taiwan. Since many broadleaf species were investigated in this study, an average R of 0.234, based on the above 3 studies, was used in the following analysis of hardwood species.

Forest carbon fraction

Studies by Lin et al. (2002) determined the carbon fractions CFs of 24 kinds of timber products in Taiwan, finding that average CF for coniferous species was 0.4821 and for broadleaf species was 0.4691, both values of which were respectively used for estimates of softwood and hardwood species in this study.

RESULTS AND DISCUSSION

Forest growth findings

This study investigated 28 sampling plots in the 5 municipalities, encompassing a total of 99 tree species and 3963 individual trees, with an average H in the individual municipalities ranging 4.83~8.35 m and an overall average height of 6.31 m. The average DBH was greatest in Kaohsiung at 28.64 cm, with an overall average DBH of 17.77 cm. The average CWs were greatest in Tainan and Kaohsiung at 5.60 and 5.54 m, respectively, with an overall average crown width at 4.53 m (Table 2). Moreover, based on standard deviation results, forest growth was extremely variable.

Timber volume and carbon stock estimates

The average individual tree BA was greatest in Kaohsiung at 0.090 m^2, with an overall average basal area of 0.040 m^2. Average tree canopy cover (CW^2) in Tainan was 30.34 m^2, with an overall average CW^2 of 21.64 m^2. The average individual tree volume (V_{tree}) was greatest in Kaohsiung at 0.389 m^3, with an overall average V_{tree} of 0.163 m^3; thus the total tree volume of all the study plots was 645.336 m^3. The average individual tree carbon storage (C_{tree}) was greatest in Kaohsiung at 0.151 tons of C, with an overall average

Table 2. Results of tree growth surveys in air quality purification zones in 5 municipalities of Taiwan

City	No. of trees	No. of tree species	Tree height (m)		Diameter at breast height (cm)		Crown width (m)	
			Average	SD	Average	SD	Average	SD
Taipei	260	17	6.77	3.08	17.90	10.54	4.55	2.15
New Taipei	413	36	6.93	2.98	20.32	14.38	5.18	3.17
Taichung	1710	68	4.83	2.13	11.79	10.93	3.40	2.19
Tainan	933	46	7.21	2.38	20.35	11.72	5.60	2.70
Kaohsiung	647	31	8.35	2.56	28.64	17.87	5.54	2.34
Total	3963	99	6.31	2.79	17.77	13.89	4.53	2.66

The same tree species appeared in different municipalities, so the sum of the number of tree species in each municipality is higher than the total. SD, standard deviation.

C_{tree} of 0.063 tons of C; thus the total forest tree carbon storage was 251.036 tons of C (Table 3).

In this study, carbon storage per hectare was 13.99 tons of C ha^{-1}, which was above the estimate for Jersey City, New Jersey, of 5.02 tons of C ha^{-1} (Nowak and Crane, 2002). Nowak (1993) estimated carbon sequestration in Oakland, California urban forests (with a forest cover rate of 21%) at 11 tons of C ha^{-1}. Some urban forests in China exhibited carbon densities of 30.25~43.70 tons of C ha^{-1} (Yang et al. 2005, Zhao et al. 2010, Liu and Li 2012), while Rowntree and Nowak (1991), in US urban forests, assessed the average biomass at 60 tons of C ha^{-1}, with carbon sequestration at 27 tons of C ha^{-1}. Based on field survey data from 10 U.S. urban forests, Nowak and Crane (2002) estimated a national average urban forest carbon storage density of 25.1 tons of C ha^{-1} (which is low compared to a forest carbon sequestration density of 53.5 tons of C ha^{-1}). This was lower than that found in other research. The lower carbon storage found in this study probably mainly resulted from different urban tree structures, tree species, forest ages, and planting densities.

Growth and carbon storage of the main tree species

The tree species present and their numbers greatly varied among the different

Table 3. Forest breast height basal area (BA), timber volume, and carbon storage capacity results in air quality purification zones in 5 municipalities of Taiwan

City	BA (m^2)		CW^2 (m^2)		V_{tree} (m^3)		C_{tree} (tons)	
	Average	SD	Average	SD	Average	SD	Average	SD
Taipei	0.034	0.041	19.90	17.59	0.133	0.179	0.052	0.070
New Taipei	0.049	0.072	28.95	34.42	0.208	0.382	0.081	0.149
Taichung	0.020	0.077	12.83	20.69	0.073	0.378	0.028	0.147
Tainan	0.043	0.059	30.34	28.55	0.177	0.290	0.069	0.113
Kaohsiung	0.090	0.124	28.44	24.03	0.389	0.625	0.151	0.243
Total Average	0.040	0.073	21.64	26.05	0.163	0.360	0.063	0.140

CW^2, average crown cover area; V_{tree}, average individual tree volume; C_{tree}, average individual tree carbon storage; SD, standard deviation.

sampled plots, with some species appearing only in particular plots or represented by only 1 individual tree. Therefore, the subsequent analysis considered only those species whose individual tree numbers were > 2% (> 79 individuals) of all trees in all species sampled, thus including 2887 individual trees of 17 species (72.8% of the total number of trees present). Among these 17 species, average individual tree height (H) was greatest for *A. scholaris* at 10.52 m, followed by *F. microcarpa*, *Pterocarpus indicus*, and *Swietenia macrophylla*, with average individual tree heights lowest (< 4 m) for *Cinnamomum burmanni*, *Jacaranda acutifolia*, and *Prunus serrulata*. The average DBH was greatest for *F. religiosa* (52 cm), followed by *F. microcarpa* (42.74 cm), with the lowest average DBH (4.89 cm) for *Sapindus mukorossi*. The average CW was greatest for *F. religiosa* (8.62 m) and lowest for *P. serrulata* and *S. mukorossi* (1.72 and 1.74 m, respectively). The average V_{tree} and average C_{tree} were greatest for *F. religiosa* and *F. microcarpa* and lowest for *J. acutifolia*, *P. serrulata*, and *S. mukorossi*, as shown in Table 4.

Growth and carbon storage of dominant tree species in the 5 municipalities

Five tree species (*T. mantalyi*, *P. pinnata*, *F. microcarpa*, *K. paniculata*, and *C. camphora*) were selected to analyze growth scenarios for the same species in different sampling plots, with the species selected being among the 10 most common tree species (in terms of individual tree numbers) in the AQPZ sampled plots surveyed in the 5 municipalities as well as occurring in all 5 of

Table 4. Growth and carbon storage of main tree species in sample plots in air quality purification zones in 5 municipalities of Taiwan

Species	No.	Height (m)	DBH (cm)	CW (m) (m)	BA (m^2)	CW^2 (m^2)	V_{tree} (m^3)	C_{tree} (ton)
Cassia fistula	304	8.27	20.60	6.67	0.037	40.26	0.151	0.059
Tabebuia chrysotricha	275	5.07	10.52	3.61	0.011	12.12	0.034	0.013
Koelrouteria paniculata	275	5.76	14.49	4.46	0.018	17.56	0.051	0.020
Terminalia mantaly	253	7.82	17.43	4.72	0.033	22.09	0.161	0.063
Prunus serrulata	242	3.49	5.42	1.72	0.003	2.96	0.005	0.002
Pongamia pinnata	232	5.32	15.27	4.73	0.021	19.82	0.056	0.022
Cinnamomum camphora	200	6.31	18.35	5.10	0.037	27.48	0.152	0.059
Ficus microcarpa	174	9.29	42.74	8.62	0.166	65.68	0.748	0.291
Melia azedarach	145	5.97	11.72	4.10	0.015	15.42	0.048	0.019
Pterocarpus indicus	134	9.01	30.13	6.89	0.080	40.35	0.349	0.136
Alstonia scholaris	113	10.52	34.17	6.67	0.106	38.46	0.554	0.216
Ficus religiosa	103	8.68	52.00	5.75	0.238	28.86	0.972	0.378
Jacaranda acutifolia	100	3.63	6.52	2.12	0.004	4.50	0.008	0.003
Liquidambar formosana	89	6.55	17.85	4.58	0.029	19.00	0.097	0.038
Sapindus mukorossi	86	4.07	4.89	1.74	0.002	2.74	0.004	0.002
Swietenia macrophylla	82	9.00	23.35	4.57	0.052	19.12	0.245	0.095
Cinnamomum burmanni	80	3.83	7.78	2.12	0.008	4.72	0.021	0.008

DBH, diameter at breast height; CW, crown width; BA, breast height basal area; CW^2, average crown cover area; V_{tree}, average individual tree volume; C_{tree}, average individual tree carbon storage.

Table 5. Growth and carbon storage performances of dominant tree species in 5 municipalities of Taiwan

Variable	City	*Terminalia mantaly*		*Pongamia pinnata*		*Ficus microcarpa*		*Koelreuteria paniculata*		*Cinnamomum camphora*	
		n	Average	*n*	Average	*n*	Average	*n*	Average	*n*	Average
H (m)	Taipei	13	10.34	9	5.31	14	6.44	1	4.70	36	5.24
	New Taipei	26	12.65	19	4.13	17	9.51	70	6.14	29	10.68
	Taichung	133	5.21	115	5.48	12	6.38	88	5.46	91	4.85
	Tainan	43	8.21	81	5.23	105	10.20	75	5.46	17	5.95
	Kaohsiung	38	12.31	8	6.76	26	8.38	41	6.33	27	8.17
	Total	253	7.82	232	5.32	174	9.29	275	5.76	200	6.31
DBH (cm)	Taipei	13	16.70	9	12.42	14	37.43	1	14.40	36	14.70
	New Taipei	26	24.03	19	11.64	17	47.82	70	15.24	29	38.18
	Taichung	133	9.66	115	17.27	12	39.99	88	13.17	91	13.07
	Tainan	43	23.16	81	13.55	105	41.29	75	14.72	17	16.33
	Kaohsiung	38	33.84	8	15.74	26	49.43	41	15.64	27	20.98
	Total	253	17.43	232	15.27	174	42.74	275	14.49	200	18.35
CW (m)	Taipei	13	4.25	9	4.37	14	7.24	1	4.65	36	3.82
	New Taipei	26	7.49	19	3.11	17	10.39	70	4.62	29	9.64
	Taichung	133	3.30	115	5.32	12	8.87	88	4.23	91	4.11
	Tainan	43	6.79	81	4.23	105	8.40	75	4.33	17	4.46
	Kaohsiung	38	5.62	8	5.44	26	8.98	41	4.87	27	5.69
	Total	253	4.72	232	4.73	174	8.62	275	4.46	200	5.10
BA (m^2)	Taipei	13	0.023	9	0.014	14	0.130	1	0.016	36	0.019
	New Taipei	26	0.052	19	0.011	17	0.202	70	0.020	29	0.120
	Taichung	133	0.009	115	0.028	12	0.204	88	0.016	91	0.020
	Tainan	43	0.045	81	0.016	105	0.146	75	0.018	17	0.023
	Kaohsiung	38	0.094	8	0.022	26	0.222	41	0.022	27	0.041
	Total	253	0.033	232	0.021	174	0.166	275	0.018	200	0.037
CW^2 (m^2)	Taipei	13	15.02	9	16.49	14	45.21	1	16.98	36	13.55
	New Taipei	26	51.56	19	8.62	17	96.88	70	18.59	29	77.84
	Taichung	133	9.64	115	24.15	12	101.09	88	16.41	91	18.02
	Tainan	43	39.32	81	16.08	105	58.27	75	15.96	17	17.55
	Kaohsiung	38	28.45	8	25.71	26	69.91	41	21.22	27	30.15
	Total	253	22.09	232	19.82	174	65.68	275	17.56	200	27.48
V_{tree} (m^3)	Taipei	13	0.114	9	0.036	14	0.414	1	0.034	36	0.050
	New Taipei	26	0.341	19	0.022	17	0.981	70	0.057	29	0.603
	Taichung	133	0.025	115	0.073	12	0.900	88	0.041	91	0.061
	Tainan	43	0.167	81	0.040	105	0.701	75	0.047	17	0.067
	Kaohsiung	38	0.525	8	0.072	26	0.898	41	0.068	27	0.166
	Total	253	0.161	232	0.056	174	0.748	275	0.051	200	0.152
C_{tree} (t)	Taipei	13	0.044	9	0.014	14	0.161	1	0.013	36	0.019
	New Taipei	26	0.133	19	0.008	17	0.382	70	0.022	29	0.235
	Taichung	133	0.010	115	0.028	12	0.350	88	0.016	91	0.024
	Tainan	43	0.065	81	0.016	105	0.273	75	0.018	17	0.026
	Kaohsiung	38	0.204	8	0.028	26	0.350	41	0.026	27	0.065
	Total	253	0.063	232	0.022	174	0.291	275	0.020	200	0.059

n, number of trees; H, tree height; DBH, diameter at breast height; CW, crown width; BA, breast height basal area; CW^2, average crown cover area; V_{tree}, average individual tree volume; C_{tree}, average individual tree carbon storage in metric tons (t).

the municipalities. If an analysis of variance (ANOVA) showed significant differences in growth and carbon storage performance among the species in each of the 5 municipalities, then Duncan's post-hoc mean comparison test was further used to explain the differences. Analytical results in Table 5 show different growth scenarios for the same species in different municipalities.

From the ANOVA results for average V_{tree} and C_{tree}, there were significant differences for *T. mantalyi*, *F. microcarpa*, *K. paniculata*, and *C. camphora* but no significant difference for *P. pinnata* among the 5 municipalities. Results of Duncan's post-hoc mean comparison tests showed that growth and carbon storage performances of *T. mantalyi* were optimal in Kaohsiung, followed by New Taipei City, and were lowest in Taichung. Growth and carbon storage performances of *F. microcarpa* were significantly greater in New Taipei City, Taichung, and Kaohsiung than in Taipei. The growth and carbon storage performances of *K. paniculata* were significantly greater in New Taipei City and Kaohsiung than in the other 3 municipalities and were lowest in Taipei. The growth and carbon storage performances of *C. camphora* were significantly greater in New Taipei City than in Taipei, Taichung, and Tainan. These results show only the current growth performance. Because suitability of each municipality for the growth of various tree species slightly differed, and because planting times, planting densities, nursery stock, site conditions, and tending methods and intensity all differed, given only the current performance results, it was not possible to compare the different municipalities.

CONCLUSIONS

The amount of carbon that can be stored by forest growth in AQPZs can be determined through growth survey results and use of suitable conversion factors. In this study 28 AQPZ in Taiwan's 5 major municipalities were investigated, encompassing 3963 individual trees of 99 species. The overall average H was 6.31 m, the overall average DBH was 17.77 cm, the overall average CW was 4.53 m, the overall average BA was 0.040 m^2, the overall average CW^2 was 21.64 m^2, the overall average V_{tree} was 0.163 m^3, the total timber volume of all sampled plots was 645.336 m^3, the overall average C_{tree} was 0.063 tons of C, and the total timber carbon storage of all sampled plots was 251.036 tons of C.

The results only showed the current growth performance. Because suitability of each municipality for growth of various tree species slightly differed, and because planting times, planting densities, nursery stock, site conditions, and tending methods and intensity all differed, given only current performance results, it was not possible to compare the growth and carbon storage performances among the different municipalities. In addition, since this study included survey data from only one time point, information on growth among different years could not be obtained, and the analysis of carbon content results applied only to currently existing carbon stocks rather than to interannual variations. Therefore, under the premises of "measureable, reportable, and verifiable," continued monitoring of AQPZs is needed to provide quantification of future national forest carbon sequestration benefits.

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